Design Features of Product-Integrated PV
An Evaluation of Various Factors under Indoor Irradiance Conditions

Apostolou, Georgia

DOI
10.4233/uuid:869ccea8-f765-418c-881f-96689f49b19d

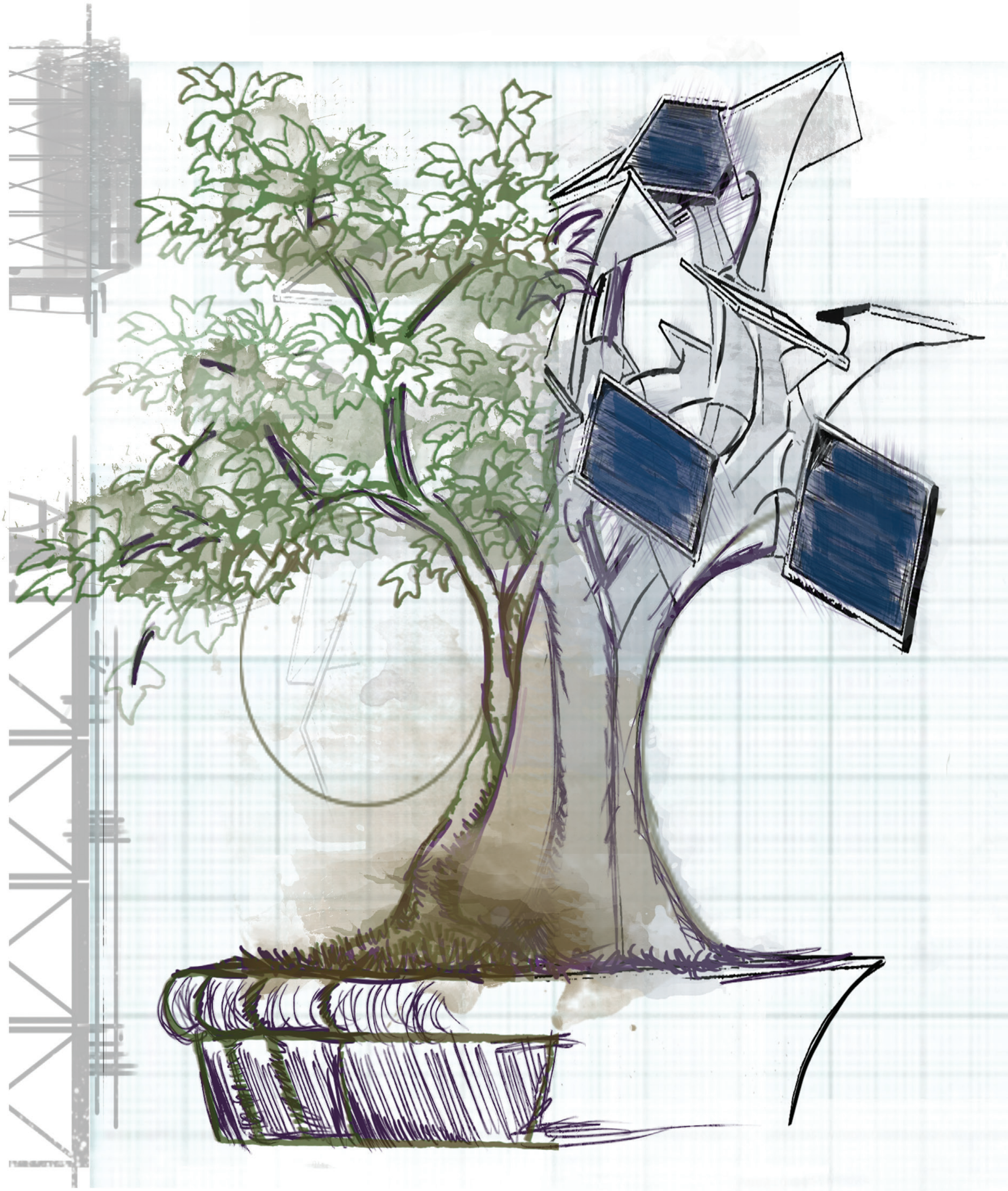
Publication date
2016

Document Version
Final published version

Citation (APA)
Apostolou, G. (2016). *Design Features of Product-Integrated PV: An Evaluation of Various Factors under Indoor Irradiance Conditions*. [Dissertation (TU Delft), Delft University of Technology]. Delft University of Technology. https://doi.org/10.4233/uuid:869ccea8-f765-418c-881f-96689f49b19d

Design Features of Product-Integrated PV

An Evaluation of Various Factors under
Indoor Irradiance Conditions



Georgia Apostolou

Georgia Apostolou
Design Features of Product-Integrated PV

Design Features of Product-Integrated PV:
An Evaluation of Various Factors under Indoor Irradiance Conditions

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof.ir. K.C.A.M. Luyben;
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op
maandag 27 juni 2016 om 12:30 uur

door

Georgia APOSTOLOU

Mechanical Engineer

National Technical University of Athens

geboren te Athene, Griekenland

This dissertation has been approved by the promotor:
Prof.dr. A.H.M.E. Reinders

Composition of the doctoral committee:

Rector Magnificus,	Chairman
Prof.dr. A.H.M.E. Reinders,	Delft University of Technology

Independent members:

Prof.dr.ir. J.M.P. Geraedts,	Delft University of Technology
Prof.dr.ir. J.C. Brezet,	Delft University of Technology
Prof.dr. S.C. Pont,	Delft University of Technology
Prof.dr.ir. A.L.P. Rosemann,	Eindhoven University of Technology
Dr. W.G.J.A.M. van Sark,	Utrecht University

Design Features of Product-Integrated PV: An Evaluation of Various Factors under Indoor Irradiance Conditions
Thesis Delft University of Technology, Delft, The Netherlands
Design for Sustainability Program
ISBN : 978-94-6186-662-2

Book design by Panagiota Sampani
Printed by Tziolas

To Yannis

SUMMARY

This thesis explores the field of product-integrated photovoltaics (PIPV), a term which is used for all types of products that contain solar cells in one or more of their surfaces, aiming at providing power during the product's use. Product-integrated photovoltaics (PIPV) began to be widely introduced around 2000, although the use of PV systems in products dates back to the 70s. PIPV includes products such as PV-powered boats, aircrafts, cars, bicycles, camping tents, street lights, recycling bins, decorative lights, PV-powered watches, calculators, PV-powered lamps, sensors, chargers, toys, low-powered kitchen appliances, entertainment appliances or PV-powered art objects. The incorporation of PV systems in products could offer various benefits, such as enhanced functionality of the product as a result of energy autonomy, and independence and freedom of use due to the absence of a connection to the electricity grid, as well as the opportunity to reduce the capacity of batteries in portable products and therefore making them more sustainable. Furthermore, photovoltaic products represent a very reliable solution for the supply of electricity in areas, which lack access to an electricity grid.

This thesis focuses on the development of scientific and technological knowledge concerning product-integrated PV (PIPV), as it focuses on the aspects that designers need to take into consideration when designing PV products. This research is interdisciplinary by nature due to its embedding in the field of industrial design engineering, regarding the technological aspects of PV technologies in products and user interaction with PV products. This research focuses on aspects related to design engineering of indoor PV products and to the design of products with an acceptable performance for users, issues that have not been completely addressed by other researchers. Its multi-disciplinary character is the point where this work significantly differentiates from previous studies.

Based on the relevance of sustainable product design for product-integrated PV, this thesis combines the technical knowledge of PV technologies, indoor irradiance conditions and performance of PV cells and PV products in environments with low irradiance together with the typical behavior of users with these products and the way this behavior influences the performance of the products themselves. Besides being directed towards researchers, results of this study are useful for industrial designers who are developing PV products. Manufacturing of PIPV and the combination of PV with other renewable energy sources have not been addressed in this dissertation.

In order to clarify the two types of PV-powered products, it is necessary to explain here that there are products that have integrated PV cells in one or more of their surfaces (and these are the PIPV, as we refer to them in this thesis) and those that are powered by PV cells, which are not attached on the product's surface, but constitute an accessory of the basic product.

The study approached the aforementioned issues by investigating:

- Why research on product- integrated PV is important?
- What is product-integrated PV and what are PV products? For example: What are the design features and function materials that these products use?
- Where are the PV products used? That is to say under which conditions and irradiance are they used?
- How do users interact with the PV products?

The sub-questions, which helped to approach the main research question in a systematic and logical way, were:

- What are the design features that existing PV products have?
- Which are the indoor irradiance conditions?
- What is the efficiency of different PV technologies indoors?
- How do users interact with PV products? How could users' interaction with indoor PV products influence the performance of the products?

Finally, this thesis intents to support designers by exploring the topic mentioned above which they should take into consideration if they want to design indoor PV products with a better performance than the existing ones.

It is worth noting that since 2011, when this research study started, many aspects of photovoltaic powered products have changed. Firstly, more PV products of various product categories for both outdoor and indoor use were launched on the markets.
The PV products that were used during the tests and the field trials of this research study are the products that were commercially available at the time of the beginning of this research.

Over four years of research, it was observed that many aspects and design features improved in PV products, such as their technical features (e.g. materials, use, electrical and mechanical components, etc.) and their aesthetics. In this research the technical features of PV products have mainly been analysed, because this knowledge is essential for the improvement of the products, mainly regarding their performance and usability. This analysis is useful for designers and researchers, as other researchers in the field have not addressed all the information that it offers as yet.

In Chapter 1 a short market analysis on PV-powered products for indoor use shows that most of the available products at present offer sub-standard and poorly designed solutions. While investigating commercially available PV lighting products, which is currently the largest area of PIPV, it can be concluded that apart from being PV-powered and portable, most products do not have any additional features. The majority of PV products that are commercially available at present are of low quality and perform insufficiently. However, there are a few PV products that have sufficient performance and that are of good quality.

In Chapter 2 various PV technologies and the basic knowledge concerning the integration of PV cells in consumer products were briefly discussed, serving as an introduction to the most common PV technologies that are used for commercial PV product applications, which are mono-crystalline, multi-crystalline and amorphous silicon solar cells. It was found that several factors exist that greatly affect the performance of PV cells in products, such as indoor irradiance conditions, the efficiency of PV cells in an indoor environment, the area of the PV cell surface, shad(ow)ing of PV cells, as well as the combination of the PV cell and battery technologies.

Subsequently, Chapter 3 focuses on identifying which product-integrated PV and PV products are and what their design features are. Various categories of product-integrated photovoltaics can be identified: consumer products with integrated PV, lighting products, business-to-business applications, recreational products, vehicles and transportation, and arts. Amongthese product categories outlined above, the majority of products are mainly high power PV products designed for outdoor use. Different product categories are modified for indoor use. The low power PV product categories for indoor use range from 1 mW up to a maximum of 10 W and they are defined as follows: consumer products (including mainly toys, calculators, watches, entertainment applications, PV chargers for indoor use), lighting products (including low power desk lamps) and art objects (Objets d' art) (requiring low energy supplies).
Moreover, an overview of PV product's general design features is provided. The overview is based on a survey of preselected PV products PIPV's power level ranges from several mWatts up to hundreds of kWatts. Four PV system categories were determined:

(1) autonomous PV system including battery,
(2) chargeable PV system including battery,
(3) autonomous PV system excluding battery and
(4) autonomous hybrid PV system including battery.

The majority, namely 65 out of 90 PV products analysed consist of an autonomous PV system with batteries. 67 % of PV products are used outdoors, while around 14 % are used indoors and 19 % both indoors and outdoors. Approximately 30 % of the low power PV products in the range of 0 to 17 Wp use thin film solar cells (a-Si), whereas 55 % of high power PV products in the range of 17 Wp to 27 kWp use crystalline silicon solar cells (x-Si) or a-Si. 86 % of PIPV products use an energy storage device, while 14 % do not use any batteries.

Chapter 4 explores the indoor environments in which PV products are used. In this chapter, results of measurements of irradiance under various conditions indoors are presented. First, the theoretical framework for indoor irradiance is given and next measurements under various conditions are presented. According to the above-presented measurements and results, it is concluded that indoor irradiance differentiates broadly according to the orientation of the room, as well as according to the type of light sources, either natural or artificial, and the distance between them.

Results showed that typical indoor irradiance (total diffuse radiation) in an office in the Netherlands during June ranges between 1 and 25 W/m^2 depending on the orientation of the room towards the sun. However, these values cannot be considered fixed, as they are strongly influenced by the latitude and longitude of the room, the season (winter, summer, etc.), weather conditions (sunny, cloudy, rainy, etc.), the use of artificial lighting (amount of lamps, type of luminaires, either LEDs, CFL or halogen lamps), objects and optical interactions (e.g. shadows, interreflections) at the indoor environment, distance between windows and artificial light sources, type of glazing etc. Indoor irradiance based on artificial lighting usually ranges between 1 and 7 W/m^2, which is sufficient for low-powered PV products to function at this environment.
Based on the above conclusions, it is inferred that very low power PV products with power consumption in the range of μW up to a few mW could be used indoors, such as clocks, calculators, excent lighting products, sensors, temperature indicators, toys, chargers or PV-powered remote controls for televisions.
During the design process of an indoor PV product, designers should consider the typical indoor irradiance range as discussed above. Taking these values as a starting point, designers will make critical decisions regarding the products that can perform sufficiently under these conditions and make the right choices beforehand.

Chapter 5 explores the efficiency of PIPV with the help of a simple model, which estimates the performance of PV cells in an indoor environment and under mixed indoor light that partially contains outdoor light. To start with, the efficiency of different PV technologies is discussed. These PV technologies, which were used indoors during the experiments and the results of the measurements are presented and analyzed. A mathematical model of the indoor performance of PV cells is proposed, which estimates the indoor efficiency of various PV materials.

The model is based on real tests and measurements of the efficiency of various PV cells under low irradiance conditions and on bibliographical data, as well. The most significant variables in this model are the spectral response (SR) of the PV product's cell and indoor irradiance. The model is validated by two different simulations: 1) using the spectral response SR as given in the literature (under Standard Test Conditions (STC); light intensity at 1000 W/m², temperature of the cell at 25° C and AM 1.5) and 2) using the SR as measured (under STC) for 12 different PV products with either x-Si or a-Si solar cells. It is due to the limited research in this field and the related lack of data from other studies regarding modelling of product-integrated PV, the spectral response of PV cells under mixed indoor lighting, as well as cells' performance under low lighting conditions, that the results of this study could not be compared to a full extent with existing findings. However, it is assumed that now that this basic model exists, students, researchers and designers can use it to design or evaluate indoor PV products with the purpose to improve their performance. The results of the model are precise enough for product design; using measured SR curves the accuracy is typically in the order of 30 %. The accuracy of the model indicates that the simulated efficiency value deviates x % from the measured value (which is taken as 100 %). In this case x % is 30 %.

The accuracy of 30 % is due to low irradiance conditions, deviations between measured SR at STC and the actual SR at low irradiance conditions and the bad quality of commercially applied PV cells in PV products.
The results of the second set of simulations show that under mixed indoor lighting conditions, the simulated PV cells' efficiency slightly deviates from the measured values, with a typical accuracy of around +82 %. Additionally, the model practically forecasts a PV product's cells performance under artificial illumination, with a typical accuracy of around +71 % for CFL and LED lighting. The accuracy of the simulation that is discussed in Chapter 5 is calculated in comparison to the measurements.

Measurements with a higher accuracy are quite difficult to obtain, since indoor irradiance reaches just a few tenths of Watts/m², which is close to the measurement limits of irradiance sensors. Apart from this, the efficiency of PV cells under these conditions is rather low. The model's results therefore expose the fact mentioned above and are considered satisfactorily accurate. It is found that under mixed indoor lighting of around 20 W/m² the efficiency of solar cells in 12 commercially available PV-products, ranges between 5 to 6 % for amorphous silicon (a-Si) cells, 4 to 6 % for multi-crystalline silicon (mc-Si) cells and 5 to 7 % for the mono-crystalline silicon (c-Si).
Measurements and results have shown that the spectral responses (SR) of tested PV cells at AM 1.5 deviate considerably from current literature. They are typically around 70 to 80 % lower and in some

cases even more than 90 % less. The significantly low spectral response of commercial PV products' cells occurs due to low quality of the cells applied. The cutting of PV cells into small pieces - to be applied in PV product surfaces - and their condition, e.g. soiling of cell's surface, possible scratches, cracks and other damage play a crucial role on the measured spectral response. Consequently, the use of low quality PV cells leads to PV products with a low performance.

Furthermore, it is essential to stress here that another reason for the dissimilarities in the spectral responses is that in this study PV products are not tested as single PV cells, but as assembled devices with several interconnected PV cells.

It is also important to be aware of the fact that the spectral response of the PV cells as measured at STC has been used for modelling at 10 W/m^2. This is due to the measurement range of solar simulators, which usually does not cover the very low irradiance range used in our model and due to the unavailability of PV cells' spectral response data under low irradiance conditions as provided by manufacturers.
Finally, because of our purpose to support designers in their design processes to realise indoor PV products with higher performance than the existing ones, we consider the accuracy of this model to be sufficiently acceptable.

Chapter 6 explores how users interact with the PV products and how this influences the performance of the products. This chapter is therefore dedicated to user interactions with PV products. It addresses user expectations before they use the product and their experience after using it, as well as the fulfilment of their expectations and needs. Here, user interaction with PIPV is examined by using real PV products and lead-users. In this study both quantitative and qualitative methods are used.
The interaction of the users (forming focus groups) with PV products is analysed, by conducting a survey, using a questionnaire to present statistical data and observational methods, where the users record themselves or write in a workbook about their daily interaction with the product. Furthermore, physical data are used, as the PV products are tested under different irradiance conditions and conclusions about their function and performance in different contexts are drawn.

In Chapter 6 we focus on user interaction with PV products through a practice- oriented approach. A questionnaire is used to identify user needs and expectations from the PV products and the methods of self- and direct- observation for the investigation of user behaviour during the interaction. The study of user behaviour is quite a difficult and challenging task and the combination of various methods is necessary for reliable results. Therefore, in this study, not only field trials are conducted, but also technical tests for a better understanding of the PV technology by the users.

The tested sample of users for the observation of their behaviour with the PV products consists of 100 students from the Industrial Design Engineering Department of Delft Technical University.
The specific sample uses high standards for the characterisation of the products' quality and offered a critical view of the products' usability, design and performance. It seems that the tested sample of users has more of a critical look than a common user, due to their educational background in the field of product design and it is more ahead than other students with less relevant educational experience.

The specific user type of this study cannot be represented as a regular user or consumer. This user may be considered as a "lead-user", since he/she was asked to follow some specific tasks for the evaluation of the products, which might not be recognisable by a regular user. Moreover, the "lead-users" of this study propose solutions and ideas about redesigning the PV products, which is fairly uncommon for regular users to provide such feedback. On the one hand, lead-users can notice and forecast problems that might occur in the future, but on the other hand due to their educational background and their knowledge in the field of product design and engineering, they understand the boundaries of design and technology in the products. These features are not visible and easily understandable by regular users, who usually criticise the outlook, usability and performance of the products, without caring about the above- mentioned limits. Hence, the beliefs of the lead-users in this study do not reflect the real behaviour of a simple user, but they could be quite influential regarding the future successful use of the PV products.

The results reveal that the usability, the design, the aesthetics and the performance of a PV product are important factors for users. Consumers are quite enthusiastic with PV products if useful and functional, but they need more reliable PV products with a more appealing design. It is noticed that user expectations before use and their experience afterwards deviate significantly. Quantitatively, results show that around 40 % of the respondents are disappointed with the PV product that they used, 38 % found the product useless, around 60 % believe that the design of the product is of low quality, 88 % of the respondents would not buy the PV product and around 70 % believe that the price of the PV product does not match with its quality and performance. It is remarkable to notice that around 66 % of the respondents would prefer a product, which can be charged by a cable with a plug, rather than a PV-powered product.

By being comprised of six PV products this testing sample is limited and general conclusions cannot yet be drawn. Nonetheless, these results are important, as they represent part of the PV products, which are commercially available and easily accessible to consumers and basic user behaviour with them.

Since the survey outcomes are strongly affected by the type of the specific user, it is not confirmed yet that regular users will have similar behaviour to the product's use. Therefore, the specific results could not be extended to all target groups. To finish, the impressions of the lead users about the PV products are not necessarily analogous to the regular users'.

Nevertheless, the results of this study and the specific users' reflections could inspire the future design and usability of PV products. We believe that the findings of this study will be valuable for designers towards a better understanding of the user behaviour and combined with technical data of PV products, could be used for the design of high efficient PV products.

From the research presented in this thesis we can conclude that the integration of PV cells in products still is a challenging task. As the market of PV products is continuously developing, to mature this market, more research should be done in the fields of marketing, end-of -life and human factors of PV products. Furthermore, studies on the environmental impacts of batteries and how to reduce their capacity by the application of product integrated PV would support the developments of a market for PV products. This thesis could therefore be a starting point for further research in this field for the improvement of PV products and their related services.

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

Symbol	Meaning	Unit
A	cell area	m^2
c	speed of light in vacuum	m/s
e	Elementary charge	Coulombs
E	Spectral irradiance	W/m^2
$E(\lambda)$	Spectral irradiance per wavelength	W/m^2 nm
E_V	illuminance	lm/m^2=lux
$E_{natural}$	spectral irradiance indoors originating from the sun	W/m^2nm
$E_{artificial}$	spectral irradiance indoors originating from artificial lights	W/m^2nm
EQE	external quantum efficiency	-
EPBT	energy payback time	α
FF	Fill factor	-
h	Planck constant	Js
I_o	saturation current	A
I_{ph}	photocurrent	A
I_{mpp}	maximum power point current	A
I_{sc}	short circuit current	A
I_{rps}	irradiance at a specific distance from the lighting point source	W/m^2
I_{ps}	radiant intensity of a point source	W/sr
I_{rs}	irradiance at a specific distance from the lighting source	W/m^2
I_s	radiant intensity of a line source	W/sr
I	Radiant intensity	W/sr

I_V	Luminous intensity	candela
J	Current density	A/m^2
J_o	saturation current density	A/m^2
J_{ph}	generated photocurrent density	A/m^2
J_{SC}	short-circuit current density	mA/cm^2
L	Radiance	W/m^2steradian
L_V	luminance	Candela/m^2
P_{mpp}	power in the maximum power point	W
P_{in}	power of the irradiance hitting a solar cell	W
P_{PV}	electrical power output	W
Q	Radiant energy	J
Q_V	Luminous energy	Lumen sec
r	Radius	m
R_{sh}	Shunt Resistance	Ω
SR	Spectral response	A/W
T	absolute temperature	K
$T_{ก}$	transmittance	-
V(ก)	luminosity function	-
V_{oc}	open circuit voltage	V
V_a	voltage	V
V_{mpp}	maximum power point voltage	V
n	conversion efficiency	-
θ	Angle of incidence	Degree (°)
k_B	Boltzmann's constant	J/K
ก	wavelength	nm
Φ	Radiant flux	W

Φ^{i}_{e}	incident radiant flux	W
Φ^{t}_{e}	transmitted radiant flux	W
Φ_{V}	Luminous flux	lumen

Abbreviations

Symbol	Meaning
a-Si	amorphous silicon
B2B	business-to-business
c-Si	monocrystalline silicon
CdTe	cadmium telluride
CFL	Compact Fluorescent Lamps
CIGS	Copper indium gallium diselenide
CIS	Copper indium selenide
CO_2	Carbon dioxide
CTG	cradle-to-grave
CZTS	copper zinc tin sulfide
DC	Direct current
DIM	Delft Innovation Model
DSSC	Dye Sensitized solar cells
EPD	Environmental product declaration
GaAs	gallium arsenide
GaInP	gallium indium phosphide
GHG	greenhouse gases
LCA	life-cycle analysis
LED	Light emitting diode
Li-ion	Lithium-ion
$LiMnO_2$	Lithium manganese dioxide
mc-Si	multi-crystalline
NiCd	Nickel cadmium
NiMH	Nickel-metal hydride
OPV	polymer organic PV
PIPV	Product integrated PV
PV	photovoltaic

SOC	System on chip
SPD	Spectral power distribution
STC	Standard test conditions
μc-Si	Microcrystalline

Subscripts

MPP	**maximum power point**
$()_{mon.light}$	monochromatic light
$()_{oc}$	open circuit
$()_{sc}$	short circuit
$()_{max}$	maximum
$()_{mpp}$	maximum power point
$()_{ph}$	photocurrent
$()_{natural}$	originating from the sun/natural irradiance
$()_{artificial}$	originating from artificial lights
$() (\lambda)$	Wavelength dependent

CHAPTER 1

Introduction

1.1 Introduction

In our daily lives we use a variety of products, which need electricity to function, such as computers, phones, lamps, chargers and kitchen appliances. Everyone has at least once experienced searching for an available socket to charge a device in public spaces and most times one can often not be found. Another scenario can be imagined in which a lamp or a phone needs to be used urgently while having no access to electricity at all. What happens in such cases? Would it for instance be possible to use products that can function independently from the grid? Everybody wants to be independent, but stay connected to the grid at the same time. Is there any way to be connected but at the same time be autonomous as well?

Since solar energy is available everywhere around the world and since it has the potential to meet the energy requirements of the entire Earth (IEA, 2014), one solution for the situation outlined here could be found in products which are partially solar-powered by photovoltaic (PV) solar cells. The incorporation of PV systems in products could offer numerous benefits to the users, such as: enhanced functionality of the product because of autonomy, independence and freedom due to the absence of connection to the electricity grid, the opportunity to reduce the capacity of batteries in portable products and therefore enhanced sustainability. Furthermore, photovoltaic products represent a very reliable solution for the supply of electricity in areas without an electricity grid at all. Due to the limited experience with products that are supplied by electricity by solar cells in this thesis several aspects of this relatively new product category will be investigated.

Firstly, it is necessary to clarify the term product integrated photovoltaic (PIPV). PIPV is used for all the types of products that contain solar cells in one or more of their surfaces, aiming to provide power during the product's use. The category of PIPV has existed for the last 15 years (since 2000) and includes products such as PV-powered boats, aircrafts, cars, bicycles, camping tents, street lights, recycling bins, decorative lights, PV-powered watches, calculators, PV-powered lamps, sensors, chargers, toys, low-powered kitchen appliances, entertainment appliances or PV-powered art objects.

There are two types of PV-powered products: those that have integrated PV cells in one or more of their surfaces (and these are the PIPV, as we refer to them in this thesis) and those that are powered by PV cells, which are not attached on the product's surface, but constitute an accessory of the basic product.
Before exploring PIPV and PV-powered products, in this chapter the current state of energy production and PV technology is discussed in Section 1.1. Next the historical context of PV is given in Section 1.2.

Then in Section 1.3 the markets of PIPV and in Section 1.4 completed research projects on PV products are introduced to the reader. To provide a framework for design-driven research in Section 1.5 innovation in the design process are presented. Chapter 1 ends with Sections 1.6 and 1.7 in which the research questions, research methods and the outline of the thesis are extensively outlined.

Current state of energy production and PV technology

There is currently a pressing need for energy transition from fossil fuels to more sustainable energy systems. The combustion of fossil fuels is the main contributor to CO_2 emissions leading to an increase in the greenhouse effect and hence global warming (IPCC, 2015). Moreover, fossil fuels are barely able to secure the world's future energy demands, which are set to increase by 1.5 % per year up to 2035, according to the World Energy Council (WEC, 2014). The main reason for the energy transition from the use of fossil fuels to new, inexpensive and sustainable sources of energy is the need to stop climate change (IPCC, 2015; IEA, 2015; REN21, 2015).
A shift away from fossil fuels and towards energy efficiency and low-carbon technologies, such as renewable energy sources seems necessary (IEA, 2015).
Among these renewable energy sources solar energy is the most powerful. Solar energy is plentiful on Earth, with about 885 million TWh reaching the Earth's surface every year, which is estimated to be 3,500 times the energy that people will consume in 2050 (IEA, 2015). Solar energy is widely available all over the world, and could contribute to the reduction of CO_2 emissions (IEA, 2015). Figure 1.1 presents a world map of global horizontal solar irradiation (SolarGIS, 2015). The red-colored areas receive very high irradiation, which reaches 7.0 kWh/m^2 per day, with an annual average of 2600 kWh/m^2 or more, while the yellow-colored areas receive less irradiation between 3.75 and 4.75 kWh/m^2 daily or on average 1400 to 1700 kWh/m^2 annually. The green-colored areas receive the lowest irradiance between 2.5 and 3.5 kWh/m^2 per day respectively, with an annual average of 900 to 1300 kWh/m^2. As can be seen in Figure 1.1, solar energy is widely available all over the world, though seasonal variations exist e.g. in Europe solar irradiance is higher during the summer, and lower during the winter with values ranging according to the location. Therefore solar energy could be used in multiple ways by replacing the high electricity load totally or partially.
Photovoltaic (PV) technology converts photons into electricity through devices called PV cells or solar cells. Their basic functional principle is the photovoltaic effect, which is the generation of voltage- potential difference- in semiconductor materials when exposed to irradiance (Williams 1960; Wórfel 2005).

Since the late 1950s, photovoltaic technologies have been continuously developed and at present, the number of PV applications all over the world is rapidly increasing. Data about large-scale PV applications are widely available. In 2014 globally, solar photovoltaic (PV) technology experienced a remarkable growth, reaching a cumulative capacity of 178 GWp of PV systems installed worldwide (EPIA, 2015). This amount can produce more than 190 TWh of electricity per year, which is considered to be adequate power to cover the yearly energy requirements for more than 50 million families in Europe (EPIA, 2015). In 2013, it was estimated that the globally installed PV capacity was around 139 GW, while in 2014 it reached 178 GWp based on historical data from the "Global Market Outlook for Photovoltaics 2014-2018". In early 2015, it is estimated that global PV installations totalled about 200 GW (Global Market Outlook for Photovoltaics 2014-2018).

However, market information is lacking about small-scale PV applications and, more specifically, products that contain PV cells. According to Reinders and van Sark, the annual global shipments of PV consumer products in 2006 was 80 MW (CRE, 2012), while the global shipments of the grid-connected PV-powered products was estimated to be just 1500 MW. Due to the present large volumes of grid-connected PV systems, details about the relatively limited market segment small-scale applications cannot be found. For this thesis information about the present capacity of small-scale PV applications is very important and therefore, it will be explored in more detail in the following paragraph.

Figure 1.2 represents the world photovoltaic application market breakdown from 1990 to 1994, in total 100 MW (European Commission, 1996). As can be seen in Figure 1.2, communication systems had the largest share of PV applications' market with 21 %

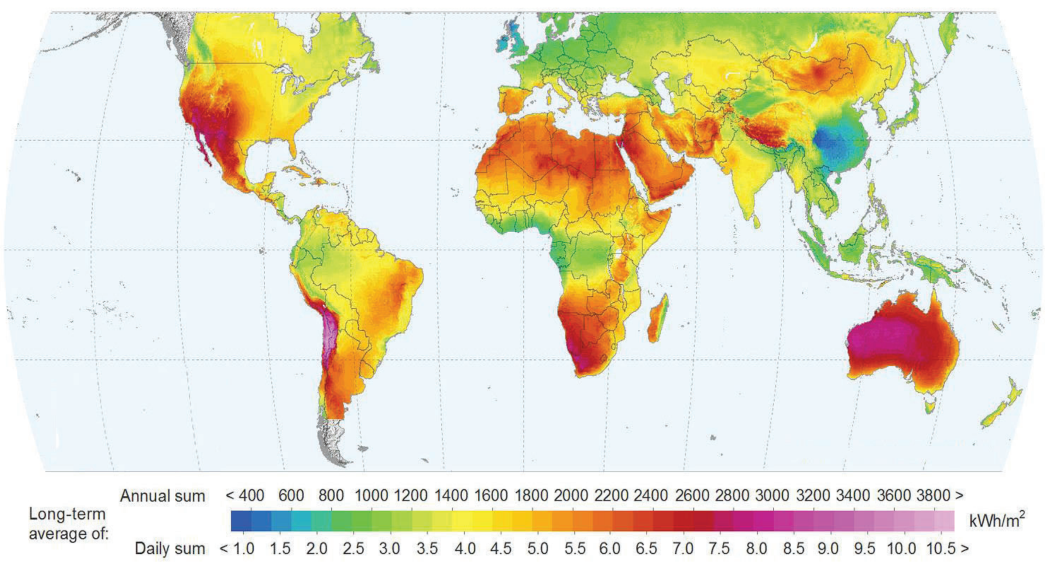


Figure 1.1: World Map of Global Horizontal Irradiation, (SolarGIS 2015).

(21 MW), while camping, boating, leisure applications and solar home systems followed with 15 % each, corresponding to installed power of 30 MW in total. Indoor consumer products contain 7 % of the total share of PV applications corresponding to 7 MW. This amount has probably not increased much up to 2015, while the PV system market grew from a MW to GW market.

Based on the Global Market Outlook for Photovoltaics 2014-2018, it is estimated that the world photovoltaic application market in 2015 reached 200 GW. Assuming that the share of indoor consumer products remained 7 MW as in 1994 (see Figure 1.2) - which is equal to 0.7 million solar lanterns of 10 Watts - it is estimated that indoor consumer products consist 0.0035 % of the total installed PV applications in 2015. The forecast of the percentage of indoor consumer PV products in 2015 is very low, since it was assumed that the amount of these products remained the same as it was twenty years ago. This amount was obviously increased from 1994 to 2015. However, a more recent estimation of indoor consumer PV products is not available and thus it was assumed that it remains the same.

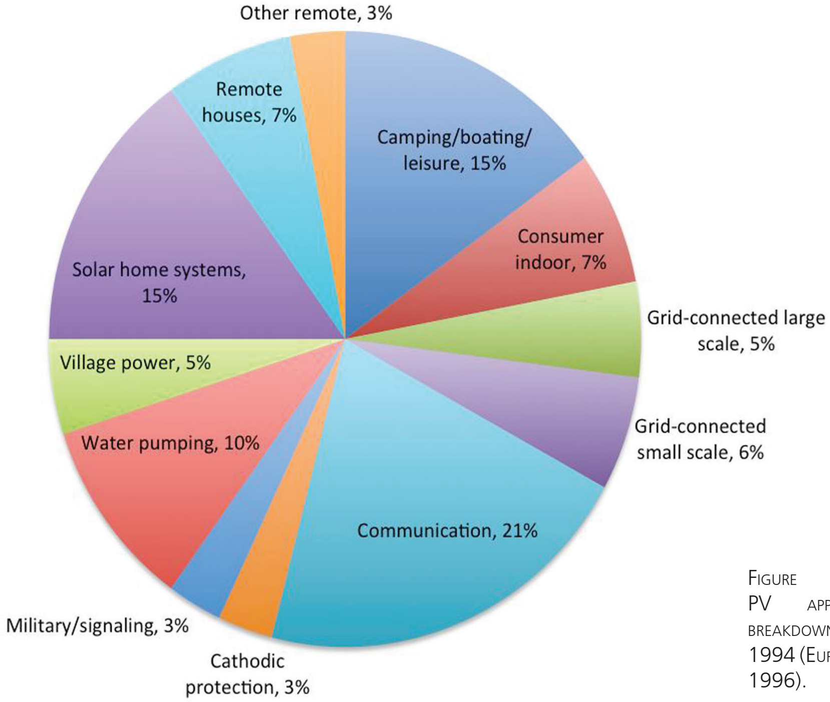


FIGURE 1.2: WORLD PV APPLICATION MARKET BREAKDOWN FROM 1990 TO 1994 (EUROPEAN COMMISSION, 1996).

1.2 Historical Context

The application of PV cells in products started in 1958, with the use of the photovoltaic technology in the area of space applications. The satellite Vanguard I (NASA, 1970) contained one of the first PV systems (see Figure 1.3). It included 6 silicon-based solar cells for powering a transmitter of 5 mW (Easton, 1959; NASA, 1970; Green, 1970; N2YO, 2015). Vanguard I was operated for 8 years. The spacecraft itself was a 1.47 kg aluminum sphere of 165 mm in diameter (Green, 1970; Easton, 1959). From that time onwards, PV was gradually incorporated into various applications and the efficiency of PV technology started to improve. Explorer III, Vanguard II, Sputnik III were other solar-powered satellites which were also launched in 1958.

It took a decade to develop applications for use on Earth. For instance, in 1963 the largest PV installation in the world was made by Sharp in Japan; it was a 242 W PV array that supplied electricity to a lighthouse. To put it into perspective, a PV array of 242 W is significantly small compared to the PV arrays use nowadays in rooftop installations, which have a nominal power of 2 to 4 kWp. Till the late 1970s however the implementation of PV cells was only feasible in autonomous systems because of the high production costs of c-Si cells of about 76$/W (1977) (Bloomberg, 2014).
At the end of the 1970s, the first grid-connected PV systems appeared in pilot plants. For instance, in 1983, a 6 MW DC power plant was installed in central California. It supplied the utility grid with sufficient power for 2,500 homes. In the meantime, the application of PV systems in buildings –so-called building-integrated photovoltaic (BIPV)- became widely used over the years. In Figure 1.4 and in Appendix A1 several examples of PV systems with interesting designs are shown. Today, around 99 % of PV are applied on roofs and in technical installations, while a fairly small share of PV (around 1 %) are integrated in buildings. Generally speaking, PV applications added to buildings' roofs are quite common, but integration in roofs is still relatively scarce.

The first application of PV in a terrestrial product context occurred in 1978 with the introduction of the solar cell powered calculators. The Teal Photon was one of the first commercially available PV-powered calculators (Reinders and van Sark, 2012). Other solar calculators released at the end of 1970s were the Teal Photon III, the Royal Solar 1 and the Sharp EL-8026, see Figure 1.5. Since the 1970s, a variety of PV products for daily use, such as solar-powered watches, flashlights, chargers, mp3 players, and solar lamps have been released on international markets. The power of the PV cells of these consumer products was in the range of 0.001 W to just a few Watts (less than 10 W).

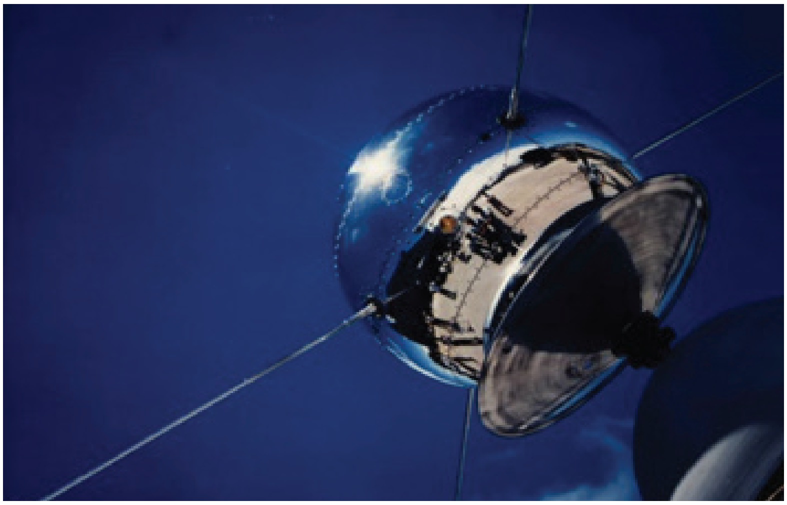


Figure 1.3: PV-powered satellite Vanguard I (NASA Vanguard), 1958 (NASA, 2015).

Photovoltaic cells were also widely used in other products with a higher power (in a power range of 30 Wp to 30 kWp approximately), such as solar boats (more than 10 kWp), solar aircrafts (more than 20 kWp), cars (5-10 kWp), bicycles (50-200 Wp), camping tents (70-200 Wp), street lights (400-800 Wp), recycling bins (300-700 Wp) (see Appendix A2).

Moreover, PV cells can also be used in the production of low power products (in a power range of 0.1 Wp to maximum 15 Wp) for daily usage, such as decorative lights (1 to 10 Wp), sensors (0.1 to 0.5 Wp), chargers (3 to 15 Wp) or calculators (0.1 to 1 Wp) (see Appendix A3).

In 1983 a 1 kW solar-powered vehicle participated in the Australia Race driving for 20 days and 4000 km. Today, solar-powered cars, which participate in the World Solar Challenge, drive with an average speed of 80-90 km/h and cover a distance of 3000 km over a maximum of 7 days (World Solar Challenge, 2015).

Figure 1.4: Left picture: Photovoltaic fahade in St. Johann in Tirol (2004-2011) (Intersolar, 2010), Right picture: Building integrated PV at the Sheik Zayad Learning Center in Al Ain Zoo in United Arab Emirates (2013) (Green. Prophet, 2013).

A special category of consumer PV products is solar lamps for rural electrification in developing countries. These solar lamps (see Figure 1.6a) entered the market in mid-90s. The first solar-powered lamps were designed for the electrification of the off-grid areas in Africa and Asia and since then many projects are in progress to support the development of PV products in off-grid communities (Lighting Africa, 2015; Akon lighting Africa, 2015). These PV-powered lights will be further discussed in paragraph 1.4.

PV-powered chargers (see Figure 1.6b) are another important category of consumer PV products. They entered the market around the mid-90s, as did the PV-powered lighting systems, and were designed to offer electricity to off-grid areas in Africa and Asia. However, the product subsequently found another target group; together with users that live in off-grid areas, there are also travellers and campers. PV-powered chargers offer freedom to users, who travel often and do not have enough time to charge their devices at home using the grid or they live in the countryside for a period of time, without electricity.

Since 2000 PV applications are available, both for use at outdoor and indoor environments. However, the majority of PV products that are commercially available today are designed for outdoor use, due to high outdoor irradiance, which is sufficient to power the products. PV applications for outdoor use have quite a wide range, from PV-powered means of transport to low power PV –powered lights for garden decoration or chargers (see Figure 1.7).

More applications of photovoltaic cells in products for outdoor use are presented in Appendix A2.

While a lot of research has been carried out in the field of photovoltaics and especially in outdoor great scale installations of PV, considerably little research has been conducted concerning PIPV, in particular PIPV which is applied indoors.

Figure 1.5: Some of the first solar cell powered calculators. From left to right side: TEAL PHOTON, Sharp EL-825, Royal Solar 1, and Sharp EL-8026, 1978-1980 (Vintage Calculators, 2015).

Figure 1.6: Left: A PV-powered lamp, called Sunnan by IKEA, 2009 (House to home, 2015). Right: A PV-powered charger, called Solio Bolt, 2011 (Gadget review, 2011).

Here, it is necessary to define the words "indoor" and "indoor environment". The term "indoor" describes something that is happening or is located in the interior of a house or a building (e.g. indoor irradiance is the irradiance that is measured inside a house, or a building or a room). The terms "indoors" or "indoor environment" describe the location, which is inside a building. However, there are some rather doubtful environments and spaces that can be considered to be either indoor or outdoor. For instance, an atrium- which is an open-roofed entrance hall- is considered to be an outdoor space, whereas a skylight- which is a window installed on a ceiling or a roof- is an indoor space.

Figure 1.7: Left: NTS Sun Cycle is powered with a 60W built-in solar panel (approximately 4 square feet) and charging system, 2014 (Treehugger, 2014). Right: PV-powered charger for outdoor use, 2011-2013 (Atlanta trails, 2015).

Benefits and drawbacks of PV products

There are both advantages and disadvantages to using photovoltaic powered products according to the lists below.

Benefits of PV products

1. The PV product is independent from the grid. Products that are operated and charged using solar energy have the potential to be totally autonomous from the grid. This characteristic gives users the freedom to use the product where they like.

2. The use of photovoltaic solar energy in products could reduce the use of batteries. It is an interesting option to totally replace the batteries with PV cells in the case of low-power products, such as calculators, watches, phone- chargers, toys, keyboards, sensors, decorative lights, or even low-power household or entertainment appliances. In other cases, the use of PV cells in products could reduce the battery capacity (e.g. solar lanterns for undeveloped countries, lamps, chargers, smartphones etc.). Consequently, by reducing the battery capacity, the cost of the product is also reduced. Even a reduction of the battery capacity by 30 %, which seems quite feasible, could significantly contribute to the reduction of the product’s cost (purchase cost or cost for the replacement of the batteries when necessary). Furthermore, in products that use PV cells for charging, the battery capacity could be decreased, since the regular charging under the sun fills the battery continuously. The removal of the batteries from a product or the reduction of the battery capacity results not only in a decreased cost, but also in environmental impact.

3. Solar PV entails no greenhouse gas (GHG) emissions during operation and does not emit other pollutants, such as oxides of nitrogen and sulphur (IEA, 2014, 2015).

Drawbacks of PV products

1. The energy payback time (EPBT) of a PV product is usually longer than the product’s lifespan, which is short and it ranges between 1 and 5 years. If EPBT exceeds the lifetime of a product, the product considered as not “green” (Flipsen et al., 2015).

2. There is limited knowledge available regarding PV technology and its use in a product context, especially for indoor use, by designers and manufacturers.

3. Users are not well informed about the benefits of using PV products, their eco-friendly status and the autonomy they could offer to them.

Even though the use of PV systems in products has been known since the 1970s, the PIPV market is growing rapidly and cannot be considered a matured market yet. Some rather critical issues that need to be answered regarding the PIPV, which are not adequately addressed from researchers at the moment, are related to the accomplishment of a higher energy efficiency of the battery systems in PIPV, the cost estimation incurred by the implementation of PV cells in products, the assessment of environmental aspects followed by this implementation, the means and techniques of the manufacturing of PIPV products, and the possible combination of PIPV with other renewable energy sources (Reinders and van Sark, 2012).

Furthermore, looking at the drawbacks of PV products, it could be assumed that these include lack of knowledge in many different aspects of the design and function of indoor PV applications. More specifically, the performance of PV cells under indoor irradiance conditions is not sufficiently addressed at the moment. Moreover, there is a lack of knowledge regarding the use of PV technology in a product context for indoor use, and how the PV cell influences the product's function and design.

1.3 Markets for PV products

Current state of PV consumer products

According to the Navigant's research report (2015), it is estimated that the global annual market for solar PV consumer products will increase from 8.2 million sales in 2014 to 64.3 million sales in the next 9 years (by 2024). Navigant Research (2015) also claims: "Solar PV consumer products are rapidly moving from specialized niches for enthusiasts and early adopters into the mainstream".

Based on the above statement, it is expected that next years PV-powered consumer products will be more familiar to users and will be widely used. The 64.3 million sales of PV consumer products in 2024 which is claimed by this report could be related to an average of 643 kW of PV cells, assuming that the average power of the majority of PV products is 10 mW.

Navigant's Research report refers to so-called pico-solar products, which are solar-powered products with power less than 10 W. The pico-solar lighting products include solar modules of less than 10 W and mainly white LEDs. Their costs are usually ranging between $10 and $40.

These products are often referred to as "solar lanterns" and could also include some extra features, such as charging. In the category of pico-solar products belong most of the PV products that will be analyzed in this dissertation. The fact that there are statistics for pico-solar products, which were lacking during previous years, is quite promising and it clearly presents the necessity to investigate this PV product category further.

It may be too early to identify final market segments and product categories, however it is obvious that PV products and PIPV would fit anywhere, where affordable, mobile power is required at low power up to several 100 Watts in devices and in the order of kiloWatts for mobility (vehicles, boats, airplanes).

Product integrated photovoltaic could be used in many different sectors, some of which:

1. Health sector

Telemedicine could improve access to medical services that would often not be consistently available in distant off-grid areas. PIPV could be used for powering solar tents that are used as medical stations in off-grid areas and provide lighting and energy to the medical equipment. The communication between patient and medical staff could be accessible with reliability, as well as the transmission of medical, imaging and health data could be possible.

That way first aid stations could be totally or partly powered by PV modules and offer valuable assistance to people when needed.

2. Rural electrification and PV powered lighting products

Around 1.5 billion people worldwide currently live in 'off-grid' areas with no access to electricity, while millions often face electricity blackouts during the day (Lighting Africa project, 2015; UN, 2015; Solar Aid, 2015). In Africa 600 Million people do not have access to electricity (Lighting Africa, 2015, Akon lighting Africa, 2015; Solar Aid, 2015; UN, 2015; UK Aid, 2015). The lack of electricity causes a significant reduction in people's quality of life. Kerosene lamps are used for lighting, which are extremely dangerous due to the high fire hazard they entail, as well as the emission of toxic gases, which have negative impacts on health and the environment (Durlinger et al., 2010, 2011, 2012). Research shows that families in Africa spend around 10 billion USD each year on kerosene lamps (Lighting Africa project, 2015; Solar Aid, 2015; UK Aid, 2015).

Based on reports and data from the IFC-World Bank Lighting Africa program, it is estimated that today more than 28.5 million people across Africa have access to solar lighting products (IFC, 2015). According to the Lighting Africa program, in 2009 less than 1 % of Africa's population was using solar lighting products, while in 2014 around 5 % of the population (Lighting Africa, 2015). Itotia Njagi, the IFC Lighting Africa Program Manager states "At this rate we are confident that sustainable energy for all in the next 15 years is indeed achievable as the market for modern solar lights doubles every year" (IFC, 2015).

Combined sales data from suppliers of certified-quality solar lighting products shows that the market recorded a growth of 110 % for the year 2014. This percentage makes it clear that there is a significant demand for solar powered lighting products in Africa. For these regions, it would be even more beneficial to offer solar lighting products with extra services and functions, such as charging of cell phones or other appliances (e.g. fans, radios, television). During the last years consumers demand products of better quality and higher durability, also including multiple functions (Lighting Africa project, 2015). Examples of two successful PV powered lighting products, designed for the off-grid households in Africa are presented in Figure 1.8.

3. Portable power

This category of consumers uses products, such as phone chargers, lights, torches while travelling. This user group needs PV products that could be easily carried and used outside the house, with adjustable capacity, durability, and stability. A product is required that is safe during usage, lightweight, and can offer autonomy to the user, with high battery capacity, high power output, speed, styling, colour, small dimensions, portability and low cost.

4. Household appliances

The range of power of most household appliances using thermal energy is too high to be of interest for PIPV but that for merely electrical applications in the low power domain there exist several options up to a maximum of 50 Watt (for laptops). A Kitchen weight scale, a cooking thermometer, decoration or ambient lights are some products that could be easily used inside the house, either for cooking, reading or just creating a nice atmosphere.

5. Entertainment appliances

Speakers, keyboards, laptops, chargers, storage devices, phones or any kind of entertainment or communication device that could be used both indoors or outdoors. These products are addressed to young people that are willing to spend money and buy a nice "gadget" that could be used in their daily life. This target group usually buy products for pleasure or curiosity.

At the moment, there are multiple PV products in product categories such as lighting, entertainment appliances and portable power. However, as discussed above, it seems that the most successful category is those for PV powered lighting products for the electrification of the off-grid areas.

Several PV lighting products have been designed for these areas e.g. Waka Waka light, Little Sun, Greenlight and so on, and numerous projects for rural electrification are in progress, such as Lighting Africa, Solar Light for Africa, Solar Aid.

However, PV lighting products designed for these areas are made for outdoor use and are therefore charged outdoors during the day and used indoors at night.

Unfortunately, PV lighting products for indoor use have not yet equally developed so far. This delay in the development of indoor photovoltaic products compels me to explore the field of indoor PIPV.

Figure 1.8: Left image: Waka Waka solar-powered light, 2012 (Waka Waka, 2015). Right image: Little Sun solar-powered light, 2012 (Little Sun, 2015).

1.4 Research and design projects on PV products

Research in the field of product-integrated photovoltaics has a very narrow basis compared to research carried out so far on large-scale PV systems. However, the design-driven research done on product-integrated PV is very focused.

On the one hand there exist experience with research on PV products and on the other hand experience with designing PV products at universities and in companies. Several research projects on PV have been conducted, some of which by Sioe Yao Kan, Monika Mueller-Freunek, Nils Reich, Julian Randall, Angele Reinders. Kan (2003, 2004, 2005, 2006, 2007, 2009) and Reich (2005, 2006, 2007, 2008, 2009, 2011) explored the use of solar cells in consumer products and indoor applications, as well as the efficiency of solar cells under low irradiance conditions and they were both participated in the development of a prototype PV product for indoor use; the so-called SoleMio (Reich, 2006, 2007, 2008), a solar-powered computer mouse, which will be described in the next paragraphs of this section. Reinders (2002, 2006, 2008, 2009, 2011, 2016) explored the use of photovoltaic cells in portable products, as well as sustainable and innovative design of product-integrated PV. Randall (2003, 2005, 2006) and Mueller-Freunek (2009, 2010) also explored the area of indoor irradiance conditions and the efficiency of PV cells under low levels of irradiance. Although they did not develop PV products, they significantly contributed towards the development of knowledge regarding the conditions under which these products are used and the efficiency of PV cells under low irradiance.

In this section several research projects conducted at universities and companies on PV products are presented. These are PV products for either indoor or outdoor use that were designed for very specific reasons, such as for instance as validation for a proposed design model, or as continued research on earlier projects and for participation in worldwide contests. These research projects offered experience regarding the integration of PV cells in products and combined with the research on PV products that was discussed in the previous paragraph, could offer valuable help for the understanding and development of high-performed PV products.
Below examples of several PIPV projects are shown.

Displo

The Displo Pad (see Figures 1.9, 1.10) is an electrophoretic Ink display powered by PV cells. It is a PV-"concept"-product, which can display static digital information for the user. The concept is a novelty desk accessory product. It is a fun accessory, which provides the user with the freedom to express and showcase their digital data such as pictures, quotes, and reminders in a physical tangible form rather than just being stored in mobile devices. Additionally, the concept is a self-sustaining product, incorporating an amorphous silicon (a-Si) photovoltaic module (5 V) with area 200 cm^2, which charges a 3.7 V, 35 mAh Lithium rechargeable battery. The incorporation of the photovoltaic module makes the product portable, reduces the need for a charging cable or constant grid connection. This project was conducted by the master student Gaurav Deshpande in 2014-2015 under the supervision of Bas Flipsen and Georgia Apostolou. The designed PV-product consists of a single Dock, which has the System on chip (SOC), the power storage unit and PV module. There are 5 EPD pads that the user gets along with the dock. The PV charging system will eliminate the need to have a constant grid connection for the product or the need to replace the batteries. The purpose of this project was to observe the design process during the development of a low-powered indoor PV product and investigate the difficulties that a designer will have to overcome.

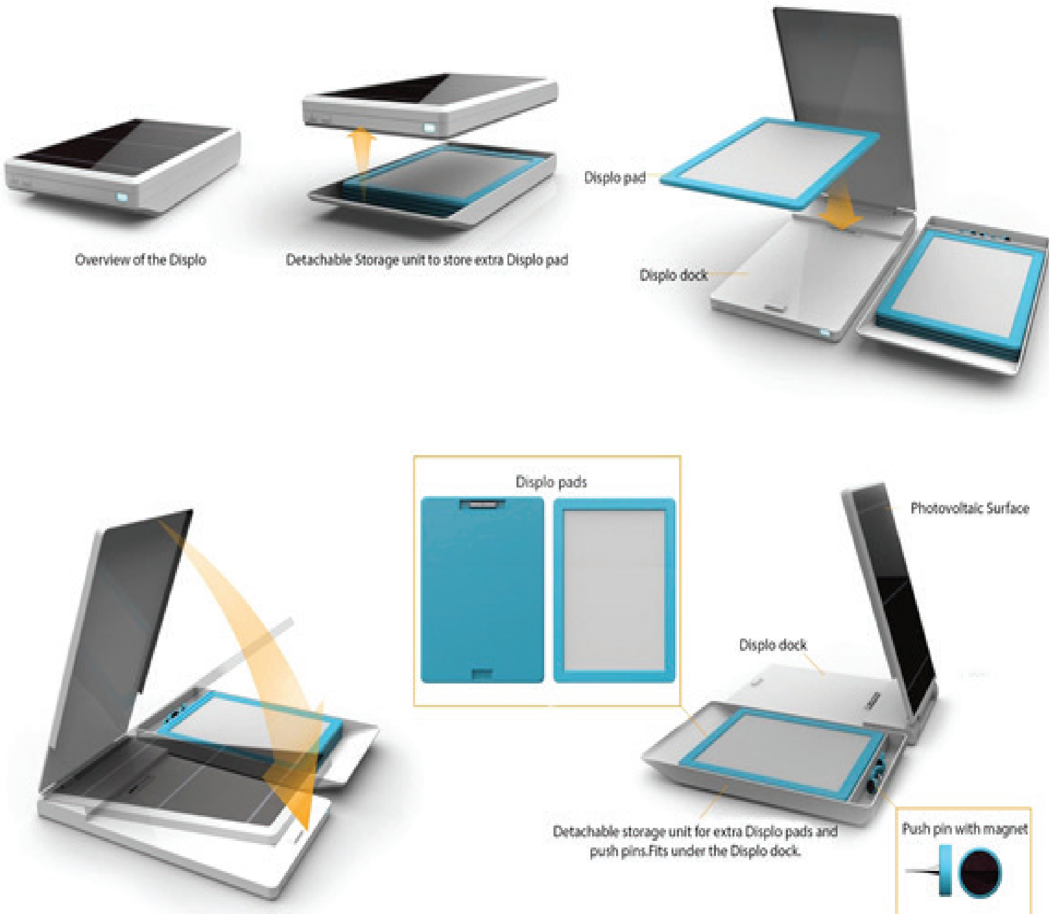


Figure 1.9: Digital representation of the concept product Displo Pad, 2015 (Image: Gaurav Deshpande, 2015).

Figure 1.10: Digital representation of the concept product Displo Pad and use of EPD pads, 2015 (Image: Gaurav Deshpande, 2015)

SoleMio

The solar-powered mouse SoleMio, designed within the Syn-Energy programme of the Netherlands Organisation for Scientific Research (NWO), in which the Universities of Twente, Utrecht, and TU Delft collaborated (Reich, 2006, 2007, 2008) (see Figure 1.11). The aim of this project was to enhance understanding of the photovoltaic-powered products. The final outcome was the development of a photovoltaic-powered wireless computer mouse, called "SoleMio". 15 SoleMio prototypes were built and tested with users, for the investigation of the product's performance, user expectations and usage. Different PV cell technologies (e.g. c-Si, mc-Si) used for the 15 prototype models, in order to see which one performs better. The solar cell area is 27 cm^2, which is considered relatively large and seems to suit to a frequent use of the product by the user, without often recharging (Reich, 2006, 2007, 2008). The product also contains a NiMH battery, AAA size and 800 mAh capacity for a PV cell of more than 0.3 V (Reich, 2006, 2007, 2008).

Figure 1.11: The solar-powered mouse SoleMio, 2007 (TU Delft, 2015) Photo by Mathhijs Netten.

Virtue of Blue

Virtue of Blue (2011) is a PV-powered chandelier, which was designed by Jeroen Verhoeven, a Dutch designer and artist. The chandelier is 144 x 144 x 162 mm in size and consists of 500 butterfly-shaped crystalline silicon PV cells (Reinders et al. 2013), (see Figure 1.12). It includes a glass bulb, and four aluminum breeds of butterflies, which seem to fly around the bulb. The butterflies collect solar energy during the day to power the lamp. This artwork is a beautiful combination of art and renewable energy.

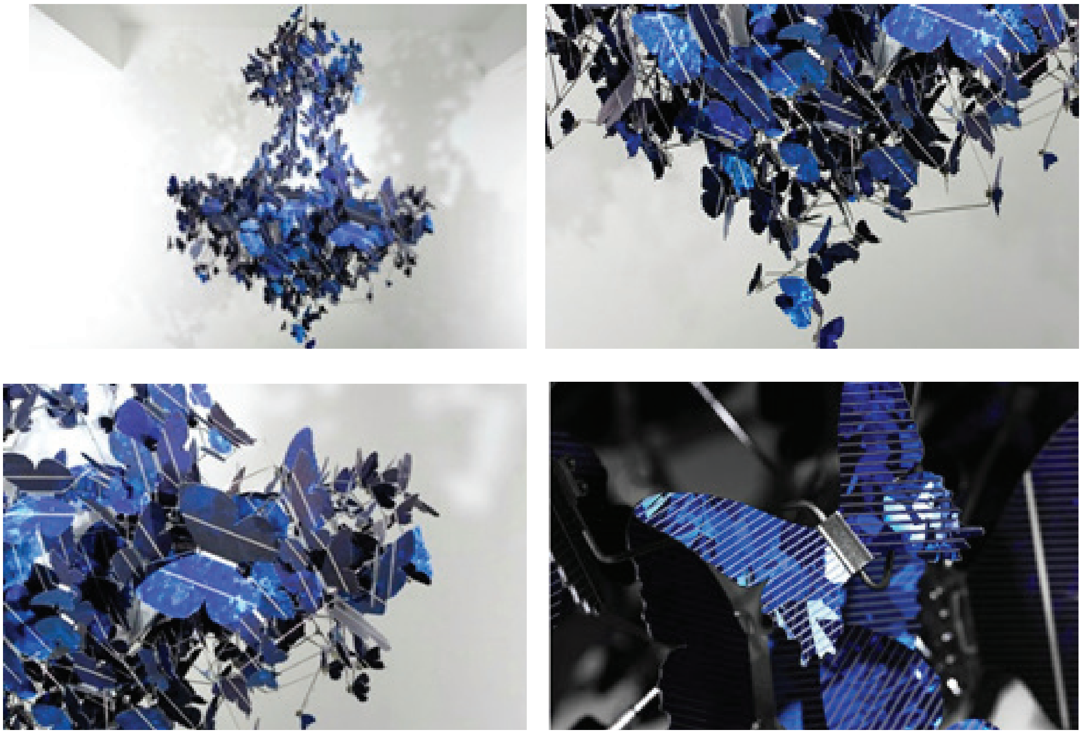


Figure 1.12: The Virtue Blue Chandelier (2011) is a PV lighting product. Images ©Giulietta Verdon Roe and Bas Helbers, Source: Inhabitat, 2011.

Moonlight

The 'MoonLight' (Diehl, 2008) is a PV-powered light produced in Cambodia. It was developed in collaboration of the Dutch charity foundation Pico Sol and the Khmer Foundation for Justice, Peace and Development, the social enterprise Kamworks and Technical University of Delft (TUD). The product was developed as an affordable light solution for the poor households in Cambodia. The aim of this project was to offer accessible sustainable energy solutions that could suit the economical and the cultural situation of the specific area. The 'MoonLight' was designed in 2008 and it was based on projects conducted at TU Delft (Boom 2005; Diesen 2008). It is a triangular-shape LED lamp, which contains a string attached at the three corners of the product for handling (see Figure 1.13). The product includes a crystalline silicon (c-Si) PV panel of 0.7Wp and a rechargeable battery. The PV panel comes separately with the product, as an extra accessory, and is not attached to the lamp.

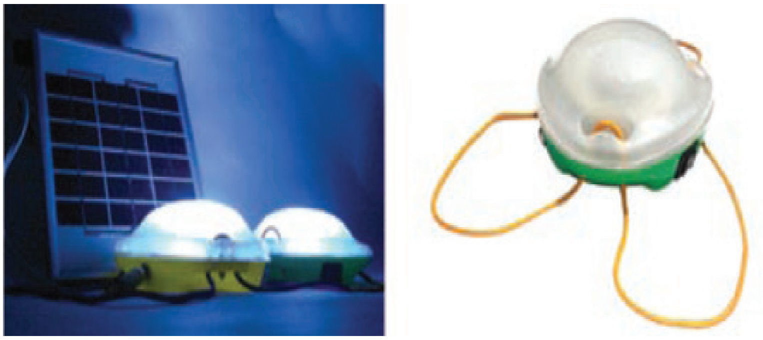


FIGURE 1.13: THE "MOONLIGHT", 2007 (DIEHL, 2007).

PV-powered cars

Nuna

The Nuna solar-powered racing car is developed by Technical University of Delft, in The Netherlands (see Figure 1.14). The team that built the car is called the Nuon Solar Team and consists of students of TU Delft.
The Nuna participated in the World solar challenge in Australia and won five times; in 2001 (Nuna 1), 2003 (Nuna 2), 2005 (Nuna 3), 2007 (Nuna 4) and 2013 (Nuna 7).
The solar cells that Nuna uses (models Nuna 1 to Nuna 5) are made of gallium arsenide (GaAs), while Nuna 6 and Nuna 8 use monocrystalline silicon (c-Si) solar cells (Nuon Solar team, 2015). The PV cell area covers the whole upper surface of the racing car, except for the cockpit. Generally, according to the regulations of the World Solar Challenge, each new model might have different features from the previous one, such as the PV cell technology and size, the type, size or weight of the battery, the number of wheels, the place of the cockpit (e.g. in the middle of the car, or on the one side), the total weight of the car or the aerodynamic drag. All changes aim to develop a faster racing car.

FIGURE 1.14: NUNA 3 SOLAR-POWERED RACING CAR, BUILT BY TECHNICAL UNIVERSITY OF DELFT, IN THE NETHERLANDS, 2004-2005 (NUON SOLAR TEAM, 2015). PHOTO BY HANS-PETER VAN VELTHOVEN.

Stella

Stella, world's first solar-powered family car, built by 20 students from the Eindhoven University of Technology in The Netherlands (see Figure 1.15). The Stella participated in the World Solar Challenge Cruiser Class in Australia in 2013 and the Stella Lux in the Bridgestone World Solar Challenge at Hidden Valley in 2015 (WSC, 2015) and won. The upper surface of the solar car is covered with PV cells. Unfortunately, more information about the type of the PV cells and the batteries of the car could not be found.

There are many successful PV-powered cars except from the Nuna, and the Stella, which were designed for their participation in worldwide contests. Some well-designed PV-powered cars with good performance in worldwide challenges are the following: the Eve by University of NSW, Australia; the Solar Spirit 3 by TAFE South Australia University; the PowerCore SunCruiser, the SolarWorld GT and the Sun Riser by Hochschule Bochum, Germany; the Apollo Solar Cruiser Car by National Kaohsiung University of Applied Sciences in Taiwan, the Red Engine by University of Twente in The Netherlands.

FIGURE 1.15: STELLA, WORLD'S FIRST SOLAR-POWERED FAMILY CAR, BUILT BY THE SOLAR TEAM EINDHOVEN, IN THE NETHERLANDS, 2013 (SOLAR TEAM EINDHOVEN, 2015).

PV-powered boats

The Liyant Boat (2011), the T-Class Boat (2012) and the A-Boat (2012) (see Figure 1.16) are PV-powered boats that were developed by the NHL Leuwarden team (Gorter, 2014). All boats participated in Energy Solar Challenges with the last one winning the second place at the DONG Energy Solar Challenge in 2015. Furthermore, Tim Gorter (2014), as team-captain and project manager of the NHL Team, offered designers support to create PV boats with better performance by developing a model to determine specific values for the PV boats' performance indicators. Gorter's work is used for the development of better performing solar boats.

There are many successful PV-powered boats, which were designed for their participation in worldwide contests, such as the PV-SB Collinda (1997), the Turanot PlanetSolar, the Sun21 (2007), the Firefly solar boat (2012), the Solar Sailor (1997).

FIGURE 1.16: THE PV-POWERED A-BOAT AT THE NHL SOLARBOAT RACING (GORTER, 2014).

From the project-based products described above it seems that there is a worldwide interest in PV-powered racing cars and boats, since many universities all over the world develop PV-powered cars and boats and participate in World Solar Challenges (e.g. World Solar Challenge, 2015; World Solar Challenge Cruiser Class, 2015; Dutch Solar Challenge, 2015; Solar Boat World Championship, 2015; NHL Solarboat Racing, 2015).

Special attention focuses on the development of sustainable energy solutions, especially for transportation, by replacing fossil fuels with solar energy and aiming at low carbon-emissions. Furthermore, there is extra interest for sustainable lighting solutions for off-grid areas and poor households (Lighting Africa project, 2015; Diehl, 2008; Durlinger et al. 2010, 2011, 2012; Gooijer et al., 2008). However, these lighting solutions are usually designed for outdoor charging and indoor use, which is not the area of research in this dissertation. Unfortunately, there is not enough research been done on indoor low-powered PV products. In order to clarify why research in indoor PV products is not efficiently addressed at the moment, in the next paragraphs we discuss the difficulties of PV products to perform indoors, as well as information already known on the field of indoor PV and the knowledge gap.

1.5 Innovation Methods in the Design Process

This dissertation has been written in a research project in the Faculty of Industrial Design Engineering and its goal is, among others, to contribute towards the development of the field of industrial design by investigating a specific product category- namely PV powered products- and hence offering knowledge that was not available so far. Since this study is embedded in design-driven research, suitable research methods and models to be implemented were sought.

A few authors in the field of PIPV have discussed issues concerning the integration of PIPV from the perspective of designers and design processes. Studies have been done by Randall (2006), Geelen et al. (2008) and Reinders et al. (2008, 2009, 2010).

For a successful application of a (new) technology in a product context, aspects that should be included in the design process are the following:

1. technology itself,
2. human factors e.g. users' experiences,
3. design and styling that suits to consumers' lifestyle,
4. societal aspects e.g. regulations and legislation and
5. product marketing.

The "innovation flower of industrial product design" (see Figure 1.17), as it is called, combines all the factors mentioned above, which are important for a successful and innovative product design.

More specifically as Figure 1.17 depicts, the technology circle refers to the materials, technologies and manufacturing. The design and styling circle refers to the products' outlook and aesthetics and the human factors' circle focuses on the user context. Last, the marketing circle centres on the cost and sales of the product and finally the society circle refers to regulations and societal acceptance.

More specifically this research focuses on the technical aspects of PV products. Human factors, such as the user context and users' interaction with PV products are also investigated here, in such detail that could help us understand typical user behaviour with the products, and user expectations. The design and styling of the products is briefly analyzed, based on user feedback and redesign ideas after their interaction with the products. Design and styling are not extensively investigated, since as a researcher and engineer it is beyond my field of expertise. Moreover, marketing is not addressed in this research, for the same reason. However, these are fields that need further analysis from researchers with more profound knowledge of

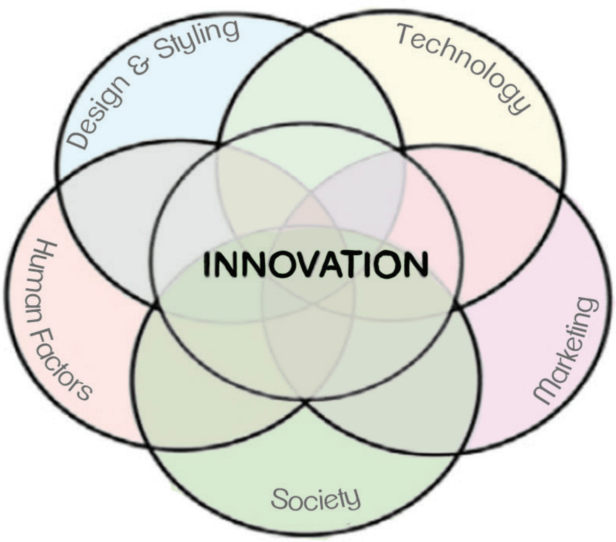


Figure 1.17: Scheme of parameters represents the design process (Reinders et al., 2012).

marketing strategies and emotional responses to products.
The Delft Innovation Model (DIM) describes product innovation processes in companies. This model was created by Buijs (2003) and can be used by designers and engineers.
The Delft Innovation Model, or the innovation phase model as it is also known, has five stages in the product innovation process (Buijs, 2003; Buijs and Valkenburg, 2005; Reinders et al. 2012):

1. Strategy formulation (generating search areas),
2. Design requirements (generating product ideas),
3. New product development,
4. Market introduction and
5. Product use.
6. After product use

The circular product innovation process ends in the product use stage, as DIM indicates, and then a new one starts again. Companies continuously repeat this process as they launch new products, which have to survive against competitors' products. The 6th stage of the circular product innovation process is not included in the DIM. However, this stage is very important and should be included, as it describes the final stage of the product after its use, such as discarding, shedding, recycling, reuse of the product.
This research largely focuses on the 5th stage of the Delft Innovation Model, which is the product use. This research project investigates a specific product category; the PV-powered products designed for indoor use. It focuses on the design features of the products, the conditions under which they are used and the way the users interact with the products. All these issues could be included in the product use stage of the Delft Innovation Model, since all contribute to the way in which a PV product is used and focus on the final product and not on the other stages of the product innovation process. The rest four stages of DIM are not addressed here.
This dissertation does not intend to propose a new research method for industrial design engineering research in the field of PV products. It aims to collect knowledge about a relatively new product category and make this expertise accessible to designers. In this thesis I aim to make recommendations and consciously advise designers towards the improvement of the design of indoor photovoltaic products. Furthermore, the conclusions of this dissertation will combine two areas of technical and user research, which are relevant for the topic of PIPV and PV powered products.

1.6 Problem Statement, Research Questions & Limitations

This research project is oriented towards the development of scientific and technological knowledge about product-integrated PV, as it identifies the aspects that designers need to take into consideration when designing PV products. The research will be interdisciplinary by nature due to it belonging to the field of industrial design engineering, which focuses on the technical aspects of PV technologies in products and user aspects of user interaction with their PV products. More specifically, my research focuses on the design features of indoor PV products and the way to design products with an acceptable performance for the users, issues that have not been addressed by other researchers to date.

The multi-disciplinary character of this research is the point where this work differentiates from the previous works. This research combines the technical knowledge of PV technologies, indoor irradiance conditions and performance of PV cells and PV products at environments with low irradiance together with the typical behavior of users with these products and the way this behavior influences the performance of the products themselves.

This dissertation does not analyze all the types of PV technologies, since at the moment most low-powered PV products use mono-crystalline silicon, multi-crystalline silicon or amorphous silicon solar cells. For that reason, these are the types of the PV cells that are investigated in this thesis. There are short references in the text to other PV technologies, such as the organic PV cells or the III-V compounds, but these technologies are excluded from further study. Furthermore, regarding the technical features of PV products, in Chapters 2 and 3 the issue of batteries is discussed. Battery type, capacity and weight seem to be very important for the design and the performance of the PV products. However this field is too broad to be analyzed in this thesis. Therefore, this thesis does not dive deeper into batteries. This field should be separately investigated in other research.

Based on the relevance of sustainable product design in product-integrated PV, this dissertation is centres on the following issues: indoor irradiance conditions, efficiency of PV materials under non-standard test conditions experienced during use of PV products and users' interaction with PIPV. Manufacturing of PIPV and the combination of PV with other renewable energy sources are not addressed in this dissertation.

The study approaches the above issue by investigating:

1. Why research on product- integrated PV is important? (Question is answered in Chapter 1).
2. What is product-integrated PV and what are PV products? For example: What are the design features and function materials that these products use? (Question is answered in Chapters 2, 3)
3. Where are the PV products used? That is to say under which conditions and irradiance they are used? (Questions are answered in Chapters 4, 5).
4. How do users interact with the PV products? (Question is answered in Chapter 6)

Each one of the questions raised above is answered in the chapters of this thesis as it is indicated above.

The main research question of this thesis can now be formulated as following:

What designers should take into consideration if they want to design indoor PV products with a better performance than the existing?

In order to refine the research question, the following sub-questions are identified, which will help to approach the main research question in a systematic and logical way.

- Which are the factors that affect the performance of PV cells in products? (Subquestion of the 2nd research question. It is answered in Chapter 2)
- What are the design features that existing PV products have? (Subquestion of the 2nd research question. It is answered in Chapter 3)
- Which are the indoor irradiance conditions? (Subquestion of the 3rd research question. It is answered in Chapter 4)
- What is the efficiency of different PV technologies indoors? How the performance of PV products could be estimated under indoor irradiance conditions? (Subquestion of the 3rd research question. It is answered in Chapter 5)
- How could users' interaction with indoor PV products influence the performance of the products? (Subquestion of the 4th research question. It is answered in Chapter 6)

1.7 Outline of the Thesis & Research Methods

The multi-disciplinary character of this study requires the use of various research methods, which are differentiated in each chapter according to the research questions. The framework of the thesis, the context of each chapter and the research methods that were used are described systematically in the following paragraphs.

In **Chapter 2** various PV technologies and the basic knowledge concerning the integration of PV cells in consumer products are briefly discussed.

Chapter 3 will provide an overview of PV product design features based on a survey of preselected PV products.

Chapter 4 addresses the indoor use of PV products focusing on the irradiance conditions under which these PV products are used. Chapter 4 presents measurements of irradiance and results under various conditions indoors. The indoor irradiance is investigated by conducting multiple irradiance measurements in different rooms, trying to explore how irradiance varies and what is the range of irradiance that could be used by the solar cells in this environment.

Chapter 5 discusses efficiency of different PV technologies, which were used indoors during the experiments; the results of the measurements are presented and analyzed.A mathematical model of the indoor performance of PV cells is proposed, which estimates the indoor efficiency of various PV materials. The model is based on real tests and measurements of the efficiency of various PV cells under low irradiance conditions and on literature data, as well.

Next, **Chapter 6** is dedicated to user interactions with PV products. It addresses user expectations before they use the product and their experience after using it, as well as the fulfillment of their expectations and needs. Here, user interaction with PIPV is examined by using real PV products and lead-users. In this study both quantitative and qualitative methods are used. The interaction of the users (forming focus groups) with PV products is analyzed, by conducting a survey, using a questionnaire to present statistical data and observational methods, where the users record themselves or write in a workbook about their daily interaction with the product. Furthermore, physical data are used, as the PV products are tested under different irradiance conditions and conclusions about their function and performance in different contexts are drawn.

The thesis ends with **Chapter 7**, where final conclusions are discussed. Some design recommendations for indoor PV products are presented in this chapter, which support the thesis's conclusions. Results derived from the previous chapters are gathered here for the establishment of useful recommendations for designers concerning the design of indoor PV products. The design recommendations, which are presented in the appendices of this thesis, support the thesis's conclusions.

Outline of the thesis is illustrated in Figure 18.

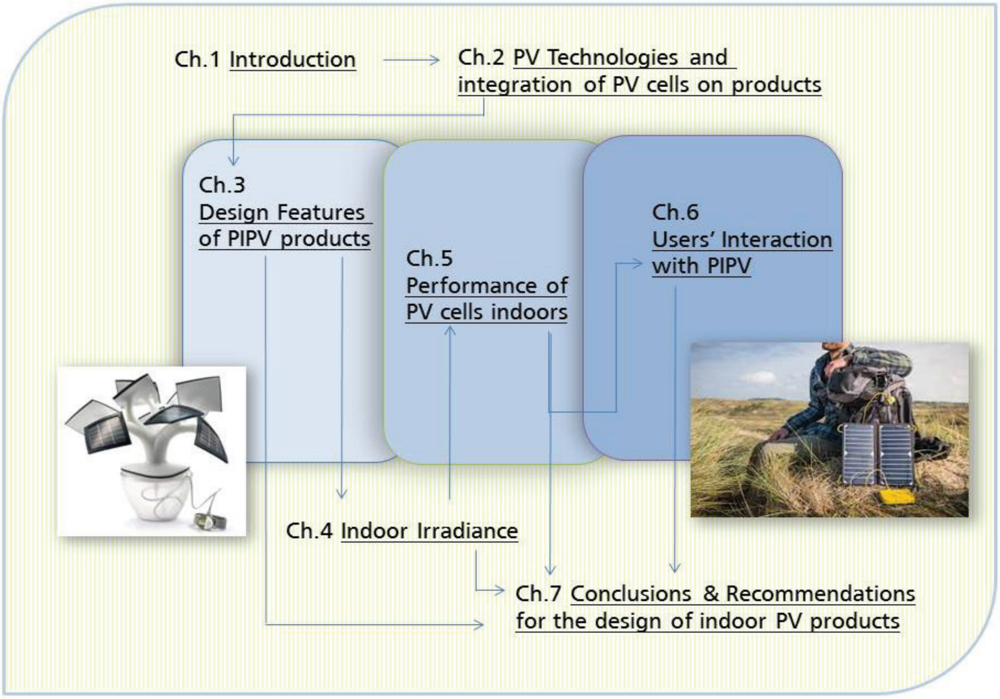


FIGURE 1.18: OUTLINE OF THE THESIS.

CHAPTER 2

PV technologies and integration of PV cells in products

2.1 Introduction

Chapter 2 is an introduction to the fundamentals of photovoltaic (PV) cells. It introduces the electrical behavior of PV solar cells in section 2.2, by presenting formulas for the calculation of the short circuit current, open circuit voltage, peak power, fill factor and conversion efficiency of a PV cell. PV cells' connections in products are also discussed here. Next, in section 2.3 an overview of the PV technologies that are available today is given. Different materials are introduced and shortly explained and basic knowledge about their integration in PV products is also provided.
Due to the many different surroundings and contexts at which PV powered products are used, in section 2.4 several factors are presented which can affect the performance of PV cells integrated in the surface of PV-powered products. The factors that are discussed here are: irradiance conditions, cell efficiency and other factors, such as the area of PV cells, shad(ow)ing of PV cells and the combination of PV cells with batteries. The chapter ends in section 2.5 with summary and conclusions.

2.2 Electrical behavior of PV solar cells

All photovoltaic (PV) technologies use energy from light originating from the sun or any other light source to convert it into electricity. In this section a short explanation is given of the functioning of photovoltaic cells as a basis for the following chapters. In photovoltaic cells the photovoltaic effect takes place, which is the generation of charge carriers, usually electrons and holes, in liquids or solid materials under exposure to photons (Becquerel, 1839, 1840). The net current that flows through the solar cell when exposed to irradiance is given by the one-diode equation shown below (Honsberg and Bowden, 2015):

$$I = I_o \left[\exp\left(\frac{qV_a}{k_B T} \right) - 1 \right] - I_{ph} \tag{2.1}$$

where: I is the current produced by the solar cell (A),
I_0 the saturation current (A),
I_{ph} the photocurrent (A),
q the elementary charge ($1.6021766208 \times 10^{-19}$ Coulombs),
V_a the solar cell voltage (V),
k_B the Boltzmann's constant ($1.3806488 \times 10^{-23}$ J/K),
T the absolute temperature (K).

The performance of a solar cell during operation is given by its current-voltage curves (I-V curves) and power-voltage curves (P-V curves), see Figure 2.1. The main parameters in this curve are the short circuit current I_{sc}, open circuit voltage V_{oc}, and maximum power P_{max} in the maximum power point (MPP). These parameters are directly related to the conversion efficiency, η, as will be explained later.

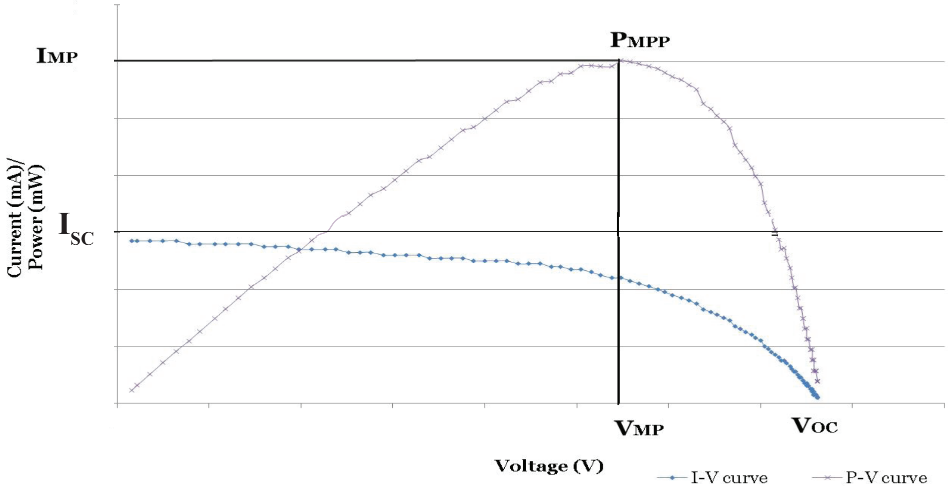


Figure 2.1: Current-Voltage (I-V) curve and Power-Voltage (P-V) curve of a multi-crystalline silicon solar cell. Source: Author's record.

The open circuit voltage V_{oc} is defined as the voltage at which no current flows through the external circuit of a solar cell. It is the maximum voltage that a solar cell can produce and it depends on the material properties of the solar cell. It can be derived from Equation 2.1, by setting I at zero:

$$V_{oc} = \frac{k_B T}{q} \ln\left(\frac{I_{ph}}{I_o} + 1\right) \quad (2.2)$$

The short circuit current I_{sc} is measured when a solar cell is illuminated at zero voltage. I_{SC} depends on the area of the solar cell, the number of photons (i.e. the power of the incident light source), the spectrum of the incident light, as well as on the optical properties of the solar cell (absorption and reflection). For STC measurements the AM 1.5 spectrum is used. In ideal cases, I_{sc} is equal to $I_{ph.}$
The peak power P_{max}, is the maximum power that a solar cell can deliver at certain irradiance level and is the product of I_{mpp} (maximum power point current) and V_{mpp} (maximum power point voltage). P_{max} can be found from the maximum power point (mpp) in the I-V curve.

$$P_{max} = I_{mpp} \cdot V_{mpp} \quad (2.3)$$

The fill factor FF is a parameter that describes the shape of the I-V curve. In conjunction with V_{oc} and I_{sc}, it can be used to determine the maximum power from a solar cell, using the following formulas:

$$FF = \frac{P_{max}}{I_{sc} V_{oc}} = \frac{I_{mmp} V_{mmp}}{I_{sc} V_{oc}} \quad (2.4)$$

The conversion efficiency η of a solar cell is defined as the ratio between the maximum power delivered by the solar cell to the incident irradiance.

Usually the efficiency is used to compare the performance of solar cells. The solar cell's efficiency is dependent on the spectrum and intensity of the incident irradiance, as well as the temperature of the solar cell. Thus, in order to compare the performance of different PV cells, the conditions under which the efficiency is measured must be cautiously controlled. Terrestrial solar cells are measured under STC. The AM0 condition is used for solar cells intended for space use.

The efficiency of a solar cell is defined as the fraction of incident power, which is converted to electricity and is given by the following equation:

$$\eta = \frac{P_{max}}{P_{in}} = \frac{I_{mmp} \ V_{mmp}}{P_{in}} = \frac{FF \ I_{sc} \ V_{oc}}{P_{in}} \qquad (2.5)$$

PV cells' connections

Due to its limited size in the order of one to tens square centimeters, a solar cell can only deliver a limited amount of power under fixed current-voltage conditions. In order to use solar power for practical devices, which requires a particular voltage and/or current to operate, a number of solar cells have to be connected together to form a solar panel, also called a PV module. Therefore most PV products use more than one PV cells in series or in parallel connection according to the required current and voltage that the product needs to properly function.

In a series connection, the solar cells are connected one after the other/in sequence and the voltage of each solar cell will add up with the other ones (see Figure 2.2a). The current of the cells connected in series does not add up but is determined by the photocurrent in each solar cell, according to the basic law of Kirchhoff. Therefore, the total current in a string of solar cells is equal to the current generated by one single solar cell.

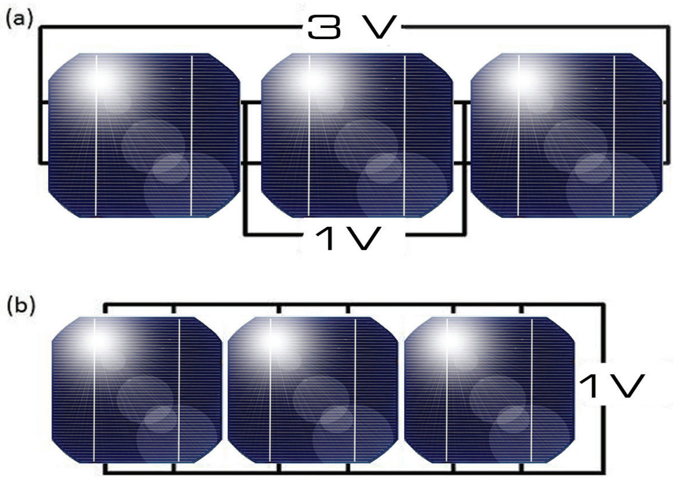


FIGURE 2.2: SOLAR CELLS CONNECTED IN SERIES WITH EACH OTHER (A) AND SOLAR CELLS CONNECTED IN PARALLEL (B).

If solar cells are connected in parallel, the voltage over all the solar cells will be similar, while their current will add up (see Figure 2.2b). If cells are connected in strings in series and these strings are connected in parallel with each other, then the voltage and current over the array of all cells can be determined by following the rules explained above for both voltage and current in each configuration.

Figure 2.3a depicts a basic power system of a PV powered product comprising the following elements: a solar cell, an energy storage device (i.e. a capacitor or battery) and a diode to prevent discharging of the battery through the solar panel. Matching of the battery voltage with the solar cell is done by creating a small solar panel with the right number of solar cells in series for an appropriate voltage. In more advanced systems (Figure 2.3b) a DC/DC converter matches the solar panel voltage and the battery voltage.

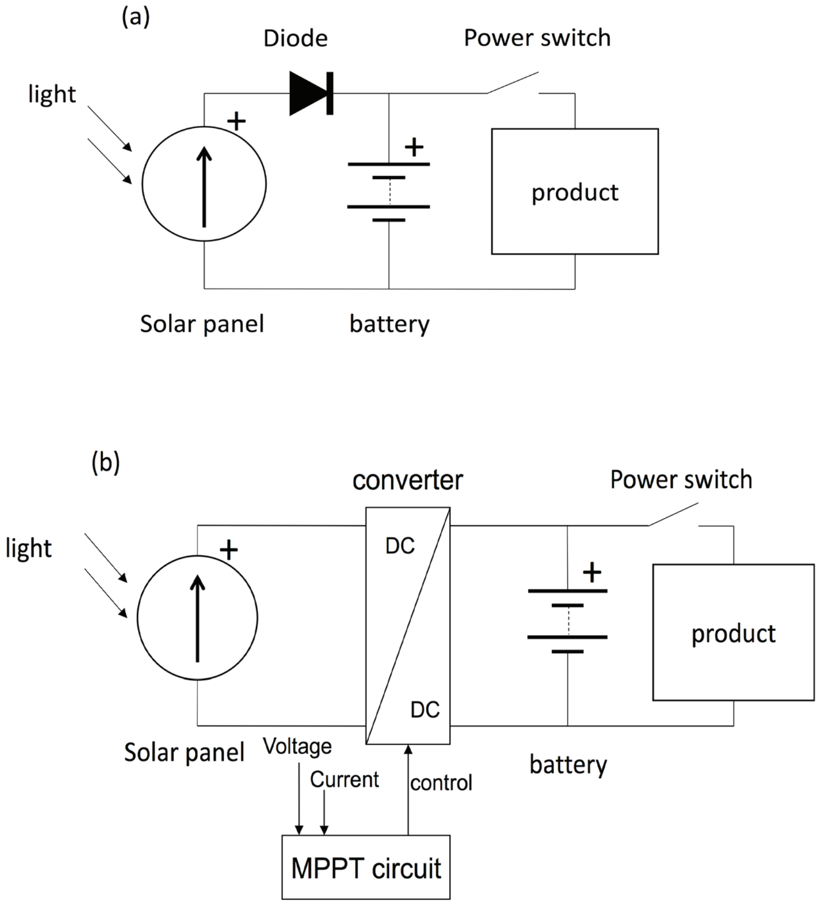


FIGURE 2.3: (A) SIMPLE AND (B) ADVANCED CIRCUIT SCHEME OF A PV PRODUCT (APOSTOLOU ET AL., 2016).

2.3 An overview of photovoltaic technologies

Various PV technologies are made of semiconductor materials, such as mono-crystalline silicon, multi-crystalline silicon, amorphous silicon and cadmium telluride. Other sorts of PV cells can be categorized as organic materials, such as polymer solar cells and dye sensitized solar cells. In this chapter these different materials will be introduced and shortly explained and basic knowledge about their integration in PV products will be provided.

Different PV materials result in varying performance in terms of efficiency and in different mechanical properties, such as flexibility and strength. According to Green (1982, 2002), Kibria (2014), Krebs (1982, 2013, 2015), and Archer (2015), based on performance and costs, at present PV technologies can be classified into three generations:

1. First-generation PV cells which use wafer-based crystalline silicon (c-Si) technology, in the form of either single crystalline (c-Si) or multi-crystalline (mc-Si). This is a mature generation of PV cells and most commonly implemented to date. Technological development is mainly focused on better manufacturing technologies and improving materials to reduce the cost of these cells, while keeping efficiencies high or making them higher. These cells generally have a rigid structure, deep blue color and are brittle.

2. Second-generation PV systems are based on thin-film PV technologies which include amorphous silicon solar cells (a-Si), multi-junction amorphous and micro-crystalline silicon technologies (a-Si/μc-Si), cadmium-telluride (CdTe) solar cells, copper-indium-selenide (CIS) cells and copper-indium-gallium-diselenide (CIGS) cells. The thin layers reduce the weight and can increase flexibility of these cells for which reason these cells are commonly applied in consumer products. These cells generally are more flexible than the first-generation PV cells and have a brown or black color.

3. Third-generation PV systems include remaining technologies like III-V compounds, such as for instance; GaAs PV cells, and organic PV cells. III-V cells consist of several p-n junctions (usually three to four), which are made of different types of semiconductor materials. The characteristic feature of this technology is that the layers of semiconductor materials absorb different range of wavelength and therefore the PV cell absorbs a broader range of wavelengths than the first- or the second-generation PV cells, which results to higher cell's efficiency. Third-generation means that these technologies are still under development or have not yet been widely commercialized (Green, 2002). Among the organic solar cells we can distinguish dye-sensitized solar cells (DSSC) and polymer organic PV (OPV) (Krebs et al., 2013). Also new concepts, such as cells made from perovskite materials and copper zinc tin sulfide (CZTS) solar cells belong to the third-generation.

Table 2.1 presents the first, second and third generation of PV cells, as discussed above.

TABLE 2.1 : TYPE OF PV CELL TECHNOLOGIES

1st Generation	2nd Generation	3rd Generation
• Mono-crystalline silicon (c-Si) • Multi-crystalline silicon (m-Si)	• Amorphous silicon • Micro-crystalline silicon (a-Si, a-Si/uc-Si) • Cadmium Telluride (CdTe) • Copper Indium Selenide (CIS) • Copper Indium Gallium Diselenide (CIGS)	• III-V compounds • Dye Sensitized solar cells DSSC/Organic PV • Polymer Organic PV OPV • New concepts, such as Perovskite PV, Copper zinc tin sulfide (CZTS) solar cells

Regarding consumer PV products and the type of PV cells, which are applied in them, it seems that not all types of PV technologies are used at present. Currently, most PV products use crystalline, multi-crystalline and amorphous silicon solar cells (Apostolou and Reinders, 2014). However, it is observed that only since recently there exist a rather limited number of PV products that use organic PV cells (Apostolou and Reinders, 2014). For these reasons this chapter and generally throughout this thesis, will focus on silicon-based PV cells such as mono-, multi- crystalline and amorphous silicon. The reasons why in particular these technologies are integrated in PV products will be further explained in the following paragraphs.

2.3.1 Crystalline silicon solar cells

Crystalline silicon solar cells dominate the PV market, approximately with an 85 % share of the total PV market in 2014 (European Commission, Joint Research Centre, 2012; REN21, 2015). This is mainly due to the fact that it is a proven technology, which cost is steadily decreasing. Preliminary estimates of PV cell production capacity in 2014 ranged from 45 GW to 60 GW (REN21, 2015). In that year the production of crystalline silicon cells and modules continued to increase (REN21, 2015). Furthermore, in 2014 average module prices for multi-crystalline silicon modules decreased to just USD 0.6/Watt (REN21, 2015).

There are two categories of crystalline silicon solar cells; mono- or single-crystalline and multi-crystalline silicon. Mono crystalline can reach high efficiencies, but the necessity for highly purified silicon and a crystal structure with as little defects as possible increases the cost (Zeman, 2011).

A process that results in more defects in the crystalline structure of silicon is casting. It is used to produce multi-crystalline silicon. Multi-crystalline silicon has therefore lower cost and lower performance than mono-crystalline silicon.
The efficiency of mono-crystalline solar cells under STC (IEC, 2008) typically lies in the range of 20 to 25 % (Green et al., 2015). However the module efficiency is slightly lower than that of the individual cells due to the area lost by frames and gaps between the cells, resulting in a module efficiency in the range of 18 to 23 % under STC (Green et al., 2015). The theoretical conversion efficiency of PV modules is also reduced due to different loss mechanisms such as optical losses, and ohmic losses. In the past period a lot of technological progress has been made. In the last 10 years, the efficiency of average commercial wafer-based silicon modules (multi-crystalline) increased from about 12 % to 16 % (Fraunhofer ISE, 2015). At present (in 2015) the record lab cell efficiency for mono-crystalline silicon is 25.6 % and for multi-crystalline silicon technology 20.8 % (Green et al., 2015). Record efficiencies of lab cells demonstrate the potential for further efficiency increases (Fraunhofer ISE, 2015) at the production level of commercial solar cells and hence PV modules.

2.3.2 Thin film solar cells

A thin-film solar cell is a solar cell that is made by depositing one or more thin layers of photovoltaic material on a substrate. The thickness range of a thin-film layer varies from a few nanometers to tens of micrometers. In silicon solar cell technology the term "thin-film" usually covers a range of 1 to 100 micrometers thick layers (Zeman, 2010).

The main reason for the development of thin film solar cells was to use less material and thus reduce the cost. The drawback is that efficiency of thin film cells is quite lower compared to crystalline silicon. Even though thin film technology is newer than bulk silicon technology, it has evolved significantly over the years and has gained a significant part of the PV market. Unfortunately, investments in new production lines of thin film cells were far less than that of conventional wafer based silicon cells. Hence, market share of thin film cells has been steadily decreasing since then (European Commission, Joint Research Centre, 2012).

In 2012, thin film's share of global PV production declined more, with production down 15 % to 4.1 GW (REN21, 2013). In 2014 however, the market share of all thin film technologies was just 9 % of the total annual production (Fraunhofer ISE, 2015).

Thin-film solar cells are usually categorized according to the photovoltaic material used:

- Silicon thin films (a-Si:H, a-SiGe:H, μc-Si:H, proto c-Si, poly c-Si:H)
- II-VI compounds (CdTe)
- II-IV-VI compounds (CuInSe2, CuInGaSe2)
- Thin film crystalline Si or GaAs (lift-off)

The highest lab efficiency in thin film technology is 21.0 % for CdTe and 21.0 % for CIGS solar cells (Green et al., 2015; Fraunhofer ISE, 2015).

2.3.3 Amorphous silicon

The material used for these cells is an alloy of silicon with hydrogen that is named hydrogenated amorphous silicon (a-Si:H). It has a higher bandgap (1.7 eV) than crystalline silicon (1.1 eV) and higher absorption coefficient. The absorption coefficient is defined as the distance that light of a specific wavelength can penetrate into a material before it is finally absorbed. The absorption coefficient depends on the material and the wavelength of light, which is absorbed.

A thin film with only 1 μm thickness can absorb 90 % of the usable solar energy (Zeman M., 2011). The layers can be deposited on almost any surface from stiff substrates like glass to flexible substrates, such as thin metallic sheets and plastics, which allows continuous production and diversity of use (Robert W. Miles, 2007). A typical a-Si:H solar cell consists of a p-i-n junction which is usually deposited on glass substrate. The substrate is coated with transparent conductive oxide (TCO), which also works as the front electrode. A metal (usually aluminum or silver) placed at the bottom of the cell operates as a back electrode (Zeman M., 2011). Amorphous silicon today is widely used in consumer products and in building integrated photovoltaics (BIPV).

Table 2.2 presents technical specifications of mono-crystalline, multi-crystalline and amorphous silicon solar cells, as presented in the above paragraphs.

TABLE 2.2: COMPARISON OF PVS' TECHNICAL SPECIFICATIONS*

Type of PV cell	V_{oc} (in mV)	I_{sc} (in mA/cm²)	Radiation Intensity (in W/m²)	Average Thickness (in μm)	EPBT** in Europe (in *a* years)	Bandgap (in eV)	Surface Color
mono-Si	620	36.7	220	180±30	1.8-3.3	1.12	Dark blue, black
multi-Si	615	35	215	200±30	1.2-2.1	1.12-1.2	Grey, light blue
a-Si	950	0.97	226	1±0.1	1.3-2.4	1.7-1.8	Brown-black

*The technical specifications of mono-crystalline, multi-crystalline and amorphous silicon solar cells, as presented in Table 2.2, are based on estimations using specification sheets of commercially available PV modules (bSolar, UniSolar, Suntech, Trina Solar, XSunX; isofoton, innergy, EverGreen, Kyocera). The values are indicative for these technologies, without being absolute.

**EPBT is the abbreviation for the 'energy payback time', which is the time required to produce an amount of energy equal to what was consumed during production.

2.3.4 Organic cells

Organic cells use organic dyes and polymers as light absorbers in order to produce electricity. They are fundamentally different from other inorganic solar cells, as the mechanism behind electricity production is not based on the creation of electrons and holes but the formation of excitons. Organic cells have very high absorption coefficient, thus making it possible to produce very thin cells (even below 1 μm) and use less material (Roncali et al., 2014; Goetzberger, 2002).

Organic cells are an attractive option for consumer products as they are flexible, semi-transparent, they have a low cost, and are easily integrated into different devices (Lizin, 2012). However, low efficiencies and lack of long term stability inhibit the large commercialization of this technology. The last decade a lot of research has been performed in this field and it is worth to refer that in 2013 a record efficiency of 12 % was achieved by Heliatek GmbH (Heliatek, 2013). Unfortunately, since then progress in towards higher efficiencies in the field of polymer solar cells has stagnated.

Dye sensitized solar cells (DSSC) are developed rapidly and currently reach efficiencies of 11.9 % (Green et al., 2015; Fraunhofer ISE, 2015).

2.3.5 Comparison of efficiency of different PV technologies

The efficiency of solar cells is measured under STC. Figure 2.4 illustrates the best research cell efficiencies of various PV technologies, according to the National Renewable Energy Laboratory (2015). Figure 2.5 demonstrates the development of laboratory solar cell efficiencies from 1993 to 2015 (Fraunhofer ISE, 2015).

Table 2.3 shows the characteristic efficiencies and spectral response range of several major PV technologies. These PV technologies are crystalline silicon, multi-crystalline silicon, amorphous silicon, nano-, micro- or poly-crystalline silicon, copper indium gallium selenide (CIGS), cadmium telluride (CdTe), III-V multi junction cells, dye-sensitized cells (DCS) and polymer solar cells. Among these technologies, efficiency varies from 12 % (Heliatek, 2013), which is the record efficiency under STC of a polymeric PV cell, up to 37.9 %, which is the efficiency of a multi-junction PV cell of III-V materials under STC (Green et al., 2015).

As shown by Table 2.3, different technologies have different efficiencies and the most important, different spectral ranges in which they operate. Mono-crystalline and multi-crystalline silicon solar cells have spectral range between 350 and 1200 nm. Nano-crystalline, a-Si, DSSC, CdTe and polymer solar cells have a range around 300 to 800 nm or maximum 850 nm. III-V solar cells have a range of 300 to 1000 nm, while multi-junction cells (InGaP/GaAs/InGaAs) 300 to 1250 nm.

The STC conditions of the efficiencies shown in Table 2.3 are closer to outdoor lighting situations, while indoors due to various reasons none of the solar cells will perform the same as outdoors. Freunek et al. (2013) have shown in simulations and measurements that in low lighting levels thin film solar cells (a-Si) perform better than under STC conditions by reaching often higher efficiency. The performance of conventional c-Si cells drops significantly in low lighting conditions to values under 1 % depending on the exact level of lighting. These are also the main reasons why thin film cells are generally more preferred for indoor applications than c-Si ones. Besides, De Rossi et al. (2015) showed that the efficiency of PV technologies intended for outdoor use reduces drastically when operating under indoor lighting. Results of the same study showed that a-Si cells optimized for indoor use, exhibit higher efficiencies under fluorescent lighting than under STC. Furthermore, based on De Rossi et al. (2015) a DSC module even not designed for use under indoor irradiance conditions, exhibited increased efficiency from 2.3 % at STC up to 6.6 % under CFL lighting.

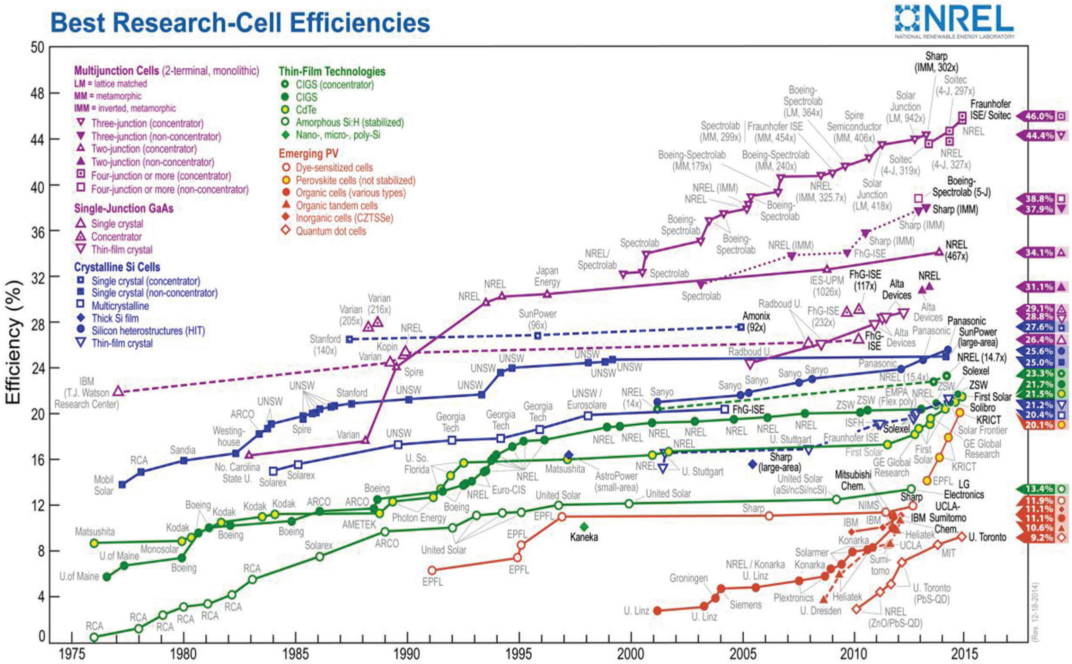


Figure 2.4: Best research cell efficiencies (National Renewable Energy Laboratory (NREL, 2015).

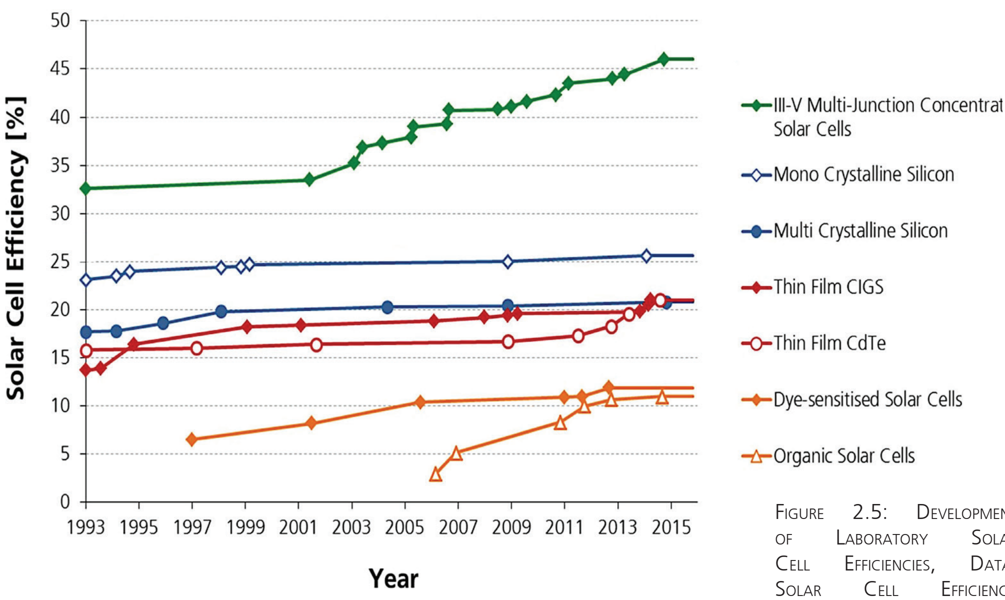


Figure 2.5: Development of Laboratory Solar Cell Efficiencies, Data: Solar Cell Efficiency Tables (Versions 1-46), Progress in Photovoltaics: Research and Applications, 1993-2015. ©Fraunhofer ISE: Photovoltaics Report, updated: 17 November 2015. Graph: Simon Philipps.

Table 2.3: Efficiencies (in Lab and commercially available) and spectral range of various types of PV cells [a].

Type of PV cell	Record lab cells	Commercially available @ STC (%)	Spectral range (nm)
c-Si	@STC (%)	18-21	350-1200
m-Si	25.6±0.5	15-17	350-1200
a-Si	20.8±0.5	10-12	300-800
Nano-, micro-or poly-Si	13.6±0.3	11-13	300-800
CIGS	16.5±0.2	15-17	300-1200
CdTe	21.0±0.6	16-17	350-850
Multijunctioncells (InGaP/ GaAs/InGaAs)	21.0±0.4	25-29	300-1250
III-V cells (GaAs)	37.9±1.2	21-23	300-850
DSC	28.8±0.9	8-10	300-800
Polymer	11.9	6-8	300-850

[a] Table adapted from Apostolou and Reinders, 2014. Updated with Green et al. 2015; Fraunhofer ISE, 2015.

2.4 Factors affecting the energy performance of PV cells

Because PV powered products are used in various surroundings and in a different context than regular PV systems, in this section several factors are presented which in particular can affect the performance of PV cells on or integrated in the surface of PV-powered products. These factors can be categorized as following:

- Irradiance conditions
- Cell efficiency
- Other factors

2.4.1 Irradiance conditions

The power produced by a PV cell depends on the spectral irradiance and the spectral sensitivity of the cell. Power is directly proportional to the irradiance falling on the photovoltaic material. The greater the intensity of incident irradiance the higher the power generated. The typical irradiance outdoors can be 1000 W/m^2 on a sunny day in the Netherlands and drops down to 350 W/m^2 on an overcast day (Kan, 2006).

For indoor condition this is drastically different. During the day, indoor irradiance can be sunlight received through windows or a mix of natural light and artificial light or completely artificial light. Generally it is in the range of 1 to 10 W/m^2 (Mueller M., 2009). This differs significantly from the above-mentioned range of 350 to 1000 W/m^2. Therefore in Chapter 4 indoor irradiance will be explored in detail taking into account important effects of distances to windows.

2.4.2 Cell Efficiency

The cell efficiency of available PV technologies is measured under STC conditions. The STC conditions can provide estimation for PV cell performance in outdoor environment. In indoor environments, these conditions can be misleading as parameters change, especially the spectral response and intensity of light.

More specifically, the efficiency of most PV technologies is higher under STC. This means that under lower irradiance, the efficiency of the PV cell is getting lower, reaching the lowest values under very low irradiance conditions in the range of a few W/m^2 (less than 10 W/m^2). A typical efficiency curve versus irradiance of a PV cell is growing rapidly until the irradiance of 300 W/m^2 and from there it is growing more smoothly until 1000 W/m^2. The performance of multiple PV technologies under low irradiance conditions, as well as the way that the spectral response of PV cells changes according to the irradiance intensity will be further investigated in Chapter 5, where PV cells of commercially available PV products are tested under indoor irradiance conditions. Given the relevance of the cell's efficiency Chapter 4 and 5 will explore this in more detail.

2.4.3 Other Factors

Other factors are factors, which have an effect on the energy generated by the PV cell irrespective of PV cell type, such as the area of PV cells, shad(ow)ing of PV cells and the combination of PV cells with batteries. Below these aspects will be shortly discussed.

2.4.3.1 Area of PV cells

The energy output of a photovoltaic system is dependent on the irradiance on the photovoltaic cells, the type of photovoltaic cells used and the effective area of the photovoltaic cells. The amount of energy generated by the PV cell is directly proportional to the active area of the PV module, if this area is irradiated by a spatially constant irradiance. The larger the surface area the more amount of irradiance can fall on the module, generating more energy. This is an important factor, which needs consideration during energy estimations. A right balance needs to be attained in the design in order to have a large enough PV module to power the product and to still be a practical size.

2.4.3.2 Shad(ow)ing on a PV cell

Both under indoor and outdoor conditions PV cells can experience disproportional radiation. This disproportional radiation is in many cases caused by shading due to surrounding objects or by so-called self-shad(ow)ing by the product that contains solar cells.

Partial shading can have significant consequences on the output of one solar cell and therefore also on the output of interconnected cells. In order to explain this, a situation will be considered in which one solar cell in an array will be partially shaded leading to a significant reduction of the current generated in the shaded cell, see Figure 2.6. In a series connection, the cell that generates the lowest current limits the current; the shaded cell thus dictates the maximum current flowing through the module. PV cells that are connected in parallel have fewer problems from partial shading because the current generated in the other cells do not need to pass through the shaded cell.

However, partial shad(ow)ing has even more drawbacks for unshaded solar cells (see Figures 2.6, 2.7). Unshaded cells start to waste energy instead of producing and consequently heat up, which can cause lower efficiency and material wear out. These problems occurring from partial shad(ow)ing can be prevented by including bypass diodes in the module but they will still not prevent the unshaded solar cells from producing less energy because of the low current dictated from the shaded ones.

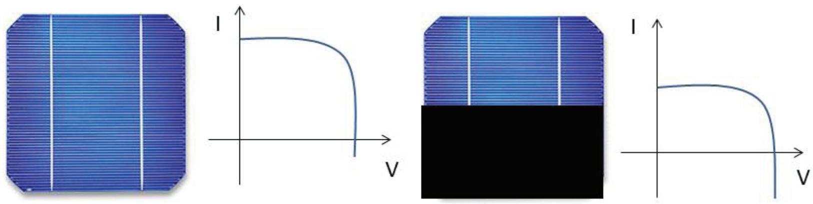


Figure 2.6: Effect on the output current, when part of the PV module is shaded (Adapted from Honsberg and Bowden, 2015).

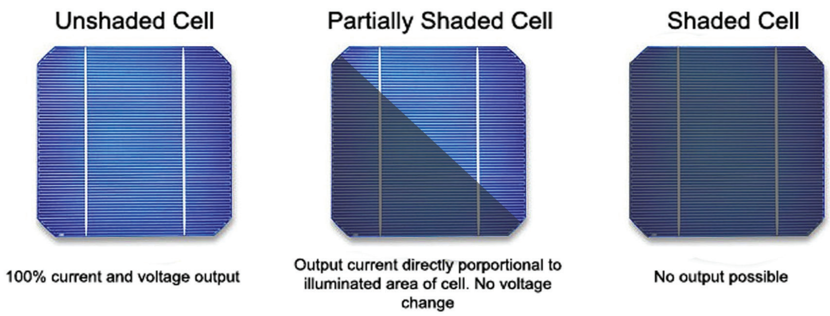


Figure 2.7: Shading on PV cells (Adapted from Sargosis, 2011).

2.4.3.3 Batteries

Energy storage in the form of batteries has been commercially available since the late 19th century (Battery University, 2016; Linden, 2001). Since then, with continuous technological progress, batteries have been used in all kinds of applications. The most widely used type of batteries in large PV systems is lead-acid batteries (Battery University, 2016). Even though lead-acid batteries have the lowest cost per kWh (around $8.50/ kWh (Battery University, 2016)) and are the most used type with PV systems, they are not suitable for product-integrated PV mainly due to their sheer size and heavy weight. In small or portable PV products usually Lithium-ion and Nickel based batteries are used. Lithium-ion batteries seem the most promising among the other types of rechargeable batteries (Battery University, 2016).

In order to have an overview of the size and weight of the batteries from different technologies, a Ragone plot has been given in Figure 2.8.

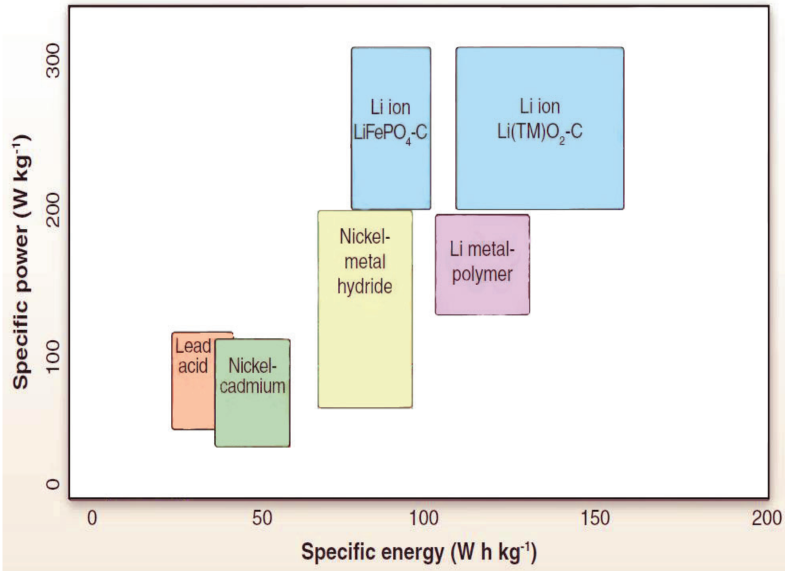


Figure 2.8: Gravimetric power and energy densities for different rechargeable batteries (Adapted from Dunn, et al., 2011).

The Ragone plot is used to compare the performance of various energy storing devices. Both axes; x and y are logarithmic. This allows presenting and comparing the performance of very low- or very high- powered energy storing devices (Christen and Carlen, 2000). In this plot, different battery technologies are compared to each other in power and energy densities. The higher the energy density of a technology, the smaller the batteries of that technology can be in size compared to lower energy density ones. High specific power means that the weight of the battery will be lower than the ones with a technology of a low specific power.

Figure 2.8 shows that Lithium based batteries have the highest specific energy and specific power. This means that batteries based on this technology are smaller and lighter than other types of technology. This is also the reason why Lithium batteries are vastly used for portable applications and consumer devices (Dunn, et al., 2011). Another type of battery technology, which is also used in consumer devices are also Nickel-metal hydride (NiMH) batteries. In Figure 2.8 it can be seen that they have also reasonable specifications for such use. According to the same plot, lead acid batteries are some of the heaviest and biggest batteries available (Dunn, et al., 2011). This is also the reason why they are never used for small applications, such as consumer devices.

Commercially available batteries are generally classified in two types: primary batteries and secondary batteries. Primary batteries are disposable batteries, which cannot be recharged after usage, while secondary batteries are rechargeable. This means that even though primary batteries are widely used in consumer devices, they cannot be used in combination with PV panels.

The main goal of the solar panels integrated in a product is to recharge product's battery and thus only secondary batteries can be used for such an application.

The choice of the appropriate PV cell for a product, in order to use the generated power for its battery charging, depends on the irradiance conditions under which the product is used, in combination with the available surface area in a product for placing the PV cells (see Table 2.4). The battery choice for a PV product is a compromise between weight, size, capacity and recharge cycle. Some products are recharged daily, some weekly and this determines the required capacity of a battery (resp. smaller or larger). It is also worth noting that PV products exist that do not use a battery, but they store energy in a capacitor. Li-ion batteries are some of the most used batteries in consumer devices. Nickel-cadmium batteries are also suitable for use in consumer devices and have been used in the past in such devices. However, in the European Union there has been a reduction in their use due to the environmental impact of the disposal of the heavy metal cadmium (Chatain, 2014).

Table 2.4: Possible combinations of PV- and battery technologies for a PV product (Apostolou G. et al., 2014).

Lighting condition	PV technology	Product's Power consumption	PV product size	Battery shape	Battery technology
Indoor	a-Si	<1 W	Thin/small	Button cell battery	Li-ion
Mixed: Indoor and Outdoor			Thick/large	AA, AAA	Alkaline, NiMH, NiZn
Outdoor	c-Si, m-Si			Li-ion batteries (cylindrical, prismatic or pouch cells)	Li-ion
Indoor	a-Si	>1 W	Thin/small	Button cell/custom made Li-ion batteries	Li-ion
Mixed: Indoor and Outdoor			Thick/large	AA, AAA	Alkaline, NiMH, NiZn
Outdoor	c-Si, m-Si			C, D, Li-ion (cylindrical, prismatic or pouch cells)	Alkaline(D), NiMH(C, D), Li-ion

2.5 Summary and conclusions

Chapter 2 provided an introduction to the most common PV technologies that are used for commercial PV product applications, which are the mono-crystalline, multi-crystalline and amorphous silicon solar cells. The basic principles of PV cell function and the factors that affect PV cell performance when integrated in products have been also addressed here. The purpose of this chapter was to provide the necessary information for PVs' integration in products, in order to better understand the following chapters, which will be more analytical and descriptive regarding each of the issues mentioned above.

To conclude, there are several factors that broadly affect the performance of PV cells in products, such as indoor irradiance conditions, the efficiency of the PV cells under indoor environment, the area of the PV cell surface, the distance of the product from the window or the artificial lighting sources, the shad(ow)ings in the room, as well as the combination of the PV cell and battery technologies.
More analytically, PV products have a different performance when used at indoor environments, where the irradiance is quite low compared to outdoor irradiance. This performance depends on the efficiency under low irradiance of the PV cell technology that is used for powering the product, as well as on the energy that the product needs to function. Apart from this, there are many other factors that affect the performance of the PV cells and the PV products indoors, such as use of artificial light, indoor shad(ow)ings, the room where the product is used and the distance of the product from the light sources. Lastly, users also play an important role in the way that a PV product is performing.

Generally three categories of PV products are distinguished; PV products for indoor use, for outdoor use and for both indoor and outdoor, called "mixed". For indoor lighting conditions, thin film cell (a-Si) is the most appropriate PV technology. For products designed to be used outdoors, c-Si and m-Si cells are the most efficient choices. A good choice for products that can be used both indoors and outdoors is a-Si or c-Si cells.

Moreover, copper indium gallium selenide (CIGS) solar cells, cadmium telluride (CdTe), and organic (polymer) PV cell technologies perform sufficiently under these conditions. However, these technologies are still under development and therefore not yet used in consumer products containing PV. Product's power consumption is also divided into two categories; low- and high-powered PV consumer products. The threshold between the two categories was set at 1 W. Another distinction made in Table 2.4 concerns the PV product size. Two categories are distinguished: the small or thin PV products and the large or thick, covering product sizes in the range of $7.5x10^{-4}$ m^2 to $80x10^{-4}$ m^2 respectively.

The specific distinctions that are presented in Table 2.4 regarding the size and the power of the products are based on a collection of PV products that will be analyzed in the following chapters of this thesis (Chapters 3, 5, 6). As Table 2.4 reveals, thin and small products typically use lithium-based batteries. However, they are more expensive (around $24.00/ kWh (Battery University, 2016)) than others technologies. Alkaline and Nickel-based batteries are less expensive (around $11.00-$18.50 /kWh (Battery University, 2016)) and can be used as a cheaper alternative.

All factors that affect the performance of the PV cells and the PV products indoors will be further discussed in the following chapters of this thesis. Chapter 3 will present an overview of the design features of PV products. The selection of batteries in PV products will be further discussed in Section 3.2. Next, Chapter 4 will explore the indoor environments in which PV products are used, by presenting measurements of indoor irradiance under various conditions. Chapter 5 will present a simple comparative model, which has been developed for the estimation of the performance of PV products' cells in indoor environments and Chapter 6 will investigate users' interaction with PV-powered products.

CHAPTER 3

An overview of design issues in product-integrated PV

Chapter 3 is based on the following publications:

Apostolou G. and Reinders A.H.M.E., "A comparison of Design Features of 80 PV-Powered Products", in Proceedings of 27th European PV Solar Energy Conference (EUPVSEC), Frankfurt, Germany, 2012, pp. 4227 – 4232

Apostolou G., Reinders A.H.M.E., "Overview of design issues in product-integrated photovoltaics", Energy Technology, Article first published online: 5 March 2014, Wiley, Issue March 2014, Volume 2, pp. 229 – 242

Reinders A.H.M.E. and Apostolou G., "Product Integrated PV", Forthcoming publication, Book Chapter in "Photovoltaic Solar Energy – From Fundamentals to Applications", Eds. Reinders, A.H.M.E., Verlinden, P., van Sark, W.G.J.H.M., and Freundlich, A., Wiley and Sons, UK, expected publication in 2016

3.1 Introduction

This chapter presents an overview of the design features and characteristics of photovoltaic (PV) powered products based on a literature study on product-integrated PV and analysis of 90 PV-powered products carried out in 2011-2013. Its purpose is to offer common knowledge about commercially available PV products regarding their basic design issues. This chapter can be used as a guide for designers and anyone else who is interested in PV products and their features, since it presents data, which were not previously available by other studies.
In the first part of this chapter results are presented based on a selection of 90 PV-powered products, see Appendix B, and their analysis concerning their power range, PV technologies used, battery technologies, manufacturers, place of use, sales price and several other design features. In the second part, an assessment of the environmental impact of user interaction with and the costs of the PV products are briefly presented and discussed.
Since the 1970s a variety of different products, such as watches, flashlights, chargers, mp3 players, solar lamps etc. has been released on the international markets for both indoor and outdoor use. Even though the use of PV systems in products has been known since then, this market is growing rapidly and cannot yet be considered as a mature market. Therefore, solutions to many issues need to be given.

First though the criteria for the characterization of a product such as a product-integrated PV (PIPV) product (Reinders and van Sark, 2012) are the following:

- The existence of an integrated PV cell on a product's casing or another surface.
- The use of the energy that is generated by the PV cells for the energy requirements of the product, during its operation.
- The option of straightforward user interaction with the product.
- Energy storage in batteries or another storage device.
- Use of the product on land.
- Easy transportation of the product.

PV systems and PIPV have many differences related to the range of the energy produced, as well as their size, design, technical features, cost, way of manufacture, life cycle and other aspects (see Table 3.1).

However, the main difference between them is that PIPV also includes product parts like plastics, iron or glass parts which consists of the housing (outer casing) of the products (Reinders and van Sark, 2012).

TABLE 3.1: BASIC CHARACTERISTICS OF PV SYSTEMS AND PIPV

	PV systems	PIPV
Power	From mW up to GW	From μW up to a few mW
Size	m^2 vs cm^2	
Design	Simple	More complex
Technical features	PV modules	PV cells, batteries, inverters, controllers
Cost	High	Low
Life cycle	Around 20 years	Around 5 years

Furthermore, PIPV includes additional PV system components, as well as mechanical and electrical parts (PV cells, batteries, inverters, controllers etc.). On the one hand, PV systems produce electricity for a wide range of purposes from microwatts to gigawatts, while on the other hand PIPV is used in a product context (Reinders and van Sark, 2012); Kan et al., 2006; Randall, 2005; Reinders, 2002; Reinders et al., 2012; Timmerman, 2008; Veefkind et al., 2006). PIPV provides multiple functions for products that require powering of electronic appliances, lighting, sound, telecommunications, heating, cooling or transportation. Moreover, with PIPV users are able to interact directly with the products. The functionality of the product depends on user habits for charging, as well as the usage profile of the product (Reich et al., 2008). Another difference between PV systems and PIPV is their lifetime. PIPV usually have a shorter life than PV systems, which is limited to a few years (1 to 5 years), as consumer products are intended to be used for a short period of time. In contrast, PV systems are designed to survive for longer periods of time; typically for more than 20 years. As a consequence, PIPV is considered as a distinct category in the wide variety of PV applications and therefore it is studied separately.

While designing a PV-integrated product (Randall, 2005; Reinders et al., 2012; Timmerman, 2008; Veefkind et al., 2006; Alsema et al., 2005; Reich et al., 2009), it is vital not only to use an alternative source of energy, but also to use inspiration from everyday products, as well as to be aware of the daily energy consumption of a product in its context of use. The product should suit the user's lifestyle, while meeting his energy requirements at the same time.

In this regard, during the analysis process not only the technical function of a product should be involved, but also the psychological, social, economic and cultural functions that a product should accomplish, as well as users' sustainable behaviour (Bakker et al., 2010, Jong and Maze, 2010; Keyson and Jin, 2009; Wever et al., 2008). Customer satisfaction and user interaction with a product appeared to have a high significance and should be also included in the design process (Jong and Maze, 2010; Scott Kakee, 2008; Scott Kakee et al., 2009). Consumers' satisfaction is an indication of by what means products and services delivered by a company approaches or surmounts users' expectations. It is a quite ambiguous and abstract concept and varies from person to person and product-service combination to product-service combination.

Users' benefits, derived from the incorporation of PV systems in products (Reinders and van Sark, 2012) can be summarized as the enhanced functionality of the product offering energy stability, security and independence, freedom due to the absence of the connection to the electricity grid, and extra autonomy in batteries which can be achieved by the reduction of their extended use.

In an attempt to introduce functionality and ecological behaviour to our lives, we target energy savings in various ways. This approach begins from simple things in everyday life that eventually are those that make the greatest difference over time. Therefore, we search for natural solutions; ecological products (eco gadgets), which are practical and have a multipurpose design for use inside and outside the house. This may constitute an important application of energy independence, whether we are talking about a calculator or even a car.

The established product categories of PIPV at the moment are (Reinders and van Sark, 2012):

- Consumer products (see Figures 3.1(a)-(d), 3.1(g))
- Lighting products (see Figures 3.1(e)-(f), 3.1(h)-(i))
- Business-to-business applications (see Figures 3.1(j)-(k)).
- Recreational products (see Figure 3.1(o))
- Vehicles and transportation (see Figure 3.1(l)-(n))
- Arts (see Figure 3.1(p))

The objective of this chapter is the investigation of the various PV product categories for indoor and outdoor use and the exploration of their basic design features in each case. The research question that is drawn on in this chapter concerns the improved design of PV products, respecting the user and the environment. Based on their relevance for sustainable product design, the chapter is centred on the following three issues: energy-efficient management of PIPV–battery systems, environmental aspects of PV technology in products and users' experiences with PIPV.

The cost estimation of PV products, mainly focused on products' sale prices, is also discussed. Manufacturing techniques of PIPV and combination of renewable energy sources are not addressed in this review chapter, due to their further generic nature for sustainable product design.
In section 3.2 an overview of existing product categories in PIPV is presented and in section 3.3 the design issues of PIPV based on a study of 90 PV-powered products are discussed. In section 3.4 the environmental aspects of PV technology in products are addressed and in section 3.5 human factors through users' experiences and profiles. An example of a mobile phone (Smartphone) is used for the investigation of its environmental impact. In section 3.6 costs of PIPV is discussed. The chapter finishes with the summary and conclusions in section 3.7.

3.2 Overview of Existing PIPV

As mentioned in section 3.1, nowadays PV solar cells are utilized in various different product categories. Therefore, a selection of 80 PV-powered products was investigated in 2011-2012 (Apostolou and Reinders, 2012). In this chapter an updated list with 90 PV products is analyzed and results are presented. The previous list of 80 PV products is updated and expanded with 10 more products, due to the limited amount of indoor and low-powered PV products of the first list. Some of these products are exposed in Figure 3.1.

The selected 90 PV products were found on the Internet during a research of commercially available PV products during the years 2011-2012. These products have been investigated in the framework of the course 'Smart Energy Products' of Sustainable Energy Technology (SET) at Technical University of Delft during the years 2011-2012 and 2012-2013. 103 Master students in 2011-2012 and 21 students in 2012-2013 participated in the course 'Smart Energy Products'. Figures of the 90 PV –powered products were distributed to the students together with a questionnaire (see Appendix B), which they were asked to answer.

The questionnaire included questions regarding the PV cell of the product (e.g. technology, area, PV power), the battery (e.g. technology, capacity), the cost, product's functions, dimensions and other technical data. The information was collected through the network, the products' data sheets if available on the Internet or by contacting the manufacturer. After receiving the initial information by the students, I executed a more detailed analysis and research for the missing information.

The main features and numerous examples of PV products for various product categories are addressed in the next paragraphs of this section.

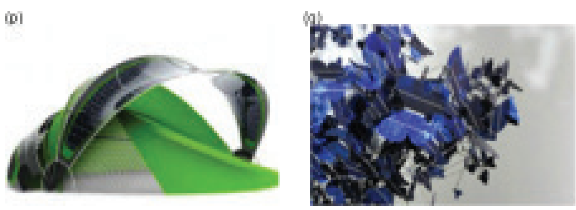


Figure 3.1: Photovoltaic products of various product-categories. (a) solar calculator, (b) solar watch, (c) iPhone charger by Vivien Muller, (d) solar-powered bag, (e) Spark lamp, (f) Ikea Sunnan lamp, (g) PC computer mouse Sole-Mio, (h) solar lantern, (i) solar garden light, (j) solar-powered parking meter in Virginia, (k) automated trash bin Big Belly, (l) solar traffic light, (m) Solar-powered car "Nuna", (n) Planet Solar Catamaran, (o) Helios solar aircraft, (p) solar-powered tent, (q) PV-powered chandelier (Apostolou and Reinders, 2014).

3.2.1 Consumer products with integrated PV

To the category "consumer products" belong products of everyday use with a PV cell's power from 0.001 W up to 10 W (Reinders and van Sark, 2012). PV cells are applied to products such as toys with integrated PV cells, solar sensors, solar thermometers, PV-powered radios, calculators, solar powered watches, solar-powered MP3 players, PV headsets, automated lawn mowers, kitchen appliances, mobile phones, PV chargers used in cell phones- which constitutes a large category by itself- lamps and portable consumer electronics.

An interesting product idea for a PV-powered consumer product is a computer mouse (see Figure 3.1g), which had been analyzed, prototyped and tested during the Dutch SYN-Energy project (Reich et al., 2007, 2008a, 2008b, 2009; Alsema et al., 2005). Unfortunately, this product is not yet commercially available. On the other hand, a solar powered keyboard for PCs by Logitech is commercially available. Figure 3.2 shows several typical categories of PV products. In the original data set of 90 PV products that were analysed, 44 are consumer PV products. Consumer PV products form a rather large share of all PIPV in this study (49 %).

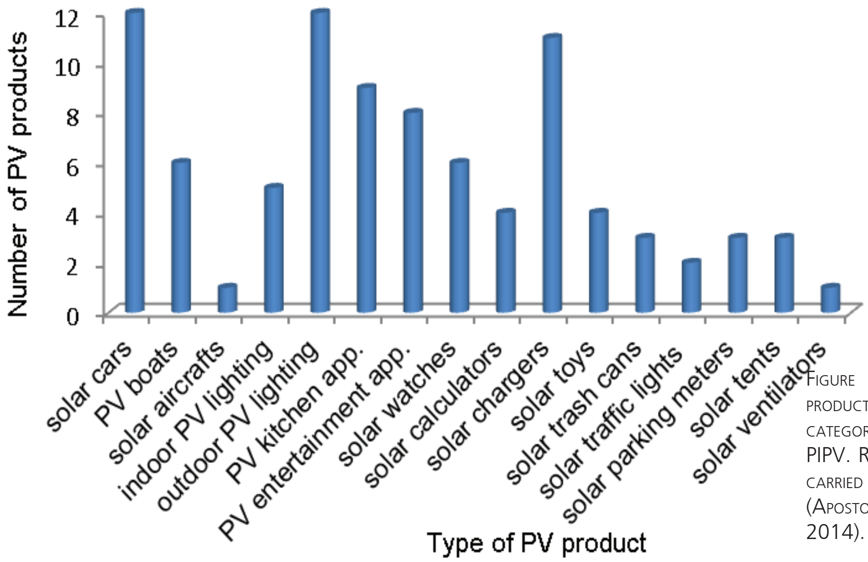


FIGURE 3.2: NUMBER OF PV PRODUCTS FOR EACH PRODUCT-CATEGORY IN OUR EVALUATION OF PIPV. RESULTS OF THE ANALYSIS CARRIED OUT IN 2011-2013 (APOSTOLOU AND REINDERS, 2014).

3.2.2 Lighting Products with Integrated PV

Numerous self-powered lighting products such as flashlights, ambient luminaires, lamps for bicycles, garden lamps, pavement lights, indoor desk lamps, street lighting systems, and other products for lighting of public spaces are commercially available. The power of lighting products varies between 1 W for one light emitting diode (LED) and 100 W, which could be the power of a street light pole (Reinders and van Sark, 2012). In Figure 3.2, 17 lighting products with integrated PV both for indoor and outdoor use are exposed; this is 19 % of the total share of PIPV evaluated in this study. 12 PV lights among 17 were used outdoors, such as garden lights, torches or street lights; and 5 PV lamps were used indoors, mainly consisting of desk lamps.

A solar lamp is a portable light device composed of an electric light source – usually an energy-efficient one, such as a fluorescent lamp or LED - an integrated photovoltaic panel, and a rechargeable battery. Outdoor lamps are typically used for garden decorations, while indoor solar lamps are often used for general illumination. Their function is based on the operating principle that they recharge during the day, they light at sunset (automatically, or using a switch) and remain powered during the night, depending on the amount of sunlight that they received during the day. Discharging time varies from one type of lamp to another; however it usually ranges from 8 to 10 hours.

3.2.3 Business-to-Business Applications with Integrated PV

In the same way as consumer and lighting products, PIPV has also been applied in business-to-business (B2B) applications. The power of solar cells of B2B products varies between 10 W to 200 W (Reinders and van Sark, 2012). Examples of business-to-business applications are: the parking meters, traffic control systems, traffic lights and trashcans. Nowadays, PV-powered public trashcans, with automated control of trash collection, are available and they are used successfully in many cities (Philadelphia, Newton, Shanghai). Their function centers on crushing trash using electricity produced by integrated solar panels. This offers a significant increase in bin capacity, by carrying approximately five times more waste or recycling compared to traditional trash bins.

Another B2B application available on the markets is the PV-powered ventilator.

PV ventilators can be operated in static boats and parked cars. The PV ventilator helps to decrease the temperature and humidity in the car, by withdrawing the hot stuffy air from inside the car and replacing it with fresher air from outside. PV also used in products for tele-communication (e.g. radiotelephone systems, microwave telephone and television repeaters), security, and environmental monitoring. In Figure 3.2, 9 PV products (10 %) of the category 'business-to-business' applications are included in the set of the 90 PV products analyzed in 2011-2013.

3.2.4 Recreational Products with Integrated PV

Products in the power range of 50 W to 500 W (Reinders and van Sark, 2012) that belong to this product group are the following: PV-powered caravans, motorhomes, campers, tents, solar-powered pond equipment (e.g. pond lights), solar-powered fountains and PV products for water sports (e.g. underwater lens).

Nowadays, modern caravans, motor homes or solar tents are gradually beginning to integrate PV panels on their roofs, which enable the use of lighting, refrigeration, laptops' charging and entertainment equipment, far away from the grid connection and supports battery charging. In figure 3.2, 3 recreational products with integrated PV were analyzed, concerning three different types of solar-powered tents.

3.2.5 Vehicles and Transportation

The 'Vehicles and transportation' category includes bikes, boats, cars, and planes; from 200 W power to 1500 W for cars and numerous kilowatts for planes (Reinders and van Sark, 2012) 19 PV-powered vehicles were analyzed (Apostolou and Reinders, 2012), (see Figure 3.2): 12 solar cars, 6 solar boats and 1 solar aircraft. The category of solar cars includes solar racing cars, bicycles and golf cars. Most of the above PV applications are still in the demonstration phase and they are not commercially available yet. Main drivers for product development in this category are contests like the Solar Challenge (World Solar Challenge, 2013) for racing cars in Australia and for solar powered boats in The Netherlands, for which reason new PV vehicles are designed, produced and investigated for potential future market implementation.

3.2.6 Arts

The category 'arts' contains mainly decorative products. The PV power of art products can vary significantly – from mW to kW- as can the location of usage (indoors and outdoors), (Reinders and van Sark, 2012). Some examples of 'art' PV products are the following: arty objectives (e.g. PV jewellery), art for public spaces (e.g. statues, fountains, art constructions for decoration of parks or squares, etc.), and indoor art (e.g. a PV-powered chandelier, decorative PV lights). In this category aesthetics are combined with usefulness. Well formed/built constructions bring imagination to life and present a beautiful visual outcome, due to the special PV features (colour, flexibility, reflexions).

3.2.7 Categories of indoor PV products

Of product categories outlined above, the majority of products are mainly high power PV products designed for outdoor use. This is due to the amount of energy that they need to function properly, which makes it rather difficult for them to be efficient indoors. The share of outdoor PV products in the sample that is investigated here is 66.7 %, while the share of indoor PV products is 14.4 %. Turning to the indoor environment, where indoor irradiance with typical levels between 0.1 and 10 W/m^2 is significantly lower than outdoors (usually up to 1000 W/m^2), fewer products are designed to survive. Therefore, different product categories are modulated for indoor use. The low power PV product categories for indoor use range between 1 mW up to a maximum of 10 W and they are defined as follows:

1. Consumer products (including mainly toys, calculators, watches, entertainment applications, PV chargers for indoor use)
2. Lighting products (including low power desk lamps)
3. Art objectives (Objets d' art) (requiring low energy supplies).

The operational voltage of low power PV products for indoor use typically ranges from 1 to 5 V. Most products (around 45 %) are completely autonomous; they do not require batteries for supplementary energy storage and they are not connected to the grid. They function exclusively using the electricity produced by PV cells.

3.2.8 Summary of PIPV

In this section product categories were investigated for both outdoor and indoor PV products. It is worth noting that PV technology is applicable to many different product categories for outdoor or indoor use, from low power consumer products at 0.001 W to high power solar cars and boats at several kW. Surprisingly, art is a new field in which PV has recently been introduced, as high-energy supplies are not required for art products to work, while, at the same time, a nice visual appeal is sought.

3.3 System Design and Energy Balance

In this section the results of the analysis of 90 PIPV are presented. Technically speaking, four PV system categories can be distinguished (see Figures 3.3, 3.4):

(1) autonomous PV system including battery,
(2) chargeable PV system including battery,
(3) autonomous PV system excluding battery and
(4) autonomous hybrid PV system including battery.

An hybrid PV system is a system consisted of two or more renewable energy sources (i.e. solar and wind energy). In the case of an autonomous hybrid PV system including battery, as category 4 indicates, the system uses PV cells and a small wind generator, which are used together to provide high system efficiency and energy balance. In Figure 3.3, the 4th scheme illustrates the autonomous hybrid PV system category including battery. RET 2 in the scheme indicates the additional renewable energy technology that is used together with the PV cells. Not surprisingly, about 65 out of 90 PV products analyzed belong to the autonomous PV systems with batteries (see Figure 3.4). It is remarkable that 13 PV products (14 %) don't use any batteries (see Figure 3.7). 67 % of the products analyzed were mainly used outdoors (see Figure 3.5). Nevertheless, many PV products (14 %) were intended for indoor use, whereas various products (19 %) could be used both indoors and outdoors.

Several different aspects such as the energy balance of the system's elements, the functionality, the design, the manufacturability, the cost, safety regulations, human factors and environmental aspects should be investigated during the design process of a PV system. Thereafter, PV system design for products, constitutes a particularly multifaceted undertaking, owing to the multidisciplinary character of the product development, as stated above.

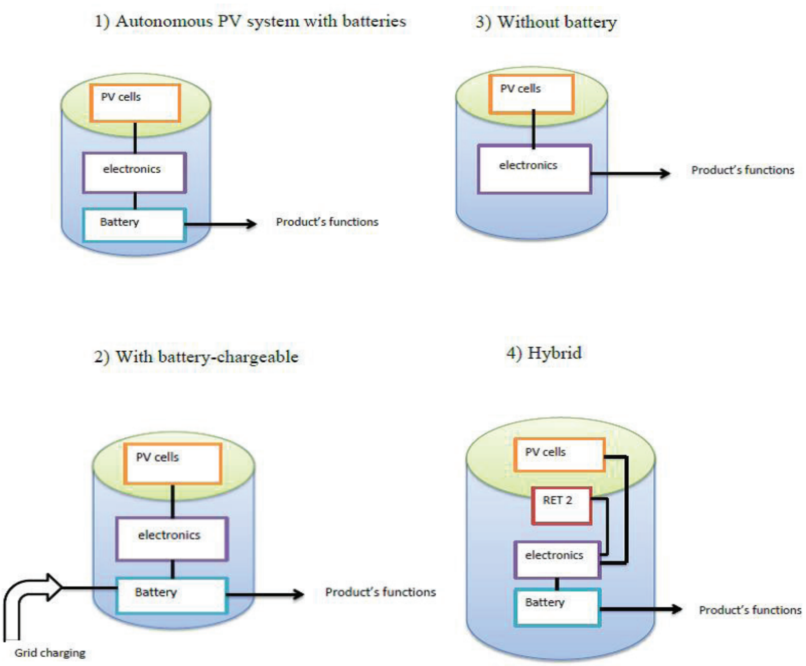


FIGURE 3.3: SCHEMATIC DEPICTION OF 4 PV SYSTEM CATEGORIES: 1) AUTONOMOUS PV SYSTEM INCLUDING BATTERY, 2) CHARGEABLE PV SYSTEM INCLUDING BATTERY, 3) AUTONOMOUS PV SYSTEM EXCLUDING BATTERY AND 4) AUTONOMOUS HYBRID PV SYSTEM INCLUDING BATTERY (APOSTOLOU AND REINDERS, 2014).

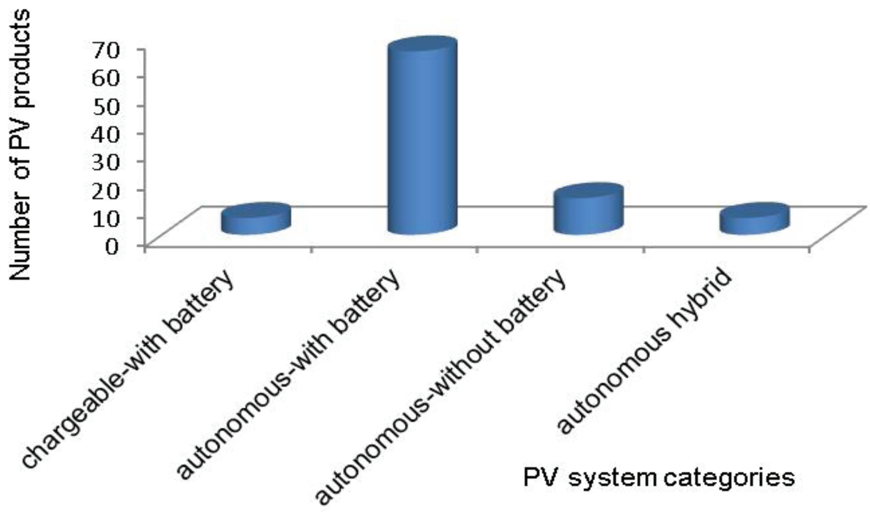


Figure 3.4: Amount of PV products of each PV system-category presented in figure 3. Results of the analysis carried out in 2011-2013 (Apostolou and Reinders, 2014).

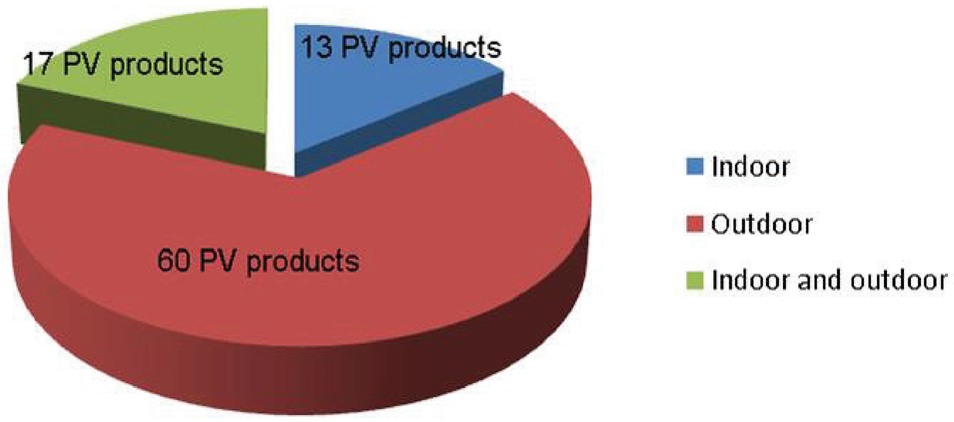


Figure 3.5: Amount of PV products, which are used under different irradiance conditions. Results of the analysis carried out in 2011-2013 (Apostolou and Reinders, 2014).

3.3.1 PV Cells

Through the design of a product-integrated photovoltaic, the efficiency of the PV solar cells plays a significant role as they determine largely, in combination with available irradiation, the power to be produced. The photovoltaic conversion efficiency η is defined by the ratio of the electrical power output P_{PV} (W) to the irradiance E (W/m^2) on a solar cell area A (m^2) and it is described by the following formula:

$$\eta = \frac{P_{PV}}{E \cdot A} \tag{3.1}$$

Efficiency depends on the PV technology selected, as well as the irradiance intensity, which is incident on the surface of the cell. The conversion efficiency η is determined under STC. Characteristic efficiencies and spectral response range of several major PV technologies, such as crystalline silicon, multi-crystalline silicon, amorphous silicon, nano-, micro- or poly-crystalline silicon, copper indium gallium selenide (CIGS), cadmium telluride (CdTe), III-V multi junction cells, dye-sensitized cells (DCS) and polymer solar cells have been presented in Chapter 2, (see Table 2.3).

Additional important factors that considerably influence efficiency are the temperature of the PV cell and the spectral distribution of the light. In indoor environments, the measured irradiance is significantly lower than outdoors and STC. However, the performance of non-optimized cells is greatly affected by indoor irradiance. This is due to the artificial lighting systems, which are used in houses or offices, and – hence - related low irradiance. We will explore indoor performance of PIPV under weak irradiance in greater detail in subsequent chapters of this thesis.

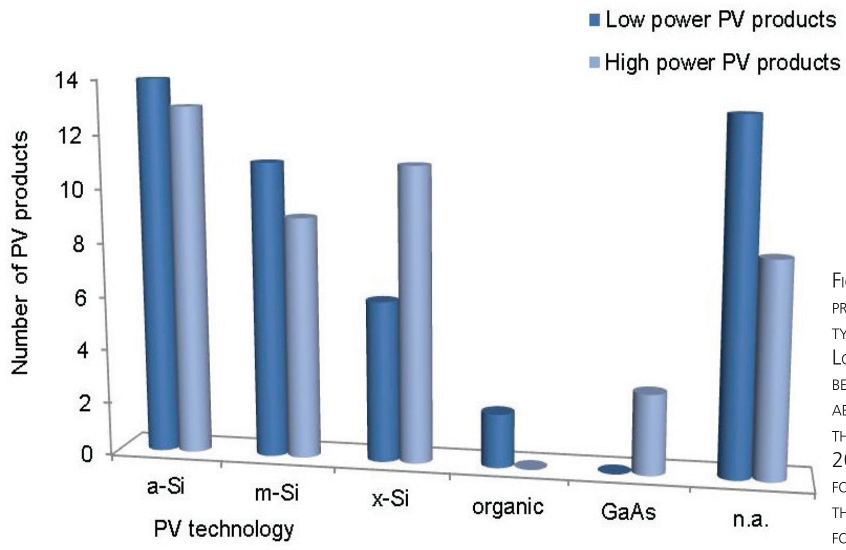


FIGURE 3.6: NUMBER OF PV PRODUCTS, WHICH USE VARIOUS TYPES OF PV TECHNOLOGIES. LOW POWER REPRESENTS POWER BELOW 17 WP, HIGH POWER ABOVE 17 WP. RESULTS OF THE ANALYSIS CARRIED OUT IN 2011-2013. ('N.A.' STANDS FOR 'NOT ANSWERED', MEANING THAT INFORMATION IS LACKING FOR SOME PRODUCTS).

Through the analysis of the design features of 90 PV-powered products it is clear that 14 low power PV products in the range of 0 to 17 Wp (16 % share of the total PIPV analyzed) use amorphous silicon cells, while 11 (12 %) use mono-crystalline silicon cells. No information was available concerning the PV technology that is used for 13 PV products (14 %). Moreover, it is worth stating that 2 PV products (2 %) of this set use organic PV cells (PV toys). This appears to be a good option for the future, as the use of organic PV could be safer for the environment, as well as an economical solution for low-cost products. On the other hand, 13 high power PV products in the range of 17 Wp to 27 kWp (14 %) use amorphous silicon solar cells, whereas 20 products (22 %) use multi-crystalline solar cells (m-Si or x-Si) (see Figure 3.6).

The extensive use of a-Si solar cells to numerous PV products is a consequence of their low price compared to other technologies, as well as the wide variety of sizes and shapes of a-Si cells, which are commercially accessible.

The threshold for low and high power, as it is presented in Figure 3.6, is set at 17 Wp, due to the gap that was noticed among the analyzed PV products with power 17 Wp and 1 kWp. More specifically, a share of 74 % of the low-powered PV products has power between 0,1 Wp and 10 Wp. Only 6 % of the low-powered PV products have power between 10 Wp and 17 Wp. Regarding the high-powered PV products, it is noticed that products of that sample have power in the range of kWp. Therefore, there is a range of power between 17 Wp and 1 kWp, where no PV products of the sample that it analysed here belong. This is the reason that the threshold is set at 17 Wp.

3.3.2 Rechargeable Batteries

Batteries are used extensively in PV products in order to store electricity for use when the PV cells are not able to function properly, or to withdraw power higher than the panel cells. About 86 % of PIPV products have an energy storage device (see Figure 3.4). This could be a capacitor, which can be used for short periods of storage (Kan, 2006) or a battery, which can be used for longer periods of energy storage. Present batteries in PIPV are sulphuric lead-acid, nickel-cadmium (NiCd), nickel metal hydride (NiMH), lithium ion (Li-ion) and lithium/ manganese dioxide ($LiMnO_2$) batteries. Among these technologies nominal cell voltage can vary from 1.2 Volts for NiMH and NiCd batteries up to 4.1 Volts for Li-ion batteries. Efficiency also varies from around 66 % for NiMH batteries to 95 to 98 % for Li-ion batteries.

In Table 3.2, characteristic specifications are given for cells of different rechargeable batteries applied in PIPV.

Table 3.2: Specifications of various rechargeable batteries' cells, which can be applied in PIPV [a].

Battery type	Nominal cell voltage (V)	Specific energy (Wh/kg)	Energy density (Wh/L)	Cycle life, 20% fading (cycles)	Specific power (W/kg)	Efficiency (%)
Lithium ion	4.1	100-265	250-730	500-1200	250-340	95-98
Lithium/ manganese dioxide	3.0	100-280	265-690	500-1000	100-315	80-95
Nickel-cadmium	1.2	40-80	50-150	1000-2000	50-200	66
Nickel metal hydride	1.2	75-120	140-300	600-1500	250-1000	80-90
Sulphuric lead-acid	2.1	30-50	80-90	500-800	75-180	

[a] Source: Apostolou and Reinders, 2014. (Adapted from Reinders and van Sark, 2012 and updated with Intertek, 2013; Duracell, 2013; ThermoAnalytics, 2013, Battery University, 2013).

**Battery efficiency: the energy efficiency of a battery is a percentage x %, which shows that x % of the energy that was put into the battery during charging is all that is available for release during discharge. The energy efficiency is given as an approximate number since discharge rates and temperature can affect it.

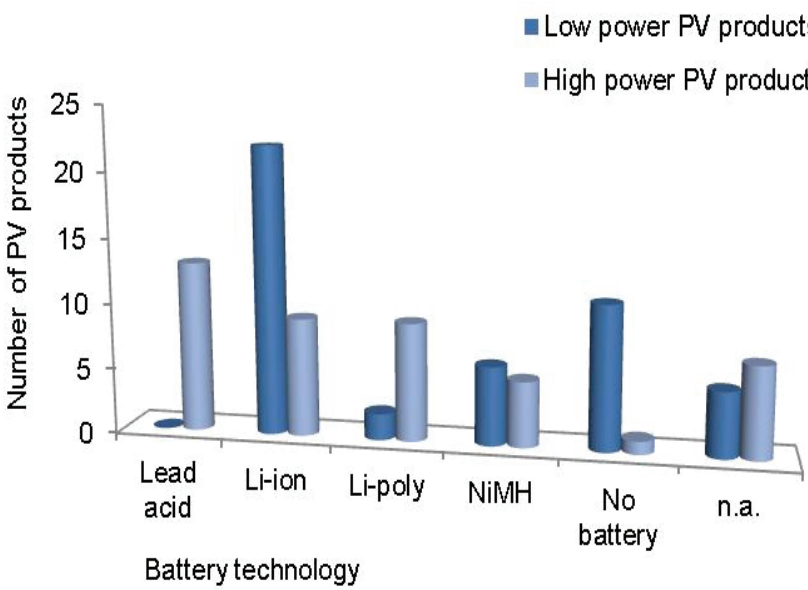


Figure 3.7: Number of PV products, which use various battery technologies. Low power represents power below 17 Wp, high power above 17 Wp. Results of the analysis carried out in 2011-2013 (Apostolou and Reinders, 2014).

The main characteristics of batteries are their voltage, their size, capacity, weight and obviously the price. The battery voltage is determined by the enclosed active materials. For example alkaline batteries have a voltage of about 1.2 V. Lead-oxide (Lead Acid) batteries deliver 2.1 V, while Lithium ion batteries provide 4.1 V.

The results from the analysis of 90 PV-powered products demonstrate that 22 low power PV products (24 % of the total) use Li-ion batteries, while 6 (7 %) use NiMH. Around 12 % of them use no batteries. Furthermore, 24 % of the low power PV products analyzed have a battery capacity of between 1 to 3 Ah, while 19 % have a capacity between 0.01 and 1 Ah. Li-ion batteries are the most common type of battery, due to their availability in a wide variety of shapes and sizes, suitable for the devices they power. On the other hand, 13 high power PV products (14 %) use lead acid batteries, whereas 18 products (20 %) use lithium batteries, either Li-ion or Li-poly, which are both the most common battery types which are used for this kind of products (see Figure 3.7). 53 % of the high power PV products analyzed use batteries with a capacity between 1 to 100 Ah. Lead acid batteries are the most common type of batteries. They are rechargeable, quite cheap and available for purchase practically everywhere.

These batteries are typically used in machinery, robotics, automobiles and several other applications. In general, when issues such as the size or the weight of the batteries used in a product are not significant enough and if there is a need for energy, lead acid batteries are usually preferred.

3.3.3 Summary of System Design

Thin film solar cells of amorphous silicon are used in most PV products examined (30 %). Secondly, crystalline silicon cells are also applied to many high and lower power PV products (around 22 % of the total number of PIPV analyzed). It is worth pointing out that the most common battery technology for low power PV products is lithium ion, while for high power PV products lead acid or lithium batteries are preferred. Generally speaking, the analysis of the 90 PV products shows that there exists a correlation between PV and battery technologies. Products with power below 17 Wp use a combination of a-Si/m-Si cells and Li-ion batteries (around 25 % of the low power products analyzed). This is due to the low costs of these technologies, as well as their availability on the markets. On the other hand, high power PV products (above 17 Wp) usually use a combination of Si cells (a-Si, m-Si, x-Si) and lead acid or lithium batteries (around 35 %). The reason is that companies try to keep the cost of production as low as possible and they choose cheap, easily available, technologies for their products. Moreover, it is essential to note that recently research is turned towards the investigation of new technologies of PV cells and batteries, whose basic features are transparency and flexibility- issues that leads to a new design of products and applications.

Alternatively, in addition to the basic categories of PV technologies, research has recently focused on the production of transparent solar cells for use in buildings or products, such as e-readers and tablets (Lunt and Bulovic, 2011; Chen et al., 2012; Venture Beat, 2013; Zhao et al., 2014; ExtremeTech, 2015; Ubiquitous Energy, 2015). Research has been conducted on the fabrication of organic and polymer photovoltaic cells, which are able to absorb light in the ultra-violet and near-infrared range of wavelength and remain transparent in visible light (Lunt and Bulovic, 2011; Chen et al., 2012; Zhao et al., 2014; Ubiquitous Energy, 2015). It is expected that in the years to come, organic and polymer PV cells with efficiencies higher than 10 % (MIT, 2013; Zhao et al., 2014; Ubiquitous Energy, 2015) and high visible transparency will be available for incorporation in buildings, smart windows, PV products and other PV applications.

Unfortunately, PIPVs with transparent PV technologies have not been explored in this thesis, because they were not commercially available at time of this study. An alternative approach to creating transparent batteries was conducted by researchers at Stanford University (Yang et al., 2011; MIT Technology Review, 2016), who were inspired by the numerous commercially available applications, such as touch screens, Smart phone displays and PV cells. It is noticeable that see-through devices have recently attracted considerable attention. Yang et al. (2011) succeeded in forming an entirely transparent lithium-ion battery, which was quite flexible and thin. The transparency of the electrode was a result of its feature dimension, which was below the limit of human eye' resolution. The outcome was a 60 % transparent battery with 10 Wh/L energy density. Recently, a research group from Japan at the Kogakuin University, prototyped a translucent lithium-ion (Li-ion) rechargeable battery, which charges itself using solar irradiance (Tech Xplore, 2015; Nikkei Technology, 2015). This battery was exhibited recently (in 2015) in Tokyo (Tech Xplore, 2015; Nikkei Technology, 2015).
Researchers claim that transparent batteries will be stronger soon and used in a wide range of applications (MIT Technology Review, 2016; Tech Xplore, 2015). Additionally, a lot of research has been done on ultrathin batteries, the so-called "paper batteries" (Noyes, 2007; Clark Liat, 2012; Di Wei et al., 2013, Williams, 2013; Chandler, 2013; Hankeun Lee and Seokheun Choi, 2015; Sastikar et al., 2015). It is expected that paper batteries will be soon used on bendable electronic devices, such as phones with roll-able displays and e-readers (Lan Yoon, 2012).

3.4 Environmental Aspects of PIPV

An effective approach to quantify the environmental impacts of products is to use life-cycle analysis (LCA) during the initial phases of design and to identify the extent of the problem by imposing priorities and focusing on effective solutions. An environmental life-cycle analysis (LCA) is defined as: "consecutive and interlinked stages of a product system, from the raw material acquisition or the creation of natural resources to the final disposal. The main stages of a product's life include: the acquisition of raw materials, the phase before construction, manufacturing, packaging and distribution, use and end of critical life" (ISO, 2006).
An LCA usually constitutes of an environmental management tool and it helps to address environmental problems through materials selection, processes of changing the product design, increased reuse, exploitation of by-products, and recycling.

"Sustainable" or "ecological" design of products establishes the incorporation of environmental features within the product design aiming to improve the conservational performance of the product throughout its lifespan. By sustainable design of PIPV products, their environmental impact should become lower than that of the current alternative designs. However, this is a quite new field of research and it is still in progress. Therefore, the environmental aspects of products with integrated PV cells have not been addressed extensively so far. For this purpose an LCA analysis can be used. Furthermore, other important indicators for sustainable product design are embodied energy and CO_2 emissions based on common data for materials and manufacturing processes. These can be used as a rough estimation. Below, two examples are given concerning a detailed environmental study on solar lanterns and a more explorative one on mobile phones.

An LCA on small PV lighting products was carried out in South East Asia (Durlinger et al., 2012), aiming to examine the environmental impact of the production, use and end of critical life of these products. Illumination in the rural areas of developing countries is usually provided by candles and oil lamps (kerosene), whereas torches and flashes often powered by car batteries or lead acid batteries are also used as a portable source of lighting.

Figure 3.8 presents five lighting options for developing countries. These options are described extensively by Durlinger et al. (2012) and are the following:

- a small PV lighting system 1, which is powered by an a-Si solar panel of 0.7 Wp. It also includes two NiCd batteries of 0.2 Ah (AA-type). This product has 6 LED lamps of 42 lumens.
- a small PV lighting system 2, which is powered by a x-Si solar panel of 4.5 Wp. It also includes a lead-acid battery of 4.5 Ah. This product has a compact fluorescent lamp (CFL) of 3 W and 150 lumens.

- a solar home system (SHS), with an x-Si solar panel of 40 Wp and a lead-acid battery of 48 Ah. It also includes 3 CFL lamps of 7 W.
- battery charged at station and CFL. The capacity of the batteries is in the order of 100 Ah. A diesel-powered generator charges the batteries.
- grid connection and CFL. This system includes a CFL lamp and it is connected to the grid. There is neither solar panel, nor battery.

The study (Durlinger et al. 2012) shows that solar PV lighting products have a lower environmental effect than the conservative options for lighting in these countries have, see Figure 3.8. The data presented in Figure 3.8 are normalized (Durlinger et al., 2012). A value of 0.01 corresponds to 1 %. Batteries' recycling is one way, whereby the eco-friendly profile of small size PV lighting products can be enhanced. The authors claim that an upgrade of 10 % up to 50 % of the environmental profile of these products can be achieved by batteries' recycling. Moreover, it is mentioned that small size PV lights have lower effect to the environment, compared to grid connected fluorescent lights. Intrinsically, PV lighting products offer an environmentally friendly and advantageous illumination service for off-grid households. Another important conclusion of this study is the possible enhancement of the environmental profile of solar lighting products by means of sufficient battery waste controlling or the use of circuit panels of a reduced size.

In section 3.3, 17 PV lighting products are analysed; 5 PV-powered lamps for indoor use and 12 for outdoor use. The low-powered PV lighting products with power in a range of a few Wp (0.1 to 10 Wp), are mainly designed to be charged outdoors and used indoors. These products have a small PV area, usually made by either mono- or multi-crystalline silicon cells, which could be integrated in the luminaire's surface or consist a separate product connected to the luminaire. The area of the PV cell depends on the available surface on the product and is usually a few cm^2. PV-powered lights also include one or more small rechargeable batteries with capacity 1.2 to 4.1 Ah each one, depending on their type (e.g. Lithium ion, NiMH, NiCd, etc.). The limited area of the PV cell, as well as the rechargeable batteries, which can be recycled, offer an environmentally friendly character to these lighting products, since these elements contribute to a safer waste controlling than the grid-connected fluorescent lamps. However, a further analysis of the environmental impact of these products is out of the scope of this research and is not included in this thesis.

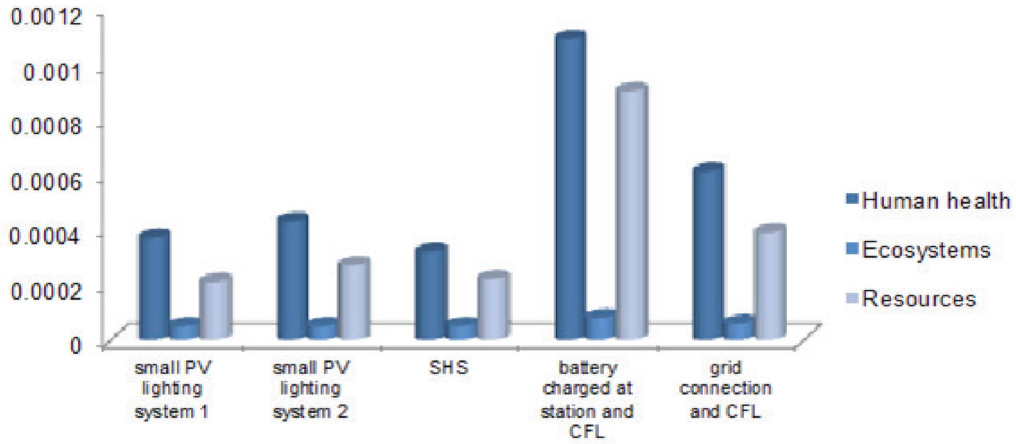


Figure 3.8: Results per functional unit in environmental effect groups of an LCA of small PV powered lighting products and conventional means to provide light in rural areas in South-East Asia. The kerosene lamp is excluded. Presentation of the results on a linear scale (Apostolou and Reinders, 2014; Durlinger et al., 2012).

Another study provides a battery life-cycle assessment for mobile phones with a focus on cradle-to-grave (CTG) energy and greenhouse gases (GHG) emissions (Flipsen et al., 2012; Dafnomilis, 2012). The study is based on bibliographical data and on a comparison of four different types of Smart phones using an original battery and after a reduction of the battery capacity while using a solar cover.

The four Smart phones, as presented in Figure 3.9 and 3.10, and their battery specifications are the following:

- Samsung Galaxy SII (Li-ion battery, 3.7 V, 6105 mWh)
- Sony Ericson Xperia mini (Li-polymer, 3.7 V, 4440 mWh)
- HTC Wildfire (Li-polymer, 3.7 V, 4810 mWh)
- Blackberry Torch (Li-ion, 3.7 V, 4700 mWh)

The modifications made to these smart phones include an x-Si solar cover and a new battery with around 30 % lower capacity than the original battery of each smart phone (Dafnomilis, 2012). The typical back area of an average smart phone is calculated around 0.0067 m^2. The 70 % of this area can be covered with a PV panel.

This means that the area of the smart phones' solar back cover will be around 0.0047 m^2 with power 72 mW (using solar energy data for The Netherlands) (Dafnomilis, 2012).

Findings from this study (Flipsen et al., 2012; Dafnomilis, 2012) indicate that a reduction of 30 % of the batteries' capacity will result in a reduction of approximately 30 % of the energy consumed during the production of raw materials, manufacturing and CO_2 emissions during the battery's lifetime. From this point of view, solar phones can be an environmentally friendly solution to oversized batteries – especially for moderate and light users or in countries with sufficient annual sunshine. Besides, they can be an ideal solution for off-grid areas.

Results from this study are presented in Figure 3.9, where the total energy comparison between two different technologies- a mobile phone without modification and one with a smaller battery including a solar cover- for four types of smart phones is indicated. In Figure 3.10 a comparison of CO_2 emissions is presented respectively.

As Figures 3.9 and 3.10 illustrate, the use of a solar back cover combined with a battery of reduced capacity offers benefits to the energy that is consumed during the extraction process of raw materials, the manufacturing process of the products, as well as to the CO_2 emissions during these procedures. CO_2 emissions required during the life cycle of the original smart phones are significantly higher than CO_2 emissions required for the modified smart phones (see Figure 3.10). The solar back cover usually has longer lifetime than the batteries. This means that when the battery is at the end of its life, the solar cover is not necessary to be changed. The solar cover could be used with a new battery on the same smart phone or else could be modified and integrated to another smart phone. This might be an advantageous opportunity for the foreseeable future; the use of product's assembling parts to other products. In that way materials are recycled and products' environmental profile is enhanced.

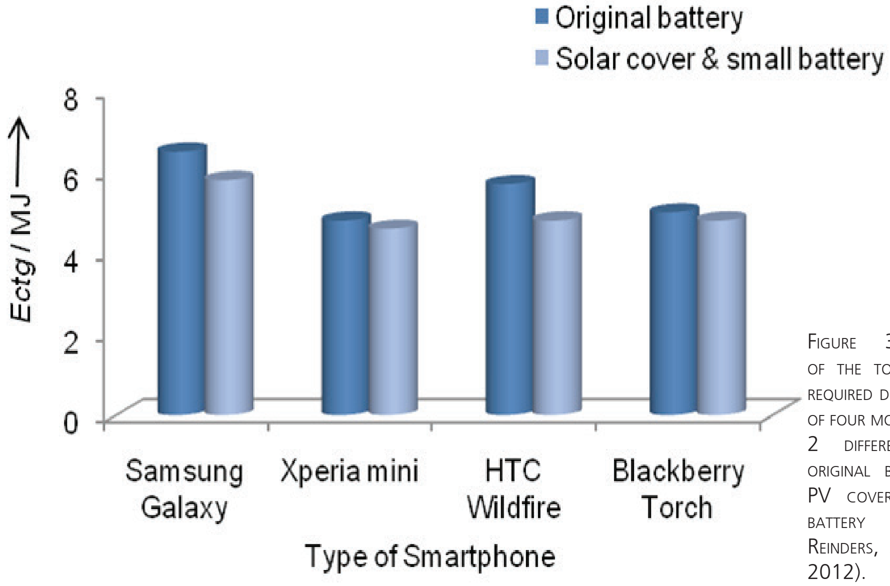


FIGURE 3.9: COMPARISON OF THE TOTAL ENERGY (ECTG) REQUIRED DURING THE LIFE CYCLE OF FOUR MOBILE PHONE, BETWEEN 2 DIFFERENT TECHNOLOGIES; ORIGINAL BATTERY AND SOLAR PV COVER WITH A SMALLER BATTERY (APOSTOLOU AND REINDERS, 2014; DAFNOMILIS, 2012).

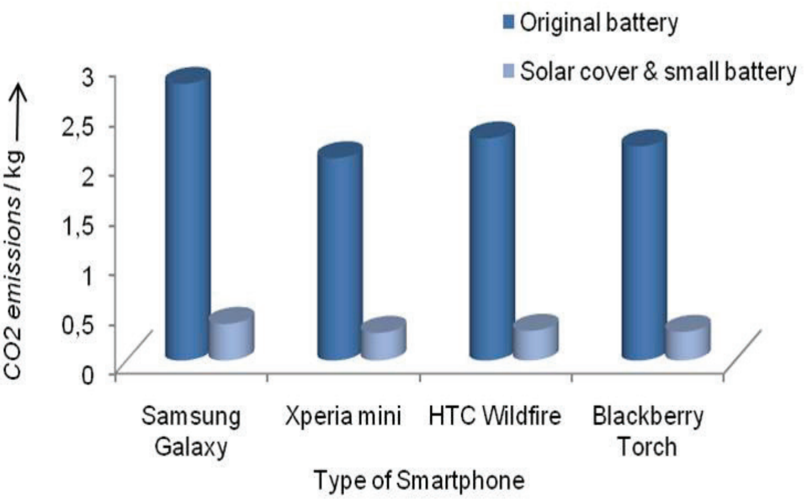


Figure 3.10: Comparison of the amount of CO_2 emissions required during the life cycle of four smart phones, between 2 different technologies; original battery and solar PV cover with a smaller battery (Apostolou and Reinders, 2014; Dafnomilis, 2012).

3.5 Human Factors of PIPV

In the stage of the implementation of PIPV products, users' involvement and awareness of the products are significant. Consumers prefer to buy products that not only have sufficient functions, but also because of their looks. They desire products with a nice visual appeal, colour, material, design, as well as products that raise their emotional reactions.

Although human factors constitute a key element for the successful transaction of a product, there is actually little research published on this subject with regards to PIPV. On the other hand studies regarding users' interactions with products have been conducted towards sustainable design (co-design) by many researchers (Bakker et al., 2010; Jong and Maze, 2010; Keyson and Jin, 2009; Wever et al., 2008; Scott Kakee, 2008; Scott Kakee et al., 2009; Verbeek and Slob, 2006; Jong et al., 2008). Regarding user's interactions with PIPV products only one extensive study is available. This study concerns the assessment of the Sole Mio; a prototype of a PC computer mouse (Figure 3.3g). It was carried out during the period September–December 2007 in the Netherlands (Reich et al., 2008). In this study, 14 people participated and asked to use the Sole Mio mouse daily for some weeks. A number of users had a test of 5 to 6 weeks, while others an extended one of 10 to 12 weeks.

Part of the results of the user tests focused on the general user expectations, experiences with charging batteries, reactions to the feedback signal for battery charging and user willingness to buy a SoleMio (Reich et al., 2008). The outcomes of the study are summarized below:

The majority of the users, at the beginning of the test procedure, were completely unaware of the test's expectations. The performance of the mouse varied significantly from one day to another and this generated a feeling of doubt about the unreliability of the product. Generally speaking, users' impression concerning the Sole Mio mouse was negative. Furthermore, the period when the test took place was during the wintertime, when the solar irradiation was considerably lower than during the other periods of the year. This was not only a difficult undertaking for the performance of the product, but it was also an interesting experiment concerning the worst-case scenario of usage. If the mouse operates sufficiently during this period, then it will perform even better during the lighter days of the year.

Regarding charging the battery of the Sole Mio, the solar cell in the product was exposed to a higher irradiance on the window sill, through so-called sunbathing. Each user followed its private charging strategy. Some users charged the mouse the entire day on the window sill, while others were charged it once per week, whenever the mouse's battery was empty. The evaluation's outcome was diverse. Undoubtedly, the mouse had a satisfactory performance when treated well by charging when required. Moreover, the mouse included a light sign, which indicated that charging is in process or that the mouse needs to be charged. Nonetheless, many users claimed that the existence and the function of the light indicator were rather vague to them.

Based on the user tests and interviews previously mentioned, it is clear that some users were more excited about the Sole Mio mouse than others. Satisfied users might be willing to spend around €50 to buy the product. However, since the mouse is still not available on the market, it is questionable whether users would still be willing to buy it or not. Unfortunately, this issue cannot be tested.

Finally, the experiment pinpointed two categories of customer. The first category includes those who were enthusiastic about the Sole Mio mouse and believed that it could be a good choice. However, they were not willing to buy it, as they would prefer a more reliable and low-priced mouse instead such as the normal wired mouse. The second category consists of customers, which would be willing to buy the Sole Mio mouse. However, they only agreed to offer about €10 more for the Sole Mio mouse than for a conventional mouse. If the cost was higher it is doubtful whether they would actually buy it.

3.6 Costs of PIPV

By the previous findings regarding the Sole Mio mouse the topic of costs of PIPV has been introduced. Cost of a product is the expense incurred by a corporation in order to sell it. It might include raw, material, production, labour, tooling, utilities, operating, shipping costs and other possible expenditure until the product will be finally commercially available. Therefore, it is quite difficult to accurately estimate the costs of a product without access to the company's data (e.g. product manufacturers, product development departments).

However, even if the cost of a product is difficult to be predicted, the sales price is easily obtainable and it is the one, which directly concerns the consumer. Industries target on low-cost products, which are affordable to consumers. In order to succeed in low sales prices, companies usually choose low cost materials and services during the manufacturing process of the product. On the one hand, this could lead to cheap products and high sales, but on the other hand to low quality products with an ambiguous performance.

Concerning the sale price of PV products, the results of the analysis carried out from 2011 to 2013 show that there is a wide range of prices either for indoor or outdoor PV products (Figure 3.11). Outdoor products, such as solar boats, aircrafts or cars are quite expensive and some of them cost several thousands of Euros. This is due to their complex production, their size, the cost of materials, the human effort that is needed and the time of manufacturing. In general, most of the products, which belong to the categories of recreational PV products, solar vehicles and transportations, business-to-business PV applications, as well as art PV products having high sale prices ranging from hundreds to thousands of Euros (see Figure 3.11). However, there are multiple outdoor PV products which are quite affordable, such as solar lighting products or consumer products. The sale price of these products ranges between 10 Euros (e.g. solar garden lights) and 100 Euros (e.g. solar lawn mowers) (Apostolou and Reinders, 2012).

Indoor PV products usually have lower costs than outdoor do. However, this is not a rule, as there are also some rather expensive indoor PV products (e.g. i-phone charger, Figure 3.1c). Several products such as indoor PV lights, solar toys, solar desk lamps, PV chargers might cost few Euros (from less than 10 Euros to 50 Euros), as Figure 3.11 indicates. The sales price of these products is defined by the design complexity, materials, originality of the idea, the concept of the product and many other factors. Over the following years it is expected that the cost of product manufacturing, as well as product sale prices will be reduced, as new technologies are investigated in PV materials and batteries with higher performances, better technical features and lower costs.

FIGURE 3.11: SALE PRICES IN EURO OF NUMEROUS PV PRODUCTS BOTH FOR INDOOR AND OUTDOOR USE. RESULTS OF THE ANALYSIS CARRIED OUT IN 2011-2013 (APOSTOLOU AND REINDERS, 2014).

3.7 Summary and Conclusions

This chapter presented several categories of product-integrated photovoltaics and addressed various features of PV products. PIPV can be applied well in different product categories of various power levels, ranging from several mW to hundreds of kW. Four PV system categories were distinguished. About 65 out of 90 PV products analyzed consist of an autonomous PV system with batteries. 67 % of PV products are used outdoors, while around 14 % are used indoors and 19 % both indoors and outdoors. Approximately 30 % of the low power PV products in the range of 0 to 17 Wp use thin film solar cells (a-Si), whereas 55 % of high power PV products in the range of 17 Wp to 27 kWp use x-Si solar cells or a-Si. 86 % of PIPV products use an energy storage device, while 14 % do not use any batteries.

The environmental impact of PIPV products was explored using the example of Smart phones and a PV lighting product in South East Asia. Human factors were also addressed, using the example of the PC computer mouse Sole Mio. On the basis of these cases it was concluded that the environmental impact could be reduced by recycling batteries, replacing original batteries with smaller ones or using an additional solar cover.
However, this is not feasible for all products or for all user types. On the other hand, concerning the environmental impact of PV materials, Durlinger's studies (2010, 2012) claim that solar lighting systems have a considerably lower environmental effect than the conservative lighting options, which are broadly used in off-grid areas.

The example of the computer mouse Sole Mio shows that the performance of the product depends mainly on the user's behaviour. In this example it was revealed that the performance of the mouse varies according to user charging tactics. Some users were willing to sunbathe the mouse for a longer period or more often than others. As a result, their mouse performed better than those that were charged infrequently. Moreover, the mouse was often found to be unreliable after sunbathing.

While designing products with integrated photovoltaic, the focus should be on both the environmental impact and human factors. These two aspects are closely related to each other and should be analysed together. They have also not been evaluated extensively so far.

Based on our evaluation of existing knowledge, it is believed that PIPV will be further developed in the years to come. Likewise, it is expected that new PV products will be launched for both outdoor and indoor use, such as sensor networks, indoor lighting, luminescent solar concentrator photovoltaic (LSC-PV) street lighting (Viswanathan at al., 2012) or art products. Furthermore, new low-cost PV technologies based on organic materials with enhanced design features such as coloring, flexibility and transparency, though not yet commercially available, might be expected in the next decade (Lunt and Bulovic, 2011; Chen et al., 2012; Lee et al., 2013; Hosel et al., 2013) as well as transparent batteries with high energy density that can power multiple future gadgets (Yang et al., 2011).

CHAPTER 4

Indoor Irradiance

Chapter 4 is partly based on the following publications:

Apostolou G., Reinders A.H.M.E., Verwaal M., 2012, "Spectral irradiance measurements in a room fit for indoor PV products", Proceedings of the 27th European PV Solar Energy Conference (EUPVSEC), Poster Presentation, Frankfurt 2012, Germany, pp. 4240-4244.

Apostolou G., Reinders A.H.M.E., Verwaal M., 2016, "Comparison of the indoor performance of 12 commercial PV products by a simple model", Energy Science & Engineering, Wiley Online Library, January 2016, Article first published online: 22 Jan 2016, Volume 4, Issue 1, pp. 69-85.

4.1 Introduction

Photovoltaic (PV) technology can be implemented in a variety of consumer products. These products can be used in indoor environments. However, in such cases on average the irradiance may be low. In that particular situation, energy from the lamps that lit a room can be harvested, by means of PV cells, to contribute to the production of electricity. In that way, not only is natural solar energy used but also indoor artificial irradiance is exploited.

Indoor irradiance usually consists of a mixture of natural light (sunlight) that enters a building through windows, as well as artificial light. Artificial light usually comes from different light sources: lamps that are used to illuminate a house, such as incandescent lamps, fluorescent lamps and light emitting diodes (LEDs). In general, indoor light conditions are typically created by artificial light sources with irradiance below 10 W/m^2 (Mueller, 2009; Kan, 2006). Therefore, the solar cells that are incorporated into the electronic products can generate limited amounts of electricity, in the order of μW to a few mW/m^2.

Due to the distance to windows, electronic products that are used indoors are usually exposed to small amounts of solar energy. Furthermore, the locations in which the PV-powered products are used can be identified by various irradiance conditions. This makes it quite difficult to exactly identify the irradiance under indoor conditions.

On the basis of an overview of the design features of PIPV as presented in Chapter 3, it is essential to identify the irradiance conditions under which these products are used indoors. More specifically, this chapter in particular addresses the irradiance under indoor conditions by giving a theoretical framework and by presenting measurements. With the results of this study, industrial designers will be better informed about weak irradiance conditions in indoor environments when developing PV products.

Moreover, there are other important reasons for conducting measurements of indoor irradiance in this thesis, namely that radiometric data are basically lacking in the literature, because most research so far is based on photometric data (Deru et al., 2005; Fakra et al., 2011; Mueller et al., 2009). Deru et al. (2005), Fakra et al. (2011), Mueller et al. (2009) and many other researchers measured indoor illuminance (in lux) or luminous exitance (in $lumens/m^2$) and proposed models for the simulation of the indoor environment.

However, these simulations are mainly based on photometric data, which are not suitable in our case. In this thesis, indoor irradiance is the focus point. Therefore, the collection of radiometric data is essential in order to test and estimate the performance of photovoltaic cells in an indoor environment.

The goal of this chapter is therefore to quantify indoor irradiance, by measurements, aiming to better understand and quantify the performance of PV solar cells in indoor conditions.
The main research questions that motivated us to carry out this study are:

1. What are the indoor irradiance conditions and
2. How the irradiance varies indoors according to the distance to the artificial light sources and according to the distance to windows.
3. Whether PV products can function properly under indoor irradiance conditions.

4.2 Literature on PIPV at indoor irradiance

An emerging challenge is to succeed in designing PV products with high performance at indoor environments, in order to cover consumers' daily energy needs. At present the typical efficiency of PV products at indoor environment is rather low, below 10 %. A reasonably high performance of PV products in an indoor environment would be between 10 and 20 %. Unfortunately, it seems rather difficult for the products at the moment to achieve higher efficiencies. Many efforts have been made for the use of PV products not only outdoors, but also in the home environment. Though, the results are disappointing, as most indoor PV products do not function properly. What is necessary to be done in order to achieve designing indoor PV products with better performance than the existing products, is to take into consideration the levels of indoor irradiance, the amount of indoor irradiance that can be used from the cells to produce electricity, the amount of electricity to be produced and the product categories that can function efficiently under these conditions. Using the term efficiency, we refer to energy efficiency, which is estimated as the ratio of the useful power output of an energy conversion device per total power input (power consumed). The useful output may be electric power, mechanical work, or heat, depending on the device and its functions.

Several studies have been devoted to solar cell performance under weak light or indoor irradiance conditions. Research on indoor irradiance shows that though indoor irradiance can exceed 500 W/m^2, basic orders of magnitude typically are about 1 to 10 W/m^2 with worst-case scenarios in the winter without the use of artificial light in the range of 0.1 W/m^2 (Mueller 2009, 2010).

Many studies on solar cell performance were also conducted by several researchers in the field (Randall, 2003, 2006; Reich et al., 2005, 2009; Girish, 2006; Gong et al., 2008). The most recent study deals with the simulation of the performance of various photovoltaic materials for different spectral distributions, in order to identify the maximum efficiencies (Freunek et al., 2013).

Results of this study show a maximum efficiency of 16 % for a GaInP cell with 1.88 eV energy gap. Generally, PV modules need further optimization for indoor applications.

When designing indoor PV products with high performance, designers should be better informed on indoor irradiance. Kan (2006), Randall (2009), Reinders et al. (2012), Reich et al. (2008), Mueller at al. (2009), Gorlatova et al. (2010), studied indoor irradiance in different ways leading to valuable knowledge to continue the research in this field. For indoor photovoltaic systems Randall (2009), Roth (1991) and Roundy (2004) have also presented studies on indoor irradiance. However, most studies do not consider the variety of factors in rooms, such as people presence, shad(ow)ings or different places of lamp installation, which can affect indoor irradiance. Furthermore weak irradiance is difficult to measure due to low values and the limited accuracy of sensors, as well as the expensive experimental equipment that is needed for this kind of measurement.

4.2.1 Photometry vs. Radiometry

Light is the electromagnetic radiation weighted by the eye sensitivity, which lies between 380 to 780 nm (Ryer, 1998). The luminosity function V(ก), which is established by the Commission Internationale de l'Iclairage (CIE), defines the luminous flux or the visible energy of a light source.

Photometry is the science that examines the visible part of the electromagnetic spectrum and specifically the spectral power weighted according to the sensitivity of the human eye. It is a quantitative science based on a statistical model of the human perception of light under carefully controlled conditions. The human perception encompasses much more than just spectral sensitivity to isolated color patches, such as psychological relevant issues (Koenderink et al., 2007). The human retina is a remarkably complex and highly nonlinear detector of electromagnetic radiation with wavelengths ranging from 380 to 780 nm. The human visual system refers to both the eye and the brain. Here only the first stage – the eye – is addressed.

Light of different wavelengths is seen as a continuum of colors ranging through the visible spectrum: 650 nm is observed as red, 540 nm as green, and 450 nm as blue. Color perception in natural scenes is however not 1-to-1 related to the wavelength of the light; natural reflectance spectra are usually very broad.

The light that enters the eye is the result of complicated interactions between illumination (source spectra) and reflectance spectra plus shading, shadowing, (inter)reflections (Boyce, 2014; CIE, 2000-2015). Higher order brain processes and psychological processes have an extremely large influence on what is actually seen.

The sensitivity of the human retina to light varies with wavelength. A light source with a radiance of one Watt/m^2-steradian of green light, for example, appears much brighter than the same source with a radiance of one Watt/m^2-steradian of red or blue light.

In photometry, no radiant energy is measured. Rather, it is attempted to measure the subjective impression produced by stimulating the human eye with radiant energy. The subjective impression of the colour sensation can be quantified for "normal" viewing conditions. In 1924, the CIE asked one hundred observers to visually match the "brightness" of monochromatic light sources with different wavelengths under controlled conditions. The statistical result, the so-called CIE photometric curve, represents the average photopic luminous efficiency of the human visual system as a function of wavelength. It provides a weighting function that can be used to convert radiometric into photometric measurements.The term that is mostly used in photometry (and most common in everyday life) is illuminance. Illuminance is an indication of the power of light per unit area and is measured in lumens/m^2 or lux (Kan, 2002). In Table 4.1 the photometric quantities and their equivalent radiometric are presented.

Table 4.1: Relation between radiometric and photometric units (Kan, 2002).

Definition	**Radiometric**			**Photometric**		
	Name	**Symbol**	**Unit (SI)**	**Name**	**Symbol**	**Unit (SI)**
Energy	Radiant Energy	Q	Joule	Luminous Energy	Q_V	lumen sec
Energy per unit time= Power	Radiant flux	Φ	Watt	Luminous Flux	Φ_V	Lumen
Power incident per unit area	Irradiance	E	W/m^2	Illuminance	E_V	lm/m^2=lux
Power per unit solid angle	Radiant Intensity	I	W/steradian	Luminous Intensity	I_V	candela
Power per unit solid angle per unit projected	Radiance	L	W/m^{2}steradian	Luminance	L_V	Candela/m^2

Radiometry deals with radiant energy (i.e. electromagnetic radiation) of any wavelength, while photometry refers to all wavelengths but it is limited by the V(λ) curve so that wavelengths between 380 nm and 780 nm contribute to the photometric quantity.
In radiometry the basic unit of power is the Watt. Irradiance (E) is measured in W/m^2. Every radiant source has a specific spectral distribution of its radiation, and therefore it will emit more radiation at certain wavelengths than others. In this thesis, radiometry is used instead of photometry, due to the use of PV cells and their various spectral ranges according to the type of the cell. In order to estimate the performance of the PV cells indoors, it is important to have a broad range of irradiance. Furthermore, as discussed above, there is a gap in the literature regarding radiometric data. Due to this lack of information, it was not possible to investigate the performance of the cells based on literature data pertaining to irradiance. For all these reasons, it was necessary to conduct irradiance measurements and to use these for the investigation and the analysis of indoor environment.

4.2.2 Indoor lighting conditions

The power produced by a solar cell is directly proportional to the irradiance received on the top of the surface of this cell, when spectral distribution is constant. The greater the incident irradiance, the higher the power the cell generates. Irradiance conditions indoors are very different than the ones encountered outdoors, as it was also discussed in the introduction of Chapter 4. A standard illuminant for average daylight in buildings is the D65 (CIE), but this is only available for light engineering and it is provided in the visible range of the spectrum. In this dissertation the indoor irradiance is examined in a broader range of the spectrum between 200 nm and 1100 nm. For this reason, there is no standard spectrum at the moment that could precisely represent the indoor irradiance.

In this section we will introduce indoor irradiance as a mixture of artificial and solar irradiance.

4.2.3 Indoor natural light

The share of solar irradiance entering a room depends on the surface area of its windows, their orientation, the degree of overcast, as well as the geographic location, the season (the date) and the time of the day.

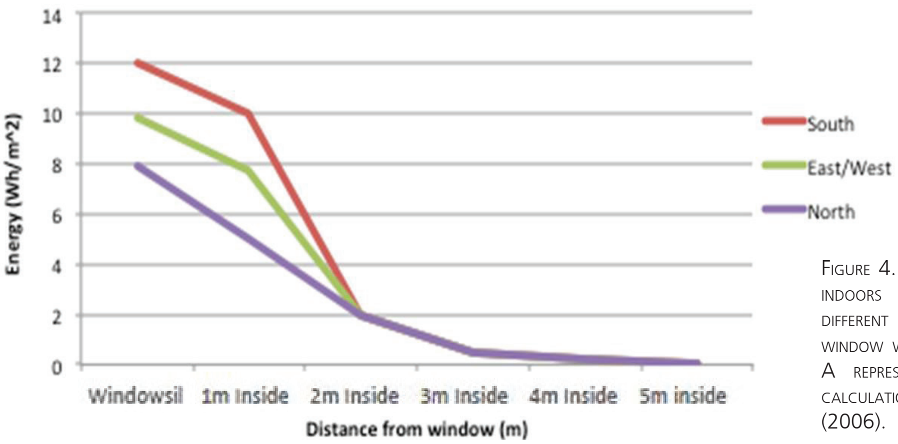


FIGURE 4.1: ENERGY GENERATED INDOORS (IN WH/M²) AT DIFFERENT DISTANCE FROM THE WINDOW WITH 1 M² PV PANEL. A REPRESENTATION BASED ON CALCULATIONS PRESENTED BY KAN (2006).

Solar irradiance that has entered a room depends on the distance between an open aperture – a window- and the point of observation and the obscuration by the open aperture. In case of large windows over the whole width of a room, the attenuation-the gradual loss in intensity of solar irradiance- is mainly caused by the distance to and the transmittance of the window. The overall irradiance level in indoor spaces therefore depends on the architecture of the building, and interior characteristics, such as the surface reflectance of the walls, ceiling and floors.

Generally, the irradiance levels outdoors, in Northern Europe, at mid-summer range between 325 W/m^2 at a diffuse day/overcast and 1000 W/m^2 at a clear day. Irradiance levels indoors are significantly lower; because the amount of transmitted light through a windowpane broadly depends on the type of glass, cover materials, size and type of frame. Kan (2006) shows that at a distance of one meter from a single glazed window, the radiant power has reduced with 40 % of the outdoor measured value (see Figure 4.1). At a greater distance e.g. five meters from the window; the radiant power decreases even more, with 93 % of the value outdoors (Kan, 2006).

The literature shows that the average irradiance indoors is between 1 and 5 W/m^2 (Muller, 2009; Randall, 2003). Muller tried to evaluate irradiance indoors both experimentally and by using a simulated environment. For the experiments she used pyranometers, luxmeters and a reference crystalline solar module. Computer simulations were performed using the ray tracing programs Radiance and DAYSIM. Two rooms were examined, one with the window looking to the north and one with the window looking to the south. The first office had an annual mean irradiance below 5 W/m^2 and the second between 20 W/m^2 and 50 W/m^2 (Muller M. W., 2009). Therefore, it can be said that window orientation is the most critical factor influencing indoor irradiation levels.

For example, for a south-facing double glass window, depending on the percentage of the direct and diffuse sunlight, the irradiance will be 160 to 900 W/m^2 during summer at a distance of about 1 m from the window. At distances greater than 1 m from the window, the size of the window will determine the contribution of diffuse sunlight. The illuminance level will drop rapidly and artificial lighting is needed occasionally. For a north-facing room mainly diffuse sunlight exist, while for an east- and west-facing window there will be also direct sunlight in addition to the diffuse light.

4.2.4 Glazing Systems

In order to achieve high efficient glazing systems, new materials are being manufactured with upgraded features, such as high thermal and visual comfort (e.g. capability to reduce heat gain/loss and permit high visible light transmission). Figure 4.2 demonstrates the solar radiation passing through a glazing surface (reflected, absorbed and transmitted light).

Generally, the amount of transmitted light through a windowpane depends on the type of glass, cover materials and type of frame. Literature shows that the glass attenuation per windowpane is estimated at around 10 %. At a distance of one meter from a single glazed window, the radiant power is reduced to below 40 % of the outdoor measured value. At a greater distance e.g. five meters from the window, the radiant power is decreased even more, reaching 93 % of the value outdoors. In case of a double-glass insulated window, the decrease of the radiant power at one and five meters from the window will be around 70 % and 97 % respectively (Kan, 2006; Wen and Smith, 2002). However, these numbers also depend on the building, the pane geometry and glass type.

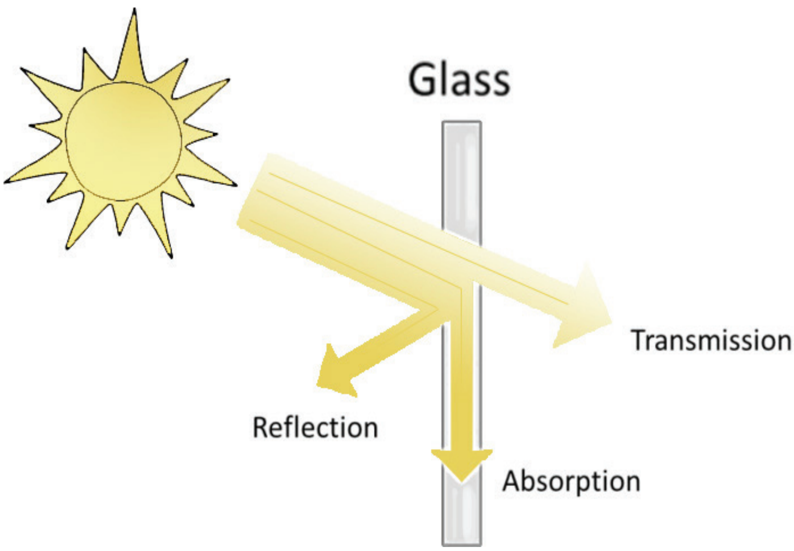


FIGURE 4.2: SOLAR RADIATION PASSING THROUGH A GLAZING SURFACE (ADAPTED FROM RANDALL, 2003).

Transmittance according to wavelength for different types of glass is presented in Figure 4.3. Transmittance depends on the type of the glass and its features; for instance, the heat absorbing glass has lower transmittance than the clear glass, as can be seen in Figure 4.3.

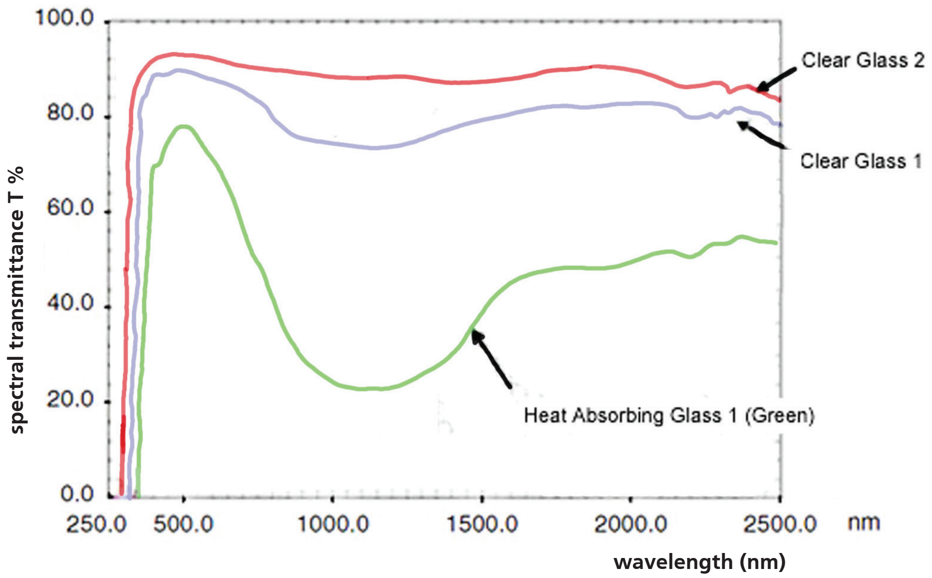


FIGURE 4.3: TRANSMITTANCE SPECTRA OF SEVERAL GLASS TYPES ACCORDING TO WAVELENGTH (ADAPTED FROM SHIMADZU.COM).

4.2.5 Indoor artificial light

Typical artificial light sources are compact fluorescent lamps, light emitting diodes (LEDs) and incandescent lamps. In this section the types of artificial lighting, fluorescent, halogen and light emitting diodes, are explained.

a. Incandescent Lamp

An incandescent lamp converts electrical energy to light using a filament wire that is heated to high temperature when electric current passes through it. Incandescent lamps are not very energy efficient as most of the radiation they emit (95 %) is close to the red and infrared region of the spectrum and is lost in the environment in the form of heat.

b. Halogen Lamp

A halogen lamp has a working principle similar to an incandescent lamp with higher efficiency and a longer lifespan. These lamps have a filament temperature of about 3100 °C and quartz is used instead of glass for the construction of the envelope. Under these high temperatures production of light from the tungsten filament is almost 2 times more compared to common incandescent lamps .

A halogen lamp produces a continuous spectrum of light, from near ultraviolet to infrared. Figure 4.4 illustrates the spectrum of two halogen lights, indicated as measurement 1 and measurement 2. From Figure 4.4 it can be seen that halogen light has a spectrum, which begins from wavelength of 200 nm and increases, reaching the highest values in the infrared area of around 1000 nm.

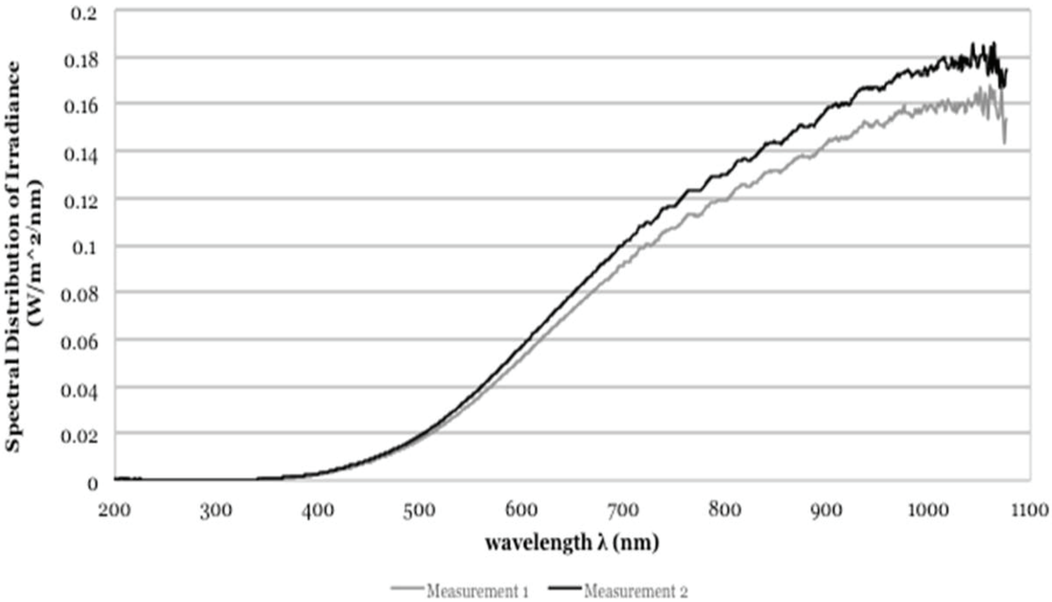


Figure 4.4: The graphs of the power delivered by a halogen lamp (Philips B9, Twistalu 35 W, 230 V) for each wavelength during two different measurements. Source: Author's records.

c. Fluorescent Lamp

Fluorescent lamps are discharge lamps. They contain a gas- usually mercury vapor- that emits light when it is ionised by an electric current. The lamp is connected to a supporting device- known as ballast, which is actually a stabiliser- that provides the necessary circuit. When the lamp is turned on an electric arc is created and then the mercury vapor starts emitting ultraviolet radiation. Fluorescent powders from phosphor compounds, which are coated on the inner walls of the glass bulb respond to this ultraviolet radiation by emitting wavelengths in the visible region of the spectrum.

There are two types of fluorescent lamps; Linear Fluorescent Lamps (TL) and Compact Fluorescent Lamps (CFL) (Lighting Research Center, 2000).

The spectrum of a CFL lamp is presented in Figure 4.5. It can be seen that the specific type of light produces a spectrum from 200 nm to around 1100 nm, with peaks at specific wavelengths on the visible spectrum, which depend on the type of phosphors in the lamp. The characteristic peaks of the CFL in Figure 4.5 are at 435 nm, 547 nm, 610 nm.

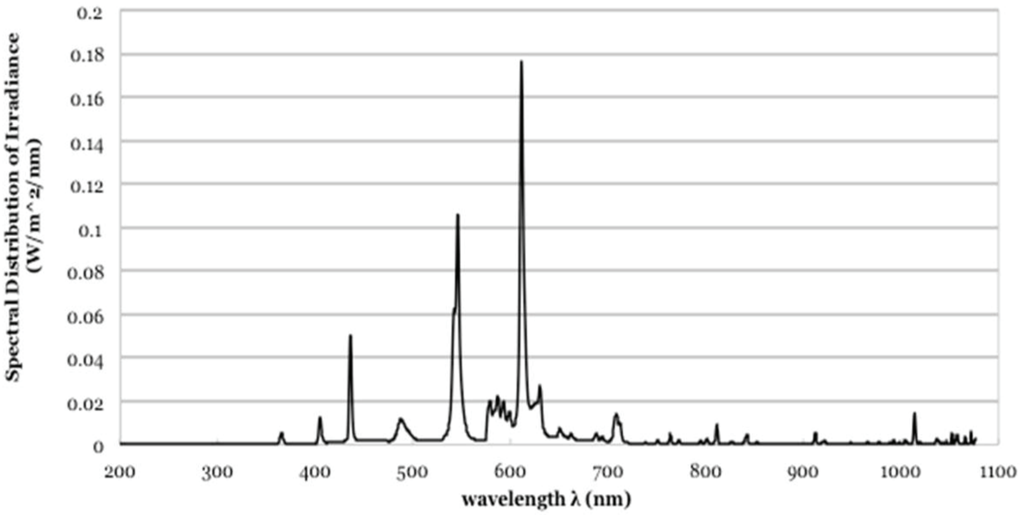


FIGURE 4.5: SPECTRUM OF A CFL LAMP (MEGAMAN, COMPACT REFLECTOR GU10, 3000 K WARMWHITE, 9 W, 78 MA, 220-240 V, 50/60 HZ). SOURCE: AUTHOR'S RECORDS.

d. Light Emitting Diode

The growing need for low power light has led to the development of solid state lamps known as Light Emitting Diodes (LED). LEDs are actually semiconductor devices that convert electrical energy directly into light. The device contains a light-generating chip, which is very small and emits light when current flows across the junctions of different materials. According to the composition of the materials the emitted light can be white, red, yellow, green and blue. LEDs have a very long lifetime (from 50,000 to 100,000 hours based on design and operating temperature) and are considered the most efficient lighting devices, because most of the radiation they emit lies on the visible range of the spectrum (Lighting Research Center, 2000; Optoelectronics, 2007; Zheludev, N., 2007;Humpston G., 2015).

The characteristic spectrum of two LEDs is presented in Figure 4.6. LED lights emit mainly in the visible spectrum of light from 380 nm to 780 nm. Depending on the type of the LED and the color of light, the characteristic curve of the spectrum is shifted to the wavelength of the emitted light color.

It is interesting to notice that two warm white LEDs with almost the same characteristics, but originating from different manufacturers, could have different spectral distribution of irradiance (see Appendix C2, Figure C2.4).Furthermore, the spectral emission of a white LED broadly depends on the operating temperature, according to Nδgele (2008). For low operating temperature, the lamp emits higher amount of energy compared to its emission at higher operating temperatures.

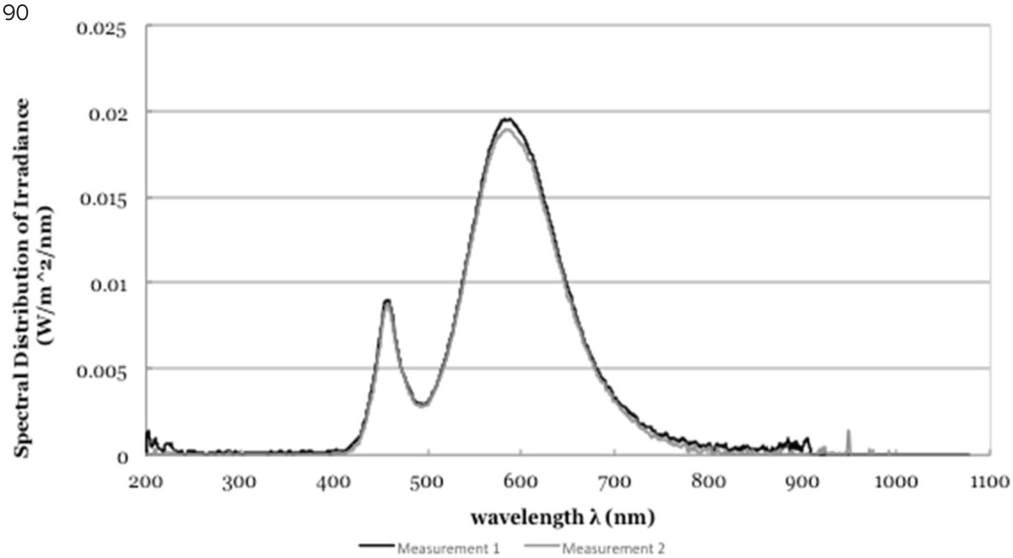


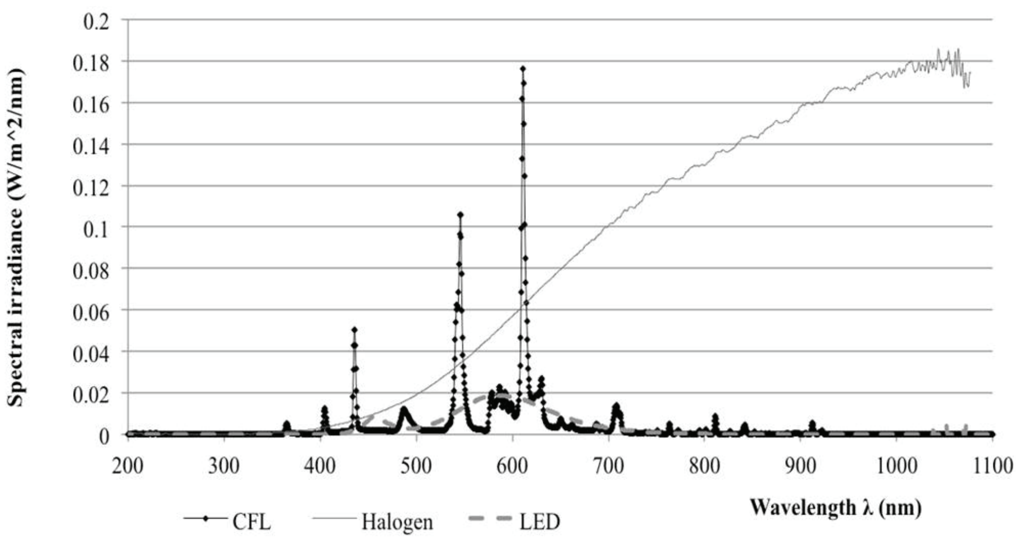
FIGURE 4.6: SPECTRUM OF LED LAMP (GAMMA, 4.2 W, 230 V, 50 HZ). SOURCE: AUTHOR'S RECORDS.

Depending on the type of semiconductor material of the LED lamp, the color of the light, the wavelength of the emitted spectrum and the voltage of the lamp vary significantly. More specifically, for GaAs semiconductor the wavelength ranges between 850 and 940 nm, radiation is infrared and voltage 1.2 V (at 20 mA). For GaInN semiconductor, the wavelength is 450 nm, the emitted light is indigo and the voltage 4 V at 20 mA current (Electronics-tutorials).

e. A comparison between artificial light sources

Figure 4.7a presents the light spectra of three types of artificial lighting sources discussed previously: fluorescent lamps, light emitting diodes and halogen lamps; CFL lamp (MEGAMAN compact reflector GU10, BR0709i, 9W, 78mA, 220-240V, 50/60Hz, 3000K Warmwhite), LED (GAMMA 230V-50Hz, 4,2W) and halogen lamp (Twistalu, Philips B9, 35W, 230V, 40D).

FIGURE 4.7A: SPECTRAL IRRADIANCE OF A CFL, LED AND HALOGEN LAMP IN $W/m^2/nm$. MEASUREMENTS TAKEN AT THE APPLIED LABS OF TU DELFT ON JANUARY 21ST, 2014 (APOSTOLOU ET AL., 2016).



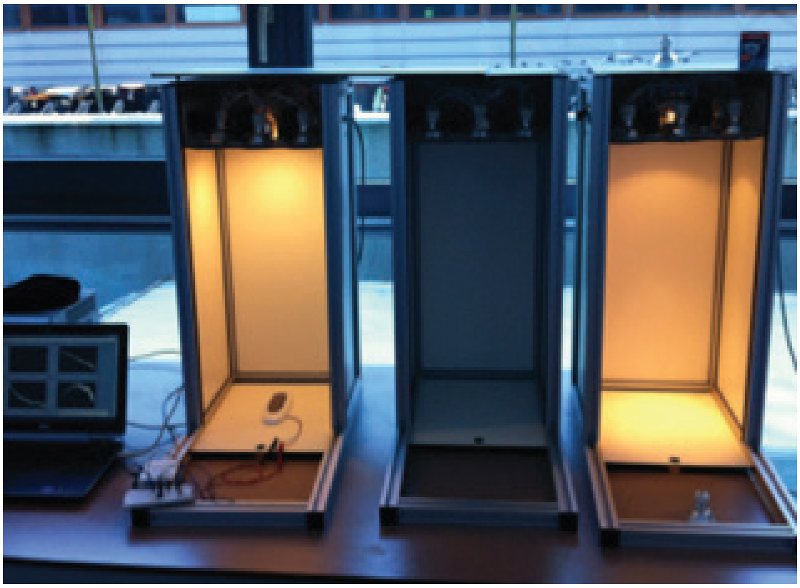


Figure 4.7b: The experimental set-up that was used for the measurements of the lamps' spectrum (Apostolou et al., 2016).

Each light source (halogen, LED and CFL) was mounted inside a specially designed box with dimensions 67 x 30 x 30 cm (see Figure 4.7b). The lamps were placed at a distance of 55 cm from the base of the box. The spectroradiometer was placed inside the boxes, so that ambient light from the room could not affect the measurements. The sensor of the spectroradiometer was placed just under the lamp at distance 35 cm from it.

The spectral irradiance of each lamp was measured using a spectroradiometer (StellarNet Fiber Optic Spectrometer SCal-C10122012, of type Black C-SR-50, BW-16) with spectral range from 185 to 1078 nm, which was connected to a computer.

It is noticeable that each light radiates at a specific range of wavelength, which is characteristic for the physical functioning of these different lamp types. Since different solar cell technologies have different band gaps and different spectral responses, they use only a dedicated part of the light spectrum. For example, artificial light emitted by incandescent lamps has a spectral range between 350 and 2500 nm, while an LED has a range of only 400 up to 800 nm (Reinders and van Sark, 2012). Lamps like LEDs and CFLs contain most of their power in certain peaks in the visible spectrum between 390 to 700 nm, whereas halogen lamps radiate a considerable amount of their power in the infrared region of the spectrum. This means that depending on the technology of the solar cells, exposure to different light technologies results in different efficiencies and power output by these solar cells.

4.2.6 Lighting in formulas

The sun can be considered a point source, if observed from great distance. An incandescent lamp can also be considered a point source at a certain minimum distance. However, point sources do not actually exist. Point sources, such as the sun or an incandescent lamp can be also considered isotropic radiators. This means that the radiation is uniform in all directions over a sphere centered on the source. Irradiance E (in W/m^2) generated by a point source emitting radiant energy with radiant intensity I, is distributed over larger and larger spherical surfaces as the distance r from the source increases (Figure 4.8). Therefore, irradiance is inversely proportional to the square of the distance (Ryer, 1998):

$$E = \frac{I}{r^2} \tag{4.1}$$

In Figure 4.8, S symbolizes the light source, while r the measured points. The radiant flux is represented by the red lines. The number of the radiant flux lines indicates the source's power. The more radiant flux lines, the stronger the field.

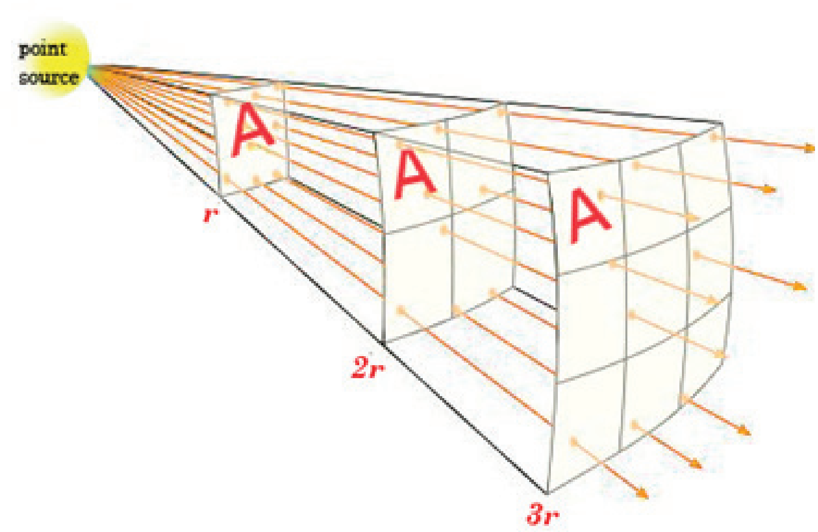


Figure 4.8: Irradiance coming from a point source (Adapted from Wikipedia, 2013), ©Borb, CC BY-SA 3.0, GNU Free Documentation License.

However, should the light source be more similar to a line source of infinite length and of intensity I, then irradiance E will change with the reciprocal of the distance r:

$$E = \frac{I}{r} \tag{4.2}$$

When a surface receives incident radiation with an angle larger than zero, then irradiance is spread over a wider area. Hence irradiance at a point on the surface is reduced by the cosine of the angle. This relationship is known as Lambert's cosine law (Ryer, 1998):

$$E_\theta = E * cos\theta \tag{4.3}$$

In this case, it is assumed that the radiant incident flux consists of parallel beams (Figure 4.5). In case the source has a spherical shape, this assumption is accurate when the distance between the source and the surface is far bigger than the radius of the source. A minimum distance/radius ratio of 10 is considered adequate (Randall, 2003).

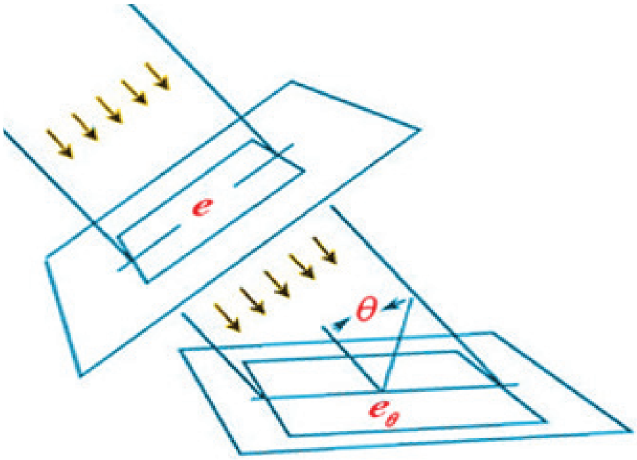


FIGURE 4.9: RADIANT ENERGY INCIDENT ON A SURFACE (ADAPTED FROM LIGHTING RESEARCH CENTER, 2000).

When solar light enters a window or a skylight, it has to penetrate the material (usually glass) that separates the interior of the building from the external environment. During this process the incident radiant flux (Φ^t_e) is subject to reflection, absorption and transmission (Figure 4.10).

Thus, the radiant flux exiting the material, called transmitted radiant flux (Φ^t_e) will have less energy compared to Φ^t_e. For a beam that is perpendicular to the surface the ratio of (Φ^t_e) to (Φ^t_e) is called transmittance, T_λ and is wavelength dependent (Ryer, 1998; Randall, 2003):

$$T_\lambda = \frac{\Phi^t_{e,\lambda}}{\Phi^i_{e,\lambda}} \qquad (4.4)$$

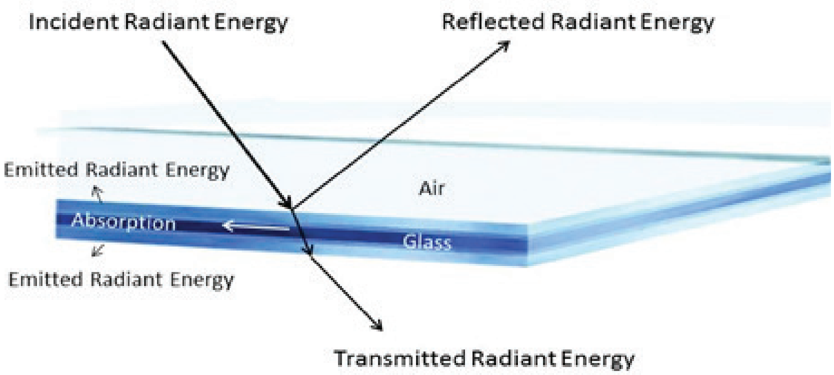


Figure 4.10: Light passing through a transparent material (Adapted from Randall, 2003).

4.3 Measurements of indoor irradiance

In order to better quantify actual indoor irradiance, measurements were conducted which can be applied for the purpose of energy performance calculations of product-integrated PV.

Therefore, in this section first the experimental set-up for these measurements is presented; subsequently the results of the measurements are presented, and finally analyzed.

In this field of research, little to no reference data exist and for this reason the measurements have been executed solely for further use in this project without having the ambition of developing a generic model for indoor irradiance and its spatial distribution in various arbitrary environments. Therefore, we prefer to refer to existing modeling software such as Radiance, which is based on raytracing. Mueller M. et al (2009) used the ray tracing programs Radiance and DAYSIM to simulate indoor environment for indoor photovoltaic (ipv) design. Mueller et al. (2009) used photometric measurements and radiometric measurements at low intensities from 0.1 to 10 W/m^2. It was found that photometric measurements are inappropriate for ipv-design, while radiometric measurements proved more reliable. Finally, the simulation of indoor environment using the two programs of Radiance and DAYSIM seemed reliable under very specific irradiance conditions, while also high efficiency modules for calibration under these conditions were necessary.

The measurements of irradiance and the models and simulations of PV cell performance that are reported in literature by Mueller et al. (2009), Kan (2006), Randall (2003), Reich (2010) focus on very specific irradiance conditions; either natural solar irradiance or artificial irradiance only. Unfortunately, there are no measurements under mixed irradiance conditions. Therefore, in this dissertation this approach of mixed irradiance conditions is chosen due to the unstable conditions and variable environment where indoor PV products are used.

4.3.1 Indoor irradiance according to distance from the light sources

4.3.1.1 Experimental Set-up sources

The measurements were taken in June 2015 at Delft University of Technology in The Netherlands. Two rooms were used for the irradiance measurements; a south- and a north-facing office.
The equipment that was used for the measurements of the irradiance indoors was a StellarNet Fiber Optic Spectrometer by StellarNet (SCal-C10122012), of type Black C-SR-50, BW-16 (see Figure 4.11). It can measure irradiance (W/m^2) in the range between 185 and 1078 nm. During experiments, the spectrometer were placed at various indoor locations such as offices, in an attempt to evaluate irradiance levels available indoors. The collected data were processed with a laptop, which is connected to the spectrometer through a USB cable. Various adjustments, concerning units, measurement duration etc., can be made through the SpectraWiz software provided by the manufacturer.

The device also includes a sensor cover; the CR2-AP~4.8 % (cosine receptor 2 – aperture ~4.8 %). CR2-AP is a 10 % aperture for the CR2 (a Ό" diameter UV-VIS-NIR cosine receptor using a polymer diffuser for 200 to 1700 nm & 180° FOV) that extends the system dynamic range by an order of magnitude, thus enabling spectral measurements of sources that are ten times brighter without the need for recalibration using a brighter IRRAD-CAL lamp. This cover is usually used for outdoor measurements or under high irradiance, which can't be measured from the sensor, because of his sensitivity. The specific cover only allows a very small percentage of solar irradiance to pass through (~4.8 %). The cosine receptor CR2 has a wavelength of 200 to 1100 nm, diameter inches and field of view 180°.

In this test the distance of the sensor from the window varied from 2 cm to 0.5, 1, 2 and 4 m. During the measurements some conditions are changed (e.g. the window is either closed or open and the lights are turned on and off). The artificial lighting that is used in the offices is fluorescent lamps (Philips Master TL-D, 58 W/830) (see Appendix C1, Figure C1.1). The spectroradiometer is connected to a computer. The sensor is placed on a tripod to have a stable height during the measurements (see Appendix C1, Figure C1.2). In the next sections the results of the measurements are presented and analyzed.

FIGURE 4.11: STELLARNET FIBER OPTIC SPECTROMETER

4.3.1.2 Results

The results consider measurements on the same day; June 10th, 2015 at Delft Technical Universityin The Netherlands. Below the sets of measurements are listed:

i. Room orientation (North, South)
ii. Distance from the window (0.5 m, 1 m, 2 m, 4 m)
iii. Window condition (opened or closed)
iv. Lights'condition (turned on or off)

Below the findings are presented for each data set.

i. North-facing office, June 10th, 2015, at Delft, The Netherlands

As Figure 4.12 indicates the total measured irradiance is higher with the lights off for a distance below 2 m from the window. This means that the irradiance close to the window (<2 m) is mainly influenced by the sunlight that passes through the windows inside the room. This difference in the measurements is reasonable, since the measurements with the lights on and the lights off took place with a time difference of around two hours. The measurements with the lights on conducted first at around 10:00 and the measurements with the lights off followed at around 12:00. During the day the irradiance increased and thus at 12:00 the total measured irradiance was higher than the one measured at 10:00. The results for distance greater than 2 m from the window show that the values of irradiance are higher when the lights are on. This means that an object that is placed more than 2 m far from the window receives irradiance mainly from the artificial light sources.

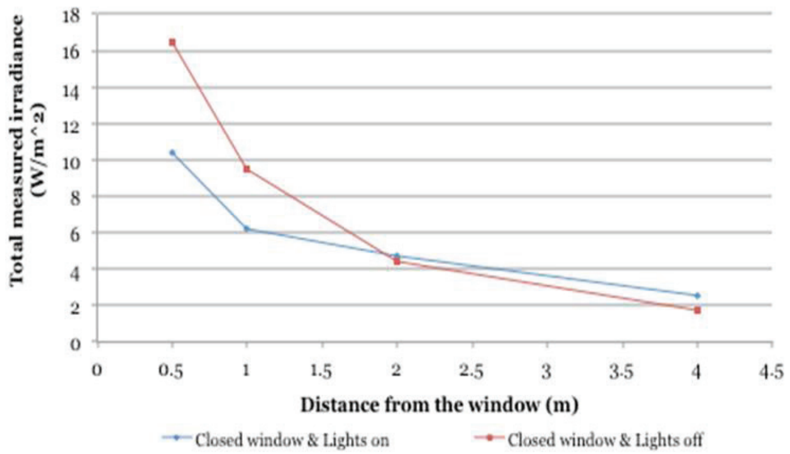


Figure 4.12: Total measured irradiance (W/m^2) at a north-facing office on June 10th, 2015, at Delft, The Netherlands. In both cases the window was closed during the measurements, while the lights were on for the blue line and off for the red one.

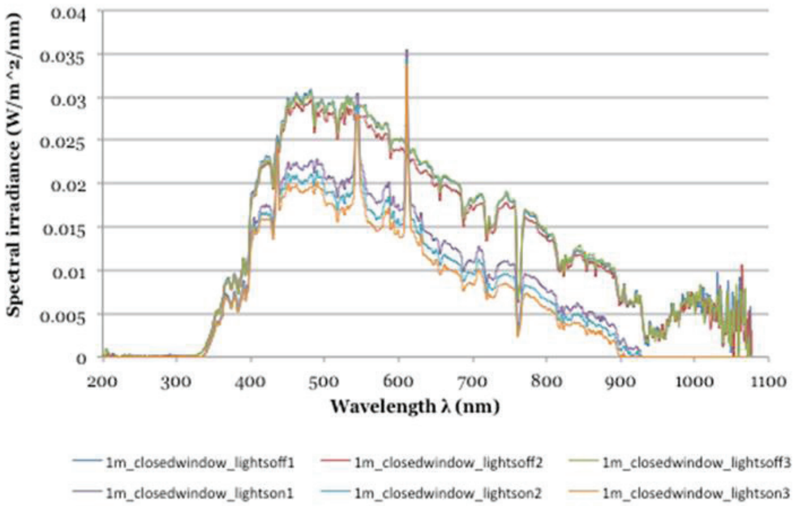


Figure 4.13: Spectral irradiance (W/m^2/nm) measured at distance 1 m from the window at a north oriented office at Delft, The Netherlands, on June 10th, 2015. The window was closed during the measurements and the lights were on and off respectively.

At a distance of 1 m from the window the total measured irradiance is typically around 43 % lower than the irradiance measured at distance 0.5 m from the window.

As Figure 4.13 shows, 1 m far from the window with closed window and the lights off, the irradiance is reaching around 10 W/m^2. When the lights are turned on, it can be seen from Figure 4.13 that the spectrum is a combination of natural and artificial light. When the lights are turned on, from it can be seen from Figure 4.13 that the spectrum is a combination of natural and artificial light. The picks of the CFL light can be easily recognized. However, the values of the total measured irradiance are not higher with the lights turned on than with the lights turned off. At a closer distance to the window (<1 m), the artificial light does not affect irradiance. The lamps are usually positioned at distance greater than 1m from the windows and thus in smaller distance and when natural light indoors is sufficient, the lamps' spectrum is not apparent.

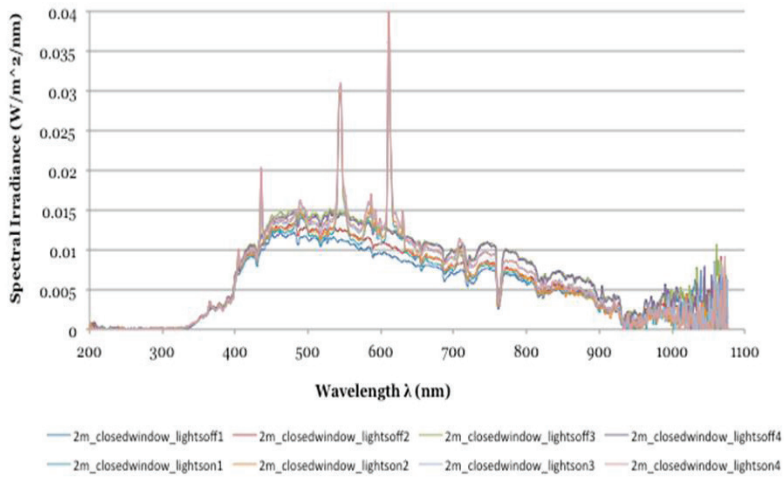


Figure 4.14: Spectral irradiance (W/m²/nm) measured at distance 2 m from the window at a north oriented office at Delft in The Netherlands on June 10th 2015. The window is closed during the measurements and the lights are on and off respectively.

Spectral irradiance measurements at a distance of 2 m and 4 m from the window (see Figures 4.14-4.15), show that artificial light sources overlap natural light indoors. The spectrum of indoor lighting at distance greater than 2 m from the window is mainly influenced by the spectrum of the artificial light sources. Results show that when the lights are turned on, the total measured irradiance is higher than with the lights turned off and it is more stable during the day. However, the values are still quite low, reaching typically 5 W/m² at distance 2 m from the window and around 3 W/m² at 4 m.

The spectral irradiance was also measured at a distance of 2 cm, by changing the condition of the window. Multiple measurements were conducted with the window open, the first window closed and both windows closed, in order to investigate the transmittance of the window. The 'first' and the 'second' window refer to the double-glazed window. Results are presented in Figures C1.3 and C1.4.Results are presented in C1.3 and C1.4. The total measured irradiance with an open window was measured around 31 W/m², while with the first window closed it was around 29 W/m² and with both windows closed around

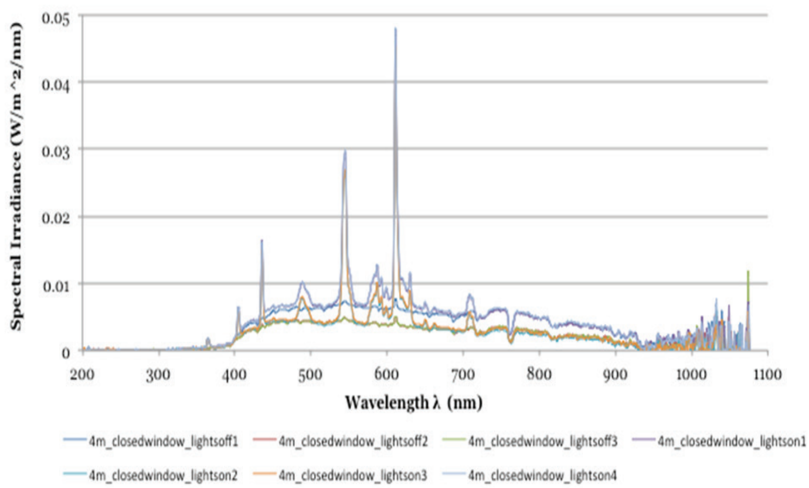


Figure 4.15: Spectral irradiance (W/m²/nm) measured at distance 4 m from the window at a north oriented office at Delft, The Netherlands, on June 10th, 2015. The window was closed during the measurements and the lights were on and off respectively.

26 W/m². The results show that a double-glazed window reduces the irradiance typically with around 16 %. However, this percentage is not the same for all the types of double-glazing windows. As described before in paragraph 3.3 the transmittance depends on the type of glazing, the color of the glass, the filters, possibly the manufacturer, as well as the orientation of the window.

ii. South-facing office, June 10th, 2015, at Delft, The Netherlands

As Figure 4.16 illustrates the measured spectral irradiance at a south-facing office and at distance 1 m from the window, with the window closed and the lights off is higher than the measured irradiance at the same distance at the north-facing office. Furthermore, when the lights in the room are turned on, spectral irradiance is influenced by the artificial lights' spectrum. This is clear in Figure 4.16, where the picks of the CFL light are obvious when the lights are on.

The three measurements named "1 m closed window_lightsoff" that are presented in the Figure 4.16 were conducted with a time difference of 1min between each other. The measurements named "1 m closed window_lightson" followed after 1,5 hour. However, the time difference between them is also 1 min. A time pace of 1 min from one measurement to the other has been chosen to see how fast the irradiance is changed. A shorter time pace even possible, is not quite practical for this kind of measurements and results' analysis.

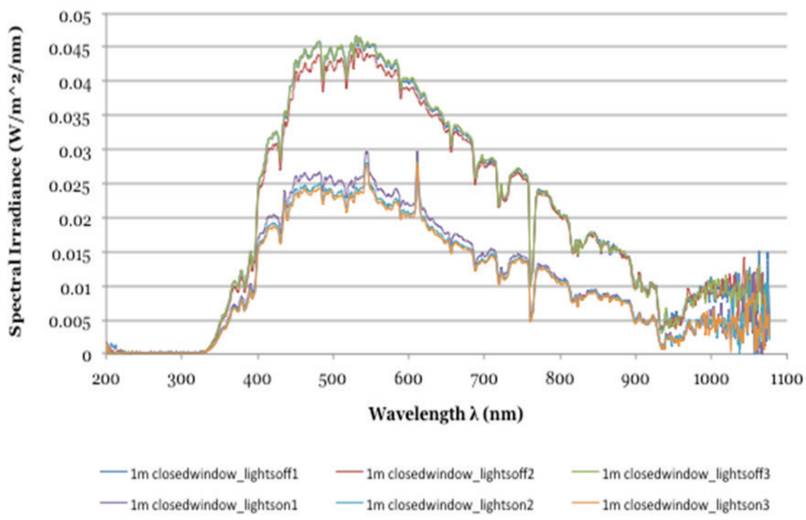


Figure 4.16: Spectral irradiance (W/m²/nm) measured at a distance of 1 m from the window at a south oriented office at Delft, The Netherlands, on June 10th, 2015. The window was closed during the measurements and the lights were on and off respectively.

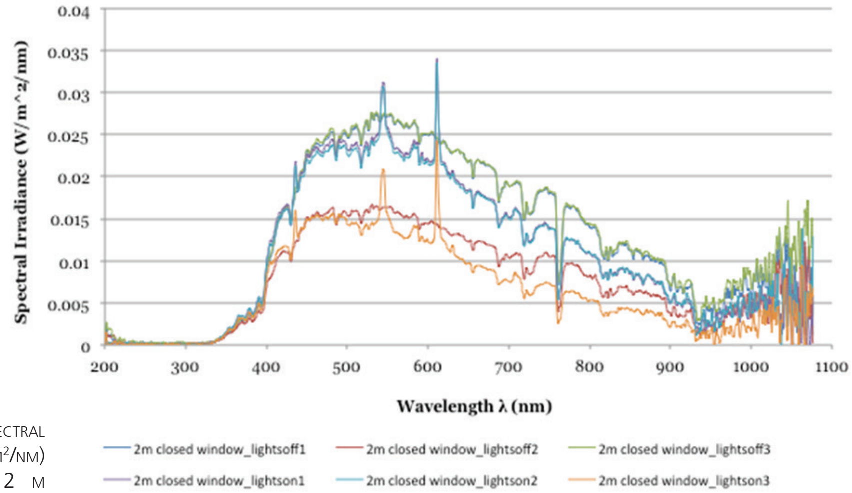
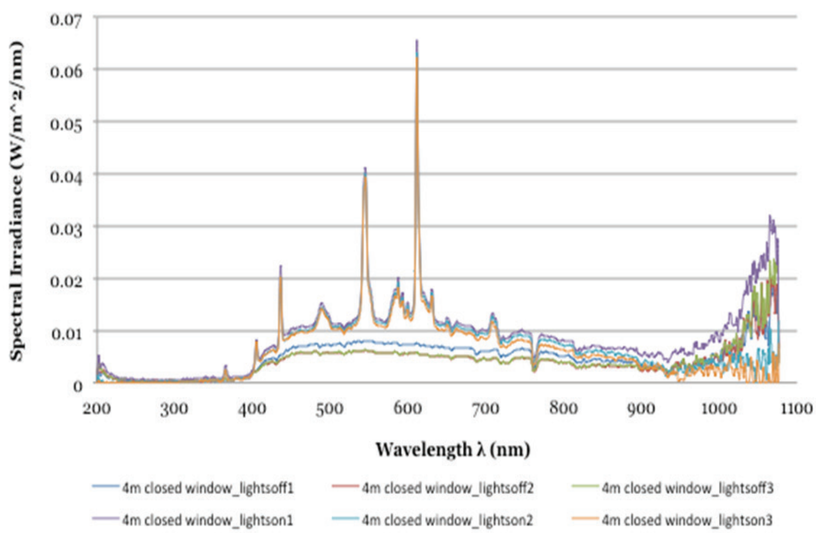


Figure 4.17: Spectral irradiance (W/m²/nm) measured at distance 2 m from the window at a south oriented office at Delft, The Netherlands, on June 10th, 2015. The window was closed during the measurements and the lights were on and off respectively.

At a distance of 2 m from the window the measured spectral irradiance is lower than the one measured at a distance of 1 m. Figure 4.17 presents 6 measurements of spectral irradiance at distance 2 m from the window with the window closed; 3 measurements with the lights turned on and 3 with the lights turned off. When the lights are on, the spectrum is a mixture of natural and artificial light. As it can be seen from Figure 4.17, there are some deviations between the measurements that conducted one after the other, with the lights on or off. This is due to the changes of the natural light indoors, which was a result of outdoor shad(ow)ing and passing clouds. The time a cloud covers the sun the irradiance indoors (near the window) falls from 190 W/m² down to 45 W/m².

Figure 4.18 presents the spectral irradiance that was measured at a distance of 4 m from the window. As it was also described above for the north-facing office, the same happens at the south-facing office; at a distance of 4 m from the window the irradiance is strongly influenced by the artificial light sources. Moreover, the irradiance that is based on an artificial light source is more stable than the measured indoor irradiance originating from the sun.

Figure 4.18: Spectral irradiance (W/m²/nm) measured at distance 4 m from the window at a south oriented office at Delft, The Netherlands, on June 10th, 2015. The window was closed during the measurements and the lights were on and off respectively.



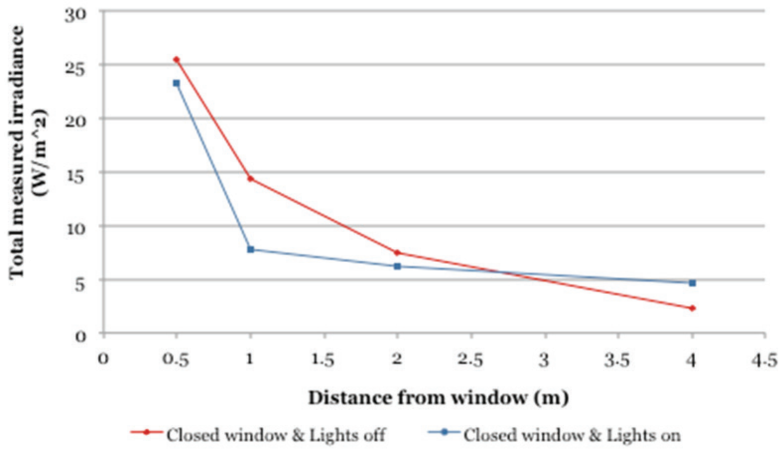


Figure 4.19: Total measured irradiance (W/m²) at a south-facing office on June 10th, 2015, at Delft, The Netherlands. In both cases the window was closed during the measurements, while the lights were on for the blue line and off for the red one.

In the south-facing office the measured indoor irradiance is higher than the one measured at the north-facing office. This happens because the sun was facing the south office for more hours during the day. Furthermore, during the day the south office had higher temperature than the north office and higher infrared irradiance. As Figure 4.19 presents, when the window is closed and the lights are off, the total measured irradiance is quite high compared to the irradiance measured at the north office at the same conditions (window and lights). However, at a distance greater than 2,5 m from the window, it seems than total irradiance falls when the lights are off, while it is higher and more stable with the lights turned on.

Figure C1.6 illustrates the spectral irradiance at a distance of 2 cm from the window. The irradiance was measured with the lights turned on and the window open and closed. In order to investigate the transmittance of the double-glazing window we conducted measurements with the first glazing closed and the second glazing closed. As Figure C1.6 presents even with the lights turned on, at distance 2 cm from the window there is only natural light indoors. From the above graph we can see that the spectrum is based on natural light and there is no influence from the artificial light sources. When the window is open the total measured irradiance is 45 W/m², with the first glazing closed it reaches 41 W/m², while with the second glazing closed it falls down around 28 W/m² (see Appendix C1, Figure C1.5).

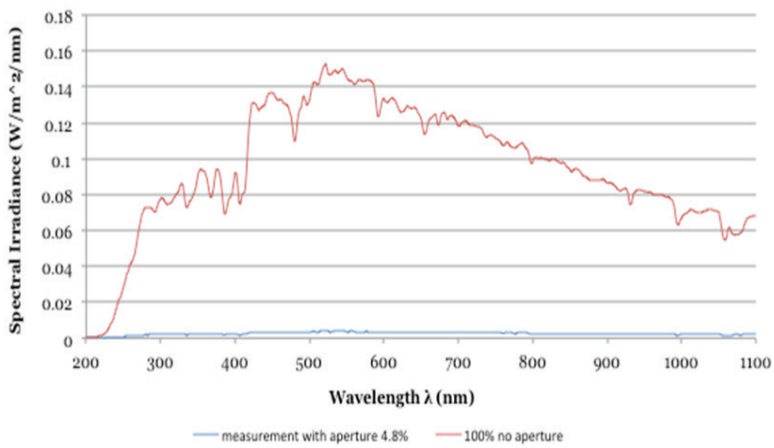


Figure 4.20: Spectral irradiance (W/m²/nm) measured at distance 2 cm from the window at a south oriented office at Delft, The Netherlands, on June 10th, 2015.

In Figure 4.20, the window was open during the measurements and lights were on. The red line is the measured spectral irradiance with the sensor uncovered, while for the blue line an aperture was used, which allows around 4.8 % of the light to pass through the cover. In case of irradiance being higher than 0.16 W/m[2]/nm, the spectroradiometer fails to give a reliable result and thus the aperture should be used.
This happens due to the sensitivity of the sensor, which is designed to measure lower irradiance.

Figure C1.7 presents the measurement of the spectral irradiance using the aperture, which was also presented in Figure 4.20. We zoom in on the blue line of Figure 4.20, in order to clearly observe the behavior of the spectrum.

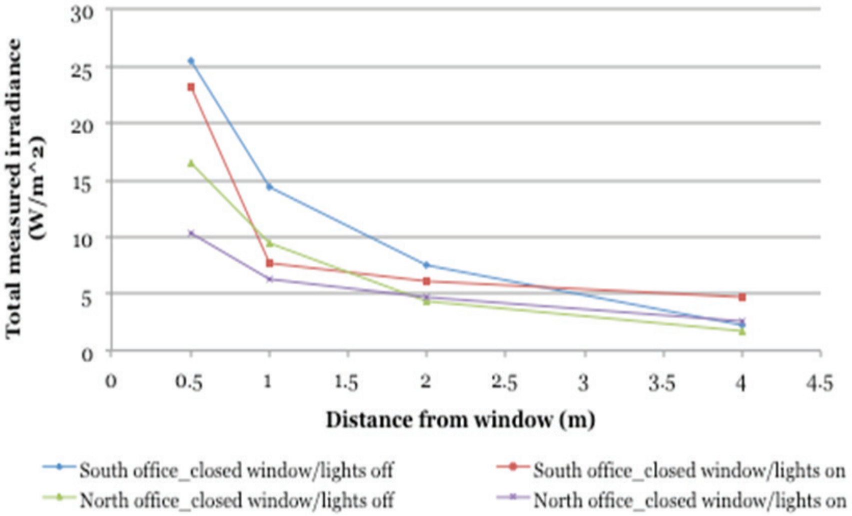


FIGURE 4.21: TOTAL MEASURED IRRADIANCE (W/M[2]) AT A NORTH- AND A SOUTH-FACING OFFICE ON JUNE 10TH, 2015, AT DELFT, THE NETHERLANDS. IN BOTH CASES THE WINDOW WAS CLOSED DURING THE MEASUREMENTS, WHILE THE LIGHTS WERE ON FOR THE RED AND THE PURPLE LINE AND OFF FOR THE BLUE AND THE GREEN.

As Figure 4.21 demonstrates, the total measured irradiance in a south-facing office is higher than in a north-facing office. This was the expected result, since a south-facing office receives more natural light during the day than a north office. As it was also explained above in Figures 4.12 and 4.19, at distance lower than 2 m from the window the natural light dominates, while for distance greater than 2 m, artificial light does.

4.3.2 A comparison of indoor irradiance between two locations

4.3.2.1 Experimental Set-up

In this experiment the measurements of indoor irradiance were conducted using a spectroradiometer by StellarNet (SCal-C10122012), of type Black C-SR-50, BW-16, as it was described in Section 3.1.1. For this experiment two different test rooms have been chosen for indoor irradiance measurements; one office at TU Delft and one office at Twente University in The Netherlands. Measurements were conducted from March to June 2012.

For the measurements of irradiance, three different positions in each room were chosen with a different height and distance from the windows. In two rooms different kind of artificial light was installed: at Delft, Philips fluorescent TLD type lamps, 58 Watt, light color 830 (warm white), while at Twente, FREETEC Holland T8 LED lamps, model no 1720014 3 M, AC 200 V-240 V, 50/60 Hz, white color, 5500 K, 8 W RoHS were used for the artificial illumination of the room. The goal of this test was to define indoor irradiance and observe how it varies according to the distance from a light source.

The first test room was a north-facing office at TU Delft in The Netherlands. The dimensions of the office were: 3,5 m x 4,54 m x 3,21 m. For artificial illumination, 2 tubes of fluorescent (CFL) lamps were installed at a distance of 1,25 m and 3 m from the southern wall respectively. In Figure 4.22 the sensor is indicated by a cycle. The position of each sensor is indicated in Table 4.2. The office was used daily by two professors and it contained 2 desks, 2 bookcases and some chairs.
The second test room was a south-facing office at Twente University in Enschede, in The Netherlands. The dimensions of the office were: horizontal block 5,40 m x 2,66 m x 2,68 m and vertical block 2,58 m x 5,38 m x 2,68 m. For the illumination of the room 2 tubes of LED lamps were installed 1,5m and 3 m from the southern window respectively. In Figure 4.22 the sensor is indicated by a cycle. The position of each sensor is indicated in Table 4.2. The office was used daily by two workers, but occasionally it was also used from a third one. It contained 4 desks, 2 bookcases and some chairs. The south-facing office had higher temperature during the day than the north-facing office, which remained during the night because the room was sunbathed many hours per day.

The measurements at the south-facing office conducted during June 2012, where the temperature was higher than in March and the hours of daylight were more.

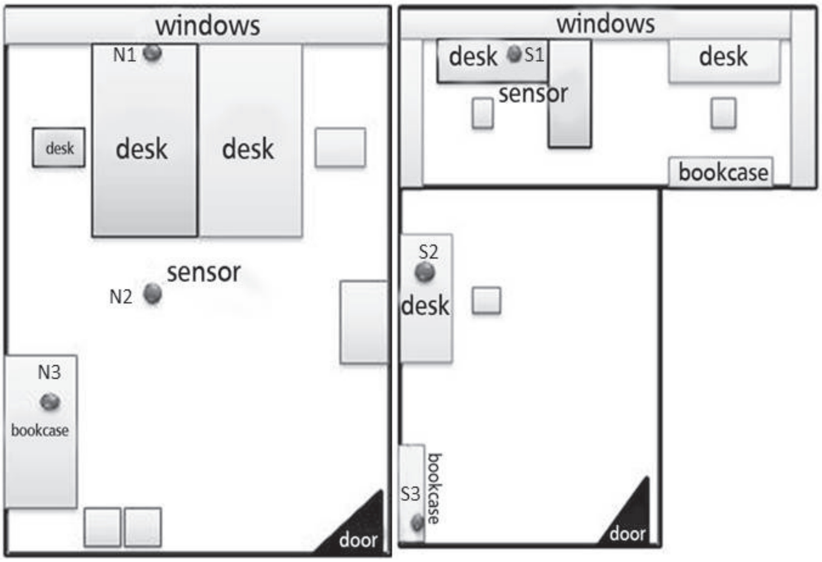


FIGURE 4.22: LEFT PICTURE: NORTH-FACING OFFICE AT DELFT. RIGHT PICTURE: SOUTH-FACING OFFICE AT ENSCHEDE, THE NETHERLANDS.

The measurements in both rooms were conducted during working hours, in order to have an uncontrolled environment (e.g. shad(ow) ing that cannot be estimated, random use of artificial light, possible movements of people and objects in the room).

The spectral distribution measured on various positions in both rooms is a combination of natural light irradiance and artificial light irradiance. Spectral power distribution (SPD) describes the power per unit area per unit wavelength of an illumination, or more. Generally, the SPD describes the contribution per-wavelength to any radiometric quantity (radiant energy, radiant flux, radiant intensity, irradiance). The installation points of the sensor for the measurements are described in Table 4.2.

TABLE 4.2: INSTALLATION POINTS OF THE SENSOR

Position (m) **Sensor**	**x**	**y**	**z**	**Sensor's position**
N1	1	0,30	1,02	Next to the window, facing ceiling
N2	1,50	2	0	on the floor, facing ceiling
N3	0,40	3,59	1,94	on the top of bookcase, facing ceiling
S1	2,4	1	0,90	Next to the window, facing ceiling
S2	0,85	3	0,90	On the small desk, facing ceiling
S3	0,50	4,08	1,30	On the top of the bookcase, facing ceiling

4.3.2.2 Results

The results consider measurements on various days at Delft Technical University, and at Twente University in The Netherlands. Below the sets of measurements are listed:

i. Room orientation (North, South)
ii. Distance from the light sources (x, y, z)
iii. Window condition (closed)
iv. Light condition (turned on)

i. North-facing office at TU Delft

The measurements at Delft began on March 2012. Figure 4.23 presents one day of the measurements (March 28th, 2012). The position of the sensor was stable at N1, near the windowsill, and it was facing the ceiling. N1 is the position, where the highest levels of irradiance are expected. The sensor is placed facing the ceiling, imitating in this way the PV products and their typical position while sunbathing.

The irradiance measured at N1 was quite low, with the highest rate at 17:00 reaching 140 W/m^2. At 19:00 when the artificial lighting is switched on, the irradiance is a mixture of natural and artificial light.

The characteristic peaks of the CFL light are apparent in the following graph.

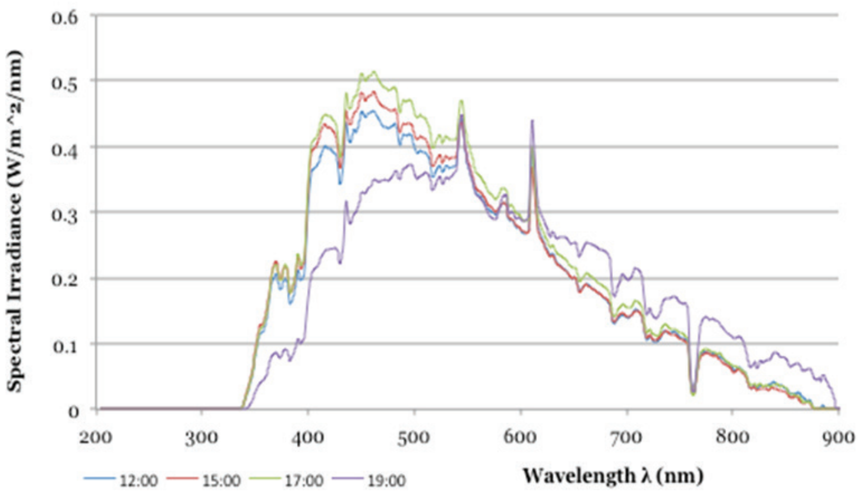


Figure 4.23: Spectral irradiance (W/m^2/nm) measured on 28.03.2012 in a north facing office, sensor's position N1, Delft.

As Figure C1.8 shows, the irradiance from 12:00 to 19:00 varies significantly. On March 28th, the highest irradiance reached 140 W/m² at 17:00, while at 19:00 the total measured irradiance was 126 W/m².

In Figure 4.24, indoor irradiance at N1 position is presented for 5 days at 12:00. Wavelengths under 200 nm and up to 900 nm were been cut, because of systematic error of the spectroradiometer. Figure 4.25 shows that the maximum total spectral irradiance was noticed for March 30th and 31st with values 500 and 530 W/m². The lowest total irradiance, 127 W/m², was noticed on March 28th. As can be seen, irradiance in the same time slot varies significantly from one day to another, mainly due to the different weather conditions.

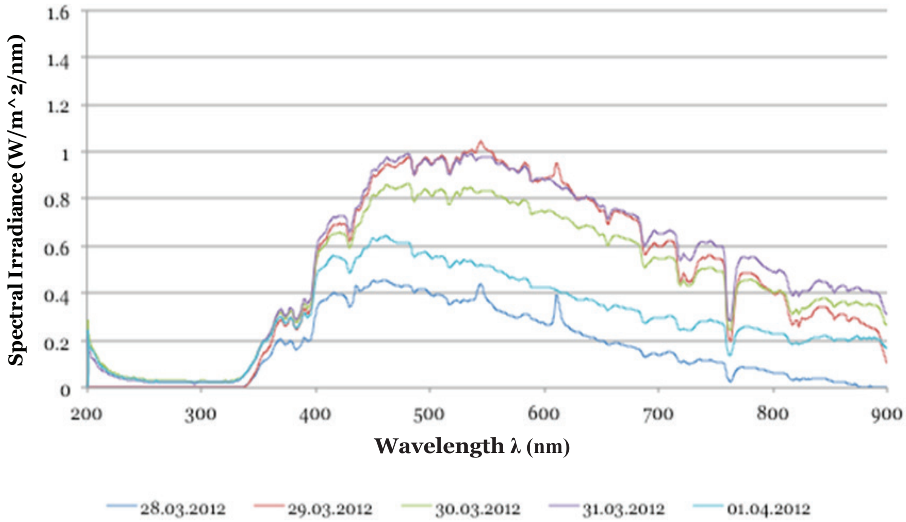


Figure 4.24: Spectral irradiance (W/m²/nm) measured at a north facing office, sensor's position N1, Delft 28.03.2012-01.04.2012 at 12:00.

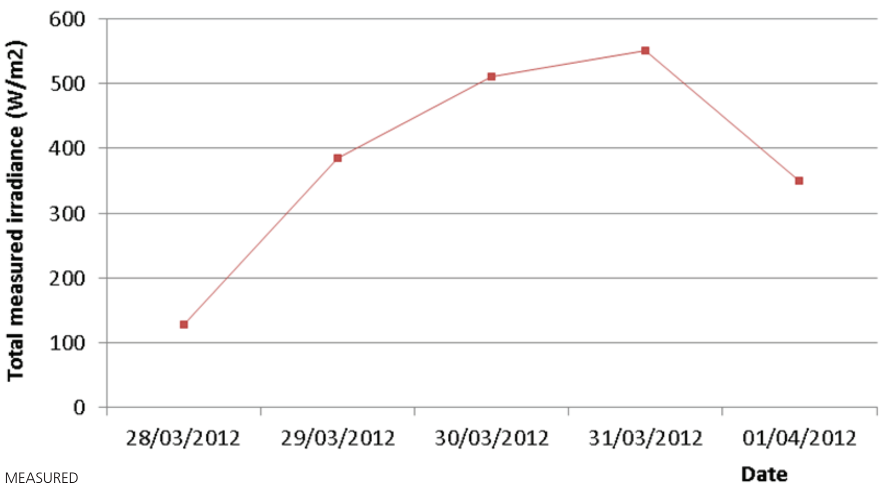
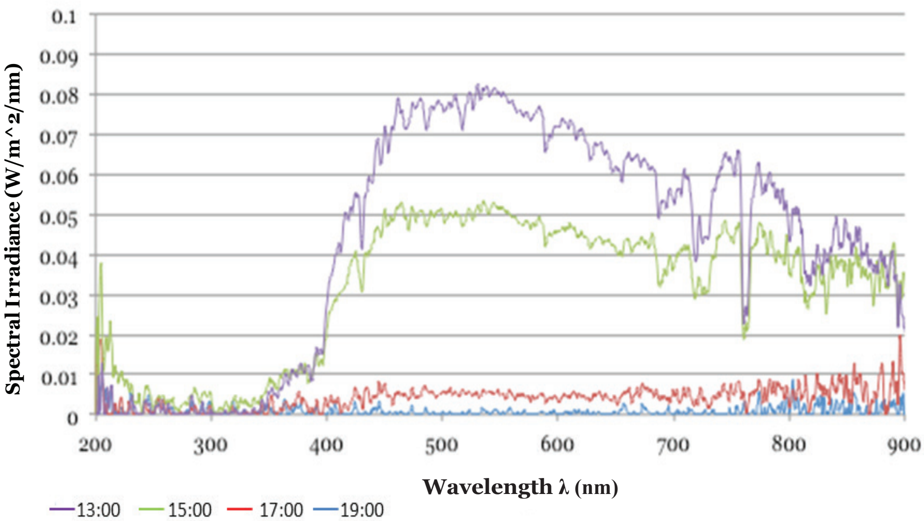


Figure 4.25: Total measured irradiance (W/m²) at a north facing office, sensor's position N1, Delft 28.03.2012 to 01.04.2012 at 12:00.

The irradiance in position N2 is really low compared to N1 and N3 positions. On the floor there are many shadings during the day, which influenced the results. The artificial light is also positioned too far from the sensor and there is no effect observed resulting from that. N2 position is considered as the worst case for a PV product to function, because the irradiance is too low (see Figure 4.26).

For N3, the sensor on the top of the bookcase, facing the ceiling, the results showed that only artificial light was measured. The irradiance measured is the irradiance of the CFL lamp, which was close to the sensor. The measurements lasted one week at N3 position and the results did not deviate significantly. There was nearly no influence on the measurements caused by natural light. As expected, spectral irradiance was under 0,2 W/m^2/nm with some peaks in the wavelengths that CFL light increases. In Figure 4.27 the measured irradiance for one day and at different time slots for position N3 is presented.

Figure 4.26: Irradiance (W/m^2/nm) measured on 31.05.2012 at a north oriented office, sensor's position N2, TU Delft.



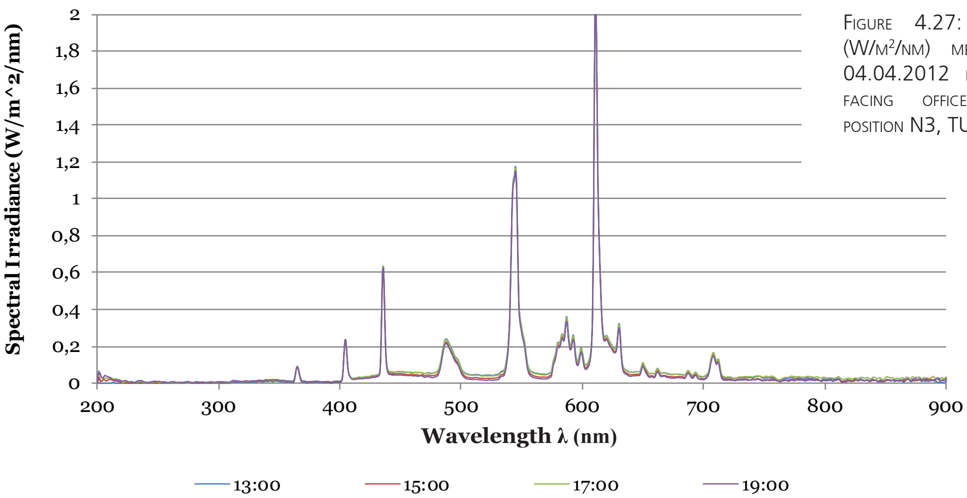


Figure 4.27: Irradiance (W/m^2/nm) measured on 04.04.2012 in a north facing office, sensor's position N3, TU Delft.

ii. South-facing office, at Twente University, Enschede

The measurements at Enschede at the University of Twente were conducted during June 2012. The measurements near the window at position S1 failed completely. Irradiance was quite high for the spectroradiometer's sensitivity and the results were invalid. For S2 sensor, the highest irradiance measured at 19:00h and it reached 128 W/m^2. This irradiance is a mixture of natural and artificial light. It is interesting to notice the behavior of the lines in the visible area of wavelengths. The spectrum of the LED lamps that were placed near the sensor is obvious in wavelengths from 393 nm to 799 nm with a peak at 454 nm. The high infrared radiation is due to the high temperature of the room during the day, while the sun faces the room.

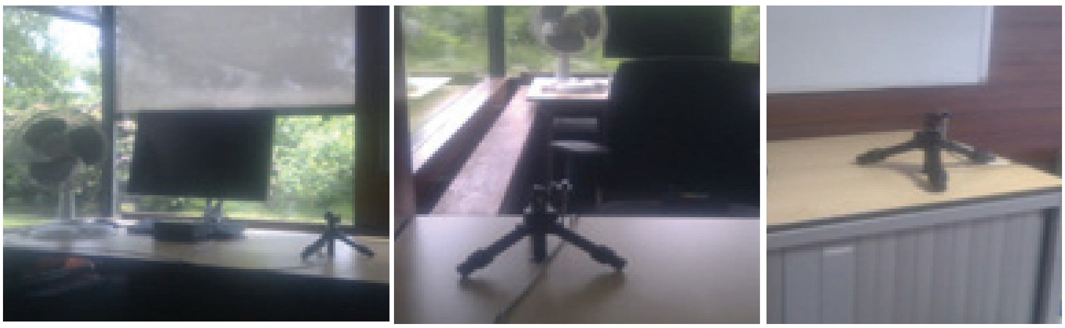


Figure 4.28: Positions of the spectroradiometer during the measurements in a south-facing office at Twente University, in Enschede. Left picture: Sensor's position S1, Middle picture: Sensor's position S2, Right picture: Sensor's position: S3.

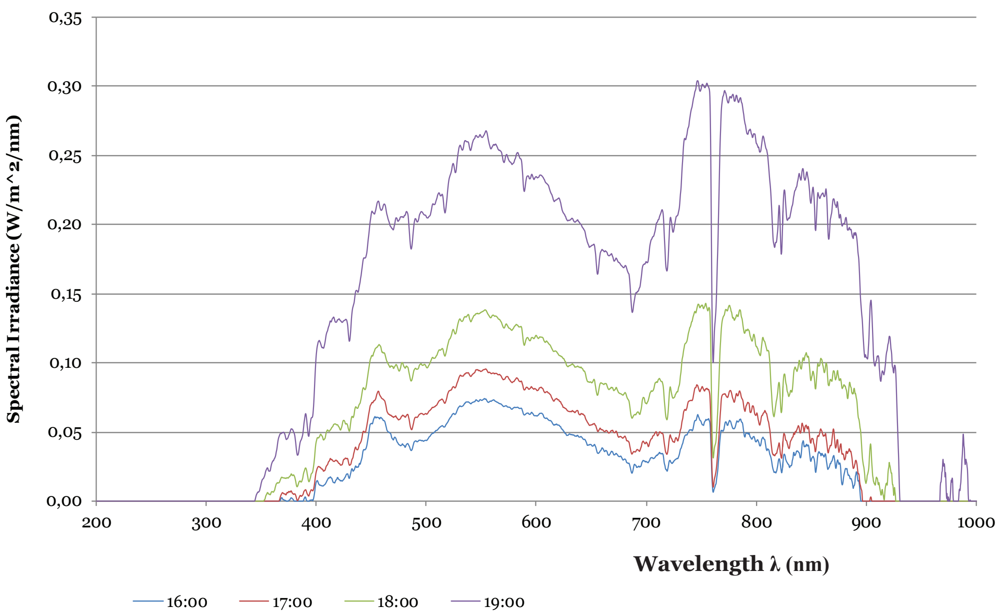


Figure 4.29: Irradiance measurements in W/m^2/nm on 18.06.2012, in a south facing office, sensor's position S2, Twente University, Enschede.

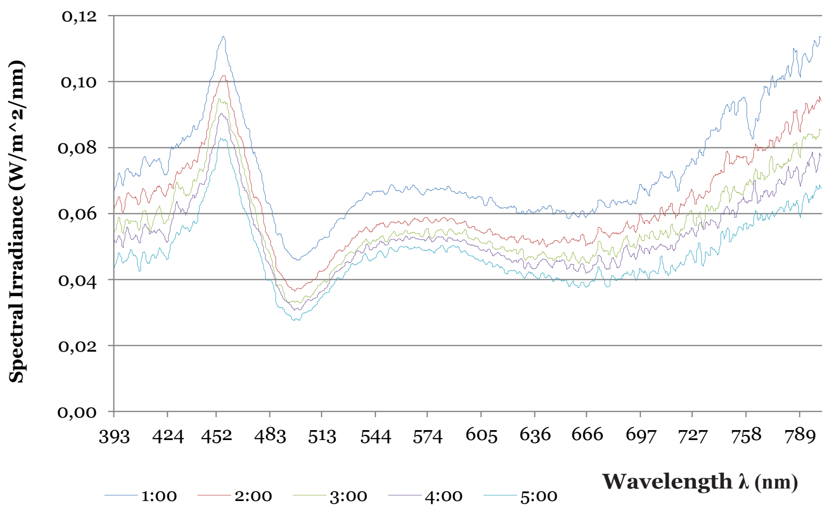


FIGURE 4.30: MEASURED IRRADIANCE IN W/M²/NM AT POSITION S2 ON 19.06.2012 AT TWENTE UNIVERSITY, ENSCHEDE. THE SPECTRAL RANGE OF THE LED LAMP IS PRESENTED.

For S3 position of the sensor, on the top of the bookcase the irradiance is lower than positions S1 and S2. The specific position of the sensor is on the backside of the room, where the sunlight barely reaches there.

However, one LED tube is located above the libraryand this is obvious in Figure 4.31, where the graphs have the same behavior as the spectrum of a common LED lamp.

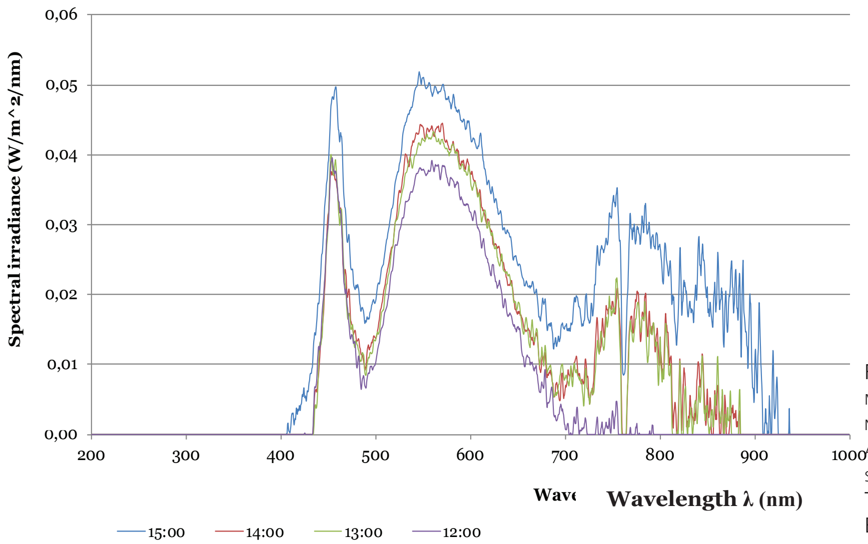


FIGURE 4.31: IRRADIANCE MEASUREMENTS IN W/M²/NM ON 20.06.2012, IN A SOUTH FACING OFFICE, SENSOR'S POSITION S3, TWENTE UNIVERSITY, ENSCHEDE.

The best scenario to use a PV product indoors was the south facing office and the position of the sensor S1 near the southern window and during June, where the maximum total irradiance reached 796 W/m².

However the results are influenced by the receptor used and also by the infrared radiation observed. The results of the measurements in both offices show that irradiance is lower than expected, because the measurements conducted under real conditions and many factors changed during this procedure.

Furthermore, irradiance indoors proved to be unstable and general conclusions for its typical range are quite difficult to be drawn. To conclude, there are many PV products that function with very low energy consumption, that could work very well in weak lighting conditions: clocks, calculators, temperature indicators or even PV powered remote controls for televisions. However, the number of applications under indoor light conditions is very limited because of the low level of energy available. Product designers should have insight in what levels of energy they can expect, so they can design products for it.

4.4 Summary and Conclusions

In this chapter, the irradiance under indoor conditions was investigated. The theoretical framework was given and measurements under various conditions were presented. The results of this study might be useful for industrial designers, who could be informed about weak irradiance conditions in indoor environments when developing PV products. According to the measurements and results presented here, it could be concluded that indoor irradiance differentiates broadly depending on the orientation of the room, as well as the type of light sources and the distance from them.

Results showed that indoor irradiance in a south-facing office in The Netherlands during summer ranged between 25 W/m^2 at a distance of 0.5 m from the window and around 5 W/m^2 at a distance of 4 m from the window. In a north-facing office, indoor irradiance ranged between 17 W/m^2 at 0.5 m from the window and 3 W/m^2 at 4 m respectively. The use of artificial lighting in the rooms appeared to be important, especially at a distance of more than 2 m from the window, where natural light indoors is not sufficient. Artificial lighting helps to keep indoor irradiance more stable away from the windows. However, indoor irradiance based on artificial lights usually ranges between 3 and 7 W/m^2, which is sufficient only for low-powered PV products to function in this environment.

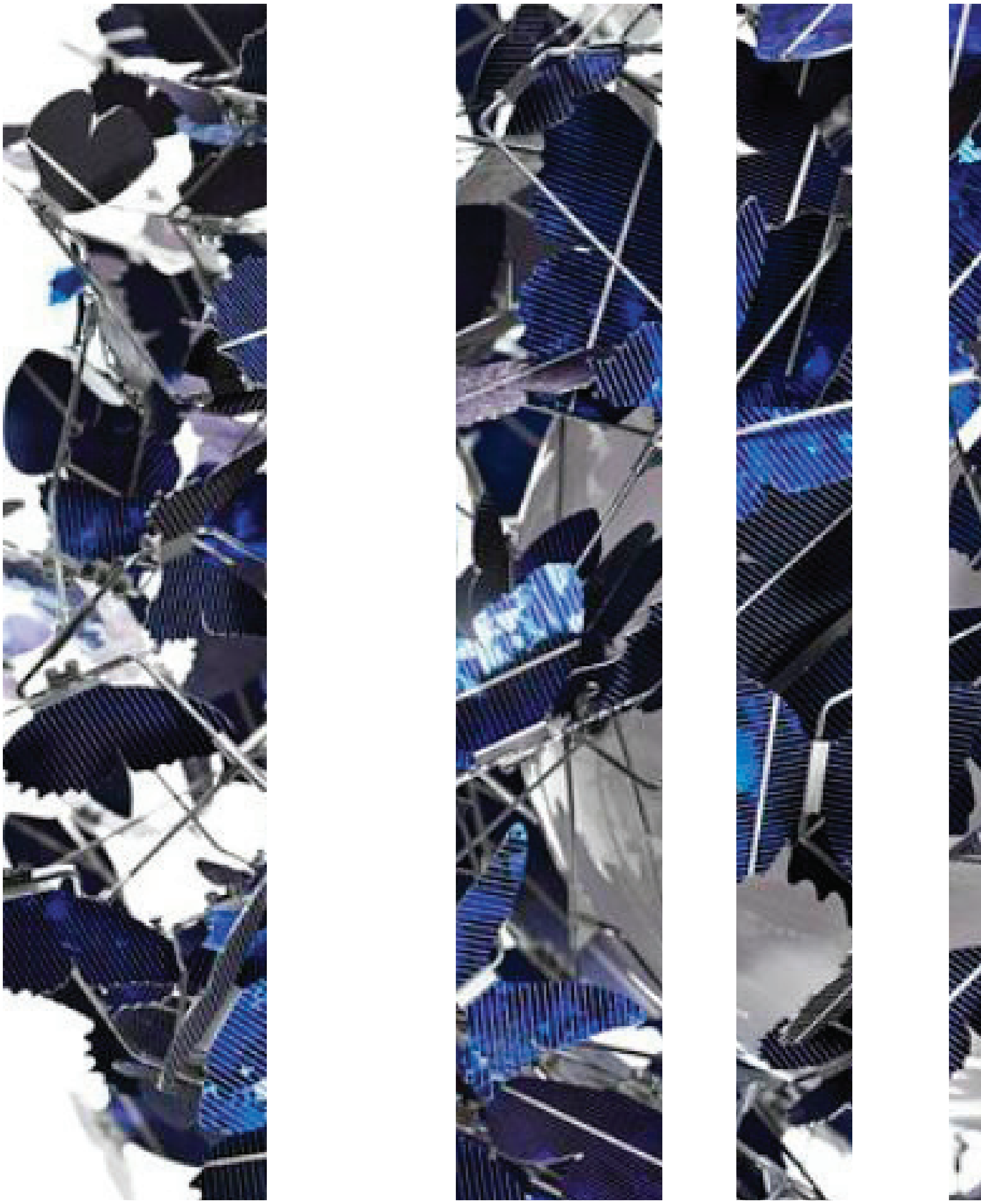
The values of indoor irradiance mentioned above cannot be considered fixed, as they are strongly influenced by the latitude and longitude of the room, the season (e.g. winter, summer), the weather conditions (e.g. sunny, cloudy, rainy), the use of artificial lighting (amount of lamps, type of lights), objects and shad(ow)ing at the indoor environment, distance from windows and artificial light sources, type of glazing etc.

Generally, it is considered that indoor irradiance typically ranges between 1 and 10 W/m^2. However, this does not exclude the possibility of having higher indoor irradiance during a summer day and quite lower irradiance on a winter day. Generally, indoor irradiance is higher near the window and lower while the distance from the window increases.

Based on the above conclusions, it is believed that only low power PV products with power consumption in the range of μW up to a few mW could be used indoors, such as clocks, calculators, ambient lighting products, sensors, temperature indicators, toys, chargers or PV-powered remote controls for televisions. During the design process of an indoor PV product, the designers should consider the typical indoor irradiance range as discussed above. Taking these values as a starting point, designers could make critical decisions regarding the products that can perform sufficiently under these conditions and make the right choices beforehand. The performance of PV technologies under low indoor irradiance conditions will be analyzed extensively in Chapter 5.

CHAPTER 5

Estimating the performance of PIPV cells indoors



Chapter 5 is based on the following journal and conference publications:

Apostolou G., Verwaal M., Reinders A.H.M.E., 2014, "Modeling the Performance of Product Integrated Photovoltaic (PIPV) Cells Indoors", Proceedings of 26th European Photovoltaic Solar Energy Conference (EU PVSEC), Amsterdam, The Netherlands, 2014, pp. 3535-3540.

Apostolou G., Verwaal M., Reinders A.H.M.E., 2014, "Estimating the performance of product integrated photovoltaic (PIPV) cells under indoor conditions for the support of design processes", Proceedings of 40th IEEE Photovoltaic Specialists Conference, Poster Presentation, Denver, Colorado, 2014, pp. 0742 – 0747.

Apostolou G., Reinders A.H.M.E., Verwaal M., 2016, "Comparison of the indoor performance of 12 commercial PV products by a simple model", Energy Science & Engineering, Wiley Online Library, January 2016, Article first published online: 22 Jan 2016, Volume 4, Issue 1, pp. 69-85.

5.1 Introduction

In this chapter a simple comparative model is presented, which has been developed for the estimation of the performance of PV products' cells in indoor environments, as a function of the distance from a light source, which emits a spectrum of artificial and natural light. It intends to support designers, which create PV-integrated products for indoor use. The model is based on physical measurements of natural and artificial irradiance indoors along with literature data of PV technologies under low irradiance conditions. For the model's validation PV cells of 12 commercially available PV-powered products with a power ranging from 0.8 mWp to 4 mWp were tested indoors under artificial illumination and natural light.

Despite the fact that PIPV market is rapidly growing (Reinders and van Sark, 2012), there are still many issues that have not been extensively analyzed, which mainly concern the use of PIPV indoors. The prominent issue is that while most of the PV products perform well under direct sunlight, they have a remarkable drop in their performance indoors (Kan, 2006). The efficiency of solar cells is usually measured under STC conditions. However, the indoor spectrum is often a combination of natural and artificial light and the irradiance levels range between 0 and 100 W/m^2. At low irradiance conditions, solar cells perform differently, which is something that should be taken along in a design of a product. This is therefore the core scope of our study; the effect of indoor irradiance conditions on the design of PV-powered product or product-integrated PV (PIPV). In this study we focused on PIPV containing PV technologies that occur most often, (Apostolou and Reinders, 2014; Apostolou and Reinders, 2012) i.e. crystalline silicon (c-Si), multi crystalline silicon (mc-Si) and amorphous silicon (a-Si), under artificial irradiance of compact fluorescent lamps (CFL), light emitting diodes (LED), incandescent light and indoor irradiance originating from solar light.

At the moment literature is limited regarding research done on solar cells' performance in an indoor environment. Several researchers studied the PV cells' performance under low irradiance conditions (Randall et al., 2001, 2003; Reich et al., 2005), indoor light conditions and light spectra (Apostolou et al., 2012; Freunek et al., 2013; Muller et al., 2009), the spectral irradiance of various PV technologies under different irradiance conditions, methods for optimal design of PV-powered products (Apostolou and Reinders, 2012, 2014; Reinders and van Sark, 2012; Alsema et al., 2005, Reinders et al., 2012; Veefkind et al., 2006; Timmerman, 2008; Reich et al., 2006) and the development of simulation tools for irradiance conditions and energy calculations of PV-powered devices (Muller et al., 2009; Reich et al., 2009, 2008).

Some studied methods are the use of CAD software for the simulation of indoor irradiance (Reich et al., 2008, 2009), the use of ray tracing programs, such as the Radiance or the DAYSIM (Muller et al., 2009), or spectral irradiance measurements of low intensities in indoor environments (Apostolou et al., 2012).

Based on literature, it seems that there are no simple and understandable models available to help designers, which estimate the performance of PV cells under low indoor irradiance, which has been measured and which comprises both natural and artificial irradiance. Most models that are available, calculate the efficiency of PV cells under high irradiance such as under STC or under very specific simulated weak irradiance (e.g. 10 or 100 W/m^2), which can differ from measured indoor irradiance.

Our modeling approach is based on the performance of the above-mentioned PV technologies under indoor irradiance conditions. For the validation of the model, we used a sample of 12 commercially available PV products for which we compare simulated results with real measurements indoors, under various irradiance conditions. The analyzed products' sample consists of small PV products for either indoor or outdoor use; 4 PV powered lighting products, 2 solar toys, 3 PV powered chargers, a solar keyboard, a solar computer mouse and one PV kitchen weight scale.

The structure of this chapter is as following; in Section 5.2 the modeling approach is explained. In Section 5.3 the experimental set-up is presented, which was used to validate our model using measurements of 12 PV products. Section 5.4 shows results derived from simulations with the model. The summary and conclusions of this study are presented in Sections 5.5.

5.2 Model Description

In order to estimate the performance of PV products' cells indoors, an analytical model was created in Microsoft Excel. The model combines measurements of natural and artificial irradiance in several rooms, with literature data and measured data regarding the performance and the spectral response of PV technologies under low irradiance levels, i.e. below 1000 W/m^2 (Randall et al., 2001, 2002, 2003; Reich et al., 2005, 2009, 2011). The input data of the model are the surface of the solar cell (in m^2), the measured spectral response (SR in A/W under STC) of the PV technology that is used by a certain PV product, the measured mixed indoor irradiance (in W/m^2/nm) and solar cell's distance from light sources (in m). The model performs spectrally distributed calculations and delivers solar cell's efficiency and power produced (in W) under specific indoor conditions (Figure 5.1). Finally, the simulated results of the efficiency and maximum power of the PV products' cells are compared with the measured values of efficiency and power of the PV cells using their measured I-V curves. This later step is executed to assess the model's accuracy.

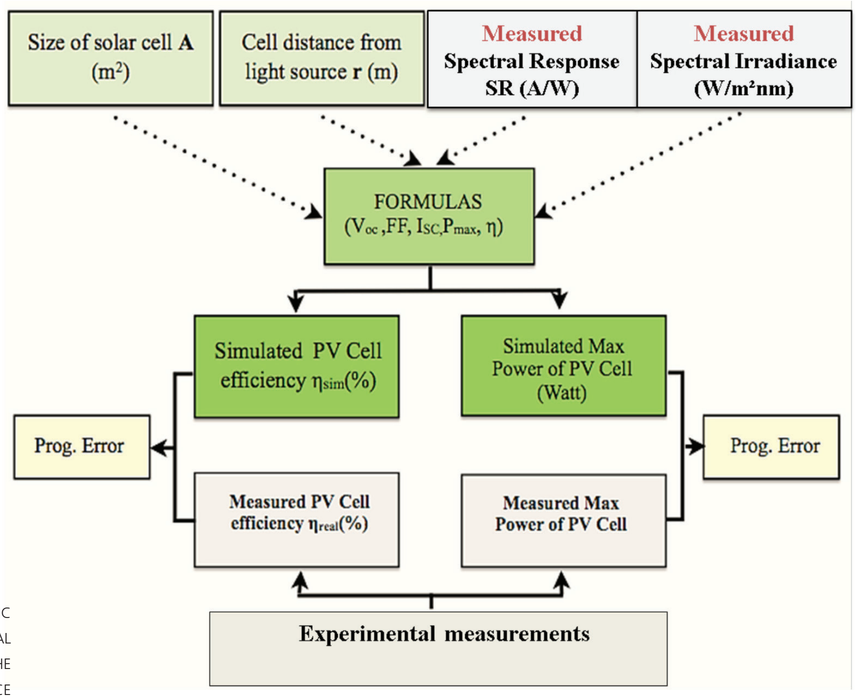


FIGURE 5.1: SCHEMATIC DEPICTION OF THE ANALYTICAL MODEL CREATED FOR THE ESTIMATION OF THE PERFORMANCE OF PIPV CELLS INDOORS (APOSTOLOU ET AL., 2014A, 2014B).

5.2.1 Mathematical equations

Equation 5.1 gives the general formula for the calculation of the efficiency n of a solar cell:

$$\eta(\%) = \frac{P_{mpp}}{P_{in}} \times 100\% = \frac{I_{SC} V_{OC} FF}{P_{in}} \times 100\% \qquad (5.1)$$

where

- I_{sc} is the short circuit current (in A),
- V_{oc} the open circuit voltage (in V),
- FF the fill factor (-)
- P_{mpp} the measured power in the maximum power point (mpp) (in W)
- P_{in} the power (in W) of the irradiance hitting a solar cell.

The FF was calculated by the following formula:

$$FF = \frac{I_{mpp} \cdot V_{mpp}}{I_{sc} \cdot V_{oc}} \qquad (5.2)$$

where the 'mpp' values are the maximum power point values (I_{mpp}) (in A): current at the maximum power point and V_{mpp} (in V): voltage at the maximum power point), which is also the maximum output of the solar cell. The I_{sc} is the short circuit current and V_{oc} the open circuit voltage. Using the Shockley equation in one-diode model, it can be assumed that ideally, the short circuit current I_{SC} is equal to the photocurrent I_{ph} (Ahmad et al., 2014; Djamila Rekioua et al., 2012; Volker Quaschning, 2005). The short circuit current I_{SC} is calculated using Equation 5.3.

$$J = J_{ph} - J_{o}\left[\exp\left(\frac{eV}{k_B T}\right) - 1\right] \tag{5.3}$$

where J is the current density produced by the solar cell (A/m²), J_o the saturation current density (A/m²), J_{ph} the generated photocurrent density (A/m²), e the elementary charge (1.60217662x10^{-19} Coulombs), V the applied voltage across the terminals of the diode (V), k_B the Boltzmann's constant (1.3806488x10^{-23} J/K), and T the temperature (K).

The short circuit current I_{SC} is calculated using Equation (5.4).

$$I_{SC}(\lambda) \cong I_{Ph}(\lambda) = \int E(\lambda) SR(\lambda)\, d\lambda \tag{5.4}$$

where E(ก) is the spectral irradiance (W/m² nm) and SR(ก) is the spectral response of the solar cell (A/W).

$$I_{SC}(\lambda) = \int \left(SR(\lambda) \times \left[E_{natural}(\lambda) + E_{artificial}(\lambda) \right] \right) d\lambda \tag{5.5}$$

where $E_{natural}$ is the spectral irradiance indoors originating from the sun (in W/m²nm), and $E_{artificial}$ the spectral irradiance indoors originating from artificial lights (in W/m²nm). The integral of the short circuit current from 191 nm to 1076 nm wavelength is the total short circuit current of the cell. The range in which the measurements were conducted is defined by the wavelength range of the measurement equipment- the spectroradiometer.

The specific spectroradiometer can measure irradiance (in W/m²) in a range of 185 and 1078 nm. For our measurements we have chosen a wavelength range from 191 nm to 1076 nm, due to irregularities of the measurements around the edges (e.g. above 1000 nm there was high infrared radiation). A presentation of results in this range does not affect the accuracy of the measurements and the calculation of the short circuit current of the PV cell.

5.2.2 Modeling of the indoor irradiance

Due to the small size of artificial lights compared to their distance to a PV product's cells, we assume in our model that lamps are point sources. Therefore, the irradiance at each point can be calculated using Formula 5.6, which follows the inverse square law.

$$I_{rps} = \frac{I_{ps}}{r^2} \tag{5.6}$$

where I_{rps} is the irradiance at a specific distance from the lighting point source (W/m^2), I_{ps} is the radiant intensity (luminous or radiant power per unit solid angle) of the lighting point source (W/sr) and r is the distance of the object from it (m). However, formula (5.6) cannot be used in case of linear light sources, such as fluorescent light tubes. However, Formula (5.6) cannot be used in case of linear light sources, such as fluorescent light tubes. Further exploration reveals that the assumption made in this study is applicable, once the hypothesis common artificial lights in a household are involved, such as lights in the living room. On the contrary, in the case of the reproduction of another indoor environment, such as an office or a working place, indoor artificial lighting cannot be considered as a point source, but as a line (e.g. a fluorescent tube) or as a surface (e.g. the window on a cloudy day). In this case, formula (5.6) cannot be used in the calculations.

For the investigation of indoor natural irradiance, associated with the distance from windows, multiple measurements were performed in an office and a workshop at TU Delft. Figure 5.2 depicts the results after three days of measurements at a northern-oriented office. The specific orientation was chosen as the worst-case scenario (less irradiance during the day) and also due to its availability to conduct tests there. On December 3rd, 2013, the measured irradiance outside of the window of the office, was 37 W/m^2, on April 2nd, 2014 it was 91 W/m^2 and on June 4th, 2014 146 W/m^2. The orientation of the measurement device (in this case a spectroradiometer) during the measurements was horizontal (placed flat on a table). In Figure 5.2 the distance-to-window rule is described, as indicated by Equation (5.7).

For the measurements that are presented in Figure 5.2, no solar cell was used. More specifically, a spectroradiometer was used, which was placed at different distance from the window. Artificial lighting is not used during this test. At each position of the spectroradiometer's sensor we got one measurement. Figure 5.2 presents the indoor irradiance as measured, including possible reflections, transmissions, etc. In the model we do not account the reflections and transmissions because it is not possible. The transmissions and reflections of irradiance differentiate broadly in each case. Thus, it is not possible to be calculated or even predicted. The only reflection that can be assumed is the one coming from the window's glass.

The measurements revealed that the irradiance changes approximately with the reciprocal of the distance:

$$I_{rs} = \frac{I_s}{r} \quad (5.7)$$

where I_{rs} is the irradiance at a specific distance from the lighting source (W/m^2), I_s is the radiant intensity (luminous or radiant power per unit solid angle) of the lighting source (W/sr) and r the distance (m). Formulas (5.6) and (5.7) are used for the calculation of the irradiance at a specific distance from the artificial light sources and windows.

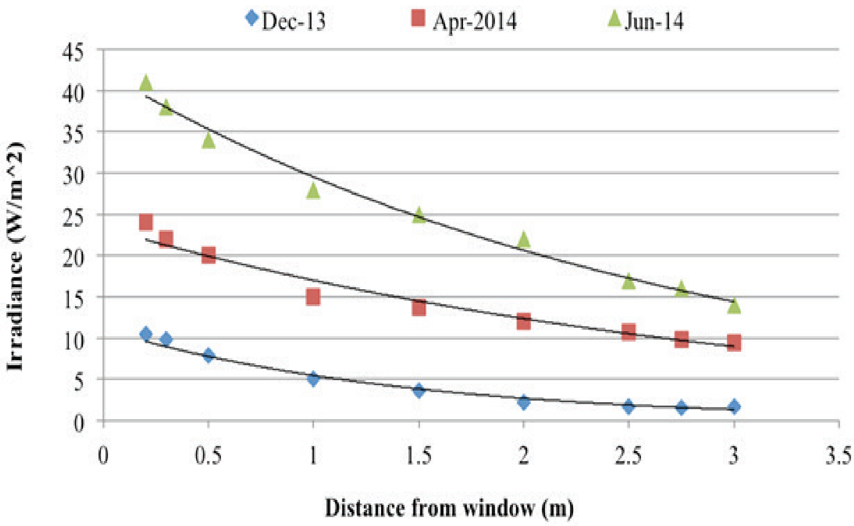


Figure 5.2: Irradiance measurements conducted on three different days: on December 3rd, 2013, on April 2nd, 2014 and on June 4th, 2014 in a North-oriented office at TU Delft, The Netherlands (Apostolou et al., 2014a; 2014b).

5.3 Experiments

5.3.1 Measuring I-V curves of PV cells

The equipment used for the measurements of the PV products' cells' performance (I-V curves) include a data acquisition module and an electronic circuit, see Figure 5.3. The I-V measurement set-up is in house designed by Martin Verwaal at the Applied Labs of the Industrial Design Engineering department of Delft Technical University. This circuit consists of a charging capacitor (C1) with low series resistance, ranging from 10 μF to 1000 μF, a current measuring resistor (R1) ranging from 1 Ω to 100 Ω, a discharging MOSFET BUK9535 (T1) and a start switch (SW1). The MOSFET has a low ON-resistance (<35 mΩ at Vgs=5 V). Resistor R2 is 1kΩ and it is added to keep the gate of the MOSFET in the normal state at a low level, so the MOSFET is not conducting.

First the PV cell of the product has to be disconnected from the products' electronic circuit and connected to the measuring circuit. The capacitor is discharged through the MOSFET by pressing switch SW1.

The capacitor is initially emptied (at 0 V). When the switch is released, the PV cell recharges the capacitor. Voltage in the capacitor does not sweep from zero to V_{oc}, but the capacitor is charged until the V_{oc}.

At the same time the data acquisition module records the solar panel voltage and charging current. A Labview program controls the measurement and presents the I-V curves of the tested PV cells.

Measurements were taking place under mixed indoor lighting conditions and with solar cells of various types. Therefore the size of the capacitor and the value of the current measuring resistor had to be adjusted each time. For indoor measurements it proved to be very important to integrate measurements over 1 or more power line cycles (multiples of 20 ms) due to the flickering of the artificial light sources. To obtain at least 100 measurements over the full charging cycle, the capacitance was chosen to get a charging time of more than 2 seconds. The value of the current measuring resistor was kept as low as possible, but high enough to keep the accuracy below 0.1 % of the total range. In our case the measuring range was 100 mV, which gives an accuracy of 100 μV. For example, in order to get a measuring range of 10 mA, a resistance of 10 Ω was used.

The accuracy in the current measurement was 1 % of the measured value, as well as the accuracy of the measuring resistor (1 %). The absolute voltage accuracy was 0.1 % of the range (10 mV). The rate of the measurement depends on the PV cell and the capacitor and it is estimated to be in a range of 100 msec to 10 sec.

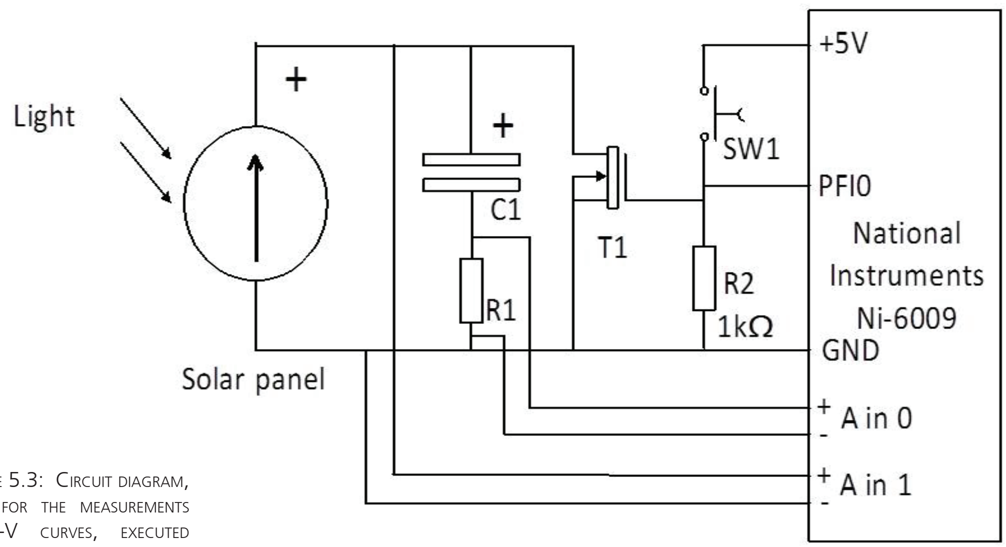


Figure 5.3: Circuit diagram, used for the measurements of I-V curves, executed with National Instruments NI-6009 (Designed by Martin Verwaal).

5.3.2 Measuring indoor irradiance

Spectrally distributed measurements of indoor irradiance were conducted in offices and laboratories of the Department of Design Engineering of TU Delft in the Netherlands. Natural light and three types of artificial light sources, as described in Section 2.2: compact fluorescent (CFL), light emitting diode (LED) and halogen were measured. A StellarNet Fiber Optic Spectroradiometer, type Black-Comet-SR, model C-SR was used for the measurements of spectrally distributed irradiance of both natural and artificial lighting. The accuracy of the instrument is 5 %, with bandwidth 0.5 nm and wavelength range of 190 to 1080 nm. It contains a probe for a CR2 miniature cosine receptor for UV-VIS-NIR.

Figure 5.4 depicts the irradiance spectrum indoors, at an office environment, under mixed light (natural light indoors and artificial light by CFL lamps 58 Watt, light color 830 Warmwhite, Philips Master TL-D, 58W/830) and the spectrum of light outdoors, just outside the window of the specific office. Both measurements were conducted at the same time. The sensor was placed horizontally during both measurements, indoors and outdoors, at distance 50cm inside and outside the window respectively.

For the outdoor measurements of irradiance the spectroradiometer described in Section 4.3.1.1 was used, together with the cosine receptor CR2-AP~4.8 %, also described in Section 4.3.1.1. Total irradiance outside the office was measured around 33 W/m^2, while indoor irradiance was around 10.5 W/m^2. It is interesting to notice the difference between these two spectra, regarding their values. The window glass (double-glazing) cuts almost two thirds of the measured outdoor irradiance and permits only one third of it to pass indoors. The glass manufacturer is Glaverbel, and the type is Thermobel 0.5 Stopray. Stopray means that there is a triple silver coating that stops direct IR sunlight with around 80 % and lets the visible sunlight through.

Observing the curve that depicts the outdoor spectral irradiance, we can see only the spectrum of natural light, while indoors the curve seems to contain both natural light that enters the room, as well as artificial light originating from fluorescent lamps. The existence of artificial fluorescent light is clear, due to the peaks of the curve at specific wavelengths, some of which are at the 437, 547, and 612 nm, typical characteristic of the specific light.

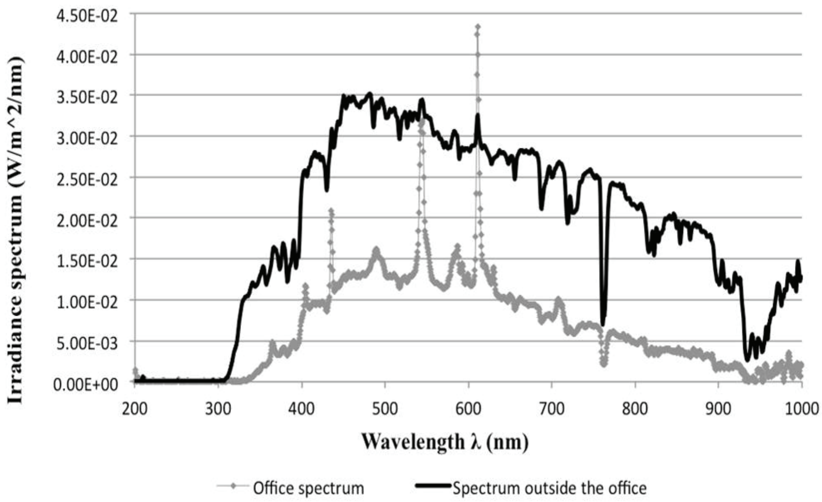


Figure 5.4: Irradiance measurements indoors under mixed indoor lighting and outside the window at the Applied Labs of TU Delft, The Netherlands, on January 21st, 2014.

5.3.3 External quantum efficiency (EQE) and spectral response (SR) measurements

Measurements were conducted for the calculation of the PV cells' spectral response (SR) under STC. For that purpose, we used a built-in house set-up of the Photovoltaic Materials and Devices (PVMD) group at TU Delft. This set-up consisted of a Newport illuminator/monochromator, a probes' holder, a chopper and a lock-in amplifier. The PV cell of each product was placed at a stable position and at distance around 2 m from the monochromatic light source to measure the external quantum efficiency (EQE). The measured EQE at this stage of the procedure was not at STC. In order to calculate the EQE and consequently the SR of the tested PV cells at STC, we also used a solar simulator calibrated at AM1.5 (Super Solar Simulator WACOM, Model WXS-90S-L2, AM1.5GMM, Serial No. 07061501, 1φ, 230V, 18A) for the calculation of the short circuit current I_{SC} of the solar cells of each product. Using the correlation of the short circuit current under STC and under the monochromatic light, we calculate the EQE at STC and from there the SR at STC, using Equations (5.8) and (5.9).

$$EQE_{STC} = EQE_{mon.light} \cdot \frac{J_{sc_{stc}}}{J_{sc_{mon.light}}} \tag{5.8}$$

where EQE is the external quantum efficiency and J_{SC} is the short-circuit current density (mA/cm^2) at STC and under the monochromatic light measurements (mon.light).

The spectral response (SR) of the PV products' cells is calculated by Equation (5.9):

$$SR = \frac{q}{hc}\lambda \cdot EQE \qquad (5.9)$$

where SR is the spectral response of the solar cell (A/W), EQE is the external quantum efficiency, λ is the wavelength (nm), q the elementary electric charge (~1.6x10^{-19} C), h is Planck constant (~6.626x10^{-34} Js) and c the speed of light in vacuum (m/s). As Equations (5.8) and (5.9) show, the EQE and SR are wavelength dependent. EQE is dependent on the J_{SC} (see Equation (5.8), which also depends on the wavelength. The PV products that were tested using the equipment outlined above are illustrated in Figure 5.5.

Figure 5.5: Tested PV products: (a) IKEA Sunnan lamp, (b) Little Sun solar-powered lamp, (c) Voltaic Solar bag, (d) Solio charger, (e) Solar mouse by Bondidea, (f) Frog toy, (g) PV kitchen weight scale, (h) Car toy, (i) WAKA WAKA light, (j) Philips remote control, (k) Solar wireless keyboard by Logitech, (l) Ranex lights (Figures attached from Google).

The PV cells are tested including encapsulant material and contacts. Figure 5.6 illustrates a sample of the tested products' PV cells, as used during the measurements. Dissimilarities in measured and simulated values are a result of the damages in PV cell's surface, the PV cells' connection, the type of the coating material or lesions of the PV cell. Figures 5.7, 5.8, and 5.9 present the results from the measurements of the spectral response data for c-Si, mc-Si, and a-Si cells at STC respectively.

The reported in literature spectral response of each technology, at irradiance levels between 1…1000 W/m^2 (Reich et al., 2005), is also included in Figures 5.7, 5.8, and 5.9 as well as the measured spectral response of each one of the products' PV cells.

Figure 5.6: Nine PV cells from the test sample of PV products.

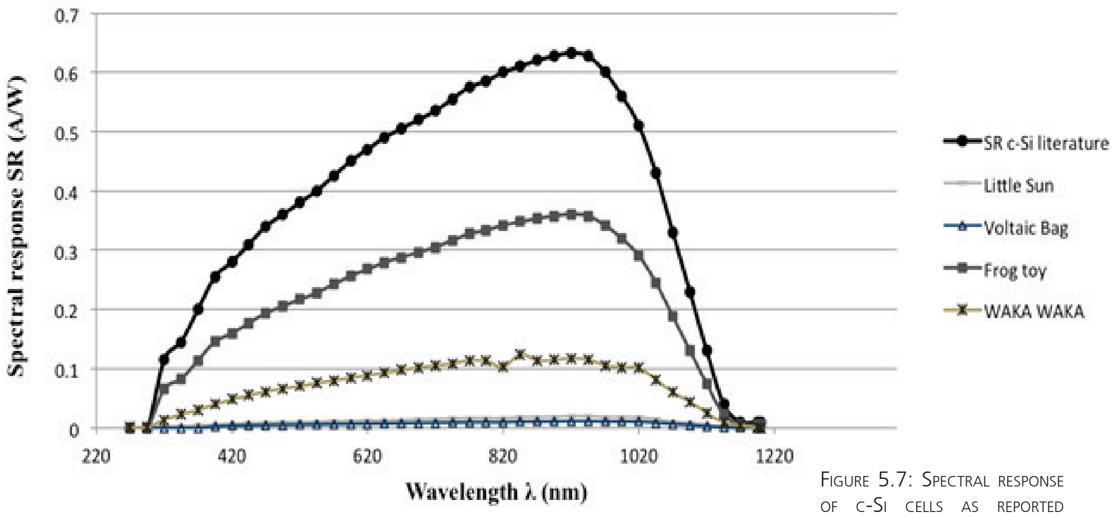


Figure 5.7: Spectral response of c-Si cells as reported in literature (Reich et al., 2005), and measured for the tested PV products (Apostolou et al., 2014a, 2014b) under STC.

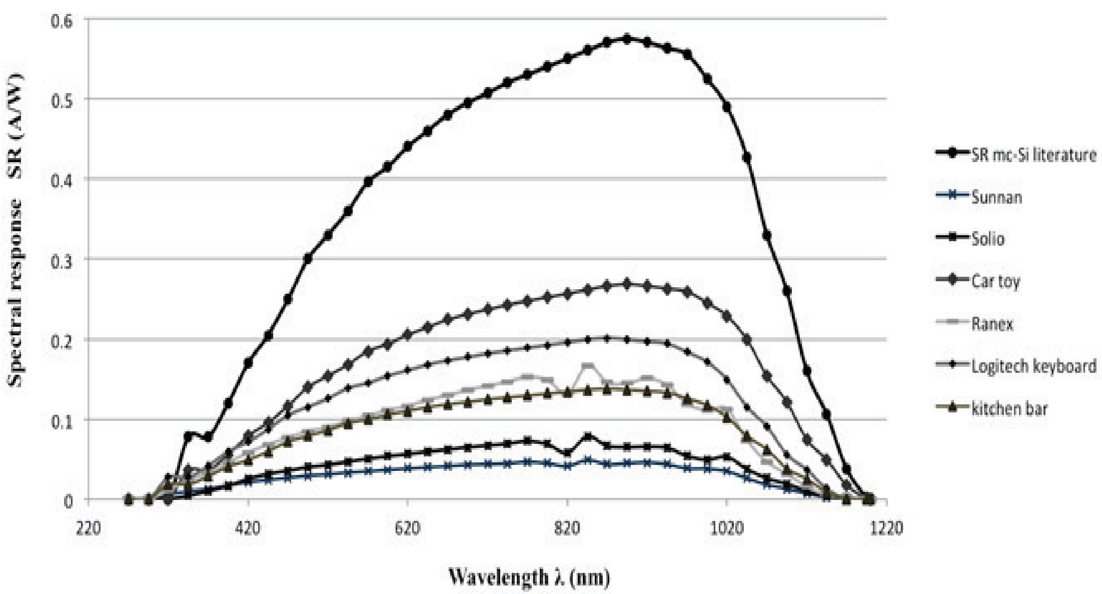


Figure 5.8: Spectral response of mc-Si cells as reported in literature (Reich et al., 2005), and measured for the tested PV products (Apostolou et al., 2014a, 2014b) under STC.

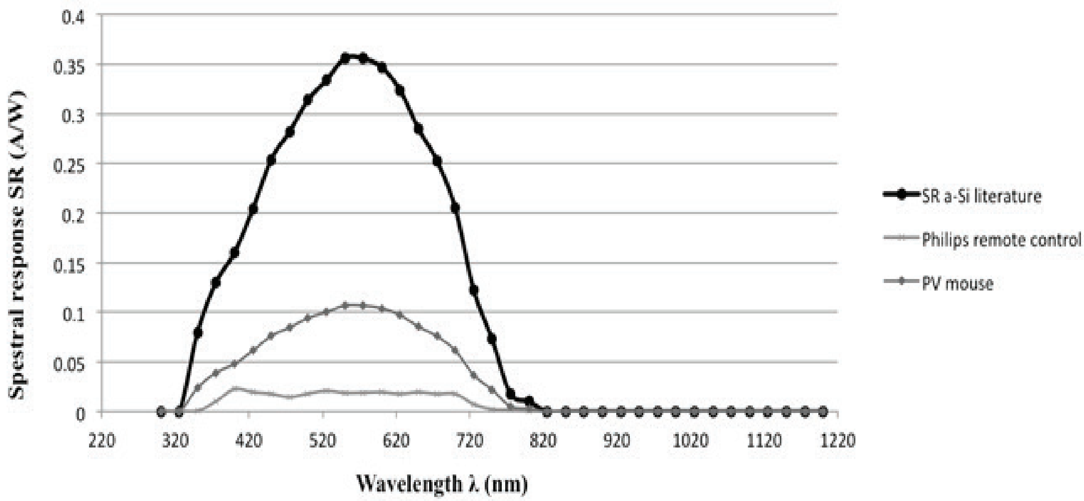


FIGURE 5.9: SPECTRAL RESPONSE OF A-SI CELLS AS REPORTED IN LITERATURE (REICH ET AL., 2005), AND MEASURED FOR THE TESTED PV PRODUCTS (APOSTOLOU ET AL., 2014A, 2014B) UNDER STC.

Figure 5.7 presents the spectral response of the c-Si cells, as measured at STC, for 4 PV products; the Little Sun light, the Voltaic bag, the frog toy and the Waka Waka light. There is also one extra line in the graph, which depicts literature data for the spectral response of c-Si. It is noticeable that the reported in literature spectral response of c-Si is far higher than the measured values. In reality, the spectral response of the cells that consumer PV products use, could hardly compare with the SR of the lab fabricated PV cells intended for larger applications. Furthermore, even PV cells of the same technology, which are fabricated by other manufacturers, could have deviations in their spectral response, as it is broadly influenced by the transmissions and reflections of the cell's surface.

The SR of the frog toy's PV cell is the highest among the other cells and reaches around 57 % of the literature data of SR for c-Si. The lowest SR is noticed for the Little Sun light and the voltaic bag, which seem to be less than 3 % of the literature values.

Figure 5.8 presents the spectral response of mc-Si cells and includes 7 lines; one for the literature-reported spectral response of mc-Si and 6 lines, which depict the SR of 6 commercial PV products that use mc-Si cells. These products are the Sunnan light, the Solio charger, the car toy, the Ranex lights, the Logitech keyboard and the kitchen weight bar. The literature-reported SR of mc-Si is the highest compared to the products' values.The spectral response of the car toy reaches around 46 % of the literature data for the mc-Si's SR, while the lowest value among the tested products is the one of the Sunnan lamp, which is around 8 % of the literature value.

Figure 5.9 presents the spectral response of a-Si cells. It includes three lines; one for the literature-reported spectral response of a-Si cells and two lines, which depict the SR of two commercial PV products

-the Philips remote control and the PV-powered mouse. Between the two products, the Philipps remote control has the lowest SR, which is around 7 % of the literature data for the SR of a-Si cells.

Looking at the spectral response curves of the Figures 5.7, 5.8 and 5.9 it arises that at wavelengths below 400 nm, the PV cell absorbs most of the incident light and therefore the spectral response of the cell is low. At wavelengths 400 to 1000 nm the cell approaches the ideal, while at wavelenghts above 1100 nm the spectral response significantly decreases, finally falling down to zero.

5.4 Results

The model described in Section 5.2, was applied twice (1st and 2nd simulation). In order to clarify the differences between the two simulations, in Table 5.1 we present the inputs, variables and measurements that took place during the first and the second simulation. As Table 5.1 shows, for the first simulation we measured the spectral irradiance indoors with the equipment described in Section 4.2, as well as the current-voltage (I-V) curves of the products' PV cells under mixed indoor light, using the equipment described in Section 3.1. The inputs of the model for the first simulation were the literature data of the spectral response of c-Si, mc-Si and a-Si cells (Reich et al., 2005), the measured indoor irradiance, the surface of the PV cell and its distance from the artificial and natural light sources. The outcomes were the calculation of the maximum power and the efficiency of the PV cells. Finally the model's outcomes are compared with the results of the maximum power and efficiency of the cells, as derived from the measurements and the model error is calculated.

For the second simulation, extra measurements took place (see Table 5.1). At this stage except from the indoor irradiance and the I-V curves of the tested PV products' cells, we also measure the external quantum efficiency and the spectral response of each PV cell at STC, using the equipment described in Section 3.3.

The inputs of the model are the same as in the first simulation with one important difference; for the second simulation we use as input the measured spectral response of the PV cells at STC and not the literature data. The model's outcomes are the maximum power and efficiency of the PV cells, which are again compared with the measured values. The purpose of these two simulations is to understand the role of the spectral response in the performance of a solar cell and the big deviations of the measured values compared to the literature data.

TABLE 5.1: MODEL'S INPUTS AND VARIABLES FOR THE FIRST AND THE SECOND SIMULATION.

Simulations	Measurements	Inputs	Variables
1st simulation	1. Spectral irradiance indoors, 2. I-V curves of products' cells under mixed indoor light	a. Literature data of SR, b. spectral irradiance indoors, c. solar cell's surface, d. cell's distance from the light sources	1. P_{max} (mW), 2. η (%)
2nd simulation	1. Spectral irradiance indoors, 2. EQE and SR under STC, 3. I-V curves of products' cells under mixed indoor light	a. Measured SR under STC, b. spectral irradiance indoors, c. solar cell's surface, d. cell's distance from the light sources	1. P_{max} (mW), 2. η (%)

For the simulations, it is important to clarify that the active solar cell surface is standardized for all the PV products at 10 cm^2. All PV products' cells were tested at a distance 50 cm from the window and the cells were horizontally placed during the measurements (flat on a table). During the 1st simulation, the estimation of the fill factor and the open circuit voltage was done according to the irradiance levels on the cell. The necessary data for this calculation were obtained from measurements performed by Randall (2001). By processing of the data in Excel, logarithmic equations were found that best fit the experimental results. It was calculated that according to Randall (2001) the voltage depends on the irradiance based on the following relation V_{OC}=0.045ln(E)+0.2931, with R^2=0.98572. This is a linear variation on a logarithmic scale. Using this equation the program computes the V_{oc} that corresponds to the irradiance reaching the surface of the cell. The V_{oc}, for the second simulation, was measured for each PV product's solar cell using the I-V curve measurement set-up that was described in Section 3.1.

There exist several reasons to present results from simulations using real solar cells adding to simulations based on theoretical values of solar cells from literature, namely:

1. We would like to show the performance of real solar cells in commercially available PIPV to show experts in the field of energy technologies, in particular PV researchers, that a lot of improvement can be made in increasing the performance of PIPV by using solar cells with a better performance, better said with a higher efficiency.

2. Secondly to show product designers that the use of literature data of variables such as SR, cells' efficiencies etc. during the design process of a PV product may result in assumptions that won't comply with the reality. If using literature data, the assumptions and calculations regarding the performance of the designed product will be too positive.

By showing the difference between simulations based on data from literature and data from existing cells we provide valuable information to researchers and product designers.

Table 5.2 presents the cells of the tested PV products, as used in the measurements. The table illustrates the PV cells of each product, it presents the PV technology of each cell, as well as the short circuit current, the open circuit voltage and the maximum power of each cell, as measured using the equipment described in Section 3.1. The values of I_{SC}, V_{OC} and P_{mpp} that are presented in this table are measured under fluorescent light. It can be seen from Equation (5.5) that I_{SC} depends on the available light spectrum. Besides, the short circuit current differs for each type of PV technology, as each material has different spectral response (SR) and solar cells have different surface area. These factors greatly explain the variation of a PV cell's performance under different types of illumination.

Table 5.2: The tested products' PV cells, as used during the experiments.

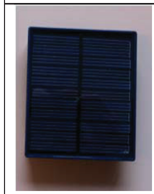
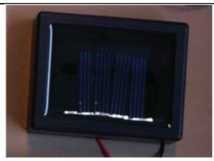
PV products' cells	Product name	PV cell type	Full cell area (cm²)	I_{SC} (mA) (under CFL light)	V_{OC} (V) (under CFL light)	P_{mpp} (mW) (under CFL light)	FF
	Sunnan	mc-Si	57	0.57	2.56	0.62	0.42
	Little Sun	c-Si	36	0.35	3.22	0.62	0.55
	Voltaic Bag	c-Si	87	0.49	6.54	1.65	0.51
	Solio	mc-Si	17	0.31	3.7	0.58	0.50
	Frog Toy	c-Si	4.8	0.24	0.52	0.076	0.61

Table 5.2: The tested products' PV cells, as used during the experiments. (cont.)

	Philips control	a-Si	30	0.27	5.37	0.77	0.53
	Car Toy	mc-Si	2.7	0.31	0.24	0.041	0.55
	Waka Waka	c-Si	65.7	1.4	1.45	1.1	0.54
	Ranex	mc-Si	8.1	0.63	1.62	0.6	0.59
	Logitech keyboard	mc-Si	35.24	0.32	4.7	1.34	0.89
	PV mouse	a-Si	9.53	0.09	6.9	0.41	0.66
	Kitchen bar	mc-Si	44	0.32	6.1	0.96	0.49

5.4.1 First simulation

For the first simulation, the model has been applied by using the spectral response SR as given in the literature (Reich et al., 2005), as it is also discussed in the introduction of Section 5.4. The measurements and results presented in Table 5.3 were conducted on January 21st, September 26th and October 3rd, 2014. The measured spectral irradiance on January 21st, 2014 outside the window of the office, where the PV products were tested, was around 33.4 W/m^2. Indoors, at the laboratory the irradiance was ranging between 8 W/m^2 and 12 W/m^2 and composed of a mixture of artificial fluorescent light and natural light. On September 26th and October 3rd, 2014 the measured irradiance at the laboratory was ranging between 10 W/m^2 and 13 W/m^2 (see Table 5.3).

Table 5.3 shows the measured and simulated results for the maximum power Pmax (mW) and efficiency η (%) of the tested PV products' cells under mixed indoor irradiance. It indicates that the simulated efficiency of the PV products' cells during the first simulation was exceeding the measured value. From Table 5.3, it seems that a well-performing PV product under low indoor irradiance is the solar keyboard, for which the measured and simulated efficiency is 10.7 % (±0.1) and 10.9 % (±1.1) respectively. Other sufficiently performing products indoors are the frog toy with measured and simulated efficiency 6.4 % (±0.2) and 7.3 % (±2.2) respectively and the PV-powered mouse with 6.2 % (±0.1) and 7.3 % (±2.3). On the other hand, bad-performing PV products for use at low indoor irradiance are the Philips remote control with measured and simulated efficiency 2.5 % (±0.1) and 7.0 % (±2.1), the Sunnan lamp with 2.1 % (±0.2) and 3.8 % (±1.1) and the Waka waka light with 1.2 % (±0.1) and 4.2 % (±1.3) respectively. The measured results that are presented in Table 5.3 were conducted using the equipment described in Section 3.1.

The results show that the model can predict the efficiency of the PV products' cells under mixed indoor irradiance with a typical inaccuracy of around +30 % (see Table 5.3). Besides, except from the irradiance (Li, 2015), it seems that there are other factors that influence PV cells' performance under mixed irradiance conditions. In order to define these factors and succeed a more accurate result, we continued with the second round of simulations of our model, where we measured the specific spectral response of the products' cells.

Table 5.3: Measured and simulated maximum power P_{max} (mW) and efficiency η (%) of various PV products' cells under mixed indoor irradiance*.

PV product	Product function	PV cell type	Total irradiance** (W/m2)	Measured Pmax (mW)	Simulated Pmax (mW)	Measured Efficiency (%)	Simulated Efficiency η (%)
Sunnan	lighting	mc-Si	9.9±0.5	1.2±0.5	1.0±0.3	2.1±0.2	3.8±1.1
Little Sun	lighting	c-Si	10.2±0.5	1.2±0.6	1.5±0.5	4.0±0.2	6.2±1.9
Voltaic Bag	charger	c-Si	8.6±0.4	3.7±0.5	2.3±0.7	5.4±0.5	6.0±1.8
Solio	charger	mc-Si	10.2±0.5	0.8±0.2	0.9±0.3	4.5±0.1	3.8±1.1
Frog Toy	moving	c-Si	10.2±0.5	1.3±0.7	1.8±0.5	6.4±0.2	7.3±2.2
Philips control	charger	a-Si	10.5±0.5	0.8±0.4	1.7±0.5	2.5±0.1	7.0±2.1
Car Toy	moving	mc-Si	10.5±0.5	1.1±0.3	1.4±0.4	5.8±0.1	6.0±1.8
WAKA WAKA	lighting	c-Si	10.9±0.5	0.8±0.3	1.5±0.5	1.2±0.1	4.2±1.3
Ranex	lighting	mc-Si	9.5±0.5	0.3±0.1	0.5±0.1	3.6±0.04	3.6±1.1
Logitech keyboard	entertainment	mc-Si	11.5±0.5	3.3±0.1	4.1±0.3	10.7±0.1	10.9±1.1
PV mouse	entertainment	a-Si	10.5±0.5	0.7±0.2	1.2±0.5	6.2±0.1	7.3±2.3
Kitchen weight bar	cooking	mc-Si	10.5±0.5	1.2±0.4	1.7±0.6	3.6±0.6	5±1.6

*Mixed indoor irradiance: Natural and artificial irradiance measured indoors.
**Irradiance measured with spectroradiometer.

5.4.2 Second simulation

During the second simulation, we used the spectral response (SR), as measured under STC, for the 12 different PV product's cells, instead of what is stated in the literature. Other inputs of the model for the second simulation were the measured indoor irradiance, the surface of the PV cell and its distance from the artificial and natural light sources, as discussed in the introduction of Section 5.5. The measured values of the spectral response of the c-Si, mc-Si and a-Si cells were significantly lower than those reported in the literature, as it is also presented in Figures 5.7, 5.8 and 5.9.

As Figure 5.10 demonstrates the PV cells' efficiency resulting from the second simulation was lower than the values of the first simulation, and they slightly deviated from the measured efficiency. The lesser the spectral response of a PV cell, the lower the short circuit current and the lower the cell efficiency. In Figure 5.11, the measured and the simulated PV cells' efficiency for the tested PV products are presented for the first and the second simulation round. The Philips remote control seems to have the biggest deviation of PV cells' efficiency between the 1st and the 2nd simulation, which ranges from 7 % to 3 % respectively. This deviation is a result of the spectral response of the product's PV cells (a-Si), whose measured spectral response is significantly lower (<10 %) than the literature data (Reich et al., 2005) (see Figure 5.9). Other products with big deviations between the first and the second simulated efficiency are: the Little Sun light, with 6.2 % efficiency during the first round and 4.2 % for the second simulation and the Waka Waka light with 4.2 % simulated efficiency in the first round and 2.3 % for the second round respectively.

As Figure 5.10 indicates the best-performing PV product is the solar-powered keyboard, with simulated efficiency for the second simulation round around 10.5 %, while the measured value is estimated at 10.7 %. The frog toy also performs sufficiently with simulated and measured efficiency around 6.3 % and 6.4 % respectively. On the other hand the Sunnan lamp seems to be one of the bad-performing products, with simulated efficiency around 2.4 % in the second round of simulations, while the measured efficiency is 2.1 %. For the second simulation, results revealed that the model can predict PV cells' efficiency under mixed indoor irradiance with higher accuracy than the first simulation, reaching a typical accuracy of approximately +82 % (see Figure 5.10).

The simulated results show that the model can sufficiently predict the performance of the PV products' cells at an indoor environment. More specifically, the simulated results of the PV cells' efficiency η for mixed indoor light were slightly different from the measured values, with a typical accuracy of around 70 %. However, the simulated results of the PV cells' maximum power P_{max} were even closer to the measured values, with a typical error around 25 % (see Table 5.3).

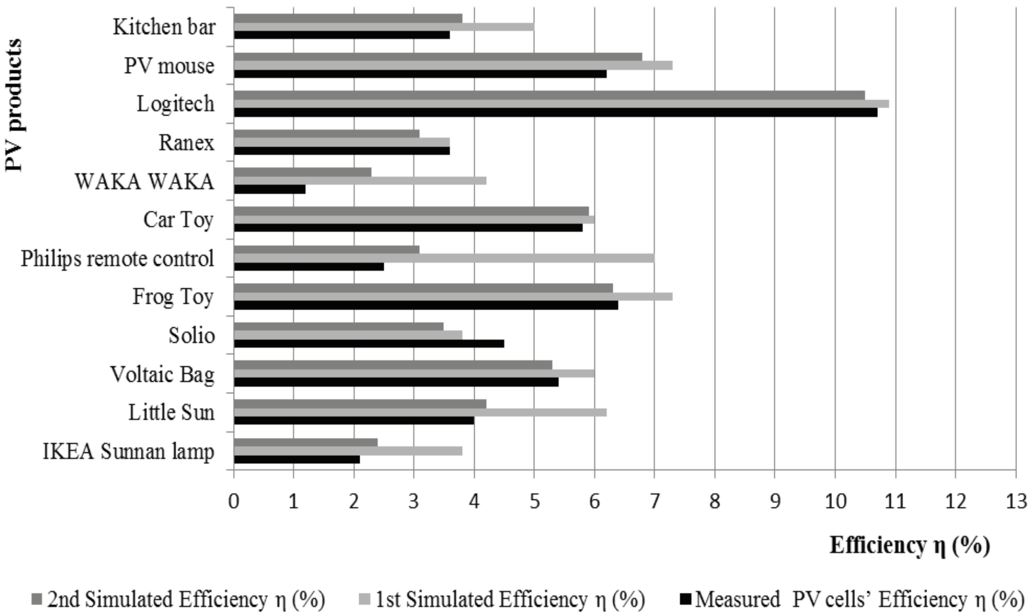


Figure 5.11: Measured and simulated PV product cell efficiency (%) under mixed indoor lighting, for the 1st and 2nd simulation (Apostolou et al., 2014a, 2014b).

Trying to increase model's accuracy, primary conditions (e.g. amount of indoor irradiance, spectrum of artificial light, distance of the PV cells from light sources, test room) were very specific. In general, model's error is a result of some unspecified conditions and features of the products. In detail, an important factor, which is responsible for the low PV cells' performance is the unknown cover-material of the PV cell (coating). Each PV cell was surrounded by a plastic surface (cover), whose material is not known. This also results to an undefined transmittance of the cover material. Other factors, which limit down the efficiency of the PV cells, are the orientation of the cell, possible damages on the product's surface (e.g. scratches, dust, fingerprints, lesions on the front cover), as well as indoor reflections of irradiance, or shadows in the interior of the room from the surroundings (e.g. furniture, curtains, outdoor shadows, etc.). However, the most important factor, which is responsible for the deviations in results, is the unknown spectral response (SR) of the PV technology that each product use. The measured spectral response of the tested PV cells at STC was significantly lower than the literature data of SR for c-Si, mc-Si and a-Si cells (see Figures 5.7, 5.8, 5.9).

5.5 Summary and Conclusions

This chapter describes a model, which estimates the performance of PV cells in an indoor environment and under mixed indoor light that partially contains outdoor light. The most significant variables in this model are the spectral response (SR) of the PV product's cell and the indoor irradiance. The model has been validated by two different simulations: 1) using the spectral response SR as given in the literature (under STC) and 2) using the SR as measured (under STC) for 12 different PV products with either x-Si or a-Si solar cells. It's due to the limited research in this field and the related lack of data from other studies regarding modeling of product-integrated PV, the spectral response of PV cells under mixed indoor lighting, as well as cells' performance under low lighting conditions, that the results of this study could not be compared in full extent with existing findings. However, we assume that now that this basic model exists, students, researchers and designers can use it to design or evaluate indoor PV products with the purpose to improve their performance. The results of the model are precise enough for product design; using measured SR curves the accuracy is typically in the order of 30 %. The accuracy of the model indicates that the simulated efficiency value deviates x % from the measured value (which is taken as 100 %). In this case x % is 30 %. This is due to the low irradiance conditions, deviations between measured SR at STC and the actual SR at low irradiance conditions and the bad quality of commercially applied PV cells in PV products.

In Figure 5.11, in literature reported efficiencies are presented for c-Si, mc-Si and a-Si cells (Apostolou and Reinders, 2014; Freunek et al., 2013; Apostolou et al., 2014; Green et al., 2015). Figure 5.10 shows that for mc-Si cells the efficiency at 100 W/m^2, which is around 12 %,

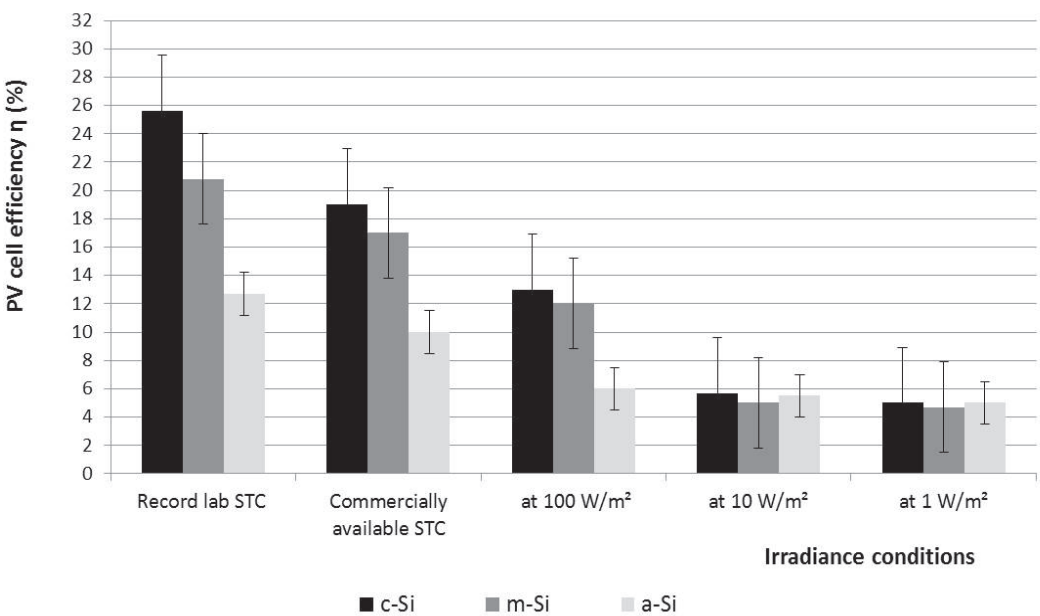


Figure 5.11: PV cell efficiencies of c-Si, mc-Si and a-Si at different irradiance conditions respectively at STC, 100 W/m^2, 10 W/mÇ and 1 W/m^2 as reported in literature (Apostolou and Reinders, 2014; Freunek et al., 2013; Apostolou et al., 2014; Green et al., 2015) with absolute error ±1%.

drops significantly at 10 W/m^2 down to 5 %, whereas the efficiency of a-Si cells seems to be relatively constant around 5 to 6 % at different levels of irradiance. Lastly, c-Si cells' efficiency decreased from 13 % at 100 W/m^2, to 5 to 6 % at 10 W/m^2, and 5 % at 1 W/m^2. The PV cell efficiencies presented in Figure 5.10 are based on literature (Kan, 2006; Green, 2013) and are not outcomes of the authors' research.

Based on the literature the spectrum and temperature of the cells are AM1.5 and 25 ^{o}C. However, the R_{sh} seems to be low in the low intensities and therefore the efficiency of the cells is low, too.

From the literature (Muller et al., 2009; Reich et al., 2008, 2009), it follows that the simulation or modeling of the PV products cells' performance indoors has still not been sufficiently investigated. There are several factors that influence the performance of PV products in an indoor environment, such as the level of indoor irradiance, the performance of the PV cells under low irradiance conditions, the interaction of the user with the product and the system's energy losses. Therefore, we propose a new simple model capable of predicting the PV performance under various illumination conditions, which would provide basic support during the design of a PV product's energy system.

The results of the second set of simulations show that under mixed indoor lighting conditions, the simulated PV cells' efficiency slightly deviates from the measured values, with a typical accuracy of around +82 %. Additionally, the model practically forecasts a PV product's cells performance under artificial illumination, with a typical accuracy of around +71 % for CFL and LED lighting. Measurements with higher accuracy are quite difficult to obtain, since indoor irradiance reaches just a few tenths of Watts/m^2, which is close to the measurement limits of irradiance sensors. Besides, the efficiency of PV cells under these conditions is rather low. The model's results hence expose the above-mentioned fact and are considered satisfactorily accurate. It was found that under mixed indoor lighting of around 20 W/m^2, the efficiency of solar cells in 12 commercially available PV-products, ranges between 5 to 6 % for amorphous silicon (a-Si) cells, 4 to 6 % for multi-crystalline silicon (mc-Si) cells and 5 to 7 % for the mono-crystalline silicon (c-Si).

Figures 5.7, 5.8, 5.9 have shown that the spectral responses (SR) of tested PV cells at AM 1.5 deviate considerably from literature data. They are typically around 70 to 80 % lower and in some cases even more than 90 % less, as presented in Section 5.4. The significantly low spectral response of commercial PV products' cells happens due to low quality of the cells applied. The cutting of PV cells in small pieces - to be applied in PV products' surfaces - and their condition, e.g. soiling of cell's surface, possible scratches, cracks and other damage play a crucial role on the measured spectral response.

Consequently, the use of low quality PV cells leads to PV products with low performance. Furthermore, it is essential to stress here that another reason for the dissimilarities in the spectral responses is that in this study PV products were not tested as single PV cells, but as assembled devices with several interconnected PV cells (see Figure 5.6 and Table 5.2).

It is also important to be aware of the fact that the spectral response of the PV cells as measured at STC (1000 W/m^2) has been used for modeling at 10 W/m^2. This is due to the measurement range of solar simulators, which usually does not cover the very low irradiance range used in our model and due to the unavailability of PV cells' spectral response data under low irradiance conditions as provided by manufacturers.

Finally, because of our purpose to support designers in their design processes to realize indoor PV products with higher performance than the existing ones, we consider the accuracy of this model as being rather acceptable.

Based on the results and conclusions of this chapter, some advices and recommendations are given to designers who like to create PV products for indoor use. These advices are presented in the Appendices D and E of this thesis.

CHAPTER 6

Users' interaction with PV-powered products

This chapter is based on the following publications:

Apostolou G., Reinders A.H.M.E., 2016, "How do users interact with photovoltaic-powered products? Investigating 100 'lead-users' and 6 PV products", J. Design Research, Vol. 14, No.1, pp. 66-93, Copyright © 2016 Inderscience Enterprises Ltd.

Apostolou G., Reinders A.H.M.E., 2015, "Users' Interaction with PV-powered Products: an Evaluation of 6 products by 100 end-users", Proceeding of 42nd IEEE Photovoltaic Specialists Conference, New Orleans, June 14-19, 2015, LA.

6.1 Introduction

User behavior is neither predicted nor controlled in any case and it broadly influences products' performance. This chapter is dedicated to users' interactions with PV products for indoor use. It emphasizes on users' expectations before they use the product and their experience after using it, as well as the fulfillment of their expectations and needs. Both questions are approached through a survey on users interaction with PV products. Questionnaires, observations, measurements and users' reports are used for this study. The results are presented in form of a statistical analysis, mainly using graphs and personal observations.

Because of the newness of PV powered products, in this study, we will look at the "lead-users" and not the regular users. Eric von Hippel first introduced the term "lead-user" in 1986 (von Hippel, 1986). Lead users have a need for products that are not identified yet by regular users and will become general in the market in the future. Lead users can forecast future needs, propose solutions and redesign ideas in order to contribute towards the innovation of products and services (von Hippel, 1982, 1986; Bakker et al., 2010). The aim of this study is to observe lead-users when interacting with PV products, to identify their expectations, needs and feelings and to finally see if PV products correspond efficiently to their wishes, abilities and prospects.

Investigating a number of PV integrated products of different categories; one can observe that there are no specific guidelines that designers can use in order to estimate the available energy from an indoor or outdoor environment and the fraction of this energy that can be extracted by the PV system of the product (Apostolou et al., 2014). As a result these products have often insufficient energy systems, which lead to poor performance, or they are too expensive because of their possible oversized energy system or the extra material they might use (Apostolou and Reinders, 2012, 2014; Apostolou et al., 2014).

Furthermore, the majority of these products are unattractive to the consumers, due to the low quality and low-cost materials that are used (e.g. for casings) or the inelegant design of the products. As these products are targeted at consumers, design guidelines should be drawn to address not only the technical aspects of these products, but also the users' interaction with them, as well as the appeal of the products' design.

Although markets have ubiquitous PV products, consumers seem rather reluctant to their performance, usability and aesthetics. Therefore it is important not only for PV products to meet adequately users' needs but for designers and manufactures to focus on the technology and on users' interaction with the products, as well.

Figure 6.1: PV products in our study: (a) Waka Waka light, (b) Waka Waka Power light and charger, (c) Sunnan IKEA lamp, (d) Little Sun light, (e) Beurer kitchen weight scale and (f) Logitech solar keyboard (Apostolou and Reinders, 2016).

Various methods could be used to identify respondents' needs, such as market research, real-life surveillance or even lab-observation for specific periods of time, focus groups and quantitative analyzes (Bakker et al., 2010; Fulton Suri, 2003; Jelsma, 2006; Scott Kakee, 2008). Nevertheless, these methods often fail to foresee precisely whether respondents will understand the tested products' technologies. In this study both quantitative and qualitative methods will be used. The hypothesis of this survey is that the tested PV products do not fully satisfy lead-users' wishes, abilities and expectations.

The feature that distinguishes this study in the field, is the fact that more than one PV product was tested in real conditions and statistics from lead-users' interaction with the products is higher than in other studies executed so far (Bakker et al., 2010; Scott Kakee, 2008; Smit et al., 2002; Vredenburg et al. 2002; Reich et al., 2007, 2008; Wever et al., 2008). The outcome of this study might be useful for designers, as they could have an overview of lead-users' thoughts about PV products and in this way they could evaluate their proposals and ideas about the products and finally offer better services or design more reliable products, which will fit respondents' desires. This study does not aim to investigate in depth user behavior from a social and psychological point of view. It intends to be used in parallel with technical and design features of PV products and to offer a perspective of lead-users' thoughts to designers.

The tested PV products (see Figure 6.1) compromise four lighting products (the Sunnan lamp by IKEA, the Waka Waka light, the Waka Waka Power and the Little Sun light), and two PV products for indoor use (a solar kitchen weight scale by Beurer and the solar keyboard by Logitech). The data in this study, as well as the observation of the lead-users during their interaction with the products, are mainly based on the selection of 21 reports regarding the tested PV products, written from 2011 to 2014. Table 6.1 gives an overview of the tested PV products, their main functions, as well as the average number of lead-users that interacted with each product. The collected data and the measurements regarding the technical analysis of the products were conducted under the supervision of the author.

A literature research on user studies (in Section 6.2) is now presented, the methodology applied (in Section 6.3), the results (Section 6.4) and in the end the chapter is finished with the conclusions and discussion of the findings (Section 6.5).

TABLE 6.1: REPORTS: USER INTERACTION WITH PV PRODUCTS (2011-2014)

PV products	Function	Designed to be Used	Number of reports	Number of users
Sunnan lamp	Lighting	Indoors/ Outdoors	10	50
Waka Waka light	Lighting	Outdoors	3	15
Waka Waka Power	Charging/ Lighting	Outdoors	1	4
Little Sun light	Lighting	Outdoors	3	15
Beurer kitchen scale	Kitchen equipment	Indoors	2	10
Logitech solar keyboard	Office equipment	Indoors	2	6
Total: 6 products			21	100

6.2 Literature research on user studies

The issues of consumer behavior and sustainable product design have been criticized extensively by many researchers (Reinders et al., 2012; Bakker et al., 2010; Smit et al., 2002; Vredenburg et al., 2002; Wever et al., 2008; Shackel, 1984; Rodriguez and Boks, 2005). However there are still questions that need to be answered.

Jelsma and Knot (2002) pointed out that user's behavior can be led and be determined by the design of a product (Wever et al., 2008; Jelsma and Knot, 2000). This approach seems applicable to the design of PV products, since the PV products need the specific attention of the user and they could control user behavior. However, it seems that users cannot easily adapt a specific behavior and therefore a design based on this approach could not be effective. Users prefer to be autonomous and independent on the product and they are not willing to change their daily behavior and habits.

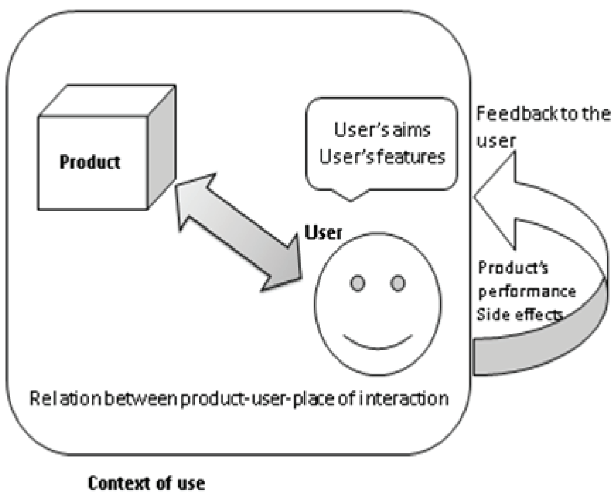


FIGURE 6.2: THE MODEL OF ROODEN AND KANIS (2000) ILLUSTRATING THE USER-PRODUCT INTERACTION (SCHEME DESIGNED BY THE AUTHOR) (WEVER ET AL., 2008; ROODEN AND KANIS, 2000).

Rodriguez and Boks (2005) chose a rather different approach, trying to adapt the design of the product to the user's needs (Wever et al., 2008; Rodriguez and Boks, 2005). Regarding the design of a PV product, it seems that Rodriguez and Boks' approach is more appropriate than Jelsma and Knot's. It could be more fruitful to design a PV product, according to the user's needs and expectations. However, in order to achieve this, it is important to discover and analyze what users expect from these products. Furthermore, Vredenburg et al. (2002) pointed out the quality of products by focusing on users' abilities and wishes, aiming to enhance user interaction with the product.

Rooden and Kanis (2000) suggested an advanced model for user-product interaction, which is based on Shackel's model (1984), and contains user's features, product's features, and details about the relation between the user, the product and the place of interaction (Wever et al., 2008; Shackel, 1984; Rooden and Kanis, 2000). The model also offers feedback information to the user on the performance of the product, as well as the possible side effects. This model is demonstrated in Figure 6.2.

The model of Rooden and Kanis will be used in our study for the investigation of the lead-users' interaction with PV products.
Through observation during the field trial, a questionnaire and written reports of respondents, we will analyze the lead-user itself, the product, the place of interaction and their relation, aiming at a user-centered design of products.

Sanders (2002) talks about the different experience characteristics of users and divide them in four categories: the 'obvious' which depicts things that people say or think, the 'visible' which refers to what people do, the 'unspoken' or 'tacit' which are things that people feel or be aware of, and the 'dormant' which are people's dreams (Sanders, 2002, 2006a, 2006b). In our study through lead-users' interaction with the PV products, their daily notes on the workbook and their thoughts, we will attempt to uncover all the above aspects and focus mainly on the unspoken and dormant features, which are important for designers.

6.3 Methodology

The study of the lead-users' interaction with PV products took place during the academic years 2013-2014 and 2014-2015 for a PV Workshop, at Technical University of Delft (TU Delft). The sample of the respondents consisted of 100 lead-users (75 men and 25 women) at the age of 20 to 35 years old. Around 90 % of the respondents are Dutch and the rest 10 % originates from EU or India. All the participants were bachelor students of the Industrial Design Engineering department. Before the field trial, which lasted one to two weeks, the lead-users could choose and decide which PV product they would like to use, among a selection of 12 PV products.

Respondents of this study may be characterized by the term "lead-users", as it was defined in the Introduction of this study. Lead-users were asked to follow some specific tasks with the products; first to use the photovoltaic-powered product in their daily routine and then to disassemble and analyze it, in order to identify its main components and to evaluate its feasibility from a technical, practical, economic and environmental point of view. From a technical point of view, the energy conversion efficiency of the solar cells was defined, the theoretical charging time of the battery, the current-voltage and power-voltage curves and the maximum power point, by conducting measurements at different levels of irradiation. Moreover, the application of solar cells in the products was evaluated and concepts or redesign ideas for a potential improvement of the PV product's system were proposed. The respondents used the PV product as a part of their daily routine. The issues that they had to note during the trial week were the following:

- Their initial expectations from the product before using it,
- Evaluation of the product after use it for a short period of time,
- User pattern and using frequency,
- The ease of usage and general functioning of the product,
- Emerging frustrations or feelings of satisfaction/dissatisfaction with the PV product,
- Suggestions for improvement,
- Ways to use the product in their daily life.

The methods that were used to gather the research elements regarding the respondents' comments before, during and after the field trial, as well as their frustrations, problems and suggestions, were notebooks for writing down their daily routine and their feedback during their interaction with the product. These notebooks were presented in formal reports written by the students and were used by the authors of this research. The authors organized the data collected from the reports, categorized them and draw conclusions. Furthermore, lead-users' interaction was based on self-observation during their daily routine with the product, while direct observation method was applied during the analysis of the technical features of the PV products, as well as during the performance's tests.

Besides the above issues, a questionnaire of 17 questions was set up in order to collect information about lead-users and their interaction with the PV products. This questionnaire can be found in Appendix F. Two sets of questions were formed; the first one consisted of closed-questions, where the possible answers were indicating users' satisfaction; whereas the second set consisted of open questions, where the respondents were asked to elaborate on their opinions and thoughts.

The questionnaire was first distributed to the lead-users, since its aim was to outline their first reactions and thoughts about the PV products after the respondents' early interaction with the product. Lead-users first answered the closed-questions of the questionnaire and after a few days of living with the product they continued with the open questions. After the questionnaire was completed and during the field trial the lead-users were self- or directly- observed interacting with the product and by the end of this period they already had prepared the report with their actual experience. Lead-users' answers from the questionnaire will be presented in the form of statistics. Further results of this study, such as possible re-design of PV products or best-fitted user context with a specific product, as proposed by the respondents in their formal reports, will be analyzed and discussed in the results' section.

6.4 Results

6.4.1 Analyzing lead-users' answers from the questionnaire

The results depicted the lead-users' expectations at a time before using the product and their evaluation after the field trial. It is interesting to observe the difference between the two stages. During the first contact of the lead-user with the product, and before the field trial starts, lead-users criticize the outlook of the product (e.g. the design, color, materials, size) and they try to predict its function and usefulness. Around 60 % of the respondents feel comfortable with the product and consider it as "a nice gadget" to use. First impression is positive. However, there are doubts concerning the functionality and performance of the product. Performance is defined as the level in which the intended function of the product performs well (e.g. typing using the keyboard). The product's performance does not refer to the performance of the product's PV cells.

After the field trial, lead-users' feedback in the form of written reports and answered questionnaires (see Appendix F), mainly concerns the product's performance; around 40 % of the respondents are totally unsatisfied (see Figure 6.3), 38 % find the product totally useless (see Figure 6.4), around 60 % find the design of the product of bad/low quality (see Figure 6.5), 54 % believe the design of the product is quite simple and can easily be used by everybody (see Figure 6.6), while only 4 % finds it difficult to use the specific product (see Figure 6.7). 88 % of the respondents would not buy the PV product or propose it to a friend (see Figure 6.8) and around 70 % believe that the price of the PV product do not correspond to its quality and performance (see Figure 6.9). Table 6.2 presents some comments regarding the general evaluation of the PV products, based on the lead-users' remarks. Last but not least, around 66 % of the respondents would prefer a product, which can be charge by a cable with a plug, instead of a PV-powered product (see Figure 6.10).

Main results show that the lead-users need more reliable PV products, made with materials of good quality that have an interesting and appealing design and perform sufficiently. Instructions on the packaging/casing of the product and reliable expectations from the manufacturer/designer seem to be important to lead-users, in order to know what to expect from the product and how to use it. Respondents are willing to pay money and buy a PV product if it is useful and works properly. Furthermore, it is noticeable that lead-users are quite positive with PV products that have an environmentally friendly or a social character (e.g. donations to the developing countries when buying a solar-powered lighting product, such as the Waka Waka or the Little Sun light).

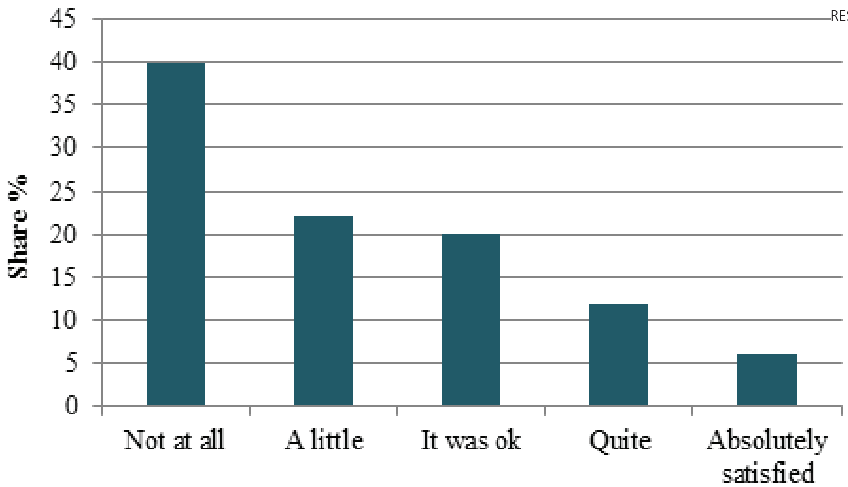


Figure 6.3: Lead-users' answers (share %) to the question: Are you satisfied by the PV product's performance? Number of respondents n=100.

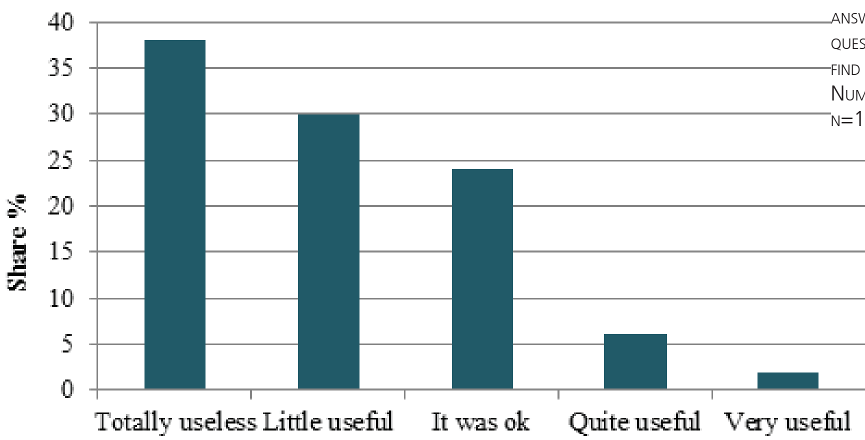


Figure 6.4: Lead-users' answers (share %) to the question: How useful did you find the specific PV product? Number of respondents n=100.

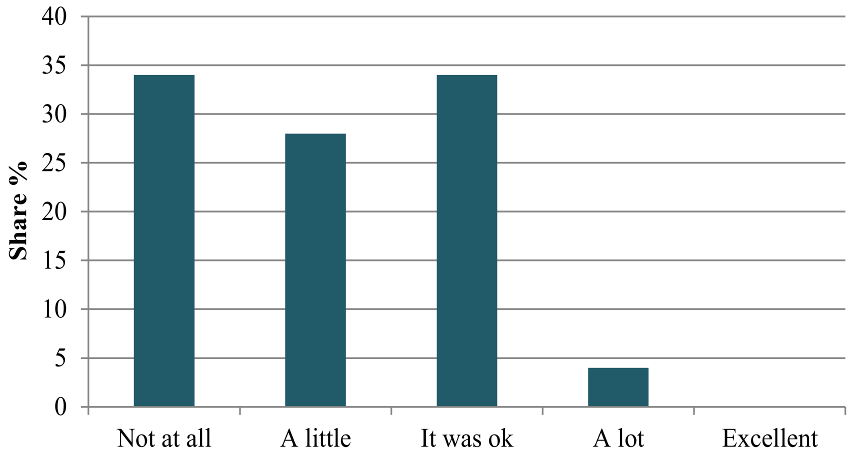


Figure 6.5: Lead-users' answers (share %) to the question: Did you like the design (look) of the PV product you used? Number of respondents n=100.

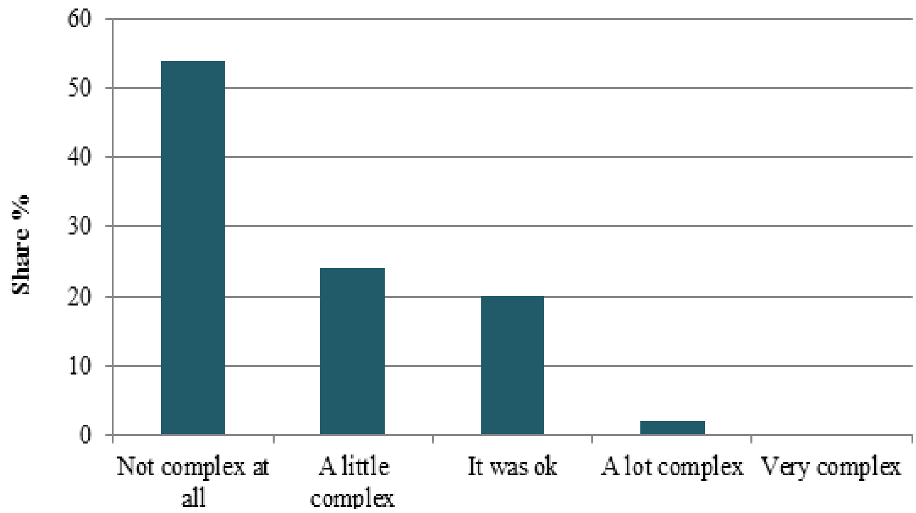


Figure 6.6: Lead-users' answers (share %) to the question: Did you find the product's design complex? Number of respondents n=100.

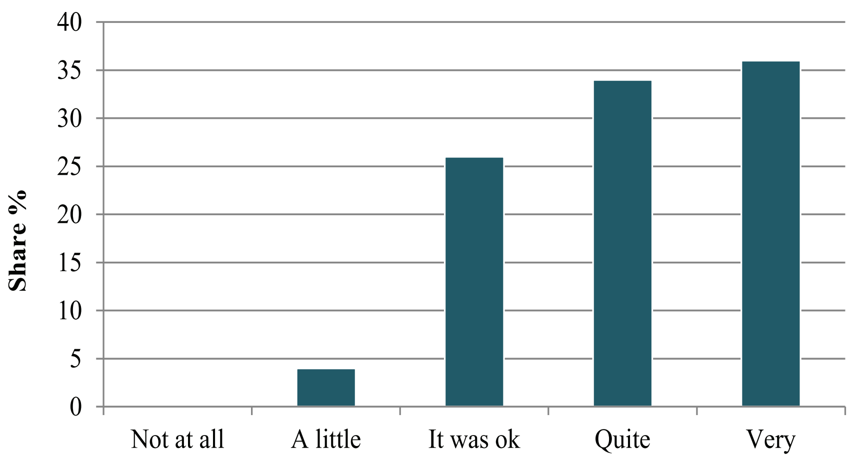


Figure 6.7: Lead-users' answers (share %) to the question: How easy was it to use the specific PV product? Number of respondents n=100.

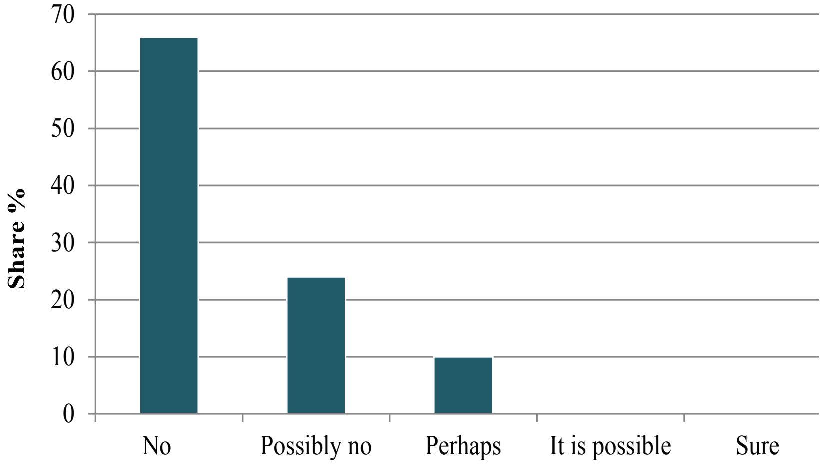


Figure 6.8: Lead-users' answers (share %) to the question: Would you buy the PV product you used during the field trial? Number of respondents n=100.

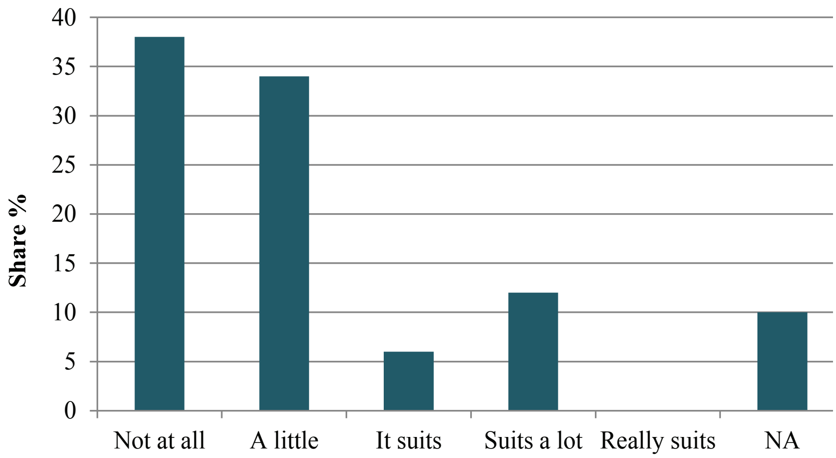


Figure 6.9: Lead-users' answers (share %) to the question: Do you think the price of the product corresponds to its quality? Number of respondents n=100.

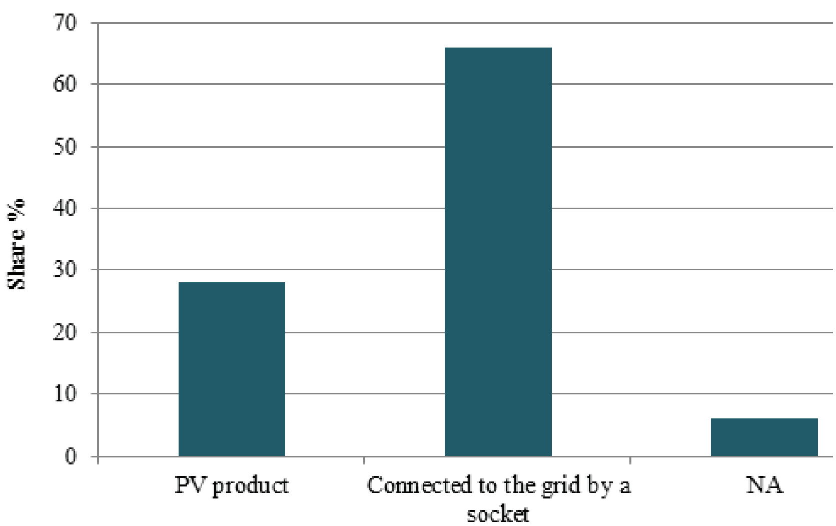


Figure 6.10: Lead-users' answers (share %) to the question: What would you choose to buy, a PV-powered product or a product with a cable and plug? Number of respondents n=100.

TABLE 6.2: EXAMPLE OF THE GENERAL EVALUATION OF THE PV PRODUCTS, ACCORDING TO THE PERCEPTION OF A SINGLE USER'S FEEDBACK.

	Sunnan lamp	Waka Waka light	Waka Waka Power	Little Sun	Beurer kitchen scale	Logitech solar keyboard
Design	Simple, Practical, unattractive	Strong/ Simple	Strong/ Simple	Interesting shape, attractive	Simple, not efficient	Premium, high quality
Usefulness	Cordless, short battery lifetime	Cordless, necessary to developing countries	Cordless, necessary to developing countries	Cordless, necessary to developing countries	Cordless, nice gadget	Cordless, power independent
Performance	Insufficient, low lighting levels	Sufficient, strong light	Rather sufficient	Depends on the charging	Not precise	Sufficient enough, battery status 100% full
Price	Affordable	High	High	High	High	High, but worth the money
Portability	+	+	+	+	+	+

6.4.2 Lead-users' feedback

We asked for respondents' personal opinions. Below you will find a selection of statements that indicate lead-users' personal opinions after their interaction with the product, as these are stated in the students' reports.

"A multi-function PV product is more desirable (e.g. lighting and charging function)"

"I would prefer to buy a product without PV cells. The PV cells must be removed and placed in the sun every day (outside). If I could just leave it inside, then I would reconsider it"

"I would buy the PV product. I do not like wires and batteries are always nowhere when needed"

"I think the specific PV-powered light is a useless product in Holland, due to the lack of sunlight, but in Africa it would be a great product"

"I find it a bit frustrating that the product works well only with heavy sunlight"

"I would definitely buy the PV-powered product. I am happy to spend a little more money for eco-friendly products that use renewable energy"

"I liked the design and the idea of using a PV-powered product. What I did not like was the fact that it did not work late at night, when the sun was down"

"I would buy the grid-connected version of the product, because it is less expensive and it performs better than the PV-powered product"

"The design of the product is ugly, the battery pack did not charge. I am really disappointed by its performance. It is the worst product of the branch"

"What wouldn't I change on the PV product……design, battery capacity, materials, color, use…"

"The overall product needs improvement, but the concept is good. A redevelopment could deliver a better product"

"I would buy the PV product just for fun, if it was cheap more than wanting to use it"

"Grid connection is more reliable than PV"

It can be concluded from the above statements, reflecting only 20 % of the total, that they are very diverse and represent both negative and positive opinions.

6.4.3 Analyzing lead-users' interaction with the tested PV products

In this section the 6 tested PV products (see Figure 6.1) are separately presented and the lead-users' interaction with them is discussed. Respondents' thoughts and ideas for redesign are also addressed, as they were evaluated in the students' reports.

6.4.3.1 IKEA Sunnan lamp

a) Product's features

The Sunnan lamp is a wireless product, which is portable and quite flexible to the user. There is only one button present on the base of the lamp, which makes the lamp's operation quite easy. Furthermore, a movable steel arm is present, as well as three LEDs. The solar cell of the lamp can be detached from the lamp and be charged outdoors or indoors near the windowsill. The Sunnan lamp can be used as:

- a desk light; for reading, writing
- a garden table light; using it outdoors on the garden table, when natural light is insufficient
- a bed light; using it on the bed, while reading a book.
- a flashlight; due to the product's portability, it can be used as a torch. However, the shape is odd and it is rather difficult to hold the lamp.

b) Lead-users' expectations before use

Initially, the fact that there are no wires permits lead-users to place the lamp where they want, without keeping it near a power socket. Secondly, it seems easy and convenient to use the lamp, since there is only one button to turn it on/off. Thirdly, the movable steel arm enables the lead-user to adjust the angle of the incoming light. Finally, the lamp uses three LEDs, which should be more than enough for a reading light. The solar cell is removable and the user needs to place it under sunlight, instead of doing so with the whole lamp.

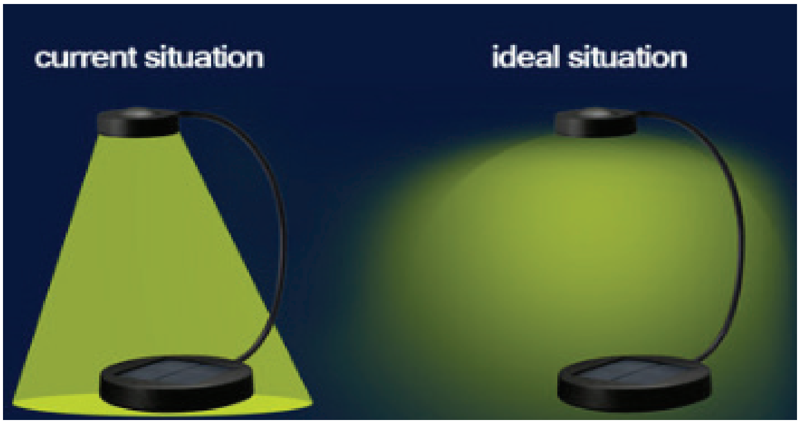


Figure 6.11: Current situation (left) vs. ideal situation (right). In the ideal situation the light diffuses more, which results in a more gradual transition between light and dark.

c) Lead-users' experience and feedback during use

After the field trial, the lead-users reconsidered some of their initial expectations. Comparing the light to a normal light bulb one issue immediately arises; the light does not diffuse. The light of the LED only covers a circular area of about 50 cm (when aimed right down from the highest point) and beyond these perimeters the surface is totally dark. The light is concentrated on one spot and does not diffuse in any direction. According to the respondents, this is a drawback of the product.

d) General conclusions and discussion after use

The lamp is solar powered, therefore the lead-user needs to take into account that the battery is charged sufficiently to use it two hours a day, three times a week for desk activities and half an hour a day, five times a week and more, when necessary. Following the manual, the lamp needs to be charged for minimal nine hours in sunny conditions and twelve hours in cloudy conditions to function for three hours. On the shortest day of the year there are less than seven light hours, which prevents full charging of the product. For that reason the lamp cannot be used to full potential.

The field trial determined that the actual burning time of the lamp is much longer than is guaranteed, so it is expected that this will compensate the shorter period of exposure to daylight.
It is anticipated that with 2/3 of the charging time the duration of light burning will drop with 2/3 also, to around a burning time of five hours.
Nevertheless, after the burning time of the three hours mentioned in the manual, the lamp color gets a different, but warmer tone. This tone is even more comfortable than the clinical light color. Therefore, it can be stated that the lamp supplies the demanded usage from the target groups, when charged outside.

In reality lead-users will charge the batteries indoors. The irradiation will drop dramatically by a factor of 20, which means those five hours of burning time anticipated would not be reached by charging it in one day. It is neither expected that indoor charging can reach the burning time for the daily use of maximum two and a half hours desired. It will be even more difficult to satisfy the needs for unexpected higher use. Overall, the resilience of the light was collectively observed.
It would not easily run out of battery power. A significant difference between high and low power performance state was noticed by the time respondents learnt how to adequately power up the product. The drop off in power was so noticeable that lead-users were forced to reconsider how useful the light was, once the brightness began to dim as the batteries discharged. This is illustrated in the contrasting images below (see Figure 6.12).

To conclude, it is favorable to view the Sunnan lamp as two different products combined; a desk lamp and a social product. When considering it as a desk lamp it can be said that it fulfills the expectations and adheres to the performance that was indicated in the manual. On the other hand, as a desk lamp it is slightly unwieldy, as it requires daily charging and hence its usability depends largely on the respondents' discipline (in putting the solar panel outside) and the grace of the weather. As such, its shortcoming is that it is slightly unreliable and compared to other lamps, it contains limited user interaction (it only has one button, while a lot of desk lamps have multiple brightness settings).

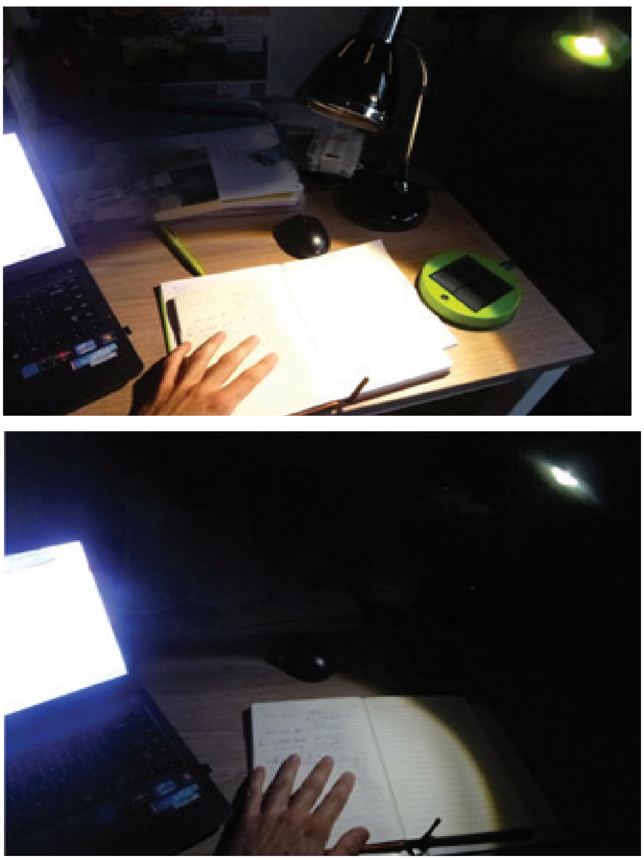


Figure 6.12: Comparison of the high and the low power performance of Sunnan lamp.

As a social product it is slightly more successful, though it is not completely obvious to the consumer. The policy of IKEA (the Light in the Dark project) stipulated that for each Sunnan bought, one is donated, so that children in countries without electricity can still read/ see after sunset, with the use of the Sunnan.
This is a noble act and combined with the educational power of the Sunnan in bringing awareness of solar-energy and the power of LED's, this lamp has definitely succeeded as a social product. However, there are still some improvements possible when it comes to making the consumer aware of this side of the Sunnan desk lamp.

e) Redesign IKEA Sunnan lamp, as proposed by 50 lead-users

In terms of general improvements for the Sunnan Lamp, lead-users suggest: a power toggle switch (Hi/Med/Low), so that different values of brightness could be selected when using the lamp according to the type of use. This would improve the length of use, when full brightness is not necessary. A folding stand like on a picture frame at the back of the battery pack could give it a better position towards the sun while charging. Easy access to the batteries is also essential. Another improvement could be on the width of the light beam and the light intensity. The beam should be significantly improved, because the current one is insufficient. Moreover, an LED indicator to display the battery level, or the charging status, would give the lead-user important feedback about repositioning the product, or reducing the power for preservation. For indoor use, the respondents believe that the product could be easily placed near a window, by using a suction cup and it might be more efficient to select a new type of PV cell that could achieve better performance indoors.

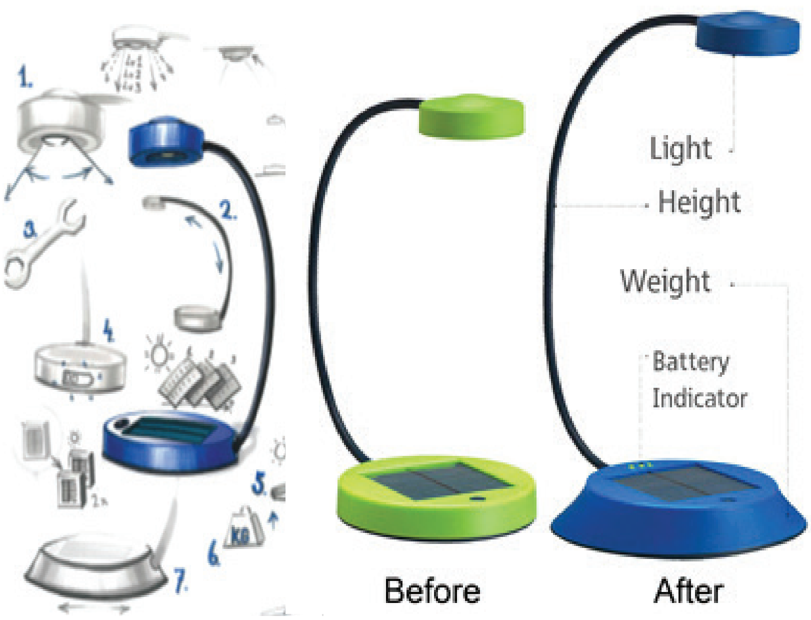


FIGURE 6.13: SUGGESTIONS FOR IMPROVEMENT OF THE SUNNAN LAMP, ACCORDING TO LEAD-USERS.

6.4.3.2. Waka Waka light and Waka Waka Power

a) Products' features

The Waka Waka light is a small electric light charged by a solar panel on its back surface. Two small LED lights can be used in three light intensity settings. There is only one button on the product; the user can push it multiple times for three different light intensities. Pressing the button for three seconds makes the product give off a Morse code SOS signal.
The product is aimed at people who live off the grid, although it can be used for different uses, such as camping. The product also has a stand, which can be used either to support the product on its own, or to prop it on a bottle by using the hole on the stand.
The next version of the Waka Waka light is the Waka Waka Power, which is a strong and solid solar charger, able to charge almost all (smart) phones or other small electronic devices within a few hours and to offer around 150 hours of lighting.

The Waka Waka Power has two target groups:
a) first world- and
b) third world- country people.

The first group could also be divided into two subgroups:
1. people who buy the Waka Waka as an act of charity and
2. people who buy the Waka Waka, because they actually need a solar charger and for whom the charity is an emerging subsequent.

For the last group of people it is likely to assume that they bought the Waka Waka because they need a light and portable charger during outdoor activities, such as camping, where they lack the possibility of charging their phones or other gadgets.

b) Lead-users' expectations before use

The initial lead-users' impression of the product's appearance was rather strange. The shape of the product looks odd and does not enhance the functionality of the product. However, the Waka Waka looks rugged, giving it a durable appearance. It is expected that the product can be used in two main scenarios. In the first scenario, the product will be used daily by people, with no access to other sources of electricity. The product can then be used either to bring light to an entire room, or for specific everyday activities that require light, e.g. reading. In the second scenario, the Waka Waka will be used by people during camping or other similar situations, where they lack easy access to electricity.

Figure 6.14: One of the multiple uses of Waka Waka light is for reading in developing countries. The product is placed on top of a plastic bottle.

c) Lead-users' experience and feedback during use

First, the Waka Waka was used by the lead-users of the field trial, as a nightstand lamp. The emitted light was quite bright, with a cold, blue tone, and it was uncomfortable when reading or looking straight at it. Moreover, the product requires no indication regarding the status of the battery. It is easy to understand that the product is not originally intended for the context that was used it in and would be more useful in different scenarios. When there is access to electricity, it seems that the product is less useful.

Figure 6.15: Waka Waka Power placed on a plastic bottle of water and on a table.

d) General conclusions and discussion after use

The Waka Waka is able to perform its functions (lighting and/or charging). However, regarding indoor activities, an alternative, non-solar powered product could also be effective. For outdoor activities and third world countries the Waka Waka Power is quite an essential product. Designers thought of sustainable solution beyond PV cells, but also used recycled plastics. Furthermore, it is a very good initiative to offer Waka Waka to people in countries that really need light in the dark.

Obviously, the people in first world countries pay indirectly for this charity project, but it is still an affordable product compared with competitors. Furthermore, it is a benefit that the Waka Waka is produced locally, when possible, so there is less transportation for shipping the products to the development countries. According to the respondents, there is still room for improvements for the Waka Waka (e.g. quality of light, brightness of the lamp, positioning of LEDs, battery status indicator, better positioning of the product).

e) Redesign the Waka Waka light, as proposed by 15 lead-users

From a practical point of view, the design of the Waka Waka light is quite minimalistic. It is an easy-to-use product, which works intuitively albeit with room for improvement. An option for upgrading would be to let the two LEDs be able to separately be pointed at any direction, no matter the position of the housing.

The well-known USB snake light could serve as an example, although this technique would renounce the protection of the LEDs and make it more vulnerable. Redesigning the LED placing could be in the form of two spherical ball hinges, which enables both LEDs separately rotation and gives the user the option to aim the lights more specifically. This means that the Waka Waka Light can still stand on a surface, while the separate LEDs can easily be pointed at any direction in order to illuminate a larger area. The big drawback of this adjustment is that it would probably cost a lot more money to develop and produce it, due to the additional hinges, in which the LEDs have to be integrated. One of the discomforts the light gives to its users is the bright peripheral light, meaning the light that directly reaches the eye if it is not placed behind the user. Placing a cap around the lights could both decrease the annoying peripheral light and also increase the amount of light, where it is actually needed. Thus, a suggestion for the redesign would be to make a small cap around the lights, so it does no longer emit light both upwards and sideward. Placing the lights a little deeper in the product and making a cap with the shell of the product could achieve this. This could also be a benefit for the LEDs, as these will be better protected.

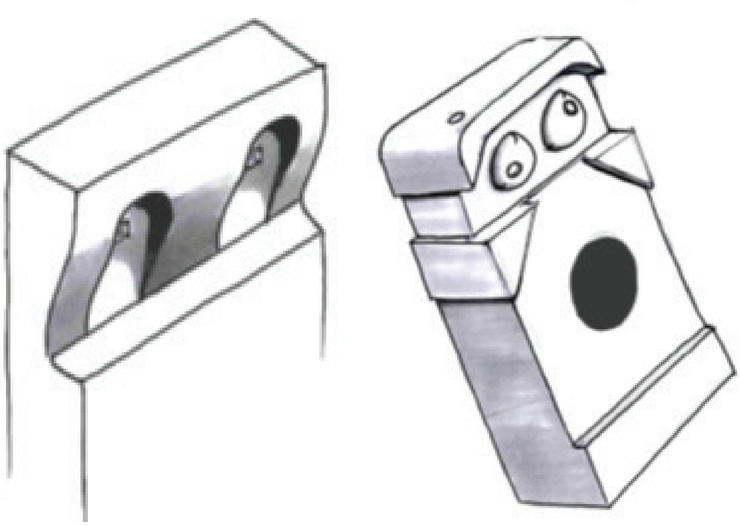


Figure 6.16: Redesign of the Waka Waka lamp, as lead-users suggest. Left picture: scan impression concept reducing unpleasant peripheral light, Right picture: scan impression concept positions of light.

f) Redesign the Waka Waka Power, as proposed by 4 lead-users

The redesign of the Waka Waka Power could contain a solar panel with a bigger surface, and possibly a new battery (1,5 time bigger than the current). These updates are necessary for the product to work properly and to support the charging of the new generation of (smart) phones.

6.4.3.3 Little Sun light

a) Product's features

Olafur Eliasson designs the Little Sun, which is a small and independent source of light, which can be used anywhere.

When charged during the day, the light can be used during the evening or night. The product is intended for people with no access to electricity. To make it affordable for the target group, the light is sold in western countries, the revenue of which is used to reduce the prices in off-grid communities. The Little Sun is a product targeted at third world communities without electricity, which means they do not have access to electrical lights in the evening. Light, which is necessary for working, studying or even just being together. A wood fire or kerosene lamps are usually used instead of electricity in third world communities. Both these light sources are dangerous, not only because they emit toxic gases, but also due to their fire hazard. This is where the Little Sun tries to help; allowing people to have a durable, safe and easy-to-use light source.

b) Lead-users' experience and feedback during and after use

Little Sun emits strong light, which can be useful in multiple situations and it is capable of lighting up an entire room. However, it is uncomfortable to handle, as it is a bulky product with sharp edges. The on/off switch can be hardly found in the dark. The chord that the product contains can be used to hang it into a hook.

The percentage of relative illuminance of the Little Sun decreases from 100 % to 0 % after around 7 hours of use, as it is presented in Figure 6.18. Generally, 7 hours of use considered a lot and therefore the performance of the product seems to be satisfactory. However, the intensity of the light is not stable during the 7 hours of use. After 2 to 3 hours, the intensity becomes less strong and the light is dimmer.

Figure 6.17: Little Sun light placed on the windowsill. Left picture: the front side of the product. Right picture: the backside of the product including the PV cell.

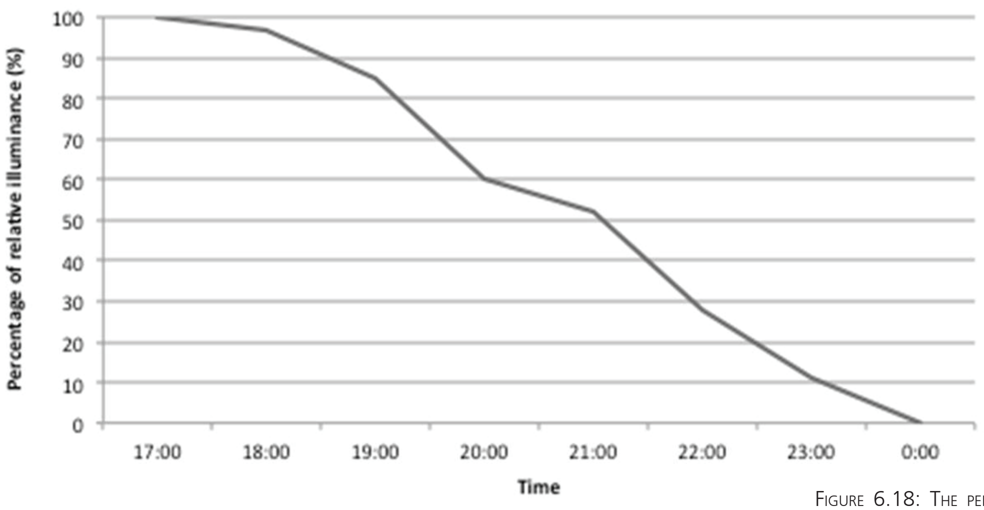


Figure 6.18: The percentage or relative illuminance of the Little Sun goes down from 100 % to 0 % after around 7 hours of use.

Figure 6.19: Redesign of the Little Sun, as lead-users suggest.

c) Redesign the Little Sun light, as proposed by 15 lead-users

In order to redesign the Little Sun, first it is necessary to abstract the problems. One of the main issues that users have is the safety while using the light. The sunflower-shape is very decorative, but has sharp edges. This is not ideal for little children, as it is possible that they could hurt themselves, while trying to use the lamp in the dark. Therefore, a new design of the product is proposed with more curved surfaces. Furthermore, a charge indicator with an LED light could be added in the product, such as the users could receive feedback regarding the status of the battery. A stand for better positioning of the product is also essential. Last but not least, lead-users propose the addition of a USB port in the product, which could offer the possibility of connection with other devices for extra charging. Below, an exploded view of the improved product is shown.

6.4.3.4 Beurer kitchen weight scale

a) Lead-users' expectations before use

Purely from the first appearances the product seeks to satisfy the Ideo-Pleasures of the respondents, fulfilling aspirations to feel "Eco", both through a purchase of the product, as well as owning the product. This is achieved through the idea of a solar powered scale, presenting itself as an "Eco" and sustainable alternative. The user will gain a greater appreciation for the product, increasing relationships and facilitating the ability to strike up a conversation about the product, also because it looks and appears modern.

b) Lead-users' experience and feedback during use

According to lead-users, it seems that the scale works fine and precisely during the day with sunlight and it does not need any charging. It works each time you need it, just as the producers promise. The scale weighs small amounts up to 5,5 kg and has a graduation of 0,1 gr. On the display, a battery bar is showed on the left top, indicating that the battery stays constantly half full even after 4 hours of sunbathing. When using the scale during the evening, the product faces difficulties catching enough light.

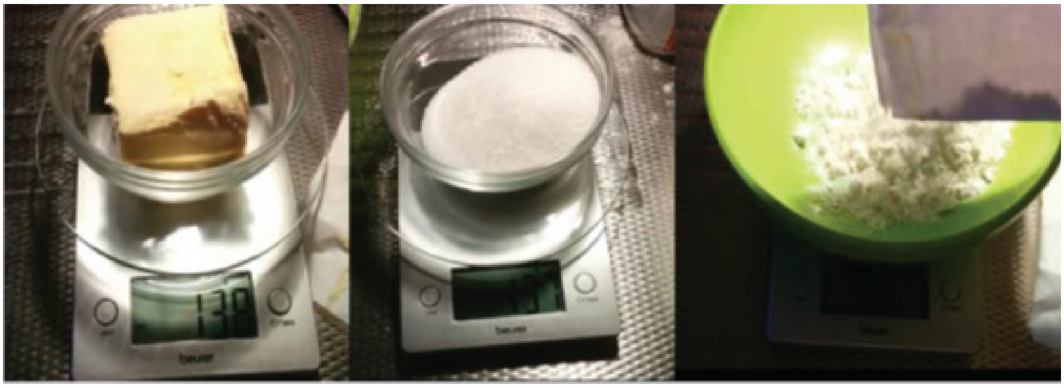


Figure 6.20: The Beurer kitchen weight scale is being used during the field trial.

c) General conclusions and discussion after use

The power on time depends on the light intensity, whereas the discharge time does not. This suggests that there may be a capacitor inside the product. The purpose of the capacitor is to power the scale, when the stream of light hitting the panel is disrupted. Being powered by a capacitor may be an issue in the scenario that a large object is placed on the scale, covering the panel and disrupting the direct light. This is not a wished feature, since it gives a limited amount of time to weigh the object. The kitchen scale weighs with an acceptable order of accuracy for its use purpose. However, this uncertainty may increase, when the object’s center of mass is not placed in the middle of the scale, since it has only one sensor in the middle. If the center of mass is placed off center, it creates a moment, increasing the measured mass. This is not an issue for the scale's functionality, since while cooking or baking, one gram more or less will not make any difference.

Overall, the scale does not meet its initial expectations as, very often, at least half a minute is required before it can be used. In the case that no natural light is available, an alternative light source is required. The fact that a more consuming energy source is required to power the product is not as efficient as directly taking the required power from the grid.

d) Redesign the Beurer kitchen scale, as proposed by 10 lead-users

The most efficient way of improving the product’s performance, without drastically altering the required technology was to allow the PV cells to catch more light. The first way to achieve this is by removing the ‘hovering’ glass plate. In order to avoid the shadow of the object that is being weighted to block out light for the PV cells, the PV cells were distributed over the surface of the product in a different way, as Figure 6.21 illustrates. In that way, they cannot both be fully blocked out, which means that there should always be some power available. The new design that is proposed would preferably have a quite similar appearance to the old one, which is a quite smooth and modern look.

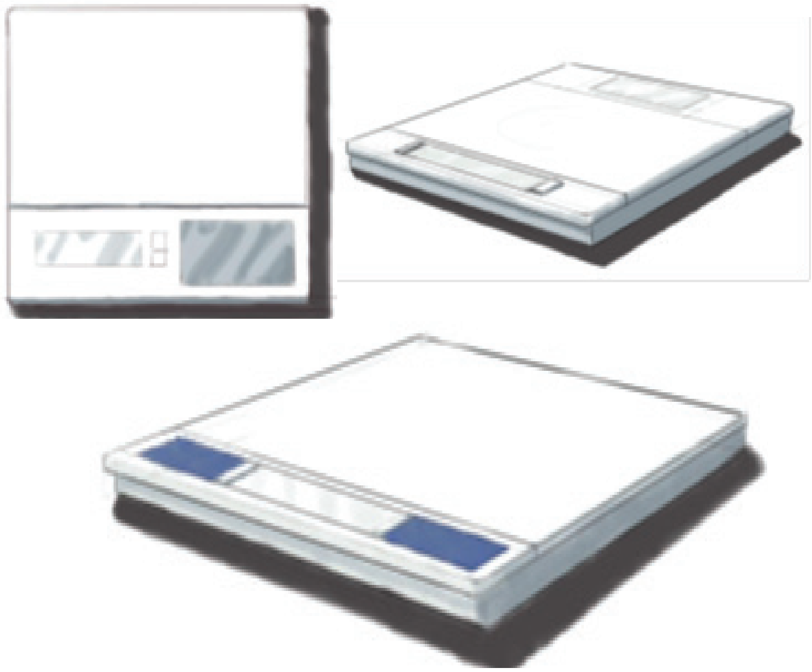


FIGURE 6.21: REDESIGN OF THE KITCHEN WEIGHT SCALE. SKETCHES BASED ON THE REPOSITIONING OF THE PV CELLS AND REMOVAL OF THE GLASS PLATE.

6.4.3.5 Logitech solar keyboard

a) Lead-users' expectations before use

Any computer or tablet can use Logitech solar keyboard. It performs absolutely powered by the sun or indoor lighting and there is no need for charging. It is possible to be used with all kinds of digital devices. It looks very sleek and professional, and it is expected that the intended use is in a work environment. Due to its portability and the solar powering, it does not need to be added to the power grid and it can be used everywhere. The PV cells intent to make the product absolutely independent on the grid and to eliminate the batteries' changing. Logitech claims that the keyboard has a three-month battery life with no light. Taking into account that a keyboard does not take much power to operate, it will most likely not drain the battery too fast.

b) Lead-users' experience and feedback during use

Generally, the keyboard worked very well and the respondents were satisfied with its performance. They felt that it is a very beautiful design, both in look as in user friendliness. Furthermore, the fact that it is solar powered is an added bonus. During the testing, the keyboard had a light interaction of less than 1 hour each day. At the fourth day of the testing, the solar application (see Figure 6.23) showed for the first time a different value than 100 %, a 99 % state of charge (SOC) of the battery. This means that with a light use of the keyboard, the battery would be able to run for one full year without charging or in total darkness. However, there are more active users, who use the keyboard more hours per day, but even in that case, the battery would

FIGURE 6.22: THE LOGITECH K750 PV KEYBOARD.

still be able to discharge at around 1 to 2 % each day, with then a total operation time of around 3 months. However, the cases that are described here are quite extreme, since the PV keyboard would normally always recharge the battery by using the installed solar cells. After the test, the battery showed the next day a SOC of 100 %.

c) General conclusions and discussion after use

The keyboard worked perfectly during the period when it was used. The PV panels integrated in the product did their work sufficiently, by keeping the battery charged up at 100 % almost continually. The simulations of the power management of the PV keyboard showed that even by a more intensive usage of the PV keyboard, the configuration of battery and PV cell by the manufacturer would in the worst case ensure at least 13 days of use till the battery would run out, under low lighting conditions. The combination of battery and PV cells made the product totally power independent from the usual keyboard, which are bound to periodical change of batteries. The negative criticism towards the PV keyboard was insignificant and subjective regarding small issues about the product's design.

According to lead-users' opinions, the PV keyboard was praised about its design, but finally it was also criticized about its price. Most respondents would not wish to pay double price for a product, just because of the integrated PV cells. However, even though the product is quite expensive, it seems reliable. The support and the service, which one can get from Logitech is also valuable. The manufacturer offers a three year warranty and also a very good forum and website, where every user can easily share with others their problems and experiences. The solar application is also very useful since it keeps the user always informed about the battery's state of charge and also about the indoor illumination.

d) Redesign the Solar keyboard by Logitech, as proposed by 6 lead-users

Generally, most respondents were satisfied with the keyboard's design. However, the easy transportation of the product is a feature that could be improved. Therefore, to make it easier to transport the keyboard, the removal of the number-pad is a possible choice.

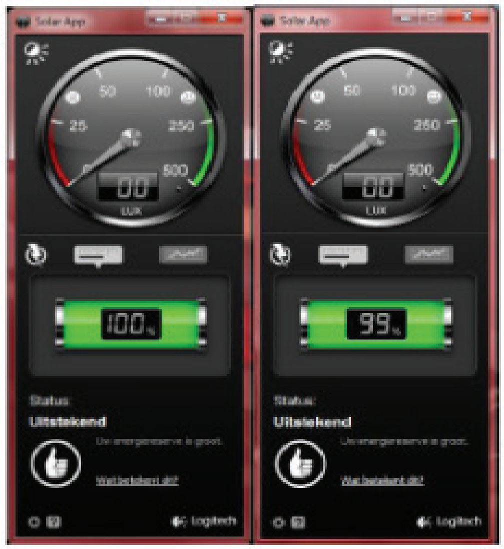


Figure 6.23: The solar application of the Logitech solar keyboard, showing the relative illuminance and the charging status of the battery before starting the test and after four days of use.

This makes the keyboard much shorter and easier to transport, as the main focus now lies in the use in combination with a tablet computer. This means that the USB connection could be replaced by a connection via Bluetooth. As the Bluetooth connection uses more power, and given the fact that the keyboard was overpowered, but reliable during the field trial, it seems that the system could support the Bluetooth connection. In a marketing sense this small adjustment will make the keyboard more versatile, as it will be introduced to the tablet market that mostly uses a Bluetooth connection.

Table 6.3: Product Comparison, According to 100 users' feedback

PV Product/ Number of users per product n	Sunnan Lamp n=50	Waka Waka Light n=15	Waka Waka Power n=4	Little Sun n=15	Beurer kitchen scale n=10	Logitech solar keyboard n=6
Form	+-	+	+	+	+-	+
Compactness	+-	+	+	+	-	+
Use and Repair	+	+	+	+-	+-	+
Safety	+	+	+	+	+	+
Solidity	-	+	+	+-	-	+-
Price affordable	+	-	-	+-	-	+-
Technical details						
Performance outdoors/indoors	+/-	+/-	+/-	+/-	-	+
Charge capacity	-	+	-	+	-	+
Efficiency	+-	+-	+-	+	-	+
Adjustability	-	-	-	+-	-	+
Durability	-	+	+	-	-	+
Sustainability	+	+	+	+	+-	+
Environmental friendly character	+	+	+	+	+	+

*The difference in quality per feature is arranged as good (+), medium (+ -) and bad (-) in Table 6.3.

6.5 Summary and Conclusions

In this study we focused on lead-users' interaction with PV products through a practice- oriented approach. We used a questionnaire to identify users' needs and expectations from the PV products and the methods of self- and direct- observation for the investigation of user behavior during the interaction. The study is a quite difficult and challenging task and the combination of various methods is necessary for reliable results. Therefore, in our study, we conducted not only field trials, but also technical tests for a better understanding of the PV technology by the users.

The tested sample of users for the observation of their behavior with the PV products consisted of 100 students of Industrial Design Engineering Department of Technical University of Delft. The specific sample used quite high standards for the characterization of the products' quality and offered a critical view of the products' usability, design and performance. It seems that the tested sample of lead-users had a greater critical look than a regular user, due to its educational background in the field of product design and it is more ahead than other students with less relevant educational experience. The specific user type of this study cannot be represented as a regular user or consumer. This user may be considered as a "lead-user", since he/she was asked to follow some specific tasks for the evaluation of the products, which might not be recognizable by a regular user. Moreover, the "lead-users" of this study proposed solutions and ideas about redesigning the PV products, which is pretty uncommon for regular users to provide such a feedback. On the one hand lead-users can notice and forecast problems that might occur in the future, but on the other hand due to their educational background and their knowledge in the field of product design and engineering, they understand the boundaries of design and technology in the products. These features are not visible and easily understandable by regular users, who usually criticize the outlook, usability and performance of the products, without caring about the above- mentioned limits. Hence, the beliefs of the lead-users in this study do not reflect the real behavior of a simple user, but they could be quite influential regarding the future successful use of the PV products.

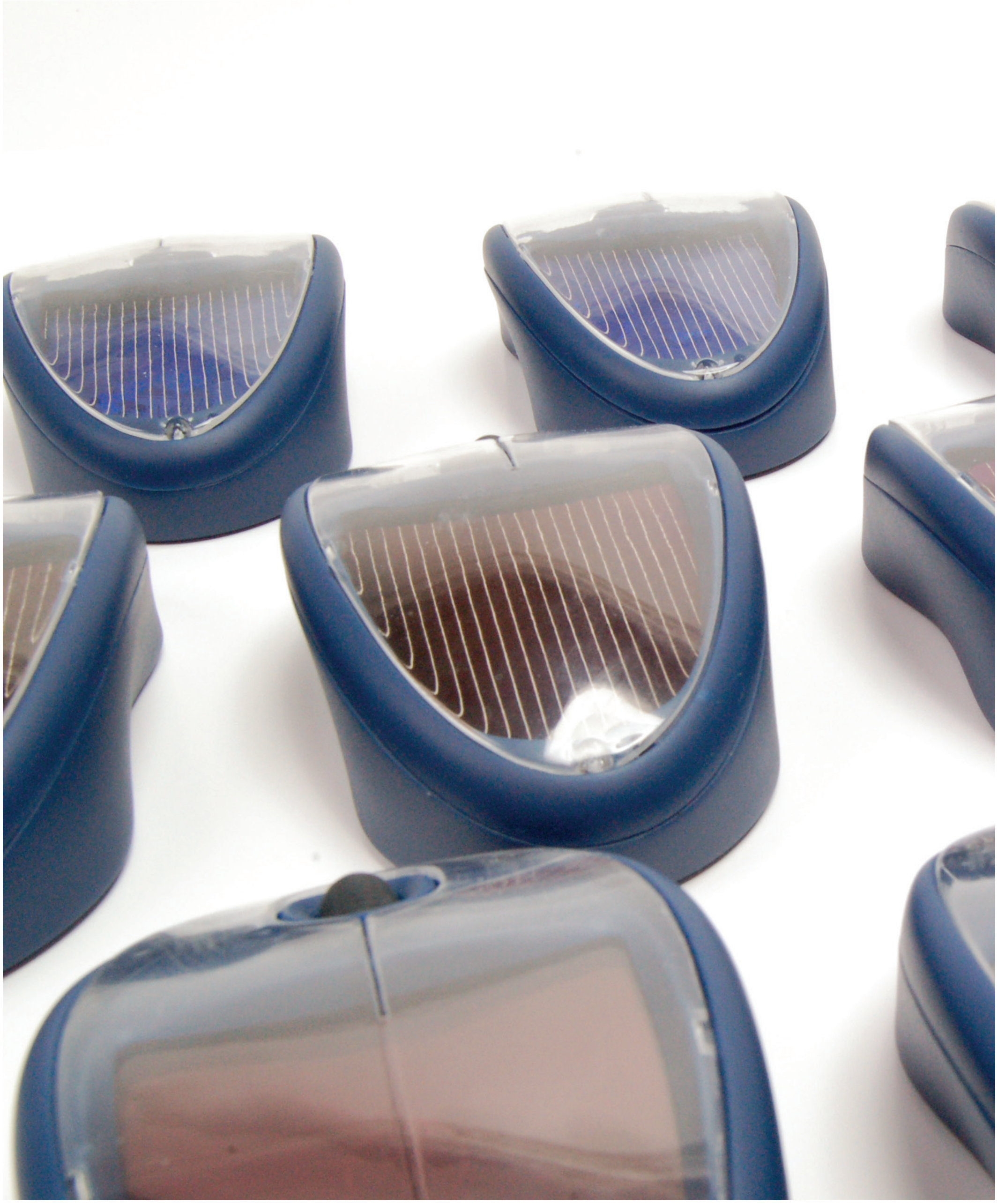
The results revealed that the usability, the design, the aesthetics and the performance of a PV product are quite important factors for lead-users. Respondents are quite enthusiastic about PV products if useful and functional, but they need more reliable PV products with a more appealing design. It was noticed that lead-users' expectations before use and their experience afterwards, deviate significantly. Quantitatively, results show that around 40 % of the respondents are disappointed with the PV product that they used, 38 % found the product useless, around 60 % believe that the design of the product is of low quality, 88 % of the respondents would not buy the PV product and around 70 % believe that the price of the PV product does not match with its quality and performance. It is remarkable to notice that around 66 % of the respondents would prefer a product, which can be charged by a cable with a plug, rather than a PV-powered product. Desired features of PV products according to users, based on the results of the user-product interaction are also presented in Appendix G of this thesis.

Going back to Sander's theory (2002) about the different user experience characteristics, we tried to distinguish the four categories of the 'obvious', the 'visible', the 'unspoken' and the 'dormant' features of users. On the one hand, observing the lead-users interacting with the products easily identified the 'obvious' and 'visible' features. First, the 'unspoken' and the 'dormant' were investigated through questions regarding users' thoughts before, during and after the field trial. Lead-users enjoyed the benefit to actively interact with the products and criticize products' characteristics, such as the design, the usability, the performance, the aesthetics or any other feature that was important for them. Furthermore, it was interesting to notice what lead-users believe regarding the significance of these products and what they propose for a possible products' redesign. Last but not least, in this study we uncovered lead-users' behavior while interacting with PV products and we focused mainly on the 'unspoken' and 'dormant' features, which are important for designers.

The testing sample is limited (6 PV products) and general conclusions cannot be drawn. However, results are important, as they represent part of the PV products, which are commercially available and easily accessible to consumers and basic user behavior with them. Since the survey outcomes are strongly affected by the type of the specific user, it is not approved that regular users will have similar behavior to the product's use. Therefore, the specific results could not be extended to all target groups. To sum up, the impressions of the lead-users about the PV products are not necessarily analogous to the regular users'. Nevertheless, the results of this study and the specific users' reflections could inspire the future design and usability of PV products. We believe that the findings of this study will be valuable for designers towards a better understanding of the user behavior and combined with technical data of PV products, could be used for the design of high efficient PV products.

CHAPTER 7

Conclusions



7 Conclusions

Trying to introduce functionality and ecological behaviour to our lives, we target energy savings in various ways. This approach begins from simple things of everyday life that eventually are those that make the greatest difference over time. Therefore, we search for natural solutions; ecological products, which are practical and have a multipurpose design for use inside and outside the home. This may constitute an important application of energy independence, whether we are talking about a calculator or even a car or about product-integrated photovoltaics.

This research project is oriented towards the development of scientific and technological knowledge about product-integrated PV (PIPV), as it focuses on the aspects that designers need to take into consideration when designing PV products. This research is interdisciplinary by nature due to its embedding in the field of industrial design engineering, regarding the technological aspects of PV technologies in products and user interaction with PV products. It focuses on aspects related to design engineering of indoor PV products and to the design of products with an acceptable performance for users, issues that have not been addressed by other researchers. Its multi-disciplinary character is the point where this work differentiates from previous studies.

Based on the relevance of sustainable product design for product-integrated PV, this thesis combines the technical knowledge of PV technologies, indoor irradiance conditions and performance of PV cells and PV products in environments with low irradiance together with the typical behavior of users with these products and the way this behavior influences the performance of the products themselves. Besides being directed towards researchers, results of this study are useful for industrial designers who are developing PV products.

Manufacturing of PIPV and the combination of PV with other renewable energy sources have not been addressed in this dissertation.

The study approached the above-mentioned issued by investigating:

1. Why research on product- integrated PV is important? (Question is answered in Chapter 1)
2. What is product-integrated PV and what are PV products? For example: What are the design features and function materials that these products use? (Question is answered in Chapters 2, 3)
3. Where are the PV products used? That is to say under which conditions and irradiance they are used? (Questions are answered in Chapters 4, 5)
4. How do users interact with the PV products? (Question is answered in Chapter 6)

The sub-questions, which helped to approach the main research question in a systematic and logical way, were:

- Which are the factors that affect the performance of PV cells in products? (Subquestion of the 2nd research question. It is answered in Chapter 2)
- What are the design features that existing PV products have? (Subquestion of the 2nd research question. It is answered in Chapter 3)
- Which are the indoor irradiance conditions? (Subquestion of the 3rd research question. It is answered in Chapter 4)
- What is the efficiency of different PV technologies indoors? How the performance of PV products could be estimated under indoor irradiance conditions? (Subquestion of the 3rd research question. It is answered in Chapter 5)
- How could users' interaction with indoor PV products influence the performance of the products? (Subquestion of the 4th research question. It is answered in Chapter 6)

Finally this thesis intents to support designers by exploring the topic above-mentioned which they should take into consideration if they want to design indoor PV products with a better performance than the existing.

It's noteworthy that since 2011, when this research study begun, many aspects of PV powered products have changed. Firstly, more PV products of various product categories for both outdoor and indoor use were launched on the markets. The PV products that were used during the tests and the field trials of this research study are the products that were commercially available at the time of the beginning of this research. Over four years of research, it was observed that many aspects and design features improved in PV products, such as their technical features (e.g. materials, use, electrical and mechanical components, etc.) and their aesthetics. The fact that these aspects of PV products were improved does not affect the final outcome of this research. In this research the technical features of the products have mainly been analysed. Therefore this analysis seems to be quite useful for designers and researchers, as other researchers in the field have not addressed the information that it offers as yet.

In the following paragraphs the conclusions of this thesis are presented as answers to the research questions.

1st research question:
Why research on product- integrated PV is important?

The incorporation of PV systems in products could offer various benefits, such as enhanced functionality of the product as a result of energy autonomy, and independence and freedom of use due

to the absence of a connection to the electricity grid, as well as the opportunity to reduce the capacity of batteries in portable products and therefore making them more sustainable. In Chapter 1 a short market analysis on PV-powered products for indoor use shows that most of the available products at present offer sub-standard and poorly designed solutions. While investigating commercially available PV lighting products, which is the largest area of PIPV at the moment, it can be concluded that apart from being PV-powered and portable, most products do not have any additional features. Figure 7.1 provides a visual representation of the currently available PV powered products, which is based on the results of this thesis. It shows that the majority of PV products that are commercially available at present are of low quality and perform insufficiently (light blue area of Figure 7.1).
However, there are only a few PV products that have sufficient performance and that are of good quality. The green area of Figure 7.1 demonstrates these products. It seems that there is a lack of good quality consumer PV products and this thesis aims to offer knowledge in order to improve their quality. Furthermore, indoor consumer PV products lacking in quality and quantity compared to the outdoor PV products and therefore it is essential to obtain knowledge aiming at their further enhancement. The goal still remains to design products that could be both of high quality and performance. Unfortunately, this goal has not been achieved yet. This thesis aims to fill this knowledge gap.

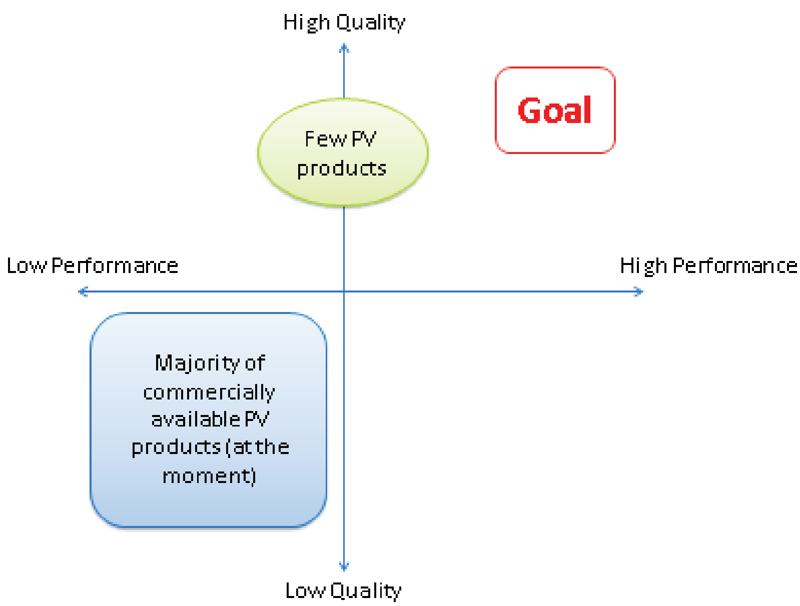


Figure 7.1: Visual representation of the currently commercially available PV powered products.

1st subquestion:
Which are the factors that affect the performance of PV cells in products?

In Chapter 2 various PV technologies and the basic knowledge concerning the integration of PV cells in consumer products were briefly discussed, serving as an introduction to the most common PV technologies that are used for commercial PV product applications, which are mono-crystalline, multi-crystalline and amorphous silicon solar cells. It was found that several factors exist that greatly affect the performance of PV cells in products, such as indoor irradiance conditions, the efficiency of PV cells in an indoor environment, the area of the PV cell surface, shading of PV cells, as well as the combination of the PV cell and battery technologies.

2nd research question:
What is product-integrated PV and what are PV products?

2nd subquestion:
What are the design features and function materials that PV products use?

Chapter 3 focuses on identifying better what product-integrated PV and PV products are and what their design features are. Various categories of product-integrated photovoltaics can be identified: consumer products with integrated PV, lighting products, business-to-business applications, recreational products, vehicles and transportation, and arts. Among these product categories outlined above, the majority of products are mainly high power PV products designed for outdoor use. Different product categories are modulated for indoor use. The low power PV product categories for indoor use range between 1 mW up to a maximum of 10 W and they are defined as follows: consumer products (including mainly toys, calculators, watches, entertainment applications, PV chargers for indoor use), lighting products (including low power desk lamps) and art objectives (Objets d' art) (requiring low energy supplies).
Also an overview of PV product's general design features is provided. The overview is based on a survey of preselected PV products. PIPV's power level ranges from several mW up to hundreds of kW.

Four PV system categories were determined:

(1) autonomous PV system including battery,
(2) chargeable PV system including battery,
(3) autonomous PV system excluding battery and
(4) autonomous hybrid PV system including battery.

The majority, namely 65 out of 90 PV products analysed consist of an autonomous PV system with batteries.

67 % of PV products are used outdoors, while around 14 % are used indoors and 19 % both indoors and outdoors. Approximately 30 % of the low power PV products in the range of 0 to 17 Wp use thin film solar cells (a-Si), whereas 55 % of high power PV products in the range of 17 Wp to 27 kWp use x-Si solar cells or a-Si. 86 % of PIPV products use an energy storage device, while 14 % do not use any batteries.

3rd research question:
Where are the PV products used? That is to say under which conditions and irradiance they are used?

3rd subquestion:
Which are the indoor irradiance conditions?

Chapter 4 explores the indoor environments in which PV products are used. In this chapter results of measurements of irradiance under various conditions indoors are presented. First, the theoretical framework for indoor irradiance is given and next measurements under various conditions are presented. According to the measurements and results presented in Chapter 4, it could be concluded that indoor irradiance differentiates broadly according to the orientation of the room, as well as according to the type of light sources, either natural or artificial, and the distance between them

Results showed that typical indoor irradiance in an office in the Netherlands during June ranges between 1 and 25 W/m^2 depending on the orientation of the room towards the sun.

However, these values cannot be considered fixed, as they are strongly influenced by the latitude and longitude of the room, the season (winter, summer, etc.), weather conditions (sunny, cloudy, rainy, etc.), the use of artificial lighting (amount of lamps, type of lights, either LEDs, CFL or halogen lamps), objects and shadings at the indoor environment, distance between windows and artificial light sources, type of glazing etc. Indoor irradiance based on artificial lighting only usually ranges between 1 and 7 W/m^2, which is sufficient only for low-powered PV products to function at this environment.

Based on the above conclusions, it is believed that only very low power PV products with power consumption in the range of μW up to a few mW could be used indoors, such as clocks, calculators, ambient lighting products, sensors, temperature indicators, toys, chargers or PV-powered remote controls for televisions. During the design process of an indoor PV product, designers should consider the typical indoor irradiance range as discussed above. Taking these values as a starting point, designers could make critical decisions regarding the products that can perform sufficiently under these conditions and make the right choices beforehand.

4th subquestion:
What is the efficiency of different PV technologies indoors? How the performance of PV products could be estimated under indoor irradiance conditions?

Chapter 5 explores the efficiency of PIPV with the help of a simple model, which estimates the performance of PV cells in an indoor environment and under mixed indoor light that partially contains outdoor light. To start with, the efficiency of different PV technologies is discussed. These PV technologies, which were used indoors during the experiments and the results of the measurements are presented and analyzed. A mathematical model of the indoor performance of PV cells is proposed, which estimates the indoor efficiency of various PV materials.

The model is based on real tests and measurements of the efficiency of various PV cells under low irradiance conditions and on literature data, as well. The most significant variables in this model are the spectral response (SR) of the PV product's cell and indoor irradiance.

The model is validated by two different simulations:
1. using the spectral response SR as given in the literature (under STC) and
2. using the SR as measured (under STC) for 12 different PV products with either x-Si or a-Si solar cells.

It is due to the limited research in this field and the related lack of data from other studies regarding modelling of product-integrated PV, the spectral response of PV cells under mixed indoor lighting, as well as cells' performance under low lighting conditions, that the results of this study could not be compared to a full extent with existing findings.

However, we assume that now that this basic model exists, students, researchers and designers can use it to design or evaluate indoor PV products with the purpose to improve their performance. The results of the model are precise enough for product design; using measured SR curves the accuracy is typically in the order of 30 %. The accuracy of the model indicates that the simulated efficiency value deviates x % from the measured value (which is taken as 100 %). In this case x % is 30 %. This is due to low irradiance conditions, deviations between measured SR at STC and the actual SR at low irradiance conditions and the bad quality of commercially applied PV cells in PV products.

The results of the second set of simulations show that under mixed indoor lighting conditions, the simulated PV cells' efficiency slightly deviates from the measured values, with a typical accuracy of around +82 %. Additionally, the model practically forecasts a PV product's cells performance under artificial illumination, with a typical accuracy of around +71 % for CFL and LED lighting. Measurements with a higher accuracy are quite difficult to obtain, since indoor irradiance reaches just a few tenths of W/m^2, which is close to the measurement limits of irradiance sensors. Apart from this, the efficiency of PV cells under these conditions is rather low. The model's results therefore expose the fact mentioned above and are considered satisfactorily accurate. It is found that under mixed indoor lighting of around 20 W/m^2, the efficiency of solar cells in 12 commercially available PV-products, ranges between 5 to 6 % for amorphous silicon (a-Si) cells, 4 to 6 % for multi-crystalline silicon (mc-Si) cells and 5 to 7 % for the mono-crystalline silicon (c-Si).

Measurements and results have shown that the spectral responses (SR) of tested PV cells at AM 1.5 deviate considerably from current literature. They are typically around 70 to 80 % lower and in some cases even more than 90 % less. The significantly low spectral response of commercial PV products' cells occurs due to low quality of the cells applied. The cutting of PV cells in small pieces - to be applied in PV product surfaces - and their condition, e.g. soiling of cell's surface, possible scratches, cracks and other damage play a crucial role on the measured spectral response. Consequently, the use of low quality PV cells leads to PV products with low performance. Furthermore, it is essential to stress here that another reason for the dissimilarities in the spectral responses is that in this study PV products are not tested as single PV cells, but as assembled devices with several interconnected PV cells.

It is also important to be aware of the fact that the spectral response of the PV cells as measured at STC (1000 W/m^2) has been used for modelling at 10 W/m^2. This is due to the measurement range of solar simulators, which usually does not cover the very low irradiance range used in our model and due to the unavailability of PV cells' spectral response data under low irradiance conditions as provided by manufacturers.

Finally, because of our purpose to support designers in their design processes to realise indoor PV products with higher performance than the existing ones, we consider the accuracy of this model to be sufficiently acceptable.

4th research question:
How do users interact with the PV products?

5th subquestion:
How could users' interaction with indoor PV products influence the performance of the products?

Chapter 6 explores how users interact with the PV products and how this influences the performance of the products. This chapter is therefore dedicated to user interactions with PV products. It addresses user expectations before they use the product and their experience after using it, as well as the fulfilment of their expectations and needs. Here, users interaction with PIPV is examined by using real PV products and lead-users. In this study both quantitative and qualitative methods are used. The interaction of the users (forming focus groups) with PV products is analysed, by conducting a survey, using a questionnaire to present statistical data and observational methods, where the users record themselves or write in a workbook about their daily interaction with the product. Furthermore, physical data are used, as the PV products are tested under different irradiance conditions and conclusions about their function and performance in different contexts are drawn.

In Chapter 6 we focus on users' interaction with PV products through a practice- oriented approach. A questionnaire is used to identify user needs and expectations from the PV products and the methods of self- and direct- observation for the investigation of the user behaviour during the interaction. The study of user behaviour is quite a difficult and challenging task and the combination of various methods is necessary for reliable results. Therefore, in this study, not only field trials are conducted, but also technical tests for a better understanding of the PV technology by the users.

The tested sample of users for the observation of their behaviour with the PV products consists of 100 students from the Industrial Design Engineering Department of Delft Technical University. The specific sample uses quite high standards for the characterisation of the products' quality and offered a critical view of the products' usability, design and performance. It seems that the tested sample of users has more of a critical look than a common user, due to their educational background in the field of product design and it is more ahead than other students with less relevant educational experience. The specific user type of this study cannot be represented as a regular user or consumer. This user may be considered as a "lead-user", since he/she was asked to follow some specific tasks for the evaluation of the products, which might not be recognisable by a regular user. Moreover, the "lead-users" of this study propose solutions and ideas about redesigning the PV products, which is pretty uncommon for regular users to provide such feedback.

On the one hand, lead-users can notice and forecast problems that might occur in the future, but on the other hand due to their educational background and their knowledge in the field of product design and engineering, they understand the boundaries of design and technology in the products. These features are not visible and easily understandable by regular users, who usually criticise the outlook, usability and performance of the products, without caring about the above- mentioned limits. Hence, the beliefs of the lead-users in this study do not reflect the real behaviour of a simple user, but they could be quite influential regarding the future successful use of the PV products.

The results reveal that the usability, the design, the aesthetics and the performance of a PV product are quite important factors for users. Consumers are quite enthusiastic with PV products if useful and functional, but they need more reliable PV products with a more appealing design. It is noticed that user expectations before use and their experience afterwards, deviate significantly. Quantitatively, results show that around 40 % of the respondents are disappointed with the PV product that they used, 38 % found the product useless, around 60 % believe that the design of the product is of low quality, 88 % of the respondents would not buy the PV product and around 70 % believe that the price of the PV product does not match with its quality and performance. It is remarkable to notice that around 66 % of the respondents would prefer a product, which can be charged by a cable with a plug, rather than a PV-powered product.
Consisted of six PV products this testing sample is limited and general conclusions cannot yet be drawn. Nonetheless, these results are important, as they represent part of the PV products, which are commercially available and easily accessible to consumers and basic user behaviour with them. Since the survey outcomes are strongly affected by the type of the specific user, it is not confirmed yet that regular users will have similar behaviour to the product's use. Therefore, the specific results could not be extended to all target groups. To finish, the impressions of the lead users about the PV products are not necessarily analogous to the regular users'.
Nevertheless, the results of this study and the specific users' reflections could inspire the future design and usability of PV products.

The findings of this study will be valuable for designers towards a better understanding of the user behaviour and combined with technical data of PV products, will be used for the design of high efficient PV products.

From the research presented by this thesis it can be concluded that the integration of PV cells in products still is a challenging task. For instance in indoor environments, irradiance is significantly lower than outdoor irradiance and the efficiency of the PV cells under these low irradiance conditions is significantly lower than under STC. Therefore, it is vital to find a way to use PV cells that perform sufficiently under low irradiance conditions.

As research of photovoltaic materials is currently still in progress, it is expected that in the next years the efficiencies of the PV cells will increase and as such the performance of the products that use PV cells will improve. In this way, more diverse applications of PV cells in a product context will be possible.
In order to create these diverse applications, designers should know the required amount of energy that a PV powered product needs to function properly. The power requirements of a PV product can be easily and accurately determined with the new simple model presented in Chapter 5. It contains realistic data of PV cells spectral response and efficiency which can be used in the design process. Also it was found that the quality of the interconnected PV cells in PV products should be a point of attention if designing new products.

To conclude, there is still room for research in the field of PIPV, as the market of PV products is continuously developing. To mature this market, more research is required in the fields of marketing, end-of -life and human factors of PV products. Also studies on the environmental impacts of batteries and how to reduce their capacity by the application of product integrated PV would support the developments of a market for PV products. This thesis is the starting point for further research in this field for the improvement of PV products and their related services.

References

Abdihoxha A. (2014) Sustainable Integration project – 2 Sustainable Energy Technology Master, TU Delft

Adelson E.H., Pentland A.P., 1996, "The perception of shading and reflectance", in Perception as Bayesian Inference Eds D. Knill,W. Richards (New York: Cambridge University Press) pp 409 – 423.

Ahmad H. Besheerab, Ahmed M. Kassemc & Almoataz Y. Abdelazizd*, 2014, "Single-diode Model Based Photovoltaic Module: Analysis and Comparison Approach", Electric Power Components and Systems, Volume 42, Issue 12, pages 1289-1300, 2014, DOI:10.1080/15325008.2014.927024.

Akon Lighting Africa, 2015, '600 Million Africans still don't have access to electricity', http://akonlightingafrica.com/our-activities/overview/

Alsema E.A., Elzen B., Reich N.H., Sark W.G.J.H.M. van, Kan S.Y., Silvester S., Veefkind M. and Jelsma J. (2005), "Towards an optimized design method for PV-powered consumer and professional applications - the Syn-energy project", In W. Palz,

Apostolou G. and Reinders A.H.M.E., 2012, "A comparison of Design Features of 80 PV-Powered Products", Proceedings of the 27th European Photovoltaic Solar Energy Conference (EUPVSEC), Frankfurt 2012, Germany, pp. 4227 – 4232.

Apostolou G., Reinders A.H.M.E., Verwaal M., 2012, "Spectral irradiance measurements in a room fit for indoor PV products", Proceedings of the 27th European Photovoltaic Solar Energy Conference (EUPVSEC), Frankfurt 2012, Germany, pp. 4240-4244.

Apostolou G., Reinders A.H.M.E., "Overview of design issues in product-integrated photovoltaics", Energy Technology, Article first published online: 5 March 2014, DOI: 10.1002/ente.201300158, © 2013 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, issue March 2014, Energy Technol. 2014, 2, pp. 229 – 242.

Apostolou G., Verwaal M., Reinders A.H.M.E., 2014, "Modeling the Performance of Product Integrated Photovoltaic (PIPV) Cells Indoors", Proceedings of 26th European Photovoltaic Solar Energy Conference (EU PVSEC), Amsterdam 2014, The Netherlands, pp. 3535-3540.

Apostolou G., Verwaal M., Reinders A.H.M.E., 2014, "Estimating the performance of product integrated photovoltaic (PIPV) cells under indoor conditions for the support of design processes", Proceedings of 40th IEEE Photovoltaic Specialists Conference, Denver 2014, Colorado, pp. 0742 – 0747.

Apostolou G., Reinders A.H.M.E., 2015, "How do users interact with photo-voltaic-powered products? Investigating 100 'lead-users' and 6 PV products", J. Design Research, Vol. X, No.Y, Copyright © 20XX Inderscience Enterprises Ltd., December 2015, Copyright © 20XX Inderscience Enterprises Ltd.

Apostolou G., Reinders A.H.M.E., 2015, "Users' Interaction with PV-powered Products: an Evaluation of 6 products by 100 end-users", Proceeding of 42nd IEEE Photovoltaic Specialists Conference, New Orleans June 14-19, 2015, LA.

Apostolou G., Reinders A.H.M.E., Verwaal M., 2016, "Comparison of the indoor performance of 12 commercial PV products by a simple model", Energy Science & Engineering, Wiley Online Library, January 2016, Article first published online: 22 Jan 2016, Volume 4, Issue 1, pp. 69-85.

Archer, Mary D., Green, Martin A, 2014, "Clean electricity from photovoltaics", 2nd Edition, London: Imperial College Press, 2015. - 677 p., (Series on photoconversion of solar energy; 4), 621.311.24, ISBN 9781848167681 (electronic version), 9781848167674 (print version, hardback).

Archer Mary D., Robert Hill. Clean Electricity from Photovoltaics. 2001.

Archinoah, Ferdinand-Braun-Institut fór Hφchstfrequenztechnik http://www.archinoah.com/architectural_photography/research_science_and_education/christian_matzke/berlin_adlershof/ferdinandbrauninstitut_fa_1/4_r_hachstfrequenztechnik-picture_details-298.html

Atlantatrails, PV-powered charger for outdoor use
http://www.atlantatrails.com/gear/enerplex-kickr-iv-review/
Ashdown, Ian. Photometry and Radiometry. 2002.

Avrutin V., N. I. (2011). Semiconductor solar cells: Recent progress in terrestrial applications. Superlattices and Microstructures.

Bakker C.A., Eijk DJ van, Silvester S., Reitenbach MEFR, Jong A.M. de, Keyson D.V., Scott K. (2010), 'Understanding and modelling user behaviour in relation to sustainable innovations: the living lab method', In I. Horvath, F. Mandorli & Z. Rusak (Eds.), Proceedings of TMCE 2010 Symposium, April 12–16, Ancona 2010, Italy, pp. 1-12, s.l.: TMCE. (TUD).

Battery University, 2016, "Lithium-based Batteries": http://batteryuniversity.com/learn/article/lithium_based_batteries (Accessed January 24, 2016)

Battery University, 2016, Battery Statistics,
http://batteryuniversity.com/learn/article/battery_statistics

Battery University, Batteries as Power Source- Cost of Power- Secondary Batteries
http://batteryuniversity.com/learn/article/cost_of_power

Batra, Rajeev and Olli T. Athola (1990), "Measuring the Hedonic and Utilitarian Sources of Consumer Attitudes," Marketing Letters, 2 (2), pp. 159-170.

Bδtzner D.L., A. R. (2001). CdTe/CdS Solar cell performance under low irradiance. Munich.

Baxter M., Product Design: Practical methods for the systematic development of new products, published by Chapman & Hall in 1995.

Becquerel (E. 1839). "Mιmoire sur les effets ιlectriques produits sous l'influence des rayons solaires". Comptes Rendus 9: 561–567.

Becquerel E. (1840). "Mιmoire sur le rayonnement chimique qui accompagne la lumiθre solaire et la lumiθre ιlectrique", Comptes Rendus 11:702–703.

Bloomberg, New Energy Finance, 2014, Wikipedia, Price history of solar cells: https://en.wikipedia.org/wiki/Price_per_watt#/media/File:Price_history_of_silicon_PV_cells_since_1977.svg

BlueBird-Electric.net, PlanetSolar Turanor:http://www.bluebird-electric.net/planetsolar.htm (Accessed July 03, 2013)

Boom, S. (2005). Design of a Solar Lantern for the Cambodian Market. Industrial Design
Engineering. Delft, Delft Univeristy of Technology. M.Sc.

Boyce Peter, Human factors in lighting, CRC Press 2014, https://books.google.nl/books?id=RAPSBQAAQBAJ&pg=PA5&lpg=PA5&dq=cie+sensitivity&source=bl&ots=bx5xhlnShG&sig=9bL7XgUYAAdlsbH_TXz0Ql592MU&hl=en&sa=X&redir_esc=y#v=onepage&q=cie%20sensitivity&f=false

BP, Issue two 2013 of BP Magazine, "The future of energy" (2013a): http://www.bp.com/en/global/corporate/press/bp-magazine/issue-two-2013/the-future-of-energy.html

BP, "BP Energy Outlook 2030" (2013b):
http://www.bp.com/content/dam/bp/pdf/statistical-review/EnergyOutlook2030/BP_Energy_Outlook_2030_PowerPoint.pptx

Brezet, JC, Silvester, S & Diehl, JC (2002). An evaluation of the sustainability impact of 10 years of design for sustainability MSc projects. In Conference engineering education in sustainable development, pp. 89-95. (TUD)

Brezet, JC & Silvester, S (2004). Design for sustainability (D4S): towards advanced product concepts. Environmental Engineering and Management Journal, 3(4), pp. 591-602. (TUD)

Buijs, J., (2003) 'Modelling Product Innovation Processes: from Linear Logic to Circular Chaos', Creativity and Innovation Management, Vol. 12 (2), pp. 766-93.

Burnett, Larry Kinney and Tony. Innovation in direct-beam daylighting systems. 2002.

Cargo Collective, Solar-powered charger designed by Qatar foundation http://cargocollective.com/paulseidler/Solar-charger-Qatar-foundation

Cengel, Y. A. (2003). Heat Transfer: A Practical Approach. McGraw-Hill.

Chandler D.L., 2013, "Research update: Team observes real-time charging of a lithium-air battery", MIT news: http://web.mit.edu/newsoffice/2013/real-time-charging-of-lithium-air-battery-0513.html

Chatain B., 2014, "European Parliament," 2014.[Online] Available:] http://www.europarl.europa.eu/news/en/news-room/content/20131004IPR21519/html/MEPs-ban-cadmium-from-power-tool-batteries-and-mercury-from-button-cells

Chen C.C., Dou L., Zhu R., Chung C.H., Song T.B., Zheng Y.B., Hawks S., Li G., Weiss P.S., Yang Y., 2012, "Visibly Transparent Polymer Solar Cells Produced

by Solution Processing", ACS Nano Publications, Vol. 6, No. 8, pp. 7185-7190.
Christen, Thomas, Carlen, Martin W., 2000, "Theory of Ragone plots". Journal of Power Sources 91 (2), pp. 210–216.

CIE International Commission on Illumination, 2000-2015, http://www.cie.co.at/index.php/LEFTMENUE/index.php?i_ca_id=298

Clark Liat, 2012, "Ultra-thin flexible lithium battery keeps powering when bent", WIRED.CO.UK: http://www.wired.co.uk/news/archive/2012-08/08/bendy-battery

Clean Technica, KudoCase http://cleantechnica.com/2012/05/20/solar-ipad-case-from-wireless-nrg-actually-powers-your-ipad/

Clean Technica, 2013, "New Plasmonic Polymer Solar Cells Achieve Record Efficiency of 8.92 %": http://cleantechnica.com/2013/05/10/new-plasmonic-polymer-solar-cells-achieve-record-efficiency-of-8-92-highest-for-any-plasmonic-polymer-solar-cells-utilizing-metal-nanoparticles/

Coated, Solar-powered traffic light http://www.coated.com/solar-powered-traffic-lights/

Commons Wikimedia, 2015, Photovoltaic solar facade on a municipal building, Social Services Centre Jose Villarreal, located in Madrid (Spain), 2013, Author Hanjin, (The file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license), https://commons.wikimedia.org/wiki/File:BAPV_solar-facade.JPG

Cultural Heritage Monument in the Philippines, Solar-powered lamp, photo number PH-00-0024, 2012, author SeamanWell, (The file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license), https://en.wikipedia.org/wiki/Solar_lamp#/media/File:SolarLampLuneta.JPG

Dafnomilis I., 2012, "Battery capacity and performance in relation to user profiling in Smartphones", Student report on System Integration Project II (SIP 2), TU Delft, Netherlands.

Dailymail, The Türanor Planet Solar catamaran http://www.dailymail.co.uk/news/article-1337381/Worlds-largest-solar-powered-boat-docks-Canc-n-giving-UN-climate-delegates-think--finishing-record-breaking-round-world-sail.html, © Planet Solar http://www.planetsolar.ch/

Davidson, Michael W. Tungsten-Halogen Incandescent Lamps.

De Rossi Francesca, Pontecorvo Tadeo, Brown M. Thomas, 2015, "Characterization of photovoltaic devices for indoor light harvesting customization of flexible dye solar cells to deliver superior efficiency under artificial lighting", Applied Energy 156, 2015, pp. 413-422

Department of energy, U.S. Color quality of LEDs. 2009.

Deru M., Blair N., and Torcellini P., 2005, "Procedure to Measure Indoor Lighting Energy Performance", National Renewable Energy Laboratory (NREL), Technical Report

Design rulz, SOFT Rockers http://www.designrulz.com/product-design/gadgets/2011/05/recharge-gadgets-solarpowered-lounge-chairs/, Arts.MIT.edu http://arts.mit.edu/events/soft-rockers/

Design 345, Starrynight LED solar-powered light http://design345.com/2011/03/01/starrynight-light/

Di Wei, Samiul Haque, Piers Andrew, Jani Kivioja, Tapani Ryhδnen, Amaia Pesquera,b Alba Centeno, Beatriz Alonso, Andrey Chuvilincd, Amaia Zurutuzab, 2013, "Ultrathin rechargeable all-solid-state batteries based on monolayer grapheme", Journal of Materials Chemistry A, 1, pp. 3177-3181, doi: 10.1039/C3TA01183F

Diehl, J. C. and H. H. C. M. Christiaans (2007). The first learning experiences of Design for the BoP. ISADR 07 Hong Kong.

Diesen, T. v. (2008). Design of a Solar Home System for rural Cambodia. Industrial Design Engineering. Delft, Delft University of Technology. MSc.

Djamila Rekioua, Ernest Matagne, "Optimization of Photovoltaic Power Systems- Modelization, Simulation and Control", Springer London Dordrecht Heidelberg New York, Copyright © Springer-Verlag London Limited 2012, DOI 10.1007/978-1-4471-2403-0.

Dunn B., Kamath H. and Tarascon J.M., 2011, "Electrical Energy Storage for the Grid: A Battery of Choices," Science, vol. 334, pp. 928-935.

Duracell, "Lithium/Manganese Dioxide": http://www.duracell.com/media/en-US/pdf/gtcl/Technical_Bulletins/Lithium%20Technical%20Bulletin.pdf

Durlinger B, Reinders A, and Toxopeus M., 2010, "Environmental benefits of PV powered lighting products for rural areas in South East Asia: A life cycle analysis with geographic allocation", Proceedings of 35th IEEE PVSC, Hawaii 2010, USA, pp. 2353-2357.

Durlinger B., Reinders A., Toxopeus M., 2012, "Life cycle assessment of solar powered lighting products for rural areas in South East Asia, Components for PV Systems, PV System Engineering and Standards, Socio-economic Aspects, and Sustainability", Proceedings of 25th EU PVSEC, Valencia, Spain, 2012, pp. 3917 – 3925.

Durlinger, B., Reinders, A.H.M.E., Toxopeus, M.E, "A comparative life cycle analysis of low power PV lighting products for rural areas in South East Asia", Accepted for publication by Renewable Energy, July 2011, online 11-11-11, pp. 96-104.

Dutch Soar Boat http://www.dutchsolarboat.com/

Easton, R. L., and M. J. Votaw, Vanguard I IGY satellite (1958 Beta), Rev. Sci. Instrum., 30, pp. 70-75, Feb. 1959.

Easygreen Store, Solar-powered helicopter http://www.easygreenstore.co.uk/solar-powered-helicopter-(ready-made)/

Easygreen Store, Solar-powered windmill kit http://www.easygreenstore.co.uk/solar-powered-windmill-kit/

Easygreen Store, Solar-powered wind turbine (Ready Made) http://www.easygreenstore.co.uk/solar-powered-wind-turbine-(ready-made)/

Ecochunk, Light Bird concept LED lamp http://www.ecochunk.com/tag/solar-lights/

EGIS. Sun and daylighting directing system.http://egis.org/helio_us.html.

Eikelboom J. A., A. H. (1997). Determination of the irradiation dependent efficiency of multicrystalline Si PV modules on basis of IV curve fitting and its influence on the annual performance, pp. 293–296, Barcelona.

El Chaar L., L. l. (2011). Review of photovoltaic technologies. Renewable and Sustainable Energy Reviews.

ElChiltepe.com, Carpa Para La Playa: http://www.elchiltepe.com/2010/11/carpa-para-la-playa.html(Accessed July 03, 2013)

Electronics Tutorials, http://www.electronics-tutorials.ws/diode/diode_8.html

ENERGY.GOV (2012), "Top 6 Things You Didn't Know About Solar Energy": http://energy.gov/articles/top-6-things-you-didnt-know-about-solar-energy

Energy Harvesting Journal, PV-powered remote control by Philips http://www.energyharvestingjournal.com/articles/2734/philips-introduces-tv-with-solar-powered-remote-control

Envirogadget, Regen's ReNu solar-powered docking station charger http://www.envirogadget.com/solar-powered/regens-renu-solar-powered-docking-station-charger/

EPFL (2013), Laboratory of photonics and interfaces LPI, News 03 June 2013, "The solar conversion of the solid state version of Dye sensitized solar cell gone up to 14.14 %": http://lpi.epfl.ch/

European Commission, Joint Research Centre. (2012). PV Status Report 2012. Luxembourg: Publications Office of the European Union.

European Commission JRC- Photovoltaic Geographical Information System - Interactive Maps http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php, (Accessed October, 30th, 2015).

European Commission, Directorate-General for Energy (1996). Photovoltaics in 2010. Office for Official Publications of the European Communities, ISBN 92-827-5347-6.

European Photovoltaic Industry Association (EPIA) (2014), "Global Market Outlook for Photovoltaics 2014-2018": http://www.kigeit.org.pl/FTP/PRCIP/Literatura/093_EPIA_Global_Market_Outlook_for_Photovoltaics_2014-2018.pdf

European Photovoltaic Industry Association (EPIA) (2015), "Global Market Outlook for Solar Power 2015-2019": http://helapco.gr/pdf/Global_Market_Outlook_2015_-2019_lr_v23.pdf

Express Watches, Seiko Men's Solar Watch SSC081P1: http://www.expresswatches.co.uk/seiko_solar_mens_sports_watch (Accessed July 03, 2013)

ExtremeTech, 2015, This fully transparent solar cell could make every window and screen a power source (updated), By Jamie Lendino on April 20, 2015, http://www.extremetech.com/extreme/188667-a-fully-transparent-solar-cell-that-could-make-every-window-and-screen-a-power-source

Fakra A. H., Miranville F., Boyer H., Guichard S., 2011, "Development of a new model to predict indoor daylighting : integration in CODYRUN software and validation", http://arxiv.org/pdf/1212.5253.pdf

Fhtenakis V.M., Kim H.C., Photovoltaics: Life-cycle analysis, Solar Energy, article in press 2010.

Firefly, "Firefly: A $2900 electric boat powered entirely by homemade solar panels", EcoChunk, 7 July 2012.

Flipsen Bas, Bakker Conny, Verwaal Martin, 2015, "Multidimensional sustainability assessment of solar products: Educating engineers and designers", EESD '15, The 7th International Conference on Engineering Education for Sustainable Development, Vancouver, Canada, June 9 to 12, 2015, pp. 127-1 – 127-9.

Flipsen B, Geraedts J, Reinders A, Bakker C, Dafnomilis I, Gudadhe A., 2012, "Environmental sizing of Smartphone batteries, Proceedings Micro-energy supplies and energy harvesting", Electronics Goes Green 2012, Berlin 2012, Germany, pp. 1-9.

Foll H., 'Semiconductors I', 5.1.4 Wavelength Engineering, University of Kiel, Faculty of Engineering, AMAT, http://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_5/backbone/r5_1_4.html

Fraunhofer Institute for Solar Energy Systems, ISE, with support of PSE AG, 2015, "Photovoltaics Report", Freiburg, 17 November 2015, https://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf

Fraunhofer FHI, 2015, Energy Payback Time, presentation slides, and photovolatic report, p. 30–32, http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf

Frederik C. Krebs, Technical University of Denmark (DTU), Coursera online courses, "3 generations of solar cells",© 2015 Coursera Inc. https://www.coursera.org/learn/solar-cell/lecture/pSJi2/introduction

Frederik C. Krebs, Markus Hφsel, Michael Corazza, Bırenger Roth, Dr. Morten V. Madsen, Dr. Suren A. Gevorgyan, Dr. Roar R. Sψndergaard, Dr. Dieter Karg, Dr. Mikkel Jψrgensen, 2013, "Freely available OPVThe fast way to progress", Energy Technology 2013, Volume 1, Issue 7, July 2013, Pages 378–381, DOI 10.1002/ente.201300057.

Freunek Monika (Muller), Member, Michael Freunek, and Leonhard M. Reindl, Member, 2013, "Maximum Efficiencies of Indoor Photovoltaic Devices", IEEE Journal of Photovoltaics, Vol. 3, No. 1, January 2013, pp. 59-64.

Fthenakis V.M., Kim H.C., Photovoltaics: Life-cycle analysis, Solar Energy, article in press 2010.

Fthenakis V., 2012, "How Long Does it Take for Photovoltaics To Produce the Energy Used?, Communities Industry, © Published by the National Society of Professional Engineers, February 2012, Pages 16-1Fulton Suri J. (2003), IDEO, 'The Experience Evolution: Developments in Design Practice', in The Design Journal, Volume 6, Issue 2, 39-48. Berg, 2003.

Gadgetreview, PV-powered charger Solio Bolt:
http://www.gadgetreview.com/2011/11/solio-bolt-review.

Gcell, Logitech Solar Keyboard Folio
http://gcell.com/case-studies/wireless-solar-keyboard

Geelen, DV, Kan, SY & Brezet, JC (2008). Photovoltaics for product designers - How to design a photovoltaic solar energy powered consumer product. In D Lincot, H Ossenbrink & P Helm (Eds.), Proceedings of the twenty third European photovoltaic solar energy conference, pp. 3329-3333. Mónchen: WIP- Renewable Energies. (TUD)

Germes online, Solar Garden Light: http://www.germes-online.com/catalog/3/127/209509/sell_solar_garden_light.html(Accessed July 03, 2013)

Global Energy Assessment (GEA), International Institute for Applied Systems Analysis (IIASA), "Global Energy Assessment-Towards a Sustainable Future", 2013: http://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA-Summary-web.pdf

Global Market Outlook for Photovoltaics 2014-2018, "European Photovoltaic Industry Association", PDF report, page 42.

Goetzberger Adolf, Luther Joachim, Willeke Gerhard, 2002, "Solar cells: past, present, future", Solar Energy Materials & Solar Cells 74 (2002) 1–11.

Goetzberger Adolf, C. H.-W. (2002). Photovoltaic materials, history, status and outlook. Materials Science and Engineering , pp. 1–46.

Gooijer H.d., Reinders A.H.M.E., Schreuder D., (2008), 'Solar powered LED lighting- Human factors of low cost lighting for developing countries'

Gooijer, H. de, Reinders, A.H.M.E. and Schreuder, D.A., Solar power and LED lighting – New opportunities for affordable indoor lighting for rural families in "Base of the Pyramid" circumstances, Oral presentation, Proceedings of CIE mid-term meeting and the light and lighting conference, Budapest, 2009.

Gorlatova M., Wallwater A., Zussman G., Networking Low-Power Energy Harvesting Devices: Measuremetns and Algorithms, Columbia, New York, 2010.

Gorter Tim, 2014, "Performance Evaluation of Photovoltaic Boats in an Early Design Stage", PhD dissertation, ISBN: 978-90-365-3643-1, Twente University, Enschede, The Netherlands.

Gorter, T., Reinders, A.H.M.E., Pascarella, F., Merola, A., Scognamiglio, A., LED/PV lighting systems for commercial buildings design of a sustainable LED/PV symbiotic system, Proceedings of 24th EU Photovoltaic Solar Energy Conference and Exhibition, Hamburg, 2009, pp. 4250-4255.

Green, C. M., Vanguard - a history, NASA, SP-4202, Wash., DC, 1970.

Green Martin A., Emery Keith, Hishikawa Yoshihiro, Warta Wilhelm and Dunlop Ewan D., "Solar cell efficiency tables (Version 45)", 2015, Progress in Photovoltaics: Research and Applications, Prog. Photovolt: Res. Appl. 2015; 23:1–9, published online in Wiley Online Library (wileyonlinelibrary.com).

Green Martin A., Keith Emery, Yoshihiro Hishikawa, Wilhelm Warta and Ewan D. Dunlop, 2015, "Solar cell efficiency tables (version 46)", PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS Prog. Photovolt: Res. Appl. 2015; 23:805–812 Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2637.

Green MA. Solar cell fill factors: General graph and empirical expressions. Solid-State Electronics. 1981 ;24:788 - 789.

Green, M.A., 1982, "Solar cells: operating principles, technology, and system applications", Book, Prentice-Hall, Inc., Englewood Cliffs, NJ, United States.

Green, M.A., 2002, "Third generation photovoltaics: solar cells for 2020 and beyond", Physica E: Low-dimensional Systems and Nanostructures, Volume 14, Issues 1-2, April 2022, Pages 65-70, doi:10.1016/S1386-9477(02)00361-2, Copyright © 2002 Elsevier Science B.V.

Green M. A., Third Generation Photovoltaics. New York, NY: Springer, 2003.

Green Diary, The Sun Flower streetlights http://www.greendiary.com/sunflower-streetlight-lights-up-your-way-with-solar-energy.html

GreenProphet, 2013, The Sheik Zayad Learning Center at the Al Ain Zoo, United Arab Emirates http://www.greenprophet.com/2013/05/ertex-building-integrated-photovoltaic/

GreenTechSolar, 2013, "First Solar Crushes CdTe Solar PV Efficiency Record": http://www.greentechmedia.com/articles/read/First-Solar-Crushes-CdTe-Solar-PV-Efficiency-Record

Grum F. C. and Becherer R. J., "Optical Radiation Measurements I. Radiometry", Academic, 1979.

GSHK, Solar Technology, Architectural Solar, Commercial buildings or homes with integrated flexible solar panels into their architecture, 2011, http://www.groupgshk.com/portfolio/portfolio-15/

Hankeun Lee and Seokheun Choi, 2015, 'An origami paper-based bacteria-powered battery', Nano Energy, Volume 15, July 2015, pp. 549–557

Heliatek, 2013, "Heliatek consolidates its technology leadership by establishing a new world record for organic solar technology with a cell efficiency of 12%", 16.01.2013, http://www.heliatek.com/en/press/press-releases/details/heliatek-consolidates-its-technology-leadership-by-establishing-a-new-world-record-for-organic-solar-technology-with-a-cell-effi

Home World Design, XD DESIGN solar chargers http://homeworlddesign.com/solar-chargers-smart-devices/

Honsberg C. and Bowden S., 2015, PV Education.Org, Photovoltaic Education Network, PV CDROM, http://www.pveducation.org/pvcdrom

Hosel M., Sondergaard R.R., Jorgensen M., Krebs F.C., 2013, "Fast inline roll-to-roll printing for indium-tin-oxide-free polymer solar cells using automatic registration", Journal of Energy Technology, Vol. 1, pp. 102-107.

Hossein Mousazadeh, Alireza Keyhani, Arzhang Javadi, Hossein Mobli, Karen Abrinia and Ahmad Sharifi. A review of principle and sun-tracking methods for maximizing solar systems output (2009).

House to Home, PV-powered lamp Sunnan by IKEA: http://www.housetohome.co.uk/product-idea/picture/solar-powered-lights-10-of-the-best/2

Humpston Giles, 2015, "LEDs Cook Eggs",Cambridge Nanotherm, LED journal, a Webcom Communications Publication, November 10th, 2015, http://www.ledjournal.com/main/blogs/leds-cook-eggs/#more-13132

IEEE Photovoltaic Specialists Conference 39th, PVSC 39 Highlights, 2013: http://www.ieee-pvsc.org/PVSC39/

IFC and the World Bank, Lighting Africa, "Solar Lighting for the Base of the Pyramid- Overview of an Emerging Market", Off-grid lighting for the Base of the Pyramid, October 2010.

iGreen Spot, The Virtue Blue Chandelier http://www.igreenspot.com/virtue-blue-a-chandelier-powered-by-solar-butterflies/

Inhabitat.com, Ralph Lauren Launches Solar-powered Waterproof Backpack for $800: http://inhabitat.com/ralph-lauren-launches-solar-powered-water-proof-backpack-for-800/ (Accessed July 03, 2013)

Inhabitat, Philips Light Blossom, sustainable city light concept, designed for the Phillips Simplicity Event in 2008, http://inhabitat.com/sustainable-city-street-lights-by-phillips/phillips-sustainable-city-light-1/?extend=1

Inhabitat, Solar Ark, Japan. Inhabitat - Sustainable Design Innovation, Eco Architecture, Green Building http://inhabitat.com/solar-ark-worlds-most-stunning-solar-building/,

Inhabitat, 2011, Stunning 'Virtue of Blue' Chandelier Made From 500 Fluttering Solar Butterflies, Images © Giulietta Verdon Roe and Bas Helbers http://inhabitat.com/stunning-virtue-of-blue-chandelier-made-from-500-fluttering-solar-butterflies/

International Energy Agency (IEA) (2015), "Energy and Climate Change", World Outlook Special Report, © OECD/IEA, 2015: https://www.iea.org/publications/freepublications/publication/WEO2015SpecialReportonEnergyandClimateChange.pdf

International Organization for Standardization ISO 14040:2006 Environmental Management – Life Cycle Assessment – Principles and Framework. Geneva, Switzerland, 2006: International Organization for Standardization.

International Renewable Energy Agency (IRENA) (2012) RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES Solar Photovoltaics Volume 1: Power Sector Issue 4/5 pp. 4-6

International Standards Organisation, Quantities and units - Part 6. - Light and related electromagnetic radiations, ISO Standards Handbook, Quantities and Units 389.15, 1993

Intersolar 2010, http://www.tga.at/tirol-als-inovatives-solar-land/696337/?__p=1

Intertek, "Battery Technologies: A General Overview & Focus on Lithium-Ion", Tom O'Hara and Maria Wesselmark, Intertek booklet available at: http://www.kta-ev.com/v/vspfiles/assets/images/intertek-battery-technologies.pdf

IPCC. (2001). Climate Change 2001: Synthesis Report-Summary for Policymakers.

IPCC Climate change 2014, Synthesis Report, © Intergovernmental Panel on Climate Change, 2015, First published 2015 ISBN 978-92-9169-143-2: http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf

Jelsma J. (2006), 'Designing 'Moralized' Products; theory and Practice', In: P.P. Verbeek and A. Slob, eds. User Behavior and Technology Development; Shaping Sustainable relations between Consumers and Technologies. Dordrecht, the Netherlands: Springer, pp. 221–231.

Jelsma J. and Knot M. (2002), 'Designing environmentally efficient services; a 'script' approach', The Journal of Sustainable Product Design 2, pp. 119–130.

Jeong Tai Kim, Gon Kim.Overview and new developments in optical daylighting systems for building a healthy indoor environment. 2010.

Jim on Light, The Kaohsiung National Stadium, A fully solar powered stadium, 2009, http://www.jimonlight.com/tags/world-games-2009/

Jong A.M., Bakker C.A., Scott K. (2008), "The Living Lab project; user centered sustainable design", Sustainable Innovation 2008, Delft University of Technology, Wuppertal Institute, Swiss Federal Institute of Technology in Zurich, Technical University of Madrid, BASF, Acciona, Proctor & Gamble.

Jong A., Mazı R. (2010), "Cultures of Sustainability- Ways of doing cooking", 14th European Roundtable on Sustainable Production and Consumption conference (ERSCP), 6th Environmental Management for Sustainable Universities conference (EMSU), Knowledge Collaboration & Learning for Sustainable Innovation, October 25-29, Delft 2010, The Netherlands.

Kakee Scott (2008), 'Co-designing sustainable user practices; an exploratory study for the Living Lab project', MSc thesis Industrial Ecology, Delft University of Technology.

Kan S.Y. (2006) "SYN-Energy in solar cell use for consumer products and indoor applications". PhD diss., Final Report 014-28-213, NWO/NOVEM, Technical University of Delft, Delft, The Netherlands.

Kan S.Y., Verwaal M., and Broekhuizen H., 2006, "The use of battery-capacitor combinations in photovoltaic powered products short communication", Journal of Power Sources, Vol. 162, pp. 971–974.

Kan, SY & Silvester, S (2003). Synergy in a smart photo voltaic (PV) battery: SYN-ENERGY. The Journal of Sustainable Product Design, 3(1-2), pp. 29-43. (TUD)

Kan, SY, Silvester, S & Brezet, JC (2004). Design applications of combined photovoltaic and energy storage units as energy supplies in mobile/wireless products. In I Horvath & P Xirouchakis (Eds.), Tools and methods of competitive engineering. Vol. I, pp. 309-318, Rotterdam: Millpress. (TUD)

Kan, SY, Verwaal, M, Veefkind, MJ, Silvester, S, Reich, NH, Sark, WGHJM van, Alsema, EA, Elzen, B & Jelsma, J. (2007). Lessons learned: power supply and battery choosing process for the photovoltaic powered wireless mouse. In R Stevens & A Ritchie (Eds.), Proceedings of the 25th International Power Sources Symposium & Exhibition, pp. 1-9, Redditch: Sovereign conference. (TUD)

Kan S.Y., Ruben Strijk, -Towards a more efficient energy use in photovoltaic powered products (2005).

Kan S.Y. -Final Report of Explorative Research Project (014-28-213) within the NWO/NOVEM,Energy Research Stimulation Program, Delft University of Technology, program SYN-energy in solar cell use for consumer products and indoor applications.

Kandachar, P., I. d. Jongh, et al. (2009). Designing for emerging markets: Design of product and services. Delft, Delft University of Technology.

Keyson D. and Jin S., 2009, (Eds.) Designing for Sustainable Living & Working, Delft, The Netherlands: VSSD

Koenderink Jan J, Pont Sylvia C, Doornτ Andrea J, Kappers Astrid M L, Todd James T, 2007, "The visual light field", a Pion publication, ISSN 1468-4233 (electronic), ISSN 0301-0066 (print), pp. 1-16, http://www.psy.ohio-state.edu/faculty/todd/group/Shape%20from%20Shading/Koenderink%20et%20al%202007.pdf

Krauter, Stefan.Solar electric power generation. 2006.

Krebs, F. C. (2008). Fabrication and processing of polymer solar cells: A review of printing and coating techniques. Solar Energy Materials & Solar Cells.

Lan Yoon, 2012, "A KAIST research team has developed a high performance flexible solid state battery", EurekAlert: http://www.eurekalert.org/pub_releases/2012-08/tkai-akr080612.php

Lars van Leeuwen, Indoor Photovoltaics: Optimization of a-Si:H solar cell under indoor illumination conditions, MSc thesis Delft University of Technology, 2010.

Laser Focus World, International Resource for Technology and Applications in the Global Photonics Industry, 2013, "Organic PV efficiency reaches 12 %: Heliatek breaks its prior record": http://www.laserfocusworld.com/articles/2013/01/Heliatek-OPV-12-percent.html

Lee J., Sagawa T., Yoshikawa S., 2013, "Fast screening of the optimal polymer ratio for organic solar cells using a spray-coating deposition method for fullerene mixture", Journal of Energy Technology, Vol. 1, pp. 85-93.

Li Y., Grabham N.J., Beeby S.P., Tudor M.J., "The effect of the type of illumination on the energy harvesting performance of solar cells", 2015, Solar Energy 111 (2015) 21–29, Available online at www.sciencedirect.com, http://dx.doi.org/10.1016/j.solener.2014.10.024, 0038-092X/© 2014 Elsevier Ltd. (Accessed October, 30th, 2015).

Lighting Africa project, https://www.lightingafrica.org/solar-lighting-products-improve-energy-access-for-28-5-million-people-in-africa/

Lighting Research Center, 2000, Illumination Fundamentals, Rensselaer Polytechnic Institute.

Linden, David, Thomas B. Reddy, 2001, "Handbook of Batteries", New York: McGraw-Hill, ISBN 0-07-135978-8.

Lindholm FA, Fossum JG, Burgess EL. Application of the superposition principle to solar-cell analysis. IEEE Transactions on Electron Devices.1979 ;26:165–171.

Little Sun, Little Sun PV-powered light http://littlesun.com/index.php?sec=light
Lizin Sebastien, S. V., 2012, The future of organic photovoltaic solar cells as a direct power source for consumer electronics, Solar Energy Materials & SolarCells.

LOT-Oriel Group Europe, Halogen light sources-Operating tungsten halogen lamps.

Lunt R.R. and Bulovic V., 2011, "Transparent, near-infrared organic photovoltaic solar cells for window and energy-scavenging applications", Applied Physics Letters, Vol. 98, doi: 10.1063/1.3567516.

Macworld, Logitech wireless solar keyboard K750 for Mac http://www.macworld.com/product/1124505/wireless-solar-keyboard-k750-for-mac.html

Martin, C. (2013, 4 8). Bloomberg. Retrieved 8 10, 2013, from http://www.bloomberg.com/news/2013-04-08/first-solar-s-global-sales-head-brown-exits-before-analyst-day.html

Mediad Public broadcasting, Israel's solar-powered trees http://www.google.nl/imgres?imgurl=http://mediad.publicbroadcasting.net/p/shared/npr/styles/x_large/nprshared/201410/358639506.jpg&imgrefurl=http://news.mpbn.net/post/israels-solar-powered-trees-smartphones-and-community&h=3200&w=2400&tbnid=6j3AUY5XmJ49pM:&zoom=1&docid=qT9-wL68B3lvOM&ei=XCVHVZ_fFMHhywOiyIG4CA&tbm=isch&ved=0CEMQMygaMBo

MIT Technology Review, 2016, MIT VIDEO, Transparent Batteries, http://video.mit.edu/watch/transparent-batteries-44/

MIT Technology Review, 2013, "Startup Engineers See-Through Solar Cells": http://www.technologyreview.com/news/511681/startup-engineers-see-through-solar-cells/

Mohammad Tawheed Kibria, Akil Ahammed, Saad Mahmud Sony, Faisal Hossain, Shams-Ul-Islam, 2014, "A Review: Comparative studies on different generation solar cells technology", Proceedings of 5th International Conference on Environmental Aspects of Bangladesh [ICEAB 2014], Paper ID E33, pp. 51-53.

Mueller M., Wienold J., Walker W.D., Reindl L.M., 2009, Characterization of indoor photovoltaic devices and light, Proc. of 34th IEEE Photovoltaic Specialist Conference, Philadelphia, 2009, pp. 738-743.

Móller M., Hildebrandt H., Walker W.D, Reindl L.M., 2009, "Simulations and measurements for indoor photovoltaic devices", In: Proc. 24th European Photovoltaic Solar Energy Conference, Hamburg, Germany, 2009, pp. 4363-4367.

Mueller M., Regenerative Mikroenergiesysteme am Biespiel von Photovoltaik in Gebauden, PhD Thesis, Osnabruck: Der Andere Verlag, September 2010.

Muller M. et al., "Simulations and measurements for indoor photovoltaic devices," in Proc. 24th European Photovoltaic Solar Energy Conference, 21-25 September 2009, Hamburg, Germany, 2009, pp. 4363–4367.

My Sunlight Solar Systems Pvt Ltd., Solar Street Light: http://mysunlight.co.in/Solar_Street_Light.html#.UdPwC2JkN_d(Accessed July 03, 2013)

Nδgele, Thomas. White Light LEDs –Importance of Accepted Measurement Standards. 2008.

Nanowerk, 2013, "Nanotechnology enhanced organic photovoltaics: Breaking the 10 % efficiency barrier": http://www.nanowerk.com/spotlight/spotid=29503.php

NASA Historical Reference Collection, NASA History Office, NASA Headquarters, Washington, DC, 1970, Vanguard- a history: http://history.nasa.gov/SP-4202/to.html

NASA, Vanguard- a history: http://history.nasa.gov/SP-4202/toc2.html (Accessed June 26, 2013)

NASA NSSDC, Vanguard I, 2015, http://nssdc.gsfc.nasa.gov/nmc/masterCatalog.do?sc=1958-002B

NASA Voyager, The Interstellar Mission, 2015: http://voyager.jpl.nasa.gov/spacecraft/index.html

National Aeronautics and Space Administration (NASA), Global Climate Change, Vital Signs of the planet, "NASA scientists react to 400 ppm carbon milestone": http://climate.nasa.gov/400ppmquotes/

National Geographic, "Solar Energy": http://environment.nationalgeographic.com/environment/global-warming/solar-power-profile/

National Oceanic and Atmospheric Administration, NOAA Research, Earth System Research Laboratory, Global Monitoring Division (2013), "Atmospheric CO_2 at Mauna Loa Observatory": http://www.esrl.noaa.gov/gmd/obop/mlo/

National Renewable Energy Laboratory (NREL), Golden, CO, United States Department of Energy, Best research cell efficiencies, 2015.

Navigant Research, Analysis of the potential future of the lighting global quality assurance program, 2015: http://www.cleanenergyministerial.org/Portals/2/pdfs/Potential_Future_of_the_Lighting_Global_QA_Program.pdf

Nelson, J. (2003). The Physics of Solar Cells.Imperial College Press.

Netcomposites, Helios Solar-Powered Aircraft Crashes: http://www.netcomposites.com/news/helios-solar-powered-aircraft-crashes/1736(Accessed July 03, 2013)

Newlaunches, BSKBW01SB solar-powered wireless keyboard by Buffalo Japan http://newlaunches.com/archives/buffalo_solar_powered_wireless_keyboard.php

NHL Solar Boat Racing http://solarboatracing.nl/en/

Nicodemus, F., "Radiometry," in Kingslake (ed.), Applied Optics and Optical Engineering, vol. 4, New York, Academic, 1967.

Nijland, D. (2010). Eindverslag: LED-buis vs Fluorescentiebuis.

Nikkei Technology, 2015, 'Translucent Li-ion Battery Charges Itself by Using Sunlight', September 1st, 2015, http://techon.nikkeibp.co.jp/atclen/news_en/15mk/090100006/?n_cid=nbptec_tecrs

Norwexrace.com Wordpress, 2014, Typical Household Energy Use, http://www.google.nl/imgres?imgurl=http://www.norwexrace.com/wordpress/wp-content/uploads/2014/11/typicalHouseholdEnergyUse.jpg&imgrefurl=http://www.norwexrace.com/wordpress/wp-content/uploads/2014/11/&h=942&w=800&tbnid=Zgo-fIJLiSBSHM:&zoom=1&docid=0Ucdmi5CfpWdCM&ei=GRVGVeWEEczhaK-CgJAP&tbm=isch&ved=0CD8QMygZMBk

NOTEBOOK CHECK, Logitech: Wireless Solar Keyboard K760 fór Mac, iPad und iPhone http://www.notebookcheck.com/Logitech-Wireless-Solar-Keyboard-K760-fuer-Mac-iPad-und-iPhone.75344.0.html, von Ronald Tiefenthδler, 30.05.2012, (Accessed October, 30th, 2015).

Noyes K., 2007, "Nanotubes Power Paper-Thin Battery", Tech News World: http://www.technewsworld.com/story/58833.html
NREL/TP-550-38602, October 2005, http://www.nrel.gov/docs/fy06osti/38602.pdf

NREL, 2013, News Release NR-3913, "NREL Reports 31.1 % Efficiency for III-V Solar Cell": http://www.nrel.gov/news/press/2013/2226.html
Nuon Solar Team, Nuna 3 by Nuon Solar Team, photo by Hans-Peter van Velthoven, http://www.nuonsolarteam.nl/

N2YO, Vanguard 1, Satellite details 1958-002B NORAD 00005", 23 January 2015. http://www.n2yo.com/satellite/?s=00005. Retrieved 25 January 2015.

Official site of Parans Solar Lighting.
http://www.parans.com/Products/tabid/892/language/en-US/Default.aspx.

"Online Etymology Dictionary." Online Etymology Dictionary.N.p., n.d. Web. 04 Aug. 2014

Ossenbrink H. and Helm P. (Eds.), Proceedings of the 20th European Photovoltaic Solar Energy Conference, Barcelona 2005, Spain, WIP-Renewable Energies, pp. 1981-1984.

Pico Solar PV Systems for Remote Homes- A new generation of small PV systems for lighting and communication, Report IEA-PVPS T9-12: 2012.

PilotOnline.com, Parking's just a swipe away in Virginia Beach: http://hamptonroads.com/2013/03/parkings-just-swipe-away-virginia-beach (Accessed July 03, 2013)

Planck M. Distribution of energy in the spectrum. Annalen der Physik. 1901 ;4:553-563.

Precker J.W., 2007, 'Simple Experimental Verification of the Relation between the Band-Gap Energy and the Energy of Photons Emitted by LEDs', European Journal of Physics, 28 (2007), pp. 493-500, IOP Publishing.

Preston, J.S. Introduction to Photovoltaics. 2010.

Randall J.F., 2005, "Designing Indoor Solar Products: Photovoltaic Technologies for AES", PhD diss., ETHZ Switzerland, John Wiley and Sons, Ltd.

Randall J.F., Droz C., Goetz M., Shah A., Jacot J., "Comparison of 6 photovoltaic materials across 4 orders of magnitude of intensity", Proceedings of 17th EUPVSEC, October 2001, Munich, Germany, pg. 603-606.

Randall J.F., Jacot J., "Is AM 1.5 applicable in practice? Modeling eight photovoltaic materials with respect to light intensity and two spectra", Renewable Energy, Vol. 28, p. 1851–1864, 2003.

Randall J.F., Jacot J., "The performance and modelling of 8 photovoltaic materials under variable light intensity and spectra", 2002, Published in World Renewable Energy Congress VII & Expo.

Randall, J. F. (2003). On the Use of Photovoltaic Ambient Energy Sources for Powering Indoor Electronic Devices. PhD Thesis, Lausanne.

Ray, D. L. (1983), Energy and civilization. Nuclear and Chemical Waste Management, pp. 3-7.

Reich N.H., van Sark W.G.J.H.M., Alsema E.A., Kan S.Y., Silvester S., van der Heide A.S.H., Lof R.W., Schropp R.E.I., "Weak light performance and spectral response of different solar cell types", Proceedings of 20th EUPVSEC, June 2005, Barcelona, Spain, pp. 2120-2123.

Reich, NH, Veefkind, MJ, Alsema, EA, Elzen, B & Sark, WGHJM van (2006). Industrial design of a PV powered consumer application: Case study of a solar powered wireless computer mouse. In S.n. (Ed.), 21st European Photovoltaic Solar Energy Conference, Proceedings of the International Confrence, pp. 2306-2311), Mónchen: Fraunhofer IWM.

Reich N.H., Sark W.G.J.H.M. van, Wit H. de, Reinders A.H.M.E., "Using CAD software to simulate complex irradiation conditions: predicting the charge yield of solar cells incorporated into PV powered consumer products", Oral presentation, Proceedings of 34th IEEE Photovoltaic Specialists Conference, Philadelphia 2009.

Reich N.H., Sark W.G.J.H.M. van, Alsema E., Lof R., Schropp R., Sinke W. and Turkenburg W., "Crystalline silicon cell performance at low light intensities," Solar Energy Materials & Solar Cells, vol. 93, p. 1471–1481, 2009.

Reich N.H., Sark, W.G.J.H.M. van, Turkenburg W.C., (2011), "Charge yield potential of indoor-operated solar cells incorporated into Product Integrated Photovoltaic (PIPV)", Renewable energy, Volume: 36, issue: 2 (2011), pp. 642 - 647.

Reich N.H., Sark W.G.J.H.M. van, Alsema E.A., Wit H. de, Reinders A.H.M.E., "A CAD based simulation tool to estimate energy balances of device integrated PV systems under indoor irradiation conditions", Proceedings of 23rd European Photovoltaic Solar Energy Conference, PV Systems, Off-grid applications, Valencia, Spain, 2008, pp. 3338 –3343.

Reich NH, Elzen B, Netten MP, van Sark W.G.J.H.M, Alsema EA, Veefkind M, Silvester S. (2008), "Practical experiences with the PV powered computer mouse 'Sole-Mio', Components for PV Systems, Engineering and System Integration in proceedings of 23rd European Photovoltaic Solar Energy Conference, Valencia 2008, Spain, pp. 3121 – 3125.

Reich NH, Netten MP, Veefkind M, van Sark W.G.J.H.M., Alsema EA, Silvester S, Elzen B, Verwaal M. (2007), "A solar powered wireless computer mouse: Design, assembly and preliminary testing of 15 prototypes", Proceedings of 22nd European Photovoltaic Solar Energy Conference, Milan 2007, Italy.

Reich NH, Veefkind M, van Sark W.G.H.M., Alsema EA, Turkenburg EA, Silvester S. (2009) "A solar powered wireless computer mouse: Industrial design concepts", Journal of Solar Energy, Vol. 83, pp. 202–210.

Reich N.H. et al.: "Industrial Design of a PV powered consumer application: Case study of a solar powered wireless computer mouse" Proc. 21st European Photovoltaic Solar Energy Conference, Dresden 2006.

Reich N.H., PhD Thesis: On the design of product integrated photovoltaic systems, (2010).

Reich, N.H., Sark, W.G.H.J.M. van, Alsema, E.A., Kan, S.Y., Silvester, S., Heide, A.S.H. van der, Lof, R.W. & Schropp, R.E.I. (2005), "Weak light performance and spectral response of different solar cell types", In s.n. (Ed.), Proceedings of the 20th European Photovoltaic Solar Energy Confererence (pp. 2120-2123). Mónchen: WIP Renewable Energies. (TUD)

Reinders A.H.M.E. and Sark W.G.J.H.M. van, 2012, "Product-Integrated Photovoltaics", in Sayigh A. (Ed.) Comprehensive Renewable Energy, Elsevier, Oxford, Vol. 1, 709-732.

Reinders A.H.M.E., 2002, "Options for photovoltaic solar energy systems in portable products". In: Horvath, I. Li, P. and Vergeest, J. Proceedings of TMCE 2002: tools and methods of competitive engineering, Forth International symposium, April 22-26, pp. 25-37, 2002, Wuhan, P.R. China ISBN 7-5609-2682-7.

Reinders, A.H.M.E., Meulen, B.J.R. van der and Eger, A.O., Development of PV powered consumer products using future scenarios, Proceedings of 21th European Photovoltaic Solar Energy Conference and Exhibition, Dresden, 2006.

Reinders A.H.M.E., Diehl J.C., Brezet H. (2012), The power of Design: Product Innovation in Sustainable Energy Technologies, October 2012, Wiley, Delft, Netherlands.

Reinders, A.H.M.E. and Boer, A. de, Product-integrated PV – Innovative design methods for PV-powered products, Oral presentation, Proceedings of 23rd EU Photovoltaic Solar Energy Conference and Exhibition, Valencia, 2008.

Reinders, A., Boer, A. de, Winter, A. de, and Haverlag, M., Designing PV powered LED products –Sensing new opportunities for advanced technologies, Oral presentation, Proceedings of 34th IEEE Photovoltaic Specialists Conference, Philadelphia 2009, pp. 415-420.

Reinders, A.H.M.E., Borga, J.M. de, Boer, A. de, Product-integrated sustainable energy technologies –Six years of experience with innovation and sustainability, 4th World Conference on Design Research, Delft, November 2011.

Reinders, A.H.M.E., Boer, A. de, Product integrated PV and innovative product design, 26th EU Photovoltaic Solar Energy Conference and Exhibition, Hamburg, 2011.

Reinders A.H.M.E. and Apostolou G., "Product Integrated PV", Forthcoming publication, Book Chapter in "Photovoltaic Solar Energy – From Fundamentals to Applications", Eds. Reinders, A.H.M.E., Verlinden, P., van Sark, W.G.J.H.M., and Freundlich, A., Wiley and Sons, UK, expected publication in 2016

Renewable Energy Magazine, PV, Bringing the butterfly effect to life: http://www.renewableenergymagazine.com/article/bringing-the-butterfly-effect-to-life (Accessed July 03, 2013)

Renewable Energy Policy Network for the 21st Century (REN21), Institute for Sustainable Energy Policies (ISEP) (2015), Renewables 2015, Global Status Report, "Annual Reporting on Renewables, Ten years of excellence": http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015_Onlinebook_low1.pdf

RenewableEnergyWorld.com (2013), "Solar Cell Efficiency Round-Up: Thin Film Closing the Gap with Silicon": http://www.renewableenergyworld.com/rea/news/article/2013/01/solar-cell-efficiency-round-up-thin-film-is-closing-the-gap-with-silicon

Rodriguez E. and Boks C. (2005), 'How design of products affects user behaviour and vice versa: the environmental implications', In: Proceedings of EcoDesign 2005. Tokyo: Union of Ecodesigners, 1–8.

Roncali, J., Leriche, P., Blanchard, P., 'Molecular Materials for Organic Photovoltaics: Small is Beautiful', Advanced Materials 2014, 26, pp. 3821–3838.

Rooden T. and Kanis H. (2000), 'Anticipation of usability problems by practitioners', Proceedings of the Human Factors and Ergonomics Society 44th Annual Meeting, San Diego.

Roozenburg N.F.M., Eekels J., Product Design: Fundamentals and Methods, TU Delft, WILEY editions, published in 1991.

Roth W., Schmid J. et al., 1991, "Photovoltaische Energieversorgung fur Gerate im kleinen und mittleren Leistungsbereich" final report, Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany, pp. 3-26.

Roundy S., Wright P.K., Rabaey J.M., Energy Scavenging for Wireless Sensor Networks: With Special Focus on Vibrations, Kluwer Academic Publishers, 2004.

RTE, "SolaRoad" bike path in The Netherlands
http://www.rte.ie/news/2014/1112/658809-dutch-solar-road/

Ryer, A., 1998, Light Measurement Handbook. International Light, Inc.
Sale Stores, Casio FX-300ES Scientific Calculator:
http://salestores.com/casiofx300es.html (Accessed July 03, 2013)

Sanders, Elizabeth (2006), 'Design Serving People'. Copenhagen Cumulus working papers. University of Art and Design Helsinki.

Sanders, E.B.N (2006), Design Research in 2006, Design Research Quarterly 1 (1), 1-8.

Sanders, Elizabeth B. N. (2002), 'From User-Centred to Participatory Design Approaches'. In Frascara, J., Design and the Social Sciences, London: Taylor & Francis, 2002.

Sargosis, 2011, Solar & Electric, PV Solar Specialists, 'How Shade Affects a Solar Array', November 2011, http://sargosis.com/articles/science/how-shade-affects-a-solar-array/

Sastikar Anushri S., Bobade Trupti S., and Tamgade Sneha, 2015, 'Carbon Nanotube Based Paper Battery And Lithium Ion Battery', International Journal of Application or Innovation in Engineering & Management (IJAIEM), Volume 4, Issue 1, January 2015, pp. 178-185, ISSN 2319 – 4847

SB Collinda, Solar Sailor, "Solar power rules the waves". New Review (34). 1997.

Scofield, John H. The Solar Spectrum. 2009.

Schropp R.E.I., Zeman M., 1998, "Amorphous and Microcrystalline Silicon Solar Cells: Modeling, Materials and Device Technology", Series: Electronic Materials: Science & Technology, Vol. 5, 1998, XX, 207 p. 11 illus, Springer.

Science Daily, Science News, Delft University Team Wins Solar-Powered Car Competition: http://www.sciencedaily.com/releases/2007/10/071026201442.htm (Accessed July 03, 2013)

Scott, Kakee (2008), "Co-designing sustainable user practices", Thesis in Industrial Ecology master program, TU Delft, Erasmus University, Leiden University, 2008.

Scott K., Quist J., Bakker C. (2009), "Co-design, social practices and sustainable innovation: involving users in a living lab exploratory study on bathing", "Joint actions on climate change" conference, 8-10 June, Aalborg 2009, Denmark.

Shackel B. (1984), 'The concept of usability', In: J. Bennet, et al, eds. Visual Display Terminals. Englewood Cliffs, NJ: Prentice-Hall, Inc., 45–88.

Shimadzu.com, Transmittance spectra of several glass types according to wavelength, http://www.shimadzu.com/an/industry/ceramicsmetalsmining/chem0501005.html

Smit E., Stevels A., Sherwin C. (2002), 'User Centred Ecodesign: Experiences From The Design Of A Human-Powered Remote Control', In: Proceedings of Care Innovation 2002 November 25-28. Vienna: IEEE.

Smith Z.A. and Taylor K.D. (2008), "Renewable and Alternative Energy Resources: A Reference Handbook", Contemporary World Issues, Library of Congress Cataloging-in-Publication Data, USA.

Solar Aid, 2015, Impact Report Autumn 2015, http://www.solar-aid.org/impact/

Solar Aid, Speed of Light, 2015, https://speedoflight.io/

Solar Energy Confererence (pp. 2120-2123). Mónchen: WIP Renewable Energies, (TUD).

Solar Feeds, Solar-powered traffic lights, Energy Refuge
http://www.solarfeeds.com/solar-traffic-lights-come-to-durban-south-africa/

SolarGIS 2015, World Map of Global Horizontal Irradiation, SolarGIS © 2015 GeoModel Solar http://solargis.info/doc/_pics/freemaps/1000px/ghi/SolarGIS-Solar-map-World-map-en.png

Solar Feeds, Solar Yacht by Novague Studio http://www.solarfeeds.com/the-10-coolest-solar-boats/

Solar-Kingdom.com: Solar Lantern SCL-05: http://www.solar-kingdom.com/ (Accessed July 03, 2013)

Solar racing, TU Delft's solar racing boat http://www.solarboatteam.nl/, http://maxonmoves.nl/blog/application/flying-on-water/

Solar Team Eindhoven, Stella, world's first solar-powered family car http://www.solarteameindhoven.nl/

Stellarnet Inc. http://www.stellarnet-inc.com/popularconfigurations_radiosystems.htm

Stonybrook Digication, Solar Recycling Bin: https://stonybrook.digication.com/Solar/Similar_Products/published/?sh_6006166=3&moduleinstid=6006166&page_mode=published (Accessed July 03, 2013)

Sun21, "Solar boat makes Atlantic history", BBC News, 30 March 2007.

Sun21, "Solar boat completes fuel-free voyage", USA Today, Associated Press. 8 May 2007.

Sunny money, 'SolarAid launches Light The Way campaign', 2015, http://www.sunnymoney.org/index.php/media/news/solaraid-launches-light-the-way-campaign/

SupportIt Desk, SOL solar-powered laptop developed by WEWI Telecommunications http://www.supportitdesk.com/laptop-works-on-solar-power/

System, Official site of HIMAWARI Solar Lighting.http://www.himawari-net.co.jp/e_page-index01.html

Tech Xplore, 2015, 'Transparent lithium-ion battery that recharges via the sun demonstrated', September 2, 2015 by Bob Yirka, http://techxplore.com/news/2015-09-transparent-lithium-ion-battery-recharges-sun.html

Texas Solar Energy Society, "Solar Energy Facts You Should Know": http://www.txses.org/solar/content/solar-energy-facts-you-should-know

The Optoelectronics Research Centre, University of Southampton,"The life and times of the LED a 100-year history",. April 2007. Retrieved September 4, 2012.

The tech journal, Solar Impulse plane and Helios NASA's solar-powered prototype aircraft http://thetechjournal.com/green-tech/solar-plane-flies-all-night-long.xhtml

ThermoAnalytics, 2013, Total Thermal Solutions, "HEV Vehicle Battery Types": http://www.thermoanalytics.com/support/publications/batterytypesdoc.html

Think Dots, 10 Creative Lamp Designs, Spark Lamp: http://thinkdots.com/blog/10-creative-lamp-designs/ (Accessed July 03, 2013)

Timmerman M.B., 2008, "Review of Existing Knowledge of Product Integrated PV for Industrial Design Engineers", Internal Research Paper, Master of Sustainable Energy Technology, University of Twente.

Treehugger, 2009, http://www.treehugger.com/clean-technology/inflatable-solar-panels-zip-together-to-power-most-anything.html

Treehugger, NTS Sun Cycle http://www.treehugger.com/solar-technology/electric-assist-cargo-bike-powered-built-solar-panel.html, ©NTS.

Toyota, Toyota Prius http://www.toyota.com/prius/

TU Delft, SoleMio: Photo's by Matthijs Netten, Delft Design Institute / SynEnergy http://www.tudelft.nl/en/current/latest-news/article/detail/minister-cramer-test-eerste-muis-op-zonnecellen/

Ubiquitous Energy, 2015, ClearView Power Technology, http://ubiquitous.energy/technology/

Ulule.com, Solar bonsai Electree, Ecological charger for mobile devices: http://www.ulule.com/electree/ (Accessed July 03, 2013)

UN-Energy, 2015, Lighting Africa, http://www.un-energy.org/activities/215-lighting-africa

U.S. Department of Energy, EERE, "The history of solar": http://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf (Accessed June 6, 2013)

Vanguard I http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=AD0419878.

Veefkind, MJ, Reich, NH, Elzen, B, Kan, SY, Silvester, S, Verwaal, M, Alsema, EA, Sark, WGHJM van & Jelsma, J. (2006). The design of a solar powered consumer product, a case study. In S.n. (Ed.), Proceedings of Going Green Care Innovation 2006, pp. 2306-2311, Vienna: International Care Electronics. (TUD)

Veefkind, MJ (2003). Industrial design and PV-power, challenges and barriers. In s.n. (Ed.), ISES solar world congress 2003: solar energy for a sustainable future. s.l.: ISES.

VentureBeat VB/GREEN, 2013, "These transparent solar cells provide 50 % more battery life for your phone-and 'infinite' standby time": http://venturebeat.com/2013/06/04/these-transparent-solar-cells-provide-50-more-battery-life-for-your-Smartphone-and-give-you-infinite-standby-time/

Verbeek Peter-Paul, Adriaan Slob, 2006, (Eds.) User Behavior and Technology Development, Eco-Efficiency in Industry and Science, Vol. 20, XVI, 409 p., ISBN 978-1-4020-5196-8.

Vet, B & Zeman, M., 2008, Relation between the open-circuit voltage and the band gap of absorber and buffer layers in a-Si:H solar cells. Thin Solid Films, 516(20), pp. 6873-6876.

Vintage Calculators Web Museum: http://www.vintagecalculators.com/ (Accessed June 19, 2013)

Viswanathan B., Reinders A.H.M.E., de Boer D.K.G., Ras A., Zahn H. & Desmet L., 2012, "System engineering and design of LSC-PV for outdoor lighting applications", Proceedings of EUPVSEC, Frankfurt 2012, Germany, pp. 4273-4279.

Vivien Muller, Electree and Electree mini http://vivien-muller.fr/#electree-original, http://vivien-muller.fr/#electreemini

Vivien Muller, Orkys http://vivien-muller.fr/#orkys

Volker Quaschning, "Understanding Renewable Energy Systems", Volume 2, First published by Earthscan in the UK and USA in 2005, Copyright © Carl Hanser Verlag GmbH & Co KG, 2005.

von Hippel, Eric (1986) "Lead Users: A Source of Novel Product Concepts," Management Science 32, no. 7 (July):791-805.

von Hippel, Eric (1982) "Appropriability of Innovation Benefit as a Predictor of the Source of Innovation," Research Policy 11 (1982), 95-115.

Vredenburg K., Isensee S. et al. (2002), 'User-Centered Design; An Integrated Approach', Upper Saddle River, NJ: Prentice-Hall.

Waka Waka PV-powered light http://us.waka-waka.com/

Watanabe K., Wang Y., Sodabanlu H., Sugiyama M., Nakano Y., 2013, 'Strain Effect for Different Phosphorus Content of InGaAs/GaAsP Super-Lattice in GaAs p-i-n Single Junction Solar Cell', On-line Journal of 17th International Conference on Crystal Growth and Epixaty-ICCGE-17, science24.com/paper/29455.

Wen J. and Smith T.F "Absorption of Solar Energy in a Room", Solar Energy, Volume 72, Issue 4, April 2002, Pages 283–297, doi:10.1016/S0038-092X(01)00107-4.

Wever R., Kuijk van J., Boks C. (2008), 'User-centred design for sustainable behaviour', International Journal of Sustainable Engineering, vol 1, issue 1, p. 9-20.

Wikipedia, Exponential growth-curve on a semi-log scale of worldwide installed photovoltaics in megawatts since 1992. ©Public domain. Uploaded by Rfassbind on 8 November 2014. Source: https://en.wikipedia.org/wiki/Growth_of_photovoltaics#/media/File:PV_cume_semi_log_chart_2014_estimate.svg

Williams M., 2013, “Hybrid ribbons a gift for powerful batteries”, Rice University News & Media: http://news.rice.edu/2013/03/25/hybrid-ribbons-a-gift-for-powerful-batteries/

Williams R., 1960, "Becquerel Photovoltaic Effect in Binary Compounds", The Journal of Chemical Physics 32 (5): 1505–1514. doi: 10.1063/1.1730950.

Wolfe William L., Introduction to Radiometry, SPIE Press, 1998.

World Energy Council (2013) “ 2013 World Energy Issues Monitor”: http://www.worldenergy.org/documents/2013_world_energy_issues_monitor_report_feb2013.pdf

World Solar Challenge, Bridgestone World Solar Challenge http://www.worldsolarchallenge.org/about_wsc_2015/overview

Wórfel P., 2005, Physics of Solar Cells: From Principles to New Concepts, Wiley-WCH, Weinheim

WWF. (2011). THE ENERGY REPORT 100% RENEWABLE ENERGY BY 2050.

XD Design, Solar chargers, https://www.xd-design.com/solar-chargers/

Yang Y., Jeong S., Hu L., Wu H., Lee S.W., Cui Y., 2011, “Transparent lithium-ion batteries”, Proceedings of the National Academy of Sciences of the United States of America PNAS, doi:10.1073/pnas.1102873108.

Yanko Design, Solar-powered notebook, by Fujitsu http://www.yankodesign.com/2011/06/01/sun-kissed-ready-notebook/

Yet Another Geek’s Blog, Gadget: Sunnan, solar charged IKEA lamp: http://yetanothergeeksblog.blogspot.gr/2010/10/gadget-sunnan-solar-charged-ikea-lamp.html (Accessed July 03, 2013)

Your Solar Link, World's first solar-powered soccer ball http://www.yoursolarlink.com/blog/tag/solar-cells/

Zahl H.A. and Ziegler H.K., 1960, “Power sources for satellites and space vehicles”, Solar Energy 4, pp. 32–38.

Zalewski, E. F., “Radiometry and Photometry,” in Handbook of Optics, vol. 2, New York, McGraw-Hill, 1995, Chap. 24.

Zeghbroeck van B., 2011, ‘Principles of Semiconductor Devices’, Chapter 2: Semiconductor Fundamentals, Energy Bands, http://ecee.colorado.edu/~bart/book/book/chapter2/ch2_3.html

Zeman, M., 2010, Thin-film silicon PV technology. Journal of Electrical Engineering, 61(5), 271-276.

Zeman, M., Isabella, O., Tichelaar, F.D. & Luxembourg, S.L., 2010, Amorphous silicon-based multilayers for photovoltaic applications.Physica Status Solidi. C: Current Topics in Solid State Physics, 7(3-4), 1057-1060.

Zeman, M., Melskens, J., Semanovi M. & Voderadski, Z., 2007, Photovoltaic solar energy: key to a sustainable energy future. International Issues & Slovak Foreign Policy Affairs, XVI(4), 36-52.

Zhao Yimu, Meek Garrett A., Levine Benjamin G. and Lunt Richard R., 2014, 'Near-Infrared Harvesting Transparent Luminescent Solar Concentrators', Advanced Optical Materials, Volume 2, Issue 7, pp. 606–611, July 2014, Wiley

Zheludev, N., 2007, "The life and times of the LED: a 100-year history", Nature Photonics 1 (4): 189–192.Bibcode:2007NaPho...1..189Z.

APPENDICES

Appendix A - PV Products

Appendix A1- Building Integrated PV


Figure A.1: Left image: Solar Ark is a PV-powered building located next to Sanyo's semiconductor factory in Gifu, Japan. It is made by monocrystalline solar cells. The construction was established in December 2001. Source: Inhabitat, 2015. Right image: Ferdinand-Braun-Institut fér Hφchstfrequenztechnik is a research and education center, located at Berlin Adlershof in Deutschland. The architect Christian Matzke designs it in 2008. Source: Archinoah, 2015.

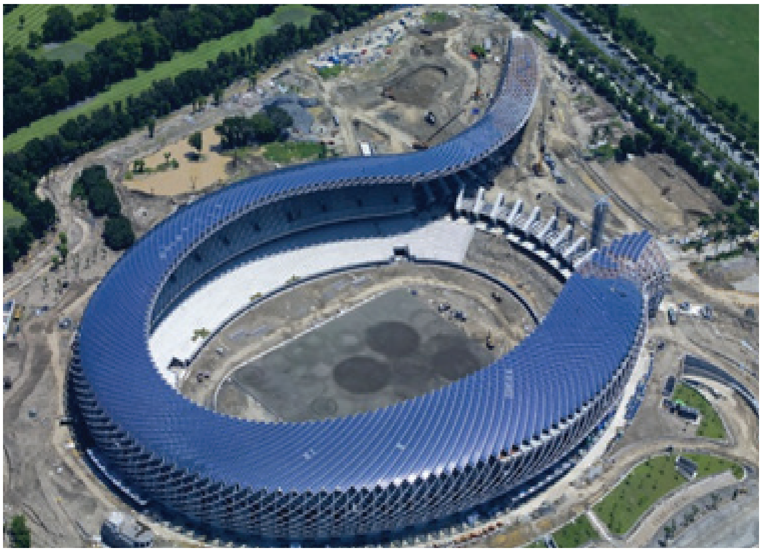


Figure A.2: The Kaohsiung National Stadium is a dragon-shaped PV-powered stadium in Taiwan. It was completed in 2009. Source: Jim on Light, 2016.

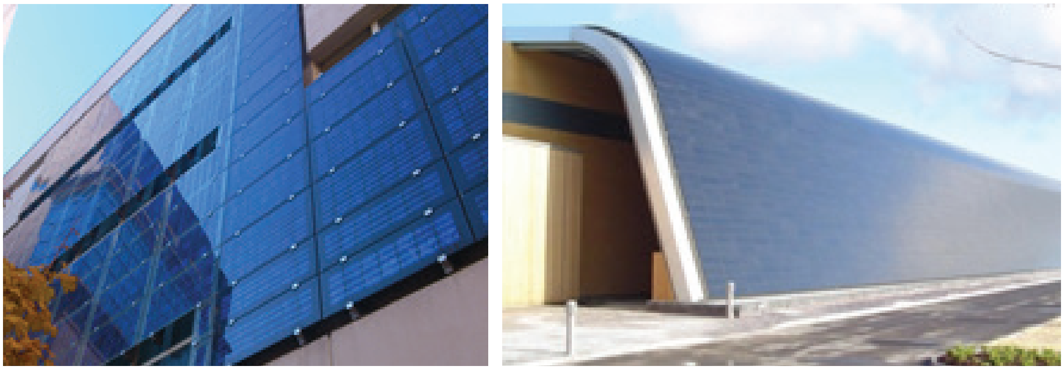


Figure A.3: Examples of commercial buildings or homes with integrated flexible solar panels into their architecture. Left image: Photovoltaic solar facade on the municipal building of Social Services Centre Jose Villarreal, in Madrid (Spain, 2013). Source: Commons Wikimedia, 2015. Right image: Application of flexible solar panels in a building's facade by GSHK Solar Technology, 2011. Source: GSHK, 2011.

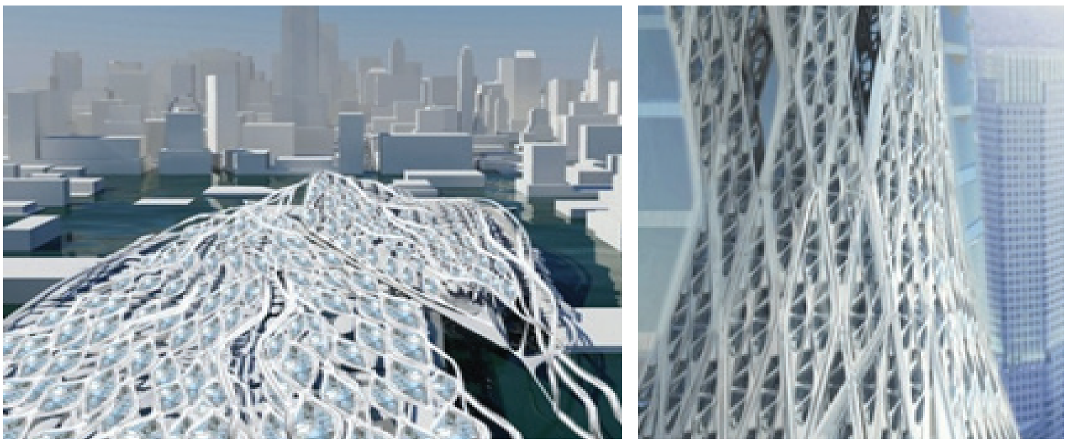


Figure A.4: This is a concept of Building Integrated PV (presented in 2009), using lightweight, thin film solar cells for energy production. The solar panels are zipped together to power the building. Illustration by Studio Formwork. Source: Treehugger, 2015.

Appendix A - PV Products

Appendix A2 - Product Integrated PV_ Products for outdoor use

Figure A.5: Left image: PV-powered lamp for road illumination in Rizal Park in Philippines. Source: Cultural Heritage Monument, 2012. Right image: PV-powered traffic lights located at the municipality of Thekwini in Durban, South Africa. Source: Solar Feeds, 2015.

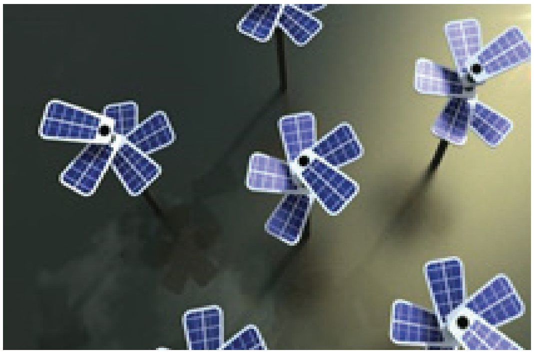


Figure A.6: The Sun Flower streetlight is powered using five PV modules, which are located on top of the pole. Left image: Top view. Right image: View from the street. Source: Greendiary, 2015.

Figure A.7: PV-powered traffic light. It is a concept idea (2010), designed by Cheng-Tsung Feng, Yao-Chieh Lin and Bo-Jin Wang. The specific traffic light uses a discolor LED light, which allows red, yellow and green colors to light up on the same space. Source: GreenPlanet, 2010.

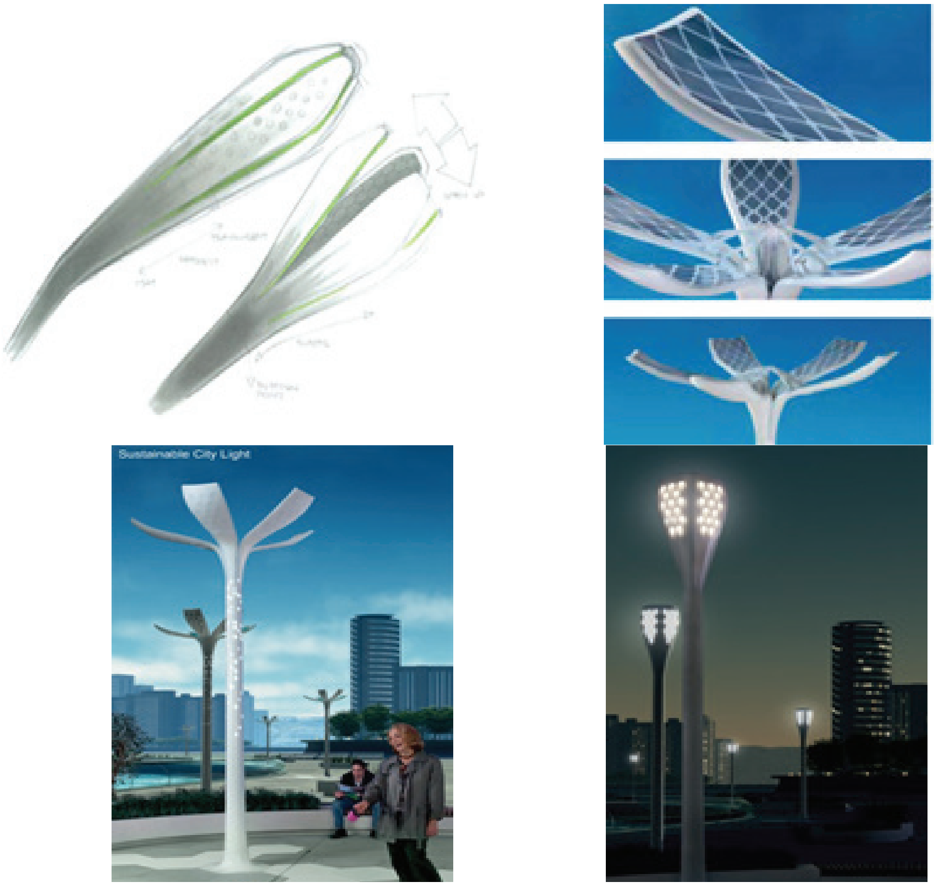


Figure A.8: Philips Light Blossom, sustainable city light concept, designed for the Philips Simplicity Event in 2008. ©Philips. Source: Inhabitat, 2010.

Figure A.9: Sun Bike is an electric tricycle, which is powered using the solar panels that are located on the cover of the cargo. Source: Tuvie, 2015.

Figure A.10: Toyota Prius (2009) includes cooling fans in its interior, which are powered using the PV panels located on the car's roof. Left image: View of the car. Right image: View of the PV-powered roof. ©Toyota. Source: Toyota, 2015.

Figure A.11: The Tÿranor Planet Solar catamaran (2010-2012), 102ft long, 29ft wide and 25ft high, is the largest PV-powered sea vessel. Source: Dailymail, 2015.

Figure A.12: TU Delft's solar racing boat, 2010-2015. Source: Solar racing, 2014 .

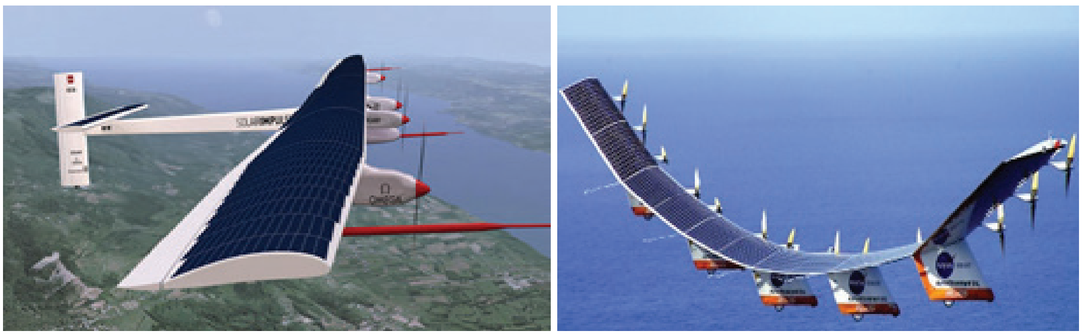


Figure A.13: Left image: Solar Impulse plane is a PV-powered, single-pilot aircraft (2009-2014). Its wings are covered with 11,000 solar cells, with a wingspan of 210 feet. Source: The tech journal, 2015. Right image: Helios is the NASA's PV-powered prototype aircraft (1999-2003). It was designed to operate at extremely high altitudes using batteries and high-efficiency solar cells spread across the upper surface of its 247-foot wingspan. Source: The tech journal, 2015.

Figure A.14: PV Yacht by Novague Studio is a concept product (2009). The solar panels fitted on the boat open on both sides like wings. Source: Solar feeds, 2015.

Figure A.15: SOFT Rockers (2011) are PV-powered charging stations, located outdoors. They are designed to recharge electronics, while relaxing outdoors. They use the human power of balance to create a solar tracking system of 35 watt. Designed by SOFT Rockers Team (2011). Source: Arts.MIT.edu, 2015.

Figure A.16: Israel's PV-powered trees (2011-2013) are planted in Israel to charge phones, offer cool drinking water and supply energy for Wi-Fi. The design of the tree is inspired by the acacia tree. A seven-panel tree can generate a maximum of 1.4 kilowatts, which is enough energy to power 35 laptops. ©2014 Emily Harris/NPR.

Figure A.17: Little Sun (2012) PV-powered light can produce five hours of light after five hours of charging under the sun. It is designed by the Icelandic artist Olafur Eliasson. ©2015 Little Sun.

Figure A.18: World's first PV-powered soccer ball (2011) uses motion-sensing technology to help blind people play soccer. The solar-powered ball's panels, developed by Greendix, can power the built-in motion sensors, as well as an audio device, which could enable visually impaired people to play. Each time the ball is kicked, it emits a tracking sound. Image by Greendix. Source: Your Solar Link Team, 2011.

Figure A.19: "SolaRoad" bike path in The Netherlands (2009-2014), is made of concrete modules with dimensions 2.5 by 3.5 meters, embedded with solar panels covered in tempered glass. The solar cells at the moment put the electricity they generate onto the national grid, but future plans include using the energy to power streetlights. Source: RTE, 2014.

Appendix A - PV Products

Appendix A3 - Product Integrated PV, Products for indoor use

Figure A.20: PV-powered remote control by Philips (2010). ©Philips. Source: Energy Harvesting journal, 2015.

Figure A.21: Solar powered toys. From left to right side: Solar-powered helicopter, Solar-powered windmill kit, Solar-powered wind turbine. Source: EasyGreen Store, 2014.

Figure A.22: PV-powered notebook, by Fujitsu (2011). It is a polycarbonate laptop with a transparent touch-keyboard, which has double solar panels (one on top and under the keypad). © Andrea Ponti. Source: Yankodesign, 2011.

Figure A.23: SOL PV-powered laptop developed by WEWI Telecommunications in Canada (2013). It will never need to be plugged in. WeWi Telecommunications Inc. CANADA. Source: SupportItDesk, 2014.

Figure A.24: Logitech Solar Keyboard Folio (2012) is a wireless solar keyboard, which uses dye-sensitized solar cells (DSSC) –the G24 solar cell- designed to be used with Apple iPads (the iPad 2 and iPad 3). The keyboard harvests indoor ambient light. Image courtesy of G24 Power Ltd. Source: Gcell, 2014.

Figure A.25: Left image: KudoCase is a solar-powered case by Wireless NRG (2012). The KudoCase powers iPads or charge other devices using a USB port. © Wireless NRG. Source: CleanTechnica, 2012. Right image: Regen's ReNu PV-powered docking station charger (2010). It is a 9-by 9-inch portable tablet weighting 498g. When placed under direct light, the ReNu's built-in PV cells collect the solar energy and charge the internal Li-ion battery. Source: EnviroGadget, 2015.

Figure A.26: Left image: Logitech PV-powered keyboard (2010), model K760 wireless Bluetooth keyboard for the Mac. Source: Notebook check, Logitech, 2012, Macworld, 2014. Right image: BSKBW01SB PV-powered wireless keyboard by Buffalo Japan (2008). It operates in frequency 2.4 Ghz with 10 meters range. Source: Newlaunches, 2014.

Figure A.27: Electree (2010-2011) (Left image) and Electree mini (2012-2013) (Right image) are modern sculptures inspired by the bonsai trees. Their leaves are photovoltaic panels; 27 solar panels are installed at the tip of their branches, which capture the solar energy and store it in a 2500 mAh battery, which is located under the panel of the bonsai. ©Vivien Muller. Sources: Vivien Muller, 2014.

Figure A.28: PV-powered chargers (the solar sunshine, the solar sunflower, the solar Suntree, the XD Window charger and the Ginko solar tree) store energy and charge mobile phones, tablets or MP3 players. Designed by the XD DESIGN team (2013). Source: Home World Design, 2014; XD Design, 2015.

Figure A.29: Orkys (2009) captures solar energy in its leaves, which are flexible photovoltaic cells, and it uses it to light up its flowers. ©Vivien Muller. Source: Vivien Muller, 2014.

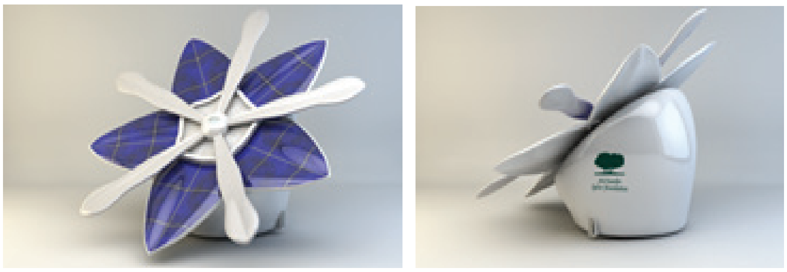


Figure A.30: PV-powered charger designed by Qatar Foundation. Source: Cargo Collective, 2014.

Figure A.31: Christened Light Bird, a concept LED lamp (2012), inspired by the feathers of birds to hide solar panels. Via: Coroflot/YankoDesign. Source: Ecochunk, 2012.

Figure A.32: Starrynight LED PV-powered light (2011) is a combined light and nightlight that recreates the starry night sky. A transparent light-collecting module (provided by Mechanical and Systems Research Laboratories [MSL]/Industrial Technology Research Institute [ITRI]) serves as an exterior lampshade. The product also collects light energy when the main bulb lights up, and converts it to electricity. Source: Design345, 2011.

Appendix B - Data of PV products analyzed in Chapter 3

Product name	Helios Racing Car IV	Solar and wind tent	Helios aircraft	BigBelly Solar Compactor	Glastonbury Solar Concept Tent
Product category (f.i. consumer product, vehicle etc)	Vehicle	Mobile Electronics Charging Station	Helios Prototype HP03	Public use product	Camping tent
Year of production	2010	2009	unmanned aerial vehicle (UAV)	2006	Designed in 2009
Manufacturer	Hautes Etudes d'Ingénieur	GotWind	2003	BigBelly Solar, Inc.	Kaleidoscope-Orange
Nationality of manufacturer	French	UK	NASA	USA	U.S.-France
Product function 1 (f.i. lighting, sound, transportation)	Transportation	Charge electronics	United States of America	Compacting trash receptacle	battery charger
Product function 1 (f.i. lighting, sound, transportation)	Competition		long endurence demonstration		lighting
Product function 3 (f.i. lighting, sound, transportation)	Study		-		heating
Product dimensions length (m)	4	10 m	-	0.657	about 3
Product dimensions width (m)	1.5	10 m	5.0 - 3.2	0.664	about 1.5
Product dimensions height (m)	0.85	7,5 m	75.3	1,281	about 1.5
Product weight (kg) (if available)	165 kg	N/A	0.9 - 0.3	136	approximately 10 kg
			1.052		
Energy system in product					
Grid connected (yes/no)	No	No	no	no	no
Irradiance conditions (indoor, outdoor)	Outdoor	Outdoor	outdoor	outdoor	outdoor
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	Lithium Polymere	6 24volt deep cycle. techn unavailable	H2-AIR fuel cell - Li-batteries	N/A	not specified, I guess Li-ion or Li-poly
Battery capacity (Ah)	50Ah	N/A	?	N/A	not specified
Operational voltage of energy system (V) (if available)	100	N/A	?	12	not specified
PV technology (a-Si, x-Si, GaAs, organic, other)	a-Si	N/A	AMO solar cells	Polycrystalline silicon cell (poly-Si/mc-Si)	Photovoltaic fabric, amorphous silicon
PV area (m2)	5	N/A	180	0.2	about 5
PV power (multiply PV area with factor 150 => Wp)	1000	880 W	27000	30	750

Other power electronics (f.i. engine, flywheel etc)	-	Wind Turbine	10 engines	Electronic control mechanism	wireless battery charger, flexible touchscreen LCD display screen, wireless control hub, Glo-cation technology, internal heating element
Power of other electronics (W) (if available)	-	1 kW	1.5 kW each	N/A	the entire available power from PV fabric
Estimated energy production (Wh/day)	5670	1,8 kWh	?	N/A	2700
User specifications					
Number of simulateous users	1	104	0	N/A	2 or 3
Average duration of use (h)	52	1 hr./user	broke down after 0.5h preparation flight	24 hours a day/7 days a week	approximately 3 years, provide energy for 100 hours
Location of use (describe)	Competition race	Used at outdoor music festivals	high altitude (15 km)	Replacing regular trash bins	sunny camping sites-concerts
Estimated energy consumption (Wh/day)	6300	app. 350 W when fully loaded	?	N/A	2700
Costs					
Retail price (Euro) (if available)		N/A	?	~2775	not on sale
Estimated price (Euro)	300000	N/A	?		1000-2000 €

Product name	**Solar LED Street Light, SS28**	**Solar steppimg stones in pond**	**Umicore Inspire Racing Car**	**Trillium Worldwide TWI-7001 AutoVent Solar-Powered Ventilator**	**Nuna 4**
Product category (f.i. consumer product, vehicle etc)	Utility	solar garden light	vehicle	consumer product	Nuna 4
Year of production	NA		2009	2005	Solar powered vehicle
Manufacturer	BBE Electronics		Group T Technical University, Leuven	Trillium Worldwide Products Ltd	2007
Nationality of manufacturer	China		Belgian	American	TU Delft
Product function 1 (f.i. lighting, sound, transportation)	Lighting	lighting	Transportation	ventilation	Dutch/The Netherlands
Product function 1 (f.i. lighting, sound, transportation)	NA	decoration	Racing	cooling	Transportation
Product function 3 (f.i. lighting, sound, transportation)	NA			Removes hot air odors	Solar car race
Product dimensions length (m)	.66--1.48--.48--NA	50cm	4.3	0,203m	
Product dimensions width (m)	.34--0.67--.17--NA	50cm	1.8	0,127m	4.72
Product dimensions height (m)	.26--0.035--.24--6	5cm	1.04	0,064m	1.68
Product weight (kg) (if available)	battery and LED system: 44.5 and 13.5 kg		60(car structure) - 187 (total)	0,385m²	1.1
					202
Energy system in product					
Grid connected (yes/no)	no	no	No	no	No
Irradiance conditions (indoor, outdoor)	outdoor	outdoor	Outdoor	outdoor	outdoor
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	VRLA (valve-regulated lead-acid)	NiMH batteries	25 kg LiPo	no batteries	Lithium-ion polymer
Battery capacity (Ah)	150Ah	1100 mA·h to 3100 mA·h	5 kWh - 31.25 Ah	no	400
Operational voltage of energy system (V) (if available)	12V DC	1.2V	160 V	N/A	12
PV technology (a-Si, x-Si, GaAs, organic, other)	monocrystalline with 15% efficiency		Germanium subtrates	a-Si	Gallium-Arsenide Triple Junction

Other power electronics (f.i. engine, flywheel etc)	NA	none	NA	N/A	InWheel Direct Drive Electric Engine
Power of other electronics (W) (if available)	NA	none	NA	N/A	2400
Estimated energy production (Wh/day)	avg. 5 hours of operation = 675Wh/day		NA	72	
User specifications					
Number of simulateous users	Public	infinite	1 (driver)	N/A	1
Average duration of use (h)	10-12 h	8	worked only 4 h due to the crash	4h	33 hours 17 minutes (during the race)
Location of use (describe)	Streets, parks, parking lots, etc.	garden	Australia, World Solar Challenge	hanged on car's door to absorb solar radiation	World Solar Challenge in Darwing - Adelaide, Australia
Estimated energy consumption (Wh/day)	max. 12 h in a day = 420 Wh/day	50Wh/kg*0,3kg/battery*1 2hour/day	33600	0	
Costs					
Retail price (Euro) (if available)	NA		not for sale	N/A	
Estimated price (Euro)	3000	aprox 40€	NA. university project (sponsors)	21.86 €	25000

Product name	Navette du Millenaire	Power House	Solar boat	Sunseeker I	solar street light
Product category (f.i. consumer product, vehicle etc)	vehicle (boat)	Experimental Energy Efficient House	Aquabus Solon C60	vehicle	street light
Year of production	2008	House	Boat	1989	onbekend
Manufacturer	Alt en (alternative energies)	2005	2009	SolarFlight	atlantis solar
Nationality of manufacturer	France		SolarWaterWorld AG	USA	united kingdom
Product function 1 (f.i. lighting, sound, transportation)	Transportation	Japanese	Germany	recreation	lighting
Product function 1 (f.i. lighting, sound, transportation)		Place for Living	Transportation	transportation	nvt
Product function 3 (f.i. lighting, sound, transportation)				-	nvt
Product dimensions length (m)	15m			7	275mm
Product dimensions width (m)	5m	14.56 m	17,65m	17	90mm
Product dimensions height (m)	4,5m	5.46 m	6,85m	~1	
Product weight (kg) (if available)	12000		-	230	120-164kg(analoogsysteem)
			approx. 13.000kg		
Energy system in product					
Grid connected (yes/no)	no		No	no	no
Irradiance conditions (indoor, outdoor)	outdoor	Yes	Outdoor	outdoor	outdoor
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	NiCd	0.86W/m²k	Lead acid	Li-ion	lead acid
Battery capacity (Ah)	110kW/h		3456000 Ah	16	2x100 Ah
Operational voltage of energy system (V) (if available)	_		48 V	200	12V
PV technology (a-Si, x-Si, GaAs, organic, other)	c-SI	c-Si	Polycrystalline modules	a-SI	mono-ci
PV area (m2)	21 m^2	37.6 m^2	34.4 m^2	11.6	0.867m2
PV power (multiply PV area with factor 150 => Wp)	2,7kWp	5,640 W	5.16 kWp	1800	130Wp
Other power electronics (f.i. engine, flywheel etc)	2*22kW engine		Engine	engine	nvt

Power of other electronics (W) (if available)	not installed		-	5500	30W led
Estimated energy production (Wh/day)	8kWh/day	14,459.67 Wh/day	8.81 Wh/day	18000	360Wh/day
User specifications					
Number of simulateous users	75 max	4	60 passengers	1	1 user, autonoom systeem
Average duration of use (h)	12 hr	336 h	Unlimited	5	12hrs/night
Location of use (describe)	Seine,Paris, France	Sendai city (Honshu Island, Japan)	Lakes, seas and oceans	At soaring sports	langs de weg
Estimated energy consumption (Wh/day)	140kW/day	38,127.85 Wh/day	-	18000	afhankelijk
Costs					
Retail price (Euro) (if available)	not available		-	-	onbekend systeem
Estimated price (Euro)	100000-200000		$18000	500,000	4500euro (analoog systeem)

Product name	**Umicore Inspire Racing Car**	**Solar Powered Bike**	**Solar Powered LED Lighting**	**Sunsei Stainless Steel Solar Vent**	**Aequus 7.0**
Product category (f.i. consumer product, vehicle etc)	Umicar Inspire	Personal Vehicle	Street Lighting	Electronic Appliances	Solar boat
Year of production	Racing car	2009	N/A		2010(still in production)
Manufacturer	2009	Mark	Bright Green Energy	ICP Solar Technologies Inc.	Aequus Boats
Nationality of manufacturer	Umicore Solar Team	American	UK	Canada	French
Product function 1 (f.i. lighting, sound, transportation)	Belgium	Transportation	Lighting	Ventilation (boat cabin)	Water Transportation
Product function 1 (f.i. lighting, sound, transportation)	Solar racing car World Solar Challange	-	-	Ventilation (conservatory)	Recreational Vehicle
Product function 3 (f.i. lighting, sound, transportation)	Transportation	-	-	Ventilation (caravan)	Luxury Good
Product dimensions length (m)	-	1.7-1.95	543 mm	0.265	7
Product dimensions width (m)	4.3	0.6	475 mm	0.265	1.8
Product dimensions height (m)	1.8	1.1	127 mm	0.15	2.4
Product weight (kg) (if available)	1.04	40	-	1.1	N/A
	187				
Energy system in product					
Grid connected (yes/no)	No	No	No	no	No, be connected to recharge
Irradiance conditions (indoor, outdoor)	Outdoor	Outdoor	Outdoor	outdoor	Outsoor
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	Li-polymer	Li-ion	Lead Acid	NiMH	Lead Acid
Battery capacity (Ah)	5kWh @ 160 V = 31.25 Ah	10	N/A	2*2Ah	Needed: 667 Ah, Commercial:1000 Ah @48 V
Operational voltage of energy system (V) (if available)	160	48	12 V	not available	48
PV technology (a-Si, x-Si, GaAs, organic, other)	2108 cells, effieciency >30%		Multi Crystalline Silicone	not available	Si
PV area (m2)	6	0.27	1200 x 537 x 46 mm = 0.644 m2	< 0,187m^2	3.4

PV power (multiply PV area with factor 150 => Wp)	900	41	96.66	< 28.05	510
Other power electronics (f.i. engine, flywheel etc)	1500	Pedalling	N/A	none	Engine:4KW brushless DC motor
Power of other electronics (W) (if available)	-		N/A	none	N/A
Estimated energy production (Wh/day)	Working for 12h then 18kWh	217	640 - 800 Wh/day	< 74,8	1190
User specifications					
Number of simulateous users		1	Public	multiple	7
Average duration of use (h)	1	upto 10	8 - 12 hr / day	24hr	8
Location of use (describe)	World Solar Challange -3000 km race, average speed 105 km/h, total time 28.6 h	Outdoor Roads	Pathway street light	boat cabin, caravan, shed	On sea up to 6 nautic miles from shore
Estimated energy consumption (Wh/day)	World Solar Challange in Australia	217	300 - 450 Wh/day	57.6	32000 Wh/day
	At 100 km/h - 1400 W				
Costs					
Retail price (Euro) (if available)	-	NA	4600	£90.00	€ 57,692.30
Estimated price (Euro)	No information. sponsorship	2500	-		€ 57,692.30

Product name	Solar Street Light (S-SL11S)	ASV Roboat	PV Prius	Solar golf cart	Solon C60 (officially SunCat 58)	Toyota Prius
Product category (f.i. consumer product, vehicle etc)	street lighting	Vehicle (Boat)	add on for a vehicle	Sunray - SX2	Vehicle (solar powered boat)	Vehicle
Year of production		2006	2006	vehicle	2009	1997-Present
Manufacturer	Greenshine New Energy Co.	INNOC research team	Solar Electrical Vehicles	2005	SolarWaterWorld AG	Toyota
Nationality of manufacturer	USA	Austrian	United States	Cruise car Inc and Eco Trance Alliance	German	Japanese
Product function 1 (f.i. lighting, sound, transportation)	lighting	Demonstration	transportation	USA	Transportation	Transportation
Product function 1 (f.i. lighting, sound, transportation)		Competition		transportation	17.65	
Product function 3 (f.i. lighting, sound, transportation)		Measuring			6.85	
Product dimensions length (m)		3.72	0.00		draft: 1 meter / freeboard: approximately 2 meters	4.46 m
Product dimensions width (m)		1.35	0.06	2.3	13,000	1.745 m
Product dimensions height (m)	8m approx.	~6	0.03	1.25		1.49 m
Product weight (kg) (if available)	Battery Weight –25kg Light Weight 14kg Box (Packed) Weight 40kg	~300	1380	1.8		1,805 Kg
				500		
Energy system in product						
Grid connected (yes/no)	no	no	no (stand alone)	It can be charched by 110 v outlet	no	originally no, now available
Irradiance conditions (indoor, outdoor)	outdoor, Designed for Zone with 4-5 Hours of daily Insulation	outdoor	outdoor	outdoor	outdoor	outdoor
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	two gel cell deep cycle batteries Lead-Acid	Li-ion	Sealed Lead Acid Battery	There is no information available	unknown	Energy system: lead acid Product (car): NiMH
Battery capacity (Ah)	100Ah	4,6 kWh	62.5	50	480	Energy system: 62.5 Ah Product (car): 6.5 Ah

Operational voltage of energy system (V) (if available)	battery 12V, controller 24V	NA	48	60	48	PV system: 70 VDC PV system batteries: 48 VDC Car batteries: 240 VDC
PV technology (a-Si, x-Si, GaAs, organic, other)	monocrystalline or polycrystalline	Unknown	mono-crystalline cells	Mon-Si	x-Si (crystalline silicon)	a-Si
PV area (m2)	0.5	1.5	0.37668	1.995=2	39.36	0.3768 m2
PV power (multiply PV area with factor 150 => Wp)	75Wp	285	56.502	300	5.6	215 W
Other power electronics (f.i. engine, flywheel etc)	solar charge controller	Direct Methanol Fuel Cell, emergency backup	battery charger, DC-DC converter	12 volt available outlet	none	Hybrid Motor
Power of other electronics (W) (if available)	24V*10A=240W	65	5% consumption		none	74,000 W for gasoline motor 60,000 W for electric motor
Estimated energy production (Wh/day)		800	5.3	in a normal summer day it produce 180 watt	13	850 - 1,300 Wh/day
User specifications						
Number of simulateous users	25 Meter distance for each Lamp	NA - autonomous	5		30 people indoors, 30 people outdoors	5
Average duration of use (h)	8 ~ 10 hours/day, 2 ~ 3 cloudy or rainy days backup	12	depends how much you drive	without sun, full charged battery run for 55 miles	10 hours without sunshine	6 years (total average lifetime) so considering a use of 2 h daily, it would be 4,380 h
Location of use (describe)	roadways,remote locations,no access to electrical grid	Lakes, open sea	it's a vehicle so it's mobile	alternative transportation cars from golf carts to street cars	Solon C60 is used as busboat on Berlin's canals	Streets (urban areas or highways)
Estimated energy consumption (Wh/day)		600	750	depends on usage		4,900 Wh/day
Costs						From
Retail price (Euro) (if available)	around 3000€[3]	NA	€ 0.00	$6000 = 8400 euro	not available	€ 23,950.00
Estimated price (Euro)		5000	€ 6,213.93	8400	150,000-250,000	€ 1,750.00

Product name	Solar powered caravan	Green Column	Solar and wind -Recharge tent	Sunseeker II aircraft	Nuna 5
Product category (f.i. consumer product, vehicle etc)	Vehicle, camping	Street lighting	Consumer product	vehicle	Vehicle
Year of production	N.A.		2008 (evolution of Orange portable wind charger,Glastonbury 2007)	2002, updated in 2006	2009
Manufacturer	Solar Force	Abacus Lighting	Orange	Solar Flight	Nuon Solar Team,TUDelft
Nationality of manufacturer	Australia	United Kingdom	United Kingdom	American	Dutch
Product function 1 (f.i. lighting, sound, transportation)		Marlec, renewable power	Generate Electricity	transportation	Transportation
Product function 1 (f.i. lighting, sound, transportation)		United Kingdom		-	
Product function 3 (f.i. lighting, sound, transportation)		Street lighting		-	
Product dimensions length (m)	3	adaptable to shore-based navigation lighting	Not available	7	4,82 m
Product dimensions width (m)	0.66	adaptable to road sign illumination	Not available	17	1,76 m
Product dimensions height (m)	0.036	adaptable to CCTV camera	7	2	0,9 m
Product weight (kg) (if available)	23,6 kg	± 0.5	Not available	120	<160Kg
		± 0.3			
Energy system in product		various, from 5 to 8 m			
Grid connected (yes/no)	no	± 150	No	no	No
Irradiance conditions (indoor, outdoor)	outdoor	no	Outdoor	outdoor	Outdoor
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	NiCd	outdoor	Not available	Li-poly	Lithium-ion polymer
Battery capacity (Ah)	97	AGM or Gel deep cycle batteries	Not available	16	*
Operational voltage of energy system (V) (if available)	12	±72 (12 V) or ± 36 (24 V)	Not available	-	*
PV technology (a-Si, x-Si, GaAs, organic, other)	Monocrystaline Si	12 and 24 were guessed as used above	Not available	c-Si	Gallium-Arsenide Triple Junction

PV area (m2)	1.98	BP Solar cell, multicrystalline,with improved silicon nitride	Not available	12	6m2
PV power (multiply PV area with factor 150 => Wp)	297	± 0.2 or ± 0.45	500W	1500	900Wp
Other power electronics (f.i. engine, flywheel etc)		30 W or 65W	Wind turbine-500W	engine	InWheel Direct Drive Electric Engine
Power of other electronics (W) (if available)		Rutland 913 Wind charger	Not available	5500	*
Estimated energy production (Wh/day)	801.9	Produces 90 W @ 19 knots and 24 W @ 10 knots	equivalent to energy for powering DJ booth for Groove Armada, marathon 88h	6000	*
User specifications		Varies, 588 (estimated, but a total power of 24(windcharger)+25(solar cell) W			
Number of simulateous users			100	1	1
Average duration of use (h)		They stand throughout England	100 phones per hour	5	*
Location of use (describe)		One night. Differs in summer and winter on average 12h	designed for electronic gadgets charging, while camping outdoors	in the air	race tracks with sufficient solar radiation
Estimated energy consumption (Wh/day)	100 Wh/d	Outside next to the place to be lit in the dark. Street, square, playground or a carpark	charge thousands of mobile phones over 3days	11000	*
		216 by a Energy usage of 18 W			
Costs					
Retail price (Euro) (if available)	2336.32		Free	-	*
Estimated price (Euro)		€ 3504.37 - € 3863.64	Not available	10,000,000	*

Product name	**21Revolution racing car**	**The Osprey**	**Solar-powered window thermometer/TFA**	**SQ 425S**	**Solar Clock**	**Solar Ana-Digi**
Product category (f.i. consumer product, vehicle etc)	Vehicle	Solar boat	Solar-powered window thermometer	Consumer product	Indoor house product	Watch
Year of production	2009	2008	no data found	Aug-10	2006	2011
Manufacturer	Solar Team Twente	Tamarack Lake Elektronics	TFA Technology Hong Kong Limited	Seiko	SUCK UK LTD	TOCS (Gemtime, Inc.)
Nationality of manufacturer	Dutch	Canadian	mainly from China	Japan	UK (but produced in China)	United States
Product function 1 (f.i. lighting, sound, transportation)	3010km ride	Transportation of up to 30 passengers	temperature display	Time	Display of the time	Portable analog and digital time display
Product function 1 (f.i. lighting, sound, transportation)	transportation in the future	Marine research	solar lighting	weather	-	
Product function 3 (f.i. lighting, sound, transportation)	sustainable technologies on automotive field	Diving boats	time display	Alarm + Radio	-	
Product dimensions length (m)	no longer than 5m	9,8m	0.12	0.162	0.07	0.230
Product dimensions width (m)	no wider than 1.80m	3,4m	0.092	0.247	0.03	0.045
Product dimensions height (m)	no heigher than 1.60m	2,3m	0.026	0.029	0.165	7.00E-04
Product weight (kg) (if available)			0.13	0.48	0.230	NA
Energy system in product						
Grid connected (yes/no)	no	no	no	No	No	no
Irradiance conditions (indoor, outdoor)	outdoor	outdoor	outdoor	indoor (>200 Lux)	Indoor	indoor and outdoor
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	Li- poly (Lithium Polymer)	Lead Acid (AGM Deep Cycle)	alkaline (non-rechargeable)	Cylindrical Lithium CR123A	NiMH	Lithium battery
Battery capacity (Ah)	6400mAh	260 Ah	1.25 (for NiMH)	1.3	0.700	225
Operational voltage of energy system (V) (if available)	3.7V	72V	1.5V + 1.2V	3	-	3
PV technology (a-Si, x-Si, GaAs, organic, other)	triple-junction GaAs efficiency around 30%	a-Si	Si (not specified which type exactly)	N/A	unknown	c-Si
PV area (m2)	6m2	29,9 (m2)	(estimated)	N/A	0,0054 m2	#N/A
PV power (multiply PV area with factor 150 => Wp)	900	4488 Wp	0.0056 * 1500 = 8.4	N/A	0,81 W	#N/A

Other power electronics (f.i. engine, flywheel etc)	CAN & PCB & MPPT	Engine	no data found	N/A	-	NA
Power of other electronics (W) (if available)		8206W	no data found	N/A	-	NA
Estimated energy production (Wh/day)		1545Wh	(assuming 8h sunshine/day, in annual	N/A	1,2 Wh/day	#N/A
User specifications			available)	N/A	6%	15
Number of simulateous users	1 for now	30				
Average duration of use (h)		n.v.t.	everyone to whom the thermometer is visible	-	1	1
Location of use (describe)	during a sollar challenge contest	flat water, lakes, rivers etc.	no data found	24	non stop	43800
Estimated energy consumption (Wh/day)		2472Wh	attaches to the outside surface of a window	Used both indoor and outdoor	On a wall or on a cabinet	portable
			duration of use	0.0043	1,2 Wh/day	2.40E-05
Costs						
Retail price (Euro) (if available)				70.50	From 34,00	
Estimated price (Euro)		36000 Dollar	30 (approximately)	-	-	33

Product name	**Casio**	**Casio EDIFICE EQS-500 (1)**	**HP-10s scientific calculator**	**Casio Scientific Solar Calculator - FX-260**	**4 in 1 solar calculator**	**Eton RAPTOR GREEN**
Product category (f.i. consumer product, vehicle etc)	EQS-500C-1A1ER	Consumer product, jewelry, watch	Consumer product	product(calculator-device)	consumer product (calculator)	Terrain Guidance Functions
Year of production	2010	production announced 14th july 2010	First edition in 1986	1992		2011
Manufacturer	Casio	Casio	Hewlett-Packard	Casio	Premium manufacturers	Eton Corp
Nationality of manufacturer	Japan	Japanese	American	USA		USA
Product function 1 (f.i. lighting, sound, transportation)	Watch	Time representation	Mathemetical calculations	mathematic calculations	lighting in terms of display of numbers	Solar Cellphone Charger
Product function 1 (f.i. lighting, sound, transportation)		fashion function		-		Altimeter, Barometer, Thermometer, Compass
Product function 3 (f.i. lighting, sound, transportation)				-		Digital Radio Tuner
Product dimensions length (m)	50,00mm	50,0 mm	0.15	24.13cm(9.5 inches)	0.1048	0.073
Product dimensions width (m)	45,80mm	45,8 mm	0.08	15.24cm(6 inches)	0.0673	0.203
Product dimensions height (m)	12,30 mm	12,3 mm	0.02	2.5cm (1 inch)	0.0158	0.032
Product weight (kg) (if available)	90 grams	164 g	0.12	47 gr		0.32
Energy system in product						
Grid connected (yes/no)	no	no	no	no	no	no
Irradiance conditions (indoor, outdoor)	indoor and outdoor	In and outdoor	indoor and outdoor	radiation	both	outdoor
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	Lithium-Ion	recharchable solar battery. Type CTL920	Battery: LR44x1 Alkaline	no battery	no battery,but button cell battery for backup	Li-ion
Battery capacity (Ah)		18mAh	150 mAh	-	-	1.8
Operational voltage of energy system (V) (if available)	3.3V	2,3V	1.5	4.3 V		3.7
PV technology (a-Si, x-Si, GaAs, organic, other)	a-Si	unknown	not available, possible a-Si	no data found	Thin film ssolar cells (a-Si)	Monocrystal Solar Panel
PV area (m2)	0.0025	around 70% of the watch surface. 1600 mm2	0.0004	0.0014 m2	around 0.00035	not available
PV power (multiply PV area with factor 150 => Wp)	0.375	240450	0.06	0.21 Wp	0.0525	not available

Other power electronics (f.i. engine, flywheel etc)	no	None		no	-	Solar Powered USB port output
Power of other electronics (W) (if available)	no	None		-	-	0.25 W
Estimated energy production (Wh/day)	16,8 W	unknown	0.225	no data found	-	not available
User specifications	6-8 %	unknown but estimated to be very high. >80%	N.A.	no data found	between 10 to 20	not available
Number of simulateous users					calculator uses around 50 mAh	
Average duration of use (h)	1	1	1	only one user	1	1
Location of use (describe)	5*24*365	estimation	1 hour	it can work 24h/day	1 or 2	30
Estimated energy consumption (Wh/day)	on the hand for indoor and outdoor usage	All places	At students will	radiation.uses only direct light.	home, office or school	outdoor
		unknown		no data found		not available
Costs						
Retail price (Euro) (if available)		179.10 €	8-15 euros	7.4 euro(10$)	around 4-5	73
Estimated price (Euro)	160	85.00 €		5euro		80-120

Product name	SoL Hybrid™ Power Pack	Solio Classic Battery Charger	Solar USB charger all-terrain guidance functions	Voltaic Fuse Solar Charger	Solar Power Iphone Charger	Solar Backpack
Product category (f.i. consumer product, vehicle etc)	mobile phone	Consumer product/gadget	Consumer product	Consumer Product	consumer product	Consumer product
Year of production	2011	2001	2011	2010	2011	2011
Manufacturer	SOL	Better Energy Systems	Etón Corporation	Voltaic	A-SOLAR	Voltaic Systems
Nationality of manufacturer	US, China	United States	American	American	Dutch	New York, USA
Product function 1 (f.i. lighting, sound, transportation)	Charge phone	Solar energy capture	Charger (cell phone)	Charging	Battery charging	Carrying / Storage
Product function 1 (f.i. lighting, sound, transportation)	flashlight LED	Charging phones, mp3,…	Sound (radio)	N.A	-	Charging handheld electronic devices
Product function 3 (f.i. lighting, sound, transportation)		Stores power	Lightning (flashlight)	N.A	-	
Product dimensions length (m)	113 mm	0.115	Altimeter, Barometer, Compass, Chronograph	0.29	0.127	0,21 (deep)
Product dimensions width (m)	66 mm	0.06	0.032	0.18	0.062	0.3
Product dimensions height (m)	21 mm	0.03	0.073	0.04	0.019	0.46
Product weight (kg) (if available)	66,5 g	0.15	0.203	0.6	0.09	2.05
			0.320			
Energy system in product						
Grid connected (yes/no)	No	No	no	No	no	No
Irradiance conditions (indoor, outdoor)	indoor and outdoor	Indoor or outdoor	outdoor	Outdoor	outdoor (sunlight needed)	Outdoor
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	Li-poly	Li-ion	Li-ion	Lithium Polymer	Li-ion	Lithium Polymer
Battery capacity (Ah)	2400mAh	1.65	1.8	3	1.6	3000 mAh
Operational voltage of energy system (V) (if available)	5,5 V	5	5	4.8-12	5	5,5 V
PV technology (a-Si, x-Si, GaAs, organic, other)	mono crystalline SI	c-Si	c-Si	Monorystalline Si	Not available information	Monocrystalline

PV area (m2)	about 40 x 100 mm	0.02	0.00593	0.01512	39.71*10^(-4)	0,03024 (2 panels with 0,01512 each)
PV power (multiply PV area with factor 150 => Wp)	0,6 Watt	3	0.890	2.268W	5.96	4.536
Other power electronics (f.i. engine, flywheel etc)		-	none		led (light emitting diode)	-
Power of other electronics (W) (if available)		-	-		0.03-0.06 W (for a typical led ind)	-
Estimated energy production (Wh/day)	average 11,8 Wh/ day	100.8	3.56	Depends on Exposure to Sunlight	59.6-83.44	40 Wh/day
User specifications	22%	High efficiency	41.6%	17	62.5	17%
Number of simulateous users						
Average duration of use (h)	1	1	1	3	1	1
Location of use (describe)	15 hours		30	number of hours that panel is exposed to sunlight	3-4	Up to 19h talk time or 48h music playback
Estimated energy consumption (Wh/day)	everywhere where is light	Charge from sun, via USB	Everywhere outdoor (desserts, woods, mountains)	Preferably in Sunny Areas	adapt charger to iPhone 4/4s	Portable
	Depends on phone use		5.33		20	44 Wh/day
Costs						
Retail price (Euro) (if available)	89,95 dollar		€ 148	N.A	50-60	170 €
Estimated price (Euro)		73.96	€ 86	92	50-60	-

Product name	Electree	Generator Solar Laptop Charger	K3 Charger: Solar and Wind Power to Go	Scorpion Solar transformer	Solar Powered Wind Turbine	solar powered helicopter kit
Product category (f.i. consumer product, vehicle etc)	Consumer product	Consumer Product	Consumer Product	Toy	Solar Models	Helicopter Kit
Year of production	2010	2008	2009		2010	Models (helicopter toy)
Manufacturer	Vivien Muller	Voltaic	Kinesis Industries	POWERPlus EcoEnergy Products	Solar Technology International	2010
Nationality of manufacturer	French	United States of America	USA	Dutch	English	international
Product function 1 (f.i. lighting, sound, transportation)	Charge internal battery	Charging	2 in 1 dual charging ability	Educational	Educational	british
Product function 1 (f.i. lighting, sound, transportation)	Charge mobile phone etc with internal battery	transportation (in the form of suitcase)	LED level indivators of power status	Entertainment	Ornamental	recreation
Product function 3 (f.i. lighting, sound, transportation)	-	none	/		Ventilating	education
Product dimensions length (m)	0.23	0.43	0.080	0.087	0.13	ornament)
Product dimensions width (m)	0.19	0.04	0.078	0.063	0.13	0.225
Product dimensions height (m)	0.4	0.31	0.236	0.102	0.265	0.13
Product weight (kg) (if available)	-	2.05	0.3	0.2	0.22	0.078
						0.15
Energy system in product						mini solar panel
Grid connected (yes/no)	No	no	No		No	no
Irradiance conditions (indoor, outdoor)	Indoor	outdoor (indoor if sunlight exists)	Outdoor		Indoor	indoor(desk light),outdoor(sunlight)
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	Li-ion	Li-ion	Li-ion	No	no battery used	no battery is needed
Battery capacity (Ah)	13.5	13.2	4	Indoor(halogen), outdoor(sunlight)	no battery used	no
Operational voltage of energy system (V) (if available)	3.7 V nominal voltage	20	5		n/a	n/a. estimation 1-3V
PV technology (a-Si, x-Si, GaAs, organic, other)	a-Si (amorphous silicon)	mono c-Si (monocrystalline)	data not available		a-Si	c-Si
PV area (m2)	27 cells with total area of 0.14 m^2	1.14E-03	(estimation) 0.00626	1.2	0.0032	not available. estimation 0.00243

PV power (multiply PV area with factor 150 => Wp)	21	16.9 Watt	0.94	0.18	0.48	1.35
Other power electronics (f.i. engine, flywheel etc)	-	not available	Flywheel, AC wallplug	0.0025 m2	Rotor	
Power of other electronics (W) (if available)	-	not available	/	0.375	n/a	engine
Estimated energy production (Wh/day)	33.3 Wh/day.	not available	(5W*24h=)120 Wh	DC Motor	n/a	Not available
User specifications	9% efficiency.	20	data not available		around 11%	whole day then 8.748Wh/day
Number of simulateous users						1.35%
Average duration of use (h)	1 simultaneous user	not available	1	1	n/a	
Location of use (describe)		5	depends on available sun and wind		8	one person or a group
Estimated energy consumption (Wh/day)	Usageindoors because it is not waterproof	outdoors	Outdoors (travelling/camping)	Everywhere	Close to sunlight and strong desklight	52560(h)
		not available			n/a	It can be set on a desk or may be in a car
Costs						2400wh/day
Retail price (Euro) (if available)	300	not available	69	16.3	20	12.99 (euro)
Estimated price (Euro)	350	340.5	/		30	

Product name	Solar Powered Cockroach	Spark lamp	SUNNAN	Polaris Solar Deck Post Cap	Solar Mate I	Solar-powered LED torch
Product category (f.i. consumer product, vehicle etc)	Consumer product / toy	consumer product	Consumer product	outdoor lighting	consumer product (Solar panel-lightning bulp)	Torch
Year of production	unknown, probably 2008 or older	2006	2009	2009	n/a	n/a
Manufacturer	Shenzhen Jie Chuangyuan technology Co., LTD.	Beverly Ng	IKEA	Aurora Deck Lighting	Solar Technology International	Solarcosa
Nationality of manufacturer	China	Swedish	Swedish	USA	UK	German
Product function 1 (f.i. lighting, sound, transportation)	Vibrating	recharging during the day?lighting up at night	lighting	lighting	Illuminates indoor areas	lighting
Product function 1 (f.i. lighting, sound, transportation)	-	monitoring device	battery charger		n/a	no
Product function 3 (f.i. lighting, sound, transportation)	-	changing color	-		n/a	no
Product dimensions length (m)	0.04	0,155m	0.135	0.14	0.315 (dimensions of the package)	0.138
Product dimensions width (m)	0.019	0,08m	0.135	0.14	0.215 (dimensions of the packagel)	0.025
Product dimensions height (m)	0.019	0,27m	0.44	0.16	0.025 (dimensions of the package-not of the PV panel)	0.025
Product weight (kg) (if available)	0.015	not available	0.7	n/a	1.6	0.104
Energy system in product						
Grid connected (yes/no)	no	yes	no	no	no	no
Irradiance conditions (indoor, outdoor)	outdoor, only works with sunlight	indoor	outdoor	outdoor	outdoor	indoor and outdoor
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	no battery	Li-ion battery	NiMH HR6/AA	NiCd	not included	2 accus NiMH
Battery capacity (Ah)	no battery	10 Wh	1,2Ah	9.8	75-85 (not included)	1.2

Operational voltage of energy system (V) (if available)	2	5V	3 x 1,2V	n/a	12	n/a
PV technology (a-Si, x-Si, GaAs, organic, other)	unknown	C-Si and Mc-Si	Si	n/a	c-Si	c-Si
PV area (m2)	0.00076	0,0015 m^2	0.005775	0.01	n/a	0.0013
PV power (multiply PV area with factor 150 => Wp)	0.114	0,225Wp	8.6625	1.5	PV area n/a	0.2
Other power electronics (f.i. engine, flywheel etc)	no	1 RGB LED,micro controller,Mc or C-Si PV cells,rechargeable 5V battery with 10 Wh capacity,wi-fi system, tilt sensor	Schottky diode (0.22V), A705N constant current LED driver, fuse (0,5A).	no	none	5 white LEDs
Power of other electronics (W) (if available)	no	1W for RGB LED, 22.5W for battery	-		n/a	500
Estimated energy production (Wh/day)	0.265479452	60 Wh/day	8.6625	7.5	35	1.2
User specifications	unknown	<12% definately	10	n/a	n/a	10
Number of simulateous users						
Average duration of use (h)	1	users at the same household	1 or 2	1 – 5 (family)	1 user	1
Location of use (describe)	unknown	during wintertime/16h - during summertime/6h	3	4 hrs/day	3-7 hours per day	0.5
Estimated energy consumption (Wh/day)	Schools, home, office	indoors near windowsill	Indoors and Outdoors	USA	Illumination of indoor areas up to 16 m2	can be useful in case of power cut
	0.265479452	120Wh/day (10 hours of use average)	4.32	7.5	15-35	0.25
Costs						
Retail price (Euro) (if available)	not availabe	not for purchase yet?	14.95	40	79.99£ including VAT (93.5€)	9.95
Estimated price (Euro)	1,5 - 4,5 euro	no estimated price found	-		n/a	4.8

Product name	**Hands-Free Bluetooth Car Kit with Caller ID**	**Q-Sound**	**Soladyne 7400 Power Pro Hand Crank Solar Flashlight Lantern AM FM Weather Radio**	**Wireless Solar Keyboard**	**NP-NC215-A01US**	**Gramo Solar Speaker**
Product category (f.i. consumer product, vehicle etc)		Consumer product (headphone)	consumer product (flashlight)	Logitech K750	Netbook	Speaker
Year of production	2011	Still in concept phase		Computer peripherals	2011	concept product
Manufacturer	China Vasion	shepeleff stephen (Designer)	21st Century Goods	2010	Samsung	doesn´t apply since it´s a concept product
Nationality of manufacturer	China	Romanian	USA	Logitech	South Corea	concept product, the Designer is Finnish, Pekka Salokannel
Product function 1 (f.i. lighting, sound, transportation)	Caller ID	sound (bluetooth headphone)	flashlight/lantern	Switzerland	All Netbook Functions	Sound
Product function 1 (f.i. lighting, sound, transportation)	MP3		radio (FM/AM/ NOAA Weather Bands	Input device for computers	-	non
Product function 3 (f.i. lighting, sound, transportation)	Radio		AC adapter included		-	non
Product dimensions length (m)	0.104	~ 0.2	23,5cm		0.26	0.16 m
Product dimensions width (m)	0.055	~ 0.1	12,2cm	0.490	0.18	0.15 m
Product dimensions height (m)	0.16	~ 0.2	10,9cm	0.200	0,024 open - 0,036 close	0.15 m
Product weight (kg) (if available)	NA	not available, but is a headphone, so maybe around 300 grams or so?	907,2gr or 0,9KG	0.040	1.3	not indicated
				1,069		
Energy system in product						
Grid connected (yes/no)	no	No	no	No	no	no

Irradiance conditions (indoor, outdoor)	Indoor	Both	both	Indoor	indoor and outdoor	not indicated
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	Rechargable LI-ion	description says NiMH, but in a picture the batteries are indicated as Li-ion	Ni-MH replaceable battery pak	Li-ion	6 cell Li-Ion	not indicated
Battery capacity (Ah)	600mAH	2x800 mAh, so 1.6 Ah	600mAh	0.18	17.6	not indicated
Operational voltage of energy system (V) (if available)	3.7	1.2 V	3,6V	3.0	7.6	not indicated
PV technology (a-Si, x-Si, GaAs, organic, other)	x-Si	a-Si	N/A	a-Si	mono-crystal Si	not indicated
PV area (m2)	0.002	appromately 0.1x0.4= 0.04m2	5,1*10^(-3) (approximation)	0.016	0.0384	estimation 0.16m*0.082m*3panels *(2/3 estimated area)
PV power (multiply PV area with factor 150 => Wp)	0.3	0.04x150= 6 Wp	0,765 Wp	2.45	5	
Other power electronics (f.i. engine, flywheel etc)	NA	No	included AC adapter to charge battery	not available	-	touch volume adjuster
Power of other electronics (W) (if available)	NA	n.a.			-	not indicated
Estimated energy production (Wh/day)	NA	0.14	52,8Wh/day	not available	-	not indicated
User specifications	NA	24	no information, estimation:15% PV module efficiency/ 97% battery efficiency/total efficiency 14%	0.54	-	not indicated
Number of simulateous users		around 0.5%, because of low irradiance indoors		6-12%		

Average duration of use (h)	Caller Id for 1 person (driver), music player as many people inside the car	1	multiple (if used as a lantern)	1	one	not indicated
Location of use (describe)	Stand by time 46 Hours, Talk time 10 hours, Music 15 hours, Charging 3 hours	2	theoretically infinite	5	14.5	not indicated
Estimated energy consumption (Wh/day)	inside a car	everywhere	camping/outdoor activities/blackout	Wherever there is a computer device	-	indoors and outdoors
	2.22 Wh	0.1 Wh/day	average use of 3 hours will consume 14,3 Wh	3	-	not indicated
Costs						
Retail price (Euro) (if available)	38.34	n.a.	46,95$	70-90	296	not indicated
Estimated price (Euro)	25.56	€ 60	approximately 34,7 Euro	70-90	296	not indicated

Product name	Solar Powered Perspex Desk Fan Kit	Solar Powered Laptop	Foliage	FX-115MS	Solar watch	Headset
Product category (f.i. consumer product, vehicle etc)	Consumer Product	Samsung Laptop - NC215S	consumer product	consumer product	CASIO PAW 1300-1V	SOLTRONIX HR-1 SOLAR-RECHARGEABLE STEREO FM/AM HEADPHONE RADIO
Year of production		Consumer electronics	2011 - concept	2000	Electronics	consumer product
Manufacturer	Solar Technology International	2011	Rami Santala	CASIO	2009	2004
Nationality of manufacturer	Englisch	Samsung	Finnish	JAPAN	Casio	Power Film Inc. Formerly known as: Iowa Thin Film Technologies
Product function 1 (f.i. lighting, sound, transportation)	Cooling (Fan)	South Korea	air conditioner	Pocket scientific calculator (two way power: solar & battery)	Japan	United States of America
Product function 1 (f.i. lighting, sound, transportation)	-	Entertainment	air cleaner	-	Multiband atomic time keeping	sound
Product function 3 (f.i. lighting, sound, transportation)	-	Portable workspace		-	Tough solar power	-
Product dimensions length (m)	0,18 m	0.26	0.25	0.1545	Digital compass	-
Product dimensions width (m)	0.072 m	0.178	0.05	0.078	0.057	0.06
Product dimensions height (m)	0.095 m	0.023	It doesn't have a fixed height. The 'leaves' are foldable	0.0127	0.047	0.18
Product weight (kg) (if available)	0,2 kg	1.32 kg	no data available	0.105	0.012	0.17
					0.06	0.140
Energy system in product						
Grid connected (yes/no)	no	No	no	No	Solar energy	
Irradiance conditions (indoor, outdoor)	indoor	outdoor	indoor	Indoor & Outdoor	No	no

Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	no battery	Li-ion	-	Alkaline	Both indoor and outdoor	optimised for outdoor, of course it works indoor as well
Battery capacity (Ah)	no battery	6.49	-	0.15	Li-ion battery	NiMH
Operational voltage of energy system (V) (if available)	~ 6 V	7.4	no data available	1.5	0.018	0.8
PV technology (a-Si, x-Si, GaAs, organic, other)	a-Si	Thin film	no data available	a-Si (Sanyo - SA3515S4 0501)	2.30	1.2
PV area (m2)	(10x20=200 cm2) = 0.02 m2	0.04 approx	not constant - depending on the need of electricity	0.000396	N/A	a-Si
PV power (multiply PV area with factor 150 => Wp)	3	6	no data available	0.0594	0.0002	0.0096
Other power electronics (f.i. engine, flywheel etc)	Electromotor (with rotors)	battery	no data available	-	0.03	1.44
Power of other electronics (W) (if available)	10-15 W (estimated)		no data available	-	N/A	-
Estimated energy production (Wh/day)	480 Wh/day (@ 20W)	32	no data available	0.0594	N/A	-
User specifications	60 % (motor efficiency)	Not enough data available	no data available		N/A	5.76
Number of simulateous users						
Average duration of use (h)	1	1	multiple users (air condtioner)	1095	1	1
Location of use (describe)	up to 6 years	10	no data available	portable product (home, office, university, etc)	87600	1-3h
Estimated energy consumption (Wh/day)	The fan can be placed on a desktop.	Laptops can be used both indoors and outdoors, in offices and homes or in remote places	indoor, near the window(to capture the light)	0.0002	at the wrist	worn on head
	80 Wh/day (4hrs per day operational)	40	no data available		N/A	1.152
Costs						
Retail price (Euro) (if available)	€28.11	N/A		20.08	N/A	€ 21.14
Estimated price (Euro)	25-35 euro	350	no data available		220	-

Product name	Iqua SUN	Royal Solar 1	Solar Energy Rat Destruction Machine/Rat Repeller	solar powered sensor	Solar powered wireless mouse	Freeplay Ranger AM/FM Solar Radio&Windup Radio
Product category (f.i. consumer product, vehicle etc)	consumer product	Pocket calculators	Consumer product	monitoring product	Sole mio	consumer product
Year of production	2008	1978	Not listed	2010	Consumer product	2001
Manufacturer	Iqua Ltd	Royal Typewriter Company	Changzhou Wujin Kaili Electronic Factory (one of many)	University of Michigan	2007	Freeplay Energy
Nationality of manufacturer	Finnish	USA	Chinese	American	SynEnergy Project	Great Britain
Product function 1 (f.i. lighting, sound, transportation)	sound (wireless headset)	Calculator	Sound (ultrasonic, designed to repell vermin)	Measuring pressure levels	Dutch	radio
Product function 1 (f.i. lighting, sound, transportation)	-	-	None	energy storage (battery)	wireless pointing computer device	
Product function 3 (f.i. lighting, sound, transportation)	-	-	None	Energy production (PV-cell)	not available	
Product dimensions length (m)	0.048	0.127	0.155	3.5mm	not available	0.205
Product dimensions width (m)	0.025	0.068	0.155	2.5mm	not available	0.06
Product dimensions height (m)	0.01	0.009	0.4385	1mm	not available	0.1
Product weight (kg) (if available)	0.012	-	0.36	approx. 0,020961 g		0.7
Energy system in product					No	
Grid connected (yes/no)	No	No	No	no	Indoor	no
Irradiance conditions (indoor, outdoor)	Mainly outdoor (direct sunlight)	Indoor	Outdoor	both	NiMH	both are ok, direct sunlight preferred
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	Lithium Polymer	NiCd	NiCd	Solid state Li	0.3	Rechargable NIMH
Battery capacity (Ah)	0.11	-	0.8	12µAh	1.2	1

Operational voltage of energy system (V) (if available)	3.7	-	2	3.6V	multi crystalline silicon (mc-Si), mono crystalline silicon (c-Si) and hydrogenated amorphous silicon (a-Si:H)	N.A
PV technology (a-Si, x-Si, GaAs, organic, other)	no data given by manufacturer	COS	Not listed	n.a.	0.0028	amorphous silicon
PV area (m2)	3.41E-06	0.001	0.00063	2 X 1mm²	0.42	about 0.0074
PV power (multiply PV area with factor 150 => Wp)	5.12E-04	-	0.945	0.0003	dc-dc converter, charge controller, data logger	1.11
Other power electronics (f.i. engine, flywheel etc)	-	LED	None	none		generator
Power of other electronics (W) (if available)	-	-	0	/		N.A
Estimated energy production (Wh/day)	no data given by manufacturer	Very little	3.78	n.a.		4.26
User specifications						
Number of simulateous users					1	
Average duration of use (h)	(without using solar power), Up to 200 h (on stanby without using solar power), Standby time Infinite (In sunlight)	1 (depends on usage)	24/d	0.0138889 (= ± 50s)	i) sun bathing (direct sun access), and ii) at office.	21900 (the company give 2 years warranty)
Location of use (describe)	everywhere	To make calculations: shops, companies, school, universities	In yard or garden, must be able to push into soil.	in the eye	10 (Wh/day) if the irradiation is 20 (kWh/m2*year)	outdoor and in those less developed non-electricity rural area
Estimated energy consumption (Wh/day)	1.085	Very little	1.6	4.63e-8		0.5
	0.049					
Costs						
Retail price (Euro) (if available)	$ 65,74	Not in production today	29-34	n.a.	not available	33
Estimated price (Euro)		10 (price pocket calculator today)	30	n.a.	not available	15

Product name	**Soltronix AM/FM Headset Solar Radio**	**Freeloader Supercharger**	**Solio Classic**	**solar cockroach**	**solio rocta H1000**	**Freeloader Pico Solar Charger**
Product category (f.i. consumer product, vehicle etc)	Electrical appliance	consumer product	Consumer product	Toy	Multi-device charger	consumer gadget
Year of production	2002	2009	2005	somewhere in 2009	2008	production started nov 2009
Manufacturer	PowerFilm	Solar Technology International	Better Energy Systems Ltd.	Shenzhen Xin Sissoko Electronic Co., Ltd.	SOLOIO(Better Energy Systems)	Solar Technology International Ltd.
Nationality of manufacturer	American	British	English	China	USA	United Kingdom
Product function 1 (f.i. lighting, sound, transportation)	sound quality=f(stress of signal, interference, location)	charger for hand held electronic devices	Charger for electronic devices	vibration	power 3200+ devices	Portable device charger
Product function 1 (f.i. lighting, sound, transportation)	working hours=f(intensigty of light, capacity of battery, changing/ lighting period)		-	(Educational)	emergency power source	Power storage battery
Product function 3 (f.i. lighting, sound, transportation)			-			-
Product dimensions length (m)	0.16	0.21	0.1194	0.03	0.198m	0.105
Product dimensions width (m)	0.0254	0.159	0.0635	0.015	0.068m	0.045
Product dimensions height (m)	0.03	0.006	0.0330	0.007	0.018m	0.0115
Product weight (kg) (if available)	0.14	0.2	0.156	0.02	0.131 kg	0.049
Energy system in product						
Grid connected (yes/no)	No	no	Yes	no	no	possible, not necessary
Irradiance conditions (indoor, outdoor)	Both	indoor & outdoor	Both	indoor	indoor and outdoor	Both indoor and outdoor use
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	NiMH	Li-ion	Li-ion	non	Li-ion	Li-ion
Battery capacity (Ah)	1	1	1.6	v.a.	1000Amh	0.8
Operational voltage of energy system (V) (if available)	n/a	6	5-6	1.25	5-6V	5 V input, 3.3-5.5 V output

PV technology (a-Si, x-Si, GaAs, organic, other)	a-Si	c-Si, poly-Si	Mono crystalline photovoltaic panels	organic	N.A	multi/mono crystalline silicon
PV area (m2)	0.04	0.02	0.0024	0.0003	N.A	0.00378
PV power (multiply PV area with factor 150 => Wp)	6	1.5	0.36	0.045	0.6W	0.567
Other power electronics (f.i. engine, flywheel etc)	built-in antenna, tuning dial, volume dial	none	-	Small vibration engine like in a cellphone	no	no other power electronics
Power of other electronics (W) (if available)	n/a	2.75	-	unknown, but very little	no	-
Estimated energy production (Wh/day)	n/a	10	6.5	0.0265625	0.6watts*12h=7.2Wh	4
User specifications						28
Number of simulateous users						
Average duration of use (h)	18-20(with fully charged battery)	1	10	1	350-500 full cycles of charge and discharge depending on care and average use.	10 hr loading time (bright solar)/3hr loading time (USB), 30 m device charging
Location of use (describe)	almost everywhere	outdoors, hiking, camping	anywhere	Indoor, maybe outdoor for when it is dry	for travel and emergency use	charging devices everywhere, loading battery in sunlight, via USB or with artificial lighting.
Estimated energy consumption (Wh/day)	n/a	2.75	13	0	0-7.2	0 Wh/day (while using sunlight as power source)
Costs						
Retail price (Euro) (if available)	28		73	€ 2.28	40-60	20-25 euros dependent on webstore
Estimated price (Euro)	n/a	75,-	73	€ 1.25	50	

Product name	Freeplay Eyemax Radio	Solar rat repeller	MicroSolar® AM/FM Armband Radio and Safety Light Perfect for Joggers	Power film R15-300	Sallivan's Solar Light
Product category (f.i. consumer product, vehicle etc)	consumer product	Consumer product	Consumer product	Charger	consumer product
Year of production	2009	not available	?	2005	prototype: 2004, presentation in exhibition from 25/9/10-30/1/11
Manufacturer	Freeplay	Greathouse Electrical industry co., Ltd.	Microsolar	Iowa Thin Film Technologies, Inc	designer: Damian O'Sullivan
Nationality of manufacturer	British	Chinese	?	USA	Franco-Irish, living in the Netherlands
Product function 1 (f.i. lighting, sound, transportation)	radio	drives away rats and underground rodents	Sound (AM/FM radio)	Charge or Direct Power 12 Volt Systems	lighting
Product function 1 (f.i. lighting, sound, transportation)	flashlight	Solar cell generates power to recharge the battery	Light (Safety light)	Charge Wireless Electronics	
Product function 3 (f.i. lighting, sound, transportation)	-		Charging (charge batteries)	Charge almost all Lithium, NiCad, or NiMH Batteries	
Product dimensions length (m)	0.186 m	0.155 max	0.105	0.531 m	diameter 185mm
Product dimensions width (m)	0.060 m	0,155 max	0.065	0.292 m	diameter 185mm
Product dimensions height (m)	0.112 m	0.34	0.023	-	300 mm
Product weight (kg) (if available)	0.700 kg	0.5	0.07	0.29 kg	
Energy system in product					
Grid connected (yes/no)	no	no	no	no	no
Irradiance conditions (indoor, outdoor)	indoor	outdoor	not stated, but outdoor is assumed since it's designed for outdoor activity	outdoor, indoor	outdoor : need sunlight for charging
Battery technology (NiMH, NiCd, lead acid, Li-ion, Li-poly, other)	NiMH	NiCd or NiMH	Ni-Mh	-	rechargeable
Battery capacity (Ah)	2.98 Ah	800mAh	0.8-1	-	not found
Operational voltage of energy system (V) (if available)	4.2 V	1.2V	2.5 V	15.4 V	4.14 V each solar cell

PV technology (a-Si, x-Si, GaAs, organic, other)	x-Si	a-Si	cSi	Silicon	36 solar cells
PV area (m2)	0.0025 m2	0.0063	0.001334	0.16 m^2	25 cm2 * 36 =0.09m2
PV power (multiply PV area with factor 150 => Wp)	0.22 Wp	0.945	0.2001	24 Wp	13.5 Wp
Other power electronics (f.i. engine, flywheel etc)	-	none	external adapter	-	
Power of other electronics (W) (if available)	-	not available		-	
Estimated energy production (Wh/day)	2.2 Wh/day	22.7	1	60 Wh/day* (*supposing a 12 hour irradiation at nominal operating point)	
User specifications					
Number of simulateous users					
Average duration of use (h)	1 hour	100	0.5 - 4	as long as there is sunlight	24 h (after collecting energy on a sunny day)
Location of use (describe)	can be anywhere indoors	Applicable to outdoor gardens, nurseries, lawn and other surface and underground flooding rat.	Outdoor, during sport activities	wherever there is sunlight	anywhere indoor or outdoor
Estimated energy consumption (Wh/day)	1 Wh/day	23.0	0.8	-	
Costs					
Retail price (Euro) (if available)	-	not available	€15 - €36	54.7 - 109.4 €	
Estimated price (Euro)	43 euro	15.00	10	-	185 euros

Appendix C - Irradiance Measurements

Appendix C1 - Extra measurements of indoor irradiance

Figure C1.1: Left picture: Artificial light sources at both offices of TU Delft; Fluorescent lamps Philips Master TL-D, 58W/830, Right picture: The sky on June 10th, 2015. View from the south-facing window at Delft.

Figure C1.2: The measurement set-up. Right picture: The aperture is placed on the sensor, to allow only 4.8 % of light to pass through.

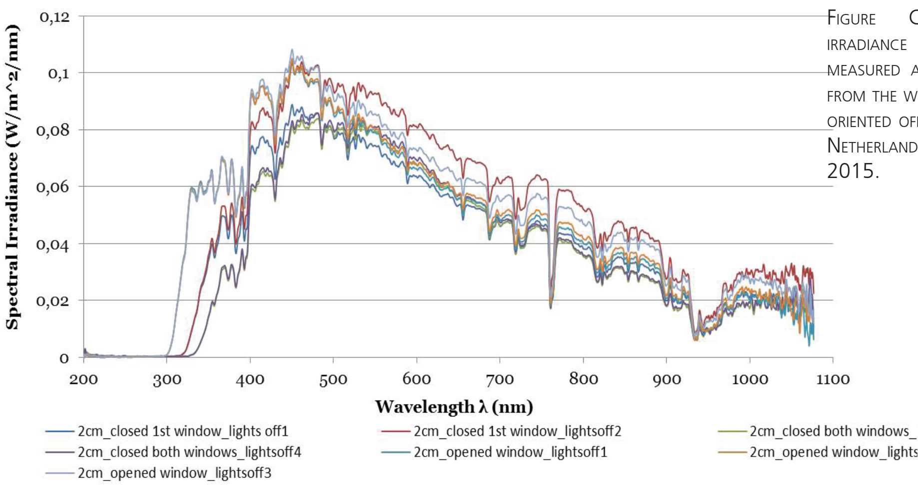


Figure C1.3: Spectral irradiance ($W/m^2/nm$) measured at distance 2 cm from the window at a north oriented office at Delft, The Netherlands, on June 10th, 2015.

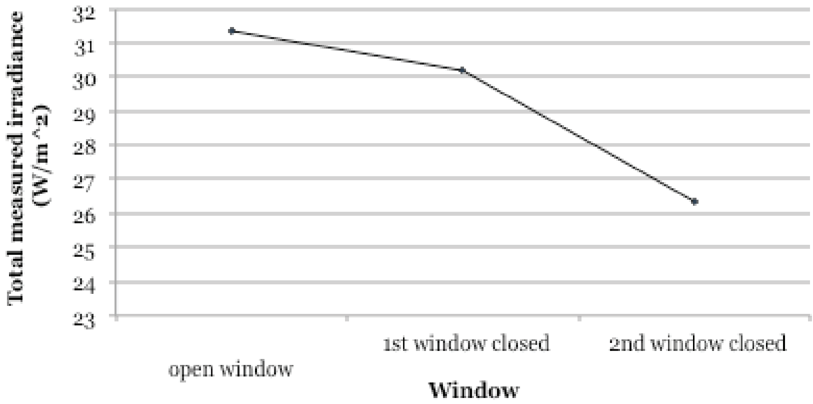


Figure C1.4: Total measured irradiance (W/m²) at distance 2 cm from the window at a north oriented office, at Delft, The Netherlands on June 10th, 2015. The window is double-glazing. We measure irradiance with window open, 1st window closed and both windows closed. We aim to investigate the transmittance of the window. The three measurements took place with time delay of 1min between each other.

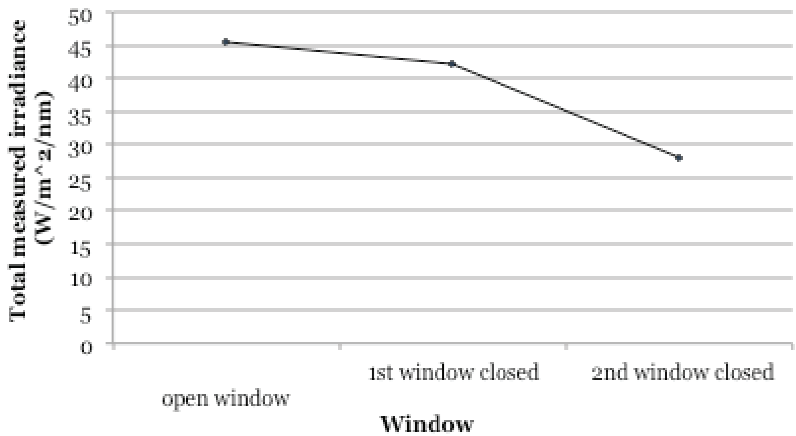


Figure C1.5: Total measured irradiance (W/m²) at distance 2 cm from the window at a south oriented office, at Delft, The Netherlands on June 10th, 2015. The window is double-glazing. We measure irradiance with window open, 1st window closed and both windows closed. We aim to investigate the transmittance of the window. The three measurements took place with time delay of 1min between each other.

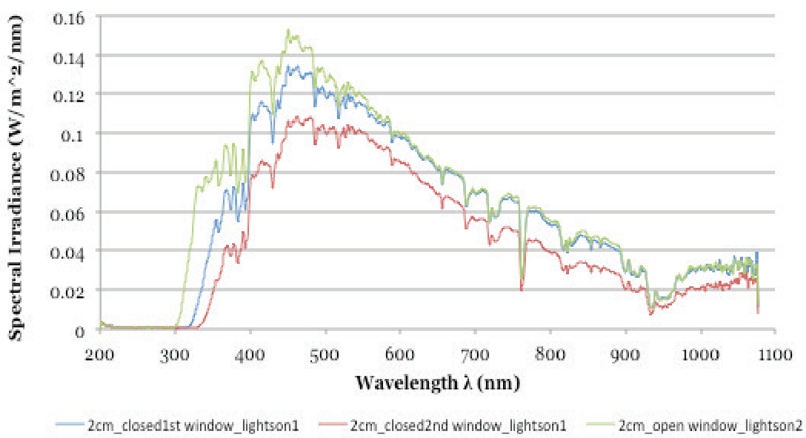


Figure C1.6: Spectral irradiance (W/m²/nm) measured at distance 2 cm from the window at a south oriented office at Delft, The Netherlands, on June 10th, 2015.

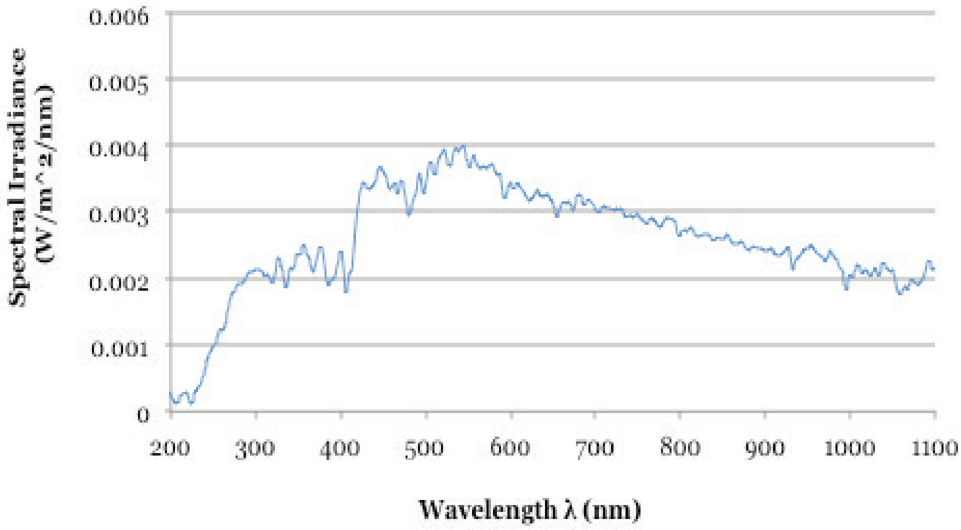


FIGURE C1.7: SPECTRAL IRRADIANCE (W/M²/NM) MEASURED AT DISTANCE 2 CM FROM THE WINDOW AT A SOUTH ORIENTED OFFICE AT DELFT, THE NETHERLANDS, ON JUNE 10TH, 2015. WINDOW IS OPEN DURING THE MEASUREMENTS AND LIGHTS ARE ON. FOR THESE MEASUREMENTS AN APERTURE WAS USED, WHICH ALLOWS AROUND 4.8 % OF THE LIGHT TO PASS THROUGH THE COVER.

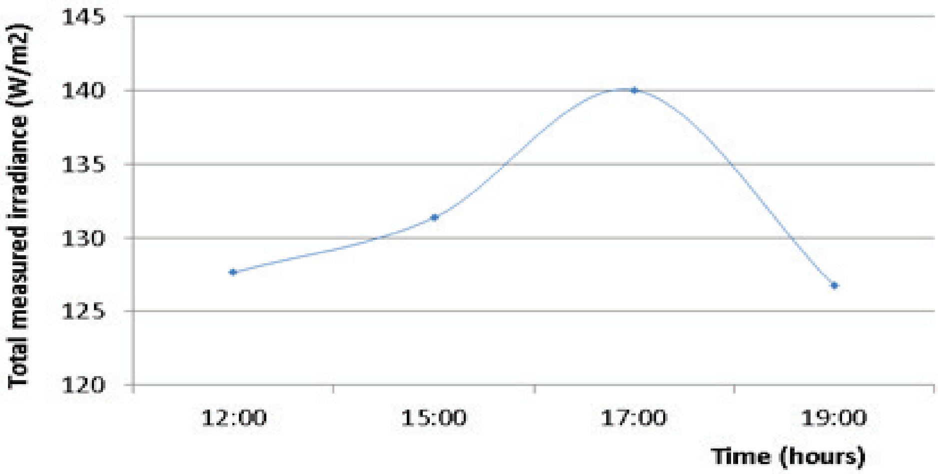


FIGURE C1.8: TOTAL MEASURED IRRADIANCE (W/M²) ON 28.03.2012 AT A NORTH ORIENTED OFFICE, SENSOR'S POSITION N1, DELFT.

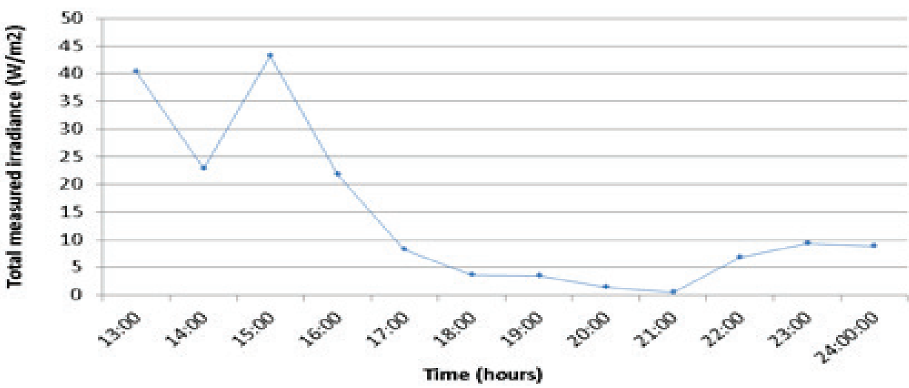


FIGURE C1.9: TOTAL MEASURED IRRADIANCE (W/M²) ON 31.05.2012 AT A NORTH ORIENTED OFFICE, SENSOR'S POSITION N2, TU DELFT.

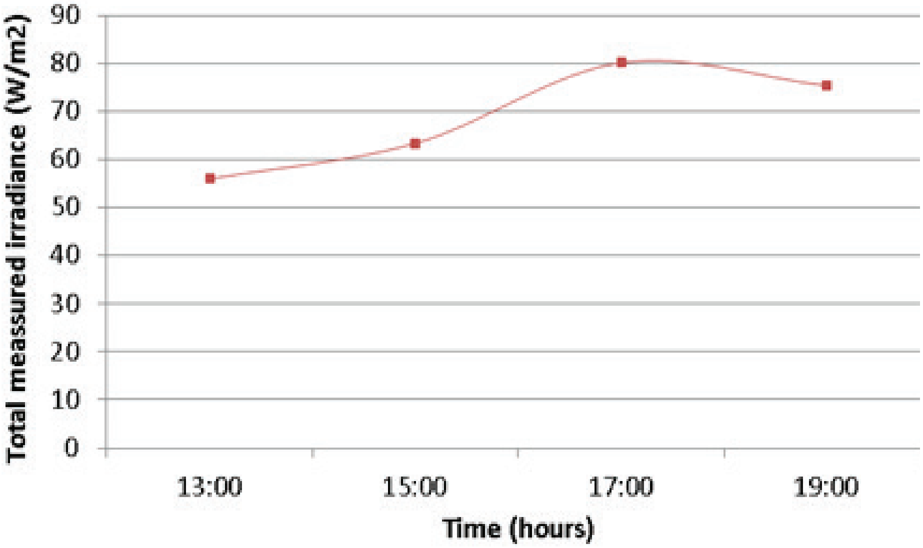


Figure C1.10: Total measured irradiance (W/m²) on 04.04.2012 at a north oriented office, sensor's position N3, TU Delft.

APPENDIX C - IRRADIANCE MEASUREMENTS

APPENDIX C2

Figure C2.1 presents measurements conducted on January 21st, 2014 at a north oriented office at TU Delft. The measurements were conducted indoors at distance 0.5 m inside the window and outdoors at 0.5 m out of the window. Indoors CFL lamps are used for artificial illumination of the room. The differences in both values and spectrum of irradiance are obvious. Indoor the light is a combination of artificial and natural light, while outdoors only natural light exists.

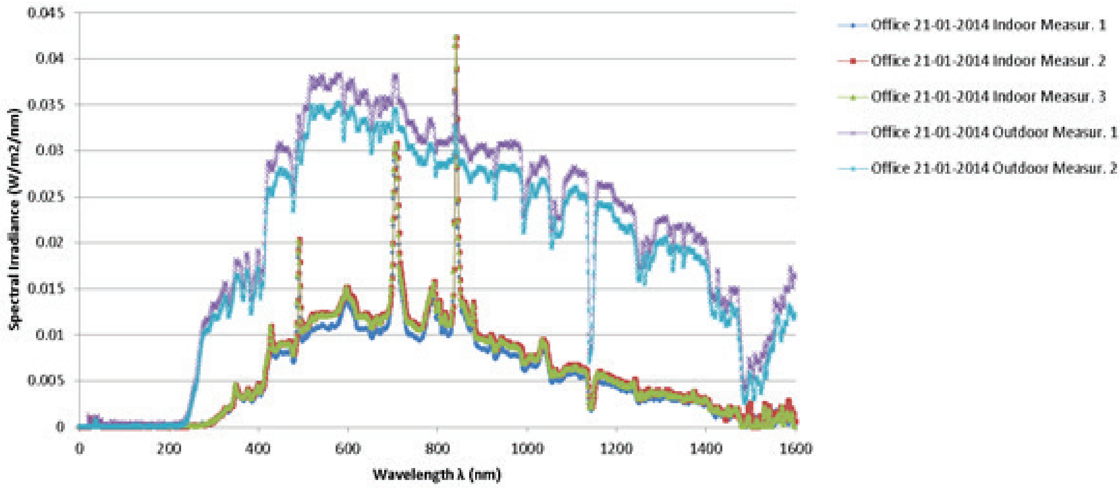


FIGURE C2.1: SPECTRAL IRRADIANCE MEASUREMENTS (W/M²/NM) ON 21.01.2014, AT A NORTH ORIENTED OFFICE AT TU DELFT.

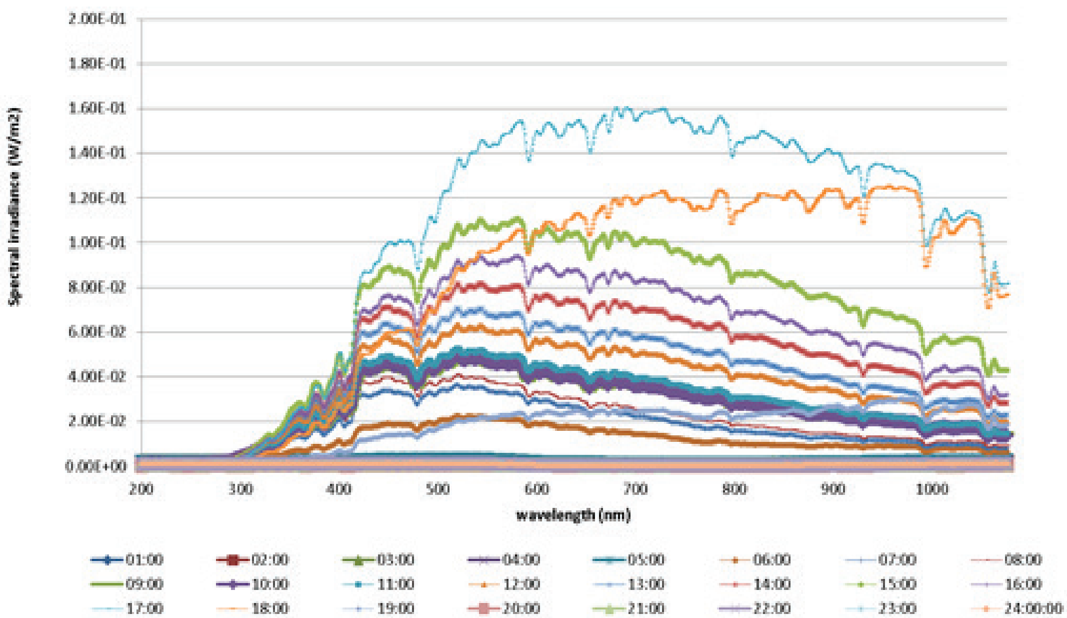


FIGURE C2.2: SPECTRAL IRRADIANCE (W/M²/NM) AS MEASURED ON MAY 2ND, 2015 AT A NORTH-FACING OFFICE AT TU DELFT, THE NETHERLANDS. THE GRAPH PRESENTS THE IRRADIANCE PER HOUR DURING THE WHOLE DAY OF MAY 2ND.

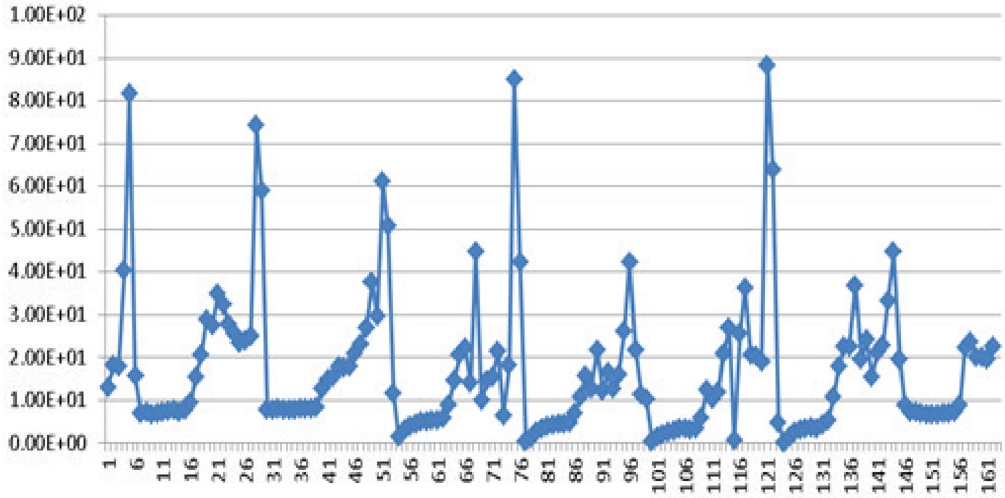


Figure C2.3: Total radiant power in (W/m²) for one week of continuous measurements per hour. The x-axis represents the number of measurements; 1 is the first measurement, which conducted on April 30th, 2015 at 15:00 and the 161 is the last measurement on May 7th, 2015 at 7:00. The pace of the spectroradiometer is 60 minutes between two measurements. The y-axis is the measured total radiant power in W/m².

Appendix D - Recommendations for designers derived by Chapter 5

Based on the results and conclusions of Chapter 5, the following seven advices can be given to designers who like to create PV products for indoor use.

1. The typical indoor irradiance ranges between 1 to 10 W/m^2. Therefore, PV products intended to use under these conditions, should have a low power of 1μW to 1 mW.
2. The efficiency of the PV technologies as can be found in literature or by companies' records does not represent the actual efficiency that the same PV cells will show indoors. The PV cells' efficiencies that one finds on spec sheets are measured under STC and are far away from the efficiencies under low indoor irradiance. There are no spec sheets for PV cells that are used in products. Using spec sheets for large modules is not accurate. Therefore, for energy calculations designers should assume that the typical efficiency of a PV cell under low irradiance is around 4-5 %. This rate is closer to the real efficiency of the PV cells indoors and will help the designer to have a better estimation of the product's real performance.
3. The amount of power that is available indoors and outdoors varies significantly. For instance, on a sunny summer day the radiation could reach more than 1000 W/m^2, whereas on a cloudy winter day the irradiation falls to 100 W/m^2. A solar cell with 5 % efficiency can deliver a power of 5 to 50 W/m^2, depending on the level of irradiance. Hence a 100 cm^2-area solar cell could give as a minimum 50 mW, which is enough to power a portable radio and many other low-powered products. However, indoors the situation is less optimistic. Here a typical insolation of 1 to 10 W/m^2 can be expected and the 100 cm^2-area solar cell will deliver less than 5 mW.
4. The performance of a PV product should be sufficient for use in the home environment, even when there is no sunlight. Therefore, it is safer to integrate PV cells in low-power products.
5. Solar powered products are usually advertised (and considered) as 'green products'. However, whether a PV product can be regarded as a green solution depends on several factors, such as the product lifespan. Solar cells take quite a lot of electricity to produce. The 'energy payback time' (EPBT) is the time required to produce an amount of energy equal to what was consumed during production. This means that the energy payback time of a PV product should not exceed its lifetime, which is usually limited to 1-5 years. In fact, it is still not possible to produce a PV product with silicon solar cells, which has an EPBT lower or equal to the lifetime of the product.
6. The integration of solar cells on a product, allow the use of rechargeable batteries with lower capacity. A battery has a very

high environmental impact (Flipsen et al., 2012; Dafnomilis, 2012), such that a reduction of battery capacity will have a strong effect on the reduction of the environmental footprint of a product. As discussed in Chapter 3, solar cells have longer lifetime than batteries. This means that when the battery of a product is at the end of its life, the solar cell is not necessary to be changed. The solar cell could be used with a new battery on the same product or be modified and integrated to another product. This does not happen at the moment with PV products, however it might be a valuable opportunity for the future; the use of product's assembling parts to other products. In that way materials are recycled and products' environmental profile is enhanced.

7. The type of batteries should be carefully chosen. Some of the cheapest products still contain NiCd batteries. Since July 2006 according to the Restriction of Hazardous Substances Directive (RoHS), the EU embargoes the use of cadmium in electrical and electronic products (Chatain, 2014). Since 2006 the sale of NiCd batteries has been banned in the EU (a few exceptions remain, such as NiCd batteries for medical use) (Battery Directive 2013/56/EU).

Appendix E - Practical Recommendations for the design of PV products for indoor use

1. First it is important for designers to decide the category of the product that they are going to develop (e.g. consumer product, entertainment product, household appliance, etc.)
2. Next, follows the research of the specific product category. For example, if one decides to design a PV-powered lamp for indoor use, one has to investigate what kind of lamps designed for the same purpose are commercially available and if they have a successful design and usability.
3. The power and the energy requirements of the product could be addressed here. Designers should know the required amount of energy that the product needs to function properly. The power requirements of a PV product could be estimated using Table E.1. Table E.1 was used for educational purposes during the course "PV Practicum" at the Department of Industrial Design Engineering of TU Delft for the academic years 2011-2015 and it is still used by students (Flipsen et al., 2015). By inserting the available irradiation (in W/m^2) at the place of use, the PV cell surface (in m^2), the assumed PV cell efficiency, according to the proposed formula (see Table E.1), and finally the time of exposure to light (in h), the energy yield of the product (in Wh) can be roughly estimated. The possible functions of the product define the energy demand and finally based on the energy balance ration Ein/Eout the feasibility of the product can be checked. Ein is the produced energy per day or per week and Eout the energy demand of the product per day or week. The Ein/Eout ratio shows if the collected energy balances with the energy use of the product (Flipsen et al., 2015).
4. It is very important to know the average irradiance conditions under which the product will be used; if it is going to be used in a room with many windows and enough natural light, or in a darker room with less natural and more artificial light. Depending on the indoor light at the specific place of use, the PV cells of the product will absorb more or less light and subsequently the batteries will be charged sufficiently or not. This knowledge is offered in this dissertation, where indoor irradiance is investigated and a typical range of indoor lighting is given.
5. Having knowledge on the field of PV technologies, batteries technologies, products' energy requirements depending on the product category and available indoor irradiance at the place of use, the designer could have a first guess on the materials that he/she is going to use. Some tools for the estimation of the energy requirements of a product are offered in this dissertation and could be used at this step of the design process.

6. After the selection of the PV cell and battery, designers, could do some calculations and see if the product will be feasible or not. If so, then they could continue with the next step. If not, then they could try the same procedure by selecting other materials that seem more suitable for the specific product.
7. Here it is important to include the basic user behavior with the product and if necessary do some recalculations regarding the combination of PV cell and battery technology that we made earlier. For example, we suppose that we continue with the example of the PV lamp: if studies show that most users do not have the desired behavior while charging the PV cell of the lamp, then we could reconsider our previous selection and replace the battery with one of higher capacity or increase the PV cell surface.

TABLE E.1: THE ENERGY BALANCE

Energy yield (E_{in}) per day/week			
Irradiation (G)			W/m²
PV cell surface A	x		m²
PV cell efficiency if G > 200 W/m², use 10% as a first estimate if G is < 200 W/m², use 5% as a first estimate	x		
Time of exposure to light	x		h
Energy yield	=		Wh
Energy demand (E_{out}) per day/week			
	P [W] x t [h] =	E [Wh]	
Function 1			Wh
Function 2	+		Wh
Function 3	+		Wh
...	+		Wh
Total energy demand	=		**Wh**
Ratio E_{in} / E_{out}	**E_{in} / $E_{out\ t}$ =**		
If E_{in} / E_{out} > 10	Feasible, PV system is over dimensioned, optimize the system		
If 1 < E_{in} / E_{out} < 10	Feasible		
If 0,1 < E_{in} / E_{out} < 1	Try to adjust parameters to make it feasible		
If E_{in} / E_{out} < 0,1	Not feasible		

APPENDIX F - QUESTIONNAIRE ABOUT USERS' INTERACTION WITH PV PRODUCTS

<u>Questionnaire about users' interaction with PV products</u>

Answer to the questions 2 to 13 by checking the boxes below.

1. What kind of PV- product did you use in this test (PV lamp, PV charger, etc)? Please write down the name of the product (e.g. WAKA WAKA, Logitech keyboard, etc).

2. Did you like the design of the PV-product you used? (e.g. How pretty it looks from the outside? How do you judge your first impression of the product?)

   o Not at all
   o A little
   o It was ok
   o A lot
   o It was excellent

3. Did you find its design complex (multiple small product parts, difficult to assemble, difficult to understand how it works)?

   o Not at all
   o A little
   o It was ok
   o A lot
   o Absolutely

4. How useful did you find the specific PV-product? In what extent this product met your expectations?

   o Not at all
   o A little
   o It was ok
   o Quite
   o Very useful

.

5. How easy was it to use the specific product? (I mean to operate the device)

- o Not at all
- o A little
- o It was ok
- o Quite
- o Very

6. How easy do you think it is for a child (8 to 15 years old) to use this product?

- o Not at all
- o A little
- o Quite
- o Very

7. How easy do you think it is for an adult to use this product?

- o Not at all
- o A little
- o Quite
- o Very

8. How easy do you think it is for a person older than 60 years old to use this product?

- o Not at all
- o A little
- o Quite
- o Very

9. Are you satisfied by the PV product's performance? To what extent did the product performance meet your expectations?

- o Not at all
- o A little
- o I am ok
- o Quite
- o Really/Absolutely satisfied

10. Would you buy it?

- o No
- o Possibly no
- o Possibly/ Perhaps
- o Definitely

11. Would you propose the product to a friend?

- o No
- o Possibly no
- o Possibly/ Perhaps
- o Definitely

12. Do you think the price of the product suits to its quality?

- o Not at all
- o A little
- o A lot
- o Definitely

13. How much money are you willing to pay for this product?

- o less than 10 Euro
- o 10 to 15 Euro
- o 15 to 20 Euro
- o 20 to 50 Euro
- o More than 50 Euro

Answer to the questions 14 to 17 by writing down your thoughts/ ideas:

14. If you could change something on the PV- product what should this be?

15. If you could choose between this PV-product and one of the same category without PV cells (for example with grid connection), which one would you prefer to buy and why?

16. During the 2 weeks that you used the product, what did you like more in the PV product and what kind of problems/frustrations did you face, if there were any?

17. Do you have any comments?

Appendix G- Desired features of PV products according to users, based on the results of the user-product interaction (Chapter 6)

Desired features of PV products according to users, based on the results of the user-product interaction (Chapter 6)

Which PV products' features are important for the users?

1. The charging and the battery status indicators are some of the most important product features according to the users (this thesis, Chapter 6). These indicators could inform the users of the status of the product and the care that the product needs at that specific moment.
2. Ease of use is significant for users, since the aim of using a product is more to help people and make their life easier than to waste their time with instructions how to use it. Furthermore, users of any educational level, intelligence quotient, sex or age could be able to use such a product (this thesis, Chapter 6).
3. Multiple functions of the product (e.g. lighting and charging function). This is a desired feature for users, who prefer to have one product with many functions than more products with only one function each. It is a matter of usability, time- saving and of course money- and material- saving (this thesis, Chapter 6).
4. Stable construction, flexible usage for different scenarios. Since users do not really care for the products and their maintenance, they need products made by strong materials that are not easily broken or damaged. Users like to use a product under different conditions and they expect from the product to perform sufficiently. This requires a solid and durable design (this thesis, Chapter 6).
5. An affordable price is also essential. The cost of the PV-powered product should not be much higher than the cost of a same-category product with no PV cells. Users are not willing to spend much more money and buy a PV powered product that might have insufficient performance. Our study on users' interaction shows that users could spend only few euros more to get the PV product instead of the plug-connected option (this thesis, Chapter 6).
6. No use of batteries (if possible) or long battery lifetime. The replacement of the batteries is always a trouble for the users. Therefore, they would prefer products with no batteries or products that do not need frequent replacement of the batteries (this thesis, Chapter 6).
7. Clear expectations and promises from the designer/manufacturer. The expectations of the product are not usually clearly indicated on the packaging or the instructions of the products. This creates wrong user expectations and a negative experience during their interaction with the product. If expectations and promises from

manufacturers are clear, then the user knows beforehand what are the limits and the performance of the product that he/she buys (this thesis, Chapter 6).

8. Attractive design and/or well-designed packaging (this thesis, Chapter 6). This is a matter of personal taste and aesthetics. These issues are not addressed in this dissertation. Therefore, they will not be further elaborated on.
9. As less user interaction as possible (e.g. user behavior for product's charging). The product should not need special treatment just because it is solar-powered. Users are often not willing to adopt a specific type of behavior in order to receive the best performance from their product.
10. Sometimes they do so during the first days of use, but afterwards they usually forget to charge the product and finally they stop using it. Thus, it is important to have products that do not need the extra care and/or attention of the user (this thesis, Chapter 6).
11. The product should function properly under different indoor irradiance conditions. Users need the freedom to use the product in everyplace inside their house (this thesis, Chapter 6). Products that should be used only under very specific irradiance conditions are not feasible indoors, because inside a house or even a room the irradiance is never stable. Therefore, the products that are intended to be used indoors should perform sufficiently even when there is not enough sunlight or artificial light in the room.
12. It is preferable that the product does not contain plugs and/or wires (this thesis, Chapter 6). The wireless products offer autonomy to the user and this is the most attractive feature of the PV products. Furthermore, the presence of cables and plugs makes the PV cells seem useless. If there are plugs, it is almost certain that the user will use them and the role of the PV cells will be directly wiped out.
13. Easy transportation of the product is important. This could be done by removing the extra accessories of the product, such as cables, plugs, and batteries and by keeping the size of the PV area limited to the product's size (this thesis, Chapter 6).

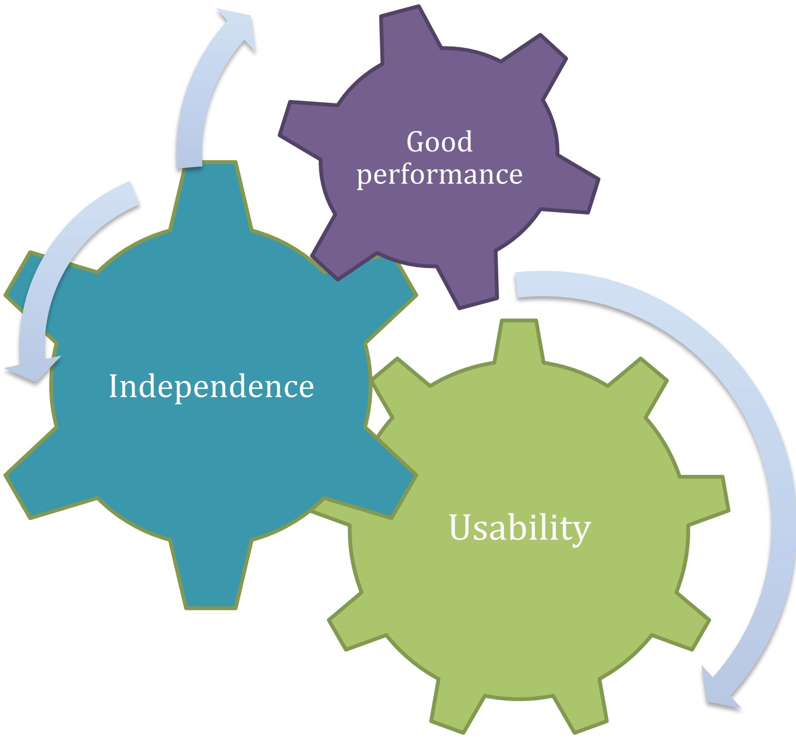


FIGURE G.1: THE THREE MOST IMPORTANT CHARACTERISTICS OF A PV PRODUCT ACCORDING TO USERS.

About the author

Georgia Apostolou was born in November 15th, 1986 in Athens, Greece. She studied Mechanical Engineering at the National Technical University of Athens (NTUA), where she graduated in 2010. She holds a MSc in Mechanical Engineering and her area of expertise is the alternative sources of energy and mainly solar energy and photovoltaics. In 2011 she moved to The Netherlands to start her PhD at the department of Industrial Design Engineering of Delft University of Technology. Since 2011 she has been working together with Prof. dr. Angele Reinders. Her research focuses on photovoltaic products for indoor use, indoor irradiance conditions and users' interaction with PV products.

Recently Georgia is working at the Center for Research & Technology Hellas (CERTH) in northern Greece, Thessaloniki. She is doing research in building sustainability and she is working on the production of a concept product, which aims to reduce the energy misuse and educate users towards a conscious energy usage.

Georgia is also a musician, studying music for over 20 years. She plays classical piano and ney (wind instrument, typical in performance of Ottoman classical repertoire).

Publications

1. Apostolou G., Reinders A.H.M.E., 2016, “How do users interact with photovoltaic-powered products? Investigating 100 ‘lead-users’ and 6 PV products”, J. Design Research, Vol. 14, No.1, pp. 66-93, Copyright © 2016 Inderscience Enterprises Ltd

2. Apostolou G., Reinders A.H.M.E., Verwaal M., 2016, “Comparison of the indoor performance of 12 commercial PV products by a simple model”, Energy Science & Engineering, Wiley Online Library, January 2016, Article first published online: 22 Jan 2016, Volume 4, Issue 1, pp. 69-85.

3. Apostolou G., Reinders A.H.M.E., 2015, "Users’ Interaction with PV-powered Products: an Evaluation of 6 products by 100 end-users", Proceeding of 42nd IEEE Photovoltaic Specialists Conference, Poster Presentation, New Orleans 2015, LA.

4. Apostolou G., Verwaal M., Reinders A.H.M.E., 2014, “Modeling the Performance of Product Integrated Photovoltaic (PIPV) Cells Indoors”, Proceedings of 26th European Photovoltaic Solar Energy Conference (EU PVSEC), Oral Presentation, Amsterdam 2014, The Netherlands, pp. 3535-3540.

5. Apostolou G., Verwaal M., Reinders A.H.M.E., 2014, “Estimating the performance of product integrated photovoltaic (PIPV) cells under indoor conditions for the support of design processes”, Proceedings of 40th IEEE Photovoltaic Specialists Conference, Poster Presentation, Denver 2014, Colorado, pp. 0742 – 0747.

6. Apostolou G., Reinders A.H.M.E., “Overview of design issues in product-integrated photovoltaics”, Energy Technology, Article first published online: 5 March 2014, © 2013 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, issue March 2014, Energy Technol. 2014, 2, pp. 229 – 242.

7. Apostolou G. and Reinders A.H.M.E., 2012, “A comparison of Design Features of 80 PV-Powered Products", Proceedings of the 27th EUPVSEC, Poster Presentation, Frankfurt 2012, Germany, pp. 4227 – 4232.

8. Apostolou G., Reinders A.H.M.E., Verwaal M., 2012, “Spectral irradiance measurements in a room fit for indoor PV products”, Proceedings of the 27th EUPVSEC, Poster Presentation, Frankfurt 2012, Germany, pp. 4240-4244.

9. Reinders A.H.M.E. and Apostolou G., “Product Integrated PV”, Forthcoming publication, Book Chapter in “Photovoltaic Solar Energy – From Fundamentals to Applications”, Eds. Reinders, A.H.M.E., Verlinden, P., van Sark, W.G.J.H.M., and Freundlich, A., Wiley and Sons, UK, expected publication in 2016.

Acknowledgements

It was end of April 2011. I was in The Netherlands visiting some friends. I had already graduated and started applying for PhD positions. I had also applied for a PhD position at TU Delft. I thought that it would be great if I were hired for this position. It was a great job opportunity and the country was familiar to me. Three days before I returned to Greece I received an e-mail for this position, where I was asked to have a Skype interview with the supervisor of the program. I immediately accepted the invitation and I informed the secretary that I was in The Netherlands and I could have the interview in person. I did it and a few days later I had a second interview. Finally, I returned to Greece mid May, just to pack a suitcase and fly to The Netherlands again at the end of June. It was July 1st 2011 when the research journey started.

It was a difficult procedure that needed a lot of effort from my side, but also from many other people around me, such as professors, supervisors, colleagues, friends, housemates and family. I think it is rather impossible to remember everyone that supported me during these five years, but I will try.

Firstly, I would like to express my sincere gratitude to my supervisor Prof. dr. Angele Reinders. Angele, thank you for this great opportunity, for your continuous support in my research, your useful comments and advice, your patience, motivation, and vast knowledge. Your guidance helped me throughout my research and the writing of this thesis.

Apart from my supervisor, I would like to thank the rest of my thesis committee: Prof. Jo Geraedts, Prof. Han Brezet, Prof. Sylvia Pont, Prof. Alex Rosemann and Dr. Wilfried van Sark, for their insightful comments.

My sincere thanks go to Bas Flipsen and Conny Baker for their advice and consultation, as well as for giving me access to the course “PV Practicum” and allowing me to work with their students. Many thanks to J.C. Diehl for his support in the final process of the thesis and to Sylvia Pont for being my mentor and helping me in many difficult situations. Special thanks to Martin Verwaal for our nice collaboration all these years and for his help and consultation with measurements, equipment, test set-ups. Thanks to the Applied Labs’ staff for always being willing to help, as well as to the IDE secretary; Mariska, Hanneke, Sara, Astrid. Thanks to Pieter Jan, Sacha, Renee, Maaike for their help and consultation, to my colleagues in the PhD room for the nice breaks and discussion; Daphne, Arno, Andreas, Ana, Sietze, Duygu, Uchechi, Farzaneh, Jotte, colleagues from Twente University; Tim and Hans for the stimulating discussions during the PhD meetings at UTwente and for the nice time we had together in conferences, colleagues from EWI; Dimitris, Remko for their help with conducting measurements at EWI labs and for access to the laboratory and research facilities.

I would also like to thank all the students from the courses “Smart Energy Products”, who participated in the course from 2011 to 2013 and “PV Practicum”, participated in the course from 2013 to 2015, for allowing me to observe them while interacting with PV products and for their help with questionnaires and the collection of PV products’ data from the network. Thanks also to Master students Diana, Kostas, Arlind, Gaurav and to all the photographers, product designers, websites and copyright owners for allowing me to use photos of their products in my dissertation.

Many thanks to all my friends in Rotterdam, for all the fun we have had in the last four years; Michalis, Marina, Alexandros, Nikos, Christos, Kostis, Georgia etc. and especially to my housemate Sofia for being so patient and supportive during the last hard year of writing my thesis. Sofaki thank you so much! I also thank my friends in Greece; Sani for her help at the last stage of writing and printing, Panagiota for her help with the graphic design of the thesis and the posters' design for conferences, Christopher for English editing, and Lena for her general support, especially during summers.

I would like to thank my family: my parents Kostas and Dimitra and my brother Antonis for supporting me spiritually throughout writing this thesis and my life in general. Μαμά, μπαμπά σας ευχαριστώ για την υποστήριξη όλα αυτά τα χρόνια και που μου δώσατε τα εφόδια να φτάσω έως εδώ.

Last but not least, many thanks to my dear Yannis for his support during these five years of research, his advice, motivation, love, serenity and compassion, without which it would be rather impossible to finalize this work. Yannis thank you for standing by me and I wish you success with your PhD. I am sure that you will do an excellent job and you will successfully defend your own thesis soon.

Without the precious support of all the aforementioned people and some more that I may have inadvertently forgotten to mention, it would not be possible to conduct this research! Sincere thanks to you all.

Georgia
Athens, April 2016

Technical University of Delft
June 2016

TU Delft