1.34 Product-Integrated Photovoltaics

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1.34.1 Introduction

1.34.1.1 What Is PIPV?

Since the beginning of this century, product-integrated photovoltaics (PIPV) has become a new research field within photovoltaics (PV). Because of its recent emergence, this PIPV research field is still being developed and as such not all topics have been fully explored. For instance, a sound generic definition of PIPV does not exist yet. This is a somewhat surprising, because PIPV, in fact, already exists since the 1970s by the introduction of the solar-powered pocket calculator, while at the same time it is a considerable market. In 2006, 5% of the annual global shipments of PV that were in the segment of consumer products equaled a nominal power of 80 MWp of PV cells (Maycock P (2008), personal communication) (see **Figure 1**). This number has been steadily growing over the years and is still increasing.

However, the category 'consumer products' does not reflect all possible applications of PIPV. From an evaluation of studies that paid attention to the definition of PIPV [1–4], it can be summarized that PIPV meets the following criteria:

1. PV technology should be integrated in the product, that is, it should be positioned on the surfaces of the product.
2. The energy generated by the PV cells is used for the functioning of the product.
3. Users directly interact with the product in different scenarios of use.
4. Energy can be temporarily stored in a battery or other storage medium.

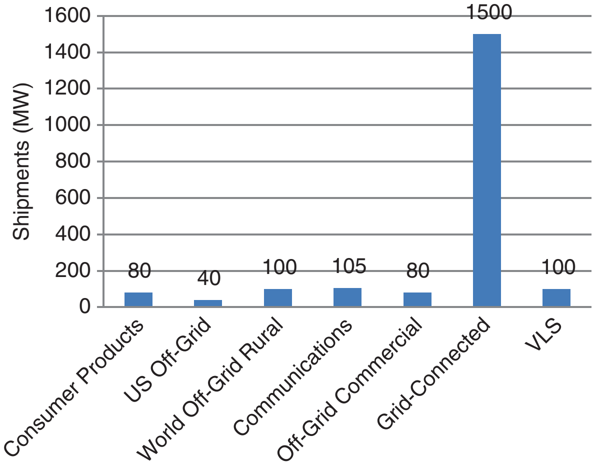


Figure 1 Annual global shipments of PV in 2006 showing PV-powered consumer products as a separate category. Source: Maycock P (2008), personal communication by Reinders, A.

5. The product is applied in a terrestrial setting.
6. Often, the product has mobile or portable features.

Due to aspect 5, the earthly application of PIPV, PV power supply for satellites and robots for the exploration of planets, will not be evaluated in this chapter. Adding to this, building-integrated photovoltaic (BIPV) is not considered either to be a large-scale version of PIPV since usually BIPV does not meet criteria 2 and 3, that is, electricity generated by BIPV is fed into the grid and a strong user interaction does not exist (yet) with grid-connected PV systems.

The main difference between PV systems and PIPV is that PIPV comprises product parts like casings as well as PV system components. And while the basic function of PV systems is to generate power, the functionality of PIPV is embedded in a product context. That is to say, PIPV provides functions that require electricity, for instance, lighting, sound, or transportation. Moreover, users can interact with PIPV by scenarios of use; that is, users impose load patterns on PIPV and they can affect the frequency at which solar cells are exposed to irradiance sources. Finally, products usually have a shorter lifetime than energy systems. Consumer products will be used for a few years, whereas PV systems are meant to survive life spans of at least 20 years without dramatic failure.

For the above-mentioned reasons, we consider PIPV with its specific generic features, as represented in Figure 2, as a separate category in the broad spectrum of PV applications.

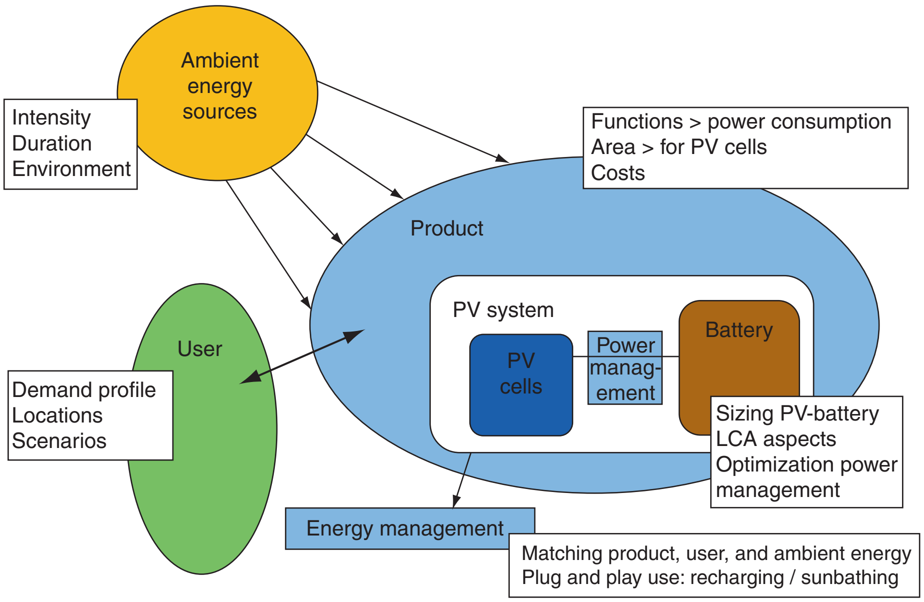


Figure 2 Schematic representation of the main generic features of PIPV.

1.34.1.2 The Structure of This Chapter

This chapter will present the following issues regarding PIPV. To start, in Section 1.34.2 we will give an overview of the existing solar-powered products. Next, the design of PIPV will be presented from the context of design processes (Section 1.34.3). Thereafter, we will discuss the technical aspects (Section 1.34.4), system design and the energy balance (Section 1.34.5), costs (Section 1.34.6), environmental aspects (Section 1.34.7), human factors (Section 1.34.8), and design and manufacturing (Section 1.34.9). Finally, we will end this chapter with an outlook on the future of PIPV and our conclusions (Section 1.34.10).

1.34.2 Overview of Existing PIPV

1.34.2.1 The Early Days of PIPV

In the 1950s, PV solar cells were developed at Bell Telephone Laboratories in the United States with the purpose to apply them in products that lacked permanent electricity supply from the mains. The solar cells were called silicon solar energy converters commonly known as the Bell Solar Battery [5]. Furnas [6] reported that "The Bell Telephone Laboratories have recently applied their findings in the transistor art to making a photovoltaic cell for power purposes. {….} and exposed to the sun, a potential of a few volts is obtained and the electrical energy so produced can be used directly or stored up in a conventional storage battery. {….} The Bell System is now experimenting with these devices for supplying current for telephone repeaters in a test circuit in Georgia. As to cost, one radio company has produced a power pack using this type of photoelectric cell for one of its small transistorized radios." The *Journal of the Franklin Institute* has mentioned already in Reference 7 that "these (*solar*) batteries can be used as power supplies for low-power portable radio and similar equipment." Expectations regarding the applicability of PV cells in products were high; Sillcox [8] reports on predictions by researchers of New York University "that small household appliances like toasters, heaters or mixers using the sun's energy might be in fairly widespread use within the next five years (i.e., 1960)." These predictions have not become reality, because at that time the costs of silicon PV cells were about $200 per Watt for high-efficiency cells [9] – where 12% was considered a high efficiency – and the costs of a dry cell to operate a radio for about 100 h would be less than a dollar [6]. Therefore, it was believed that the solar battery could be an economical source for all except the most special purposes. As such, by the end of the 1950s, silicon PV solar cells were applied as a power supply for satellites [10]. The Vanguard TV-4 test satellite launched on 17 March 1960 was the first satellite ever equipped with a solar power system, and it announced a new area of space technology with solar-powered satellites. It took about 20 years until interest in PIPV resumed again by the introduction of the first solar-powered calculators in 1978; the Royal Solar 1, Teal Photon, see **Figure 3** and the Sharp EL-8028.

1.34.2.1.1 Consumer products with integrated PV

Probably, the solar-powered pocket calculator has been the most apparent application of PV in commercially available consumer products in our daily lives during the past 30 years. Japanese manufacturers are leading in this field together with the production of PV-powered wrist watches with advanced electronic features.

Nowadays, we can commercially purchase PV-powered radios, solar-powered MP3 players, PV headsets, and automated lawn mowers. PV solar cells are widely applied in chargers used in cell phones and portable consumer electronics. These chargers are sometimes designed as a separate product solely meant to charge batteries in small electronic handhelds, sometimes they are

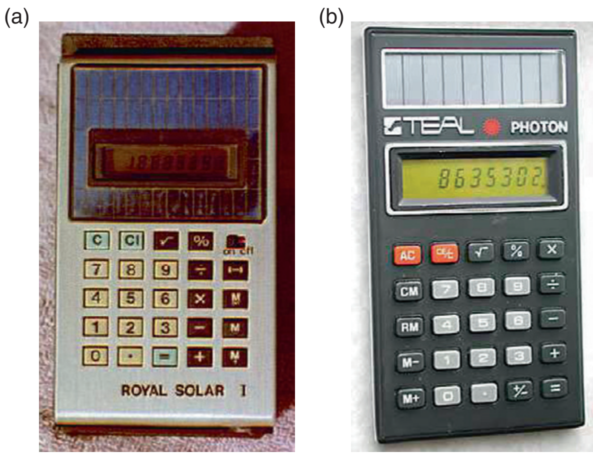


Figure 3 The first solar-powered pocket calculators appeared during the late 1970s on the market. Shown here are (a) the Royal Solar 1 and (b) the Teal Photon. Source: Vintage Calculators. http://www.vintagecalculators.com/ (accessed 23 October 2010) [11]. Courtesy of Nigel Tout & Guy Ball.

Figure 4 Examples of PIPV consumer products. (a) Solar-powered wrist watch by Casio. (b) Freeplay PV-powered radio. (c) Iqua 603 Sun bluetooth headset with integrated PV. (d) PV toy resembling a frog.

integrated in a handbag, backpack, or bicycle bag, allowing charging of small devices in the bag while being carried around outdoors exposed to sunlight.

Toys with integrated PV cells are rather common; they include small animals or cars that can move once exposed to light. Toys such as do-it-yourself (DIY) kits for the construction of PV-powered toy houses function sometimes as educational demonstration materials.

An interesting product concept for a PV-powered computer mouse had been explored in great detail and has been prototyped and tested in the framework of the Dutch SYN-Energy project [12–16]. Unfortunately, this product is not commercially available yet.

The nominal power of solar cells in the category 'consumer products' typically ranges from 0.001 W up to about 10 W (see Figure 4). The added value of PIPV in this category is portable energy supply. Some products have been designed for indoor use under artificial light conditions.

1.34.2.2 Lighting Products with Integrated PV

Since the mid-1990s, the emergence of energy-efficient light sources such as fluorescent lamps and light-emitting diodes (LEDs) in combination with PV technology resulted in numerous self-powered lighting products such as flash lights, ambient lights, lamps for bicycles, garden lights, pavement lights, indoor desk lamps, street lighting systems, and other products for lighting of public spaces [66, 78, 79].

In particular, in the past few years PV-powered lamps have been developed for markets at the bottom of the pyramid (BOP) in developing countries, fulfilling a need for an affordable, healthy, and clean alternative for candles, kerosene lamps, or fluorescent lamps that are powered by rechargeable car batteries [17–19].

The nominal power of solar cells in the category 'lighting products' typically ranges from 1 W up to about 100 W (see Figure 5). The added values of PIPV in this category are portable energy supply or remote lighting services. Some products have been designed for indoor use, wherein the energy is collected during daytime from sunlight either outdoors or indoors directly behind a glass window.

1.34.2.3 Business-to-Business Applications with Integrated PV

Since the 1990s, PIPV has been applied in business-to-business applications such as traffic control systems, traffic lights, and parking meters. Roth and Steinhueser [20] published an interesting status overview of PV energy supply in devices and small systems showing the technical and financial feasibility of PV in this market segment. Nowadays, public trash bins with automated control of trash collection are successfully powered by PV. PV cells are also applied in small ventilators for boats and cars that can be operated in stationary situations. In products for telecommunication, security, and environmental monitoring, PV systems can serve as an autonomous energy source. PV cells can be well integrated in surfaces of business-to-business products.

Figure 5 Examples of PIPV lighting products. (a) Garden light. (b) Ambient light corona. (c) Indoor table lamp by IKEA. (d) Street light for public spaces.

Figure 6 Examples of PIPV business-to-business products. (a) Parking meter in New York City. (b) Automated trash bin Big Belly.

The nominal power of solar cells in the category 'business-to-business applications' typically ranges from 10 W up to about 200 W (see Figure 6). The added value of PIPV in this category is automated operation of devices. Most products have been designed for outdoor use.

1.34.2.4 Recreational Products with Integrated PV

In this category, the following products can be found: PV-powered caravans and campers, solar-powered tents, solar-powered fountains, solar-powered pond equipment, and PV products for water sports. The nominal power of solar cells in the category 'recreational products' typically ranges from 50 W up to about 500 W (see Figure 7). The added value of PIPV in this category is mobile and remote energy supply. The products have been designed for outdoor use. At present, PIPV in recreational products is at the edge of financial viability; depending on the price developments of PV technology, this market segment might grow in the forthcoming decade.

Figure 7 Examples of PIPV recreational products: a conceptual design of a solar-powered tent.

1.34.2.5 Vehicles and Transportation

In the category 'vehicles and transportation', the following subcategories can be distinguished: bikes, boats, cars, and planes.

The nominal power of solar cells in the category 'vehicles and transportation' typically ranges from 200 W up to about 1500 W for electric cars, and several tens of kilowatts for planes (see Figures 8–10). The added value of PIPV in this category is mobile energy supply. The products have been designed for outdoor use only. Most of these PV applications are still in the demonstration phase.

PIPV in bikes is mainly meant to provide auxiliary power for navigation equipment and to charge batteries in the drive train. This application is not commercially available yet; however, at present, lead users are developing their own solutions for PIPV in bikes [23].

PV-powered boats can serve several different purposes: transportation of groups of people, recreation, research, and to participate in a contest called the Fryslan Solar Challenge. Gorter *et al.* [24] evaluated all PV-powered boats that have been developed. A typical PV-powered boat with a length of 7 m has a power of 1000 W and a 1 kWh battery; it can reach a speed of 10 km h^{-1} by electric propulsion in the water. Because of many environmental advantages and the high exposure of boats to sunlight, this application of PIPV seems promising.

A well-known example of a PV-powered vehicle is the golf cart. At present, Toyota explores the integration of solar cells in the roof of the Prius hybrid car. Adding to this, the World Solar Challenge that takes place every 2 years in Australia can be considered as an important incubator for future innovations of solar-powered electric vehicles. The required power of about 1500 W in combination with the costs of high-efficient solar cells and high-performance batteries are too high to expect commercial availability of PV-powered passenger cars on the short run.

Projects that aim at the realization of PV-powered air crafts such as Solar Impulse [22] have a highly innovative character [65]. The combination of lightweight constructions and a high power demand in the order of tens of kilowatts yields beautiful solutions, as shown in Figure 10.

1.34.2.6 Arts

The category 'arts' comprises products with decorative features and artistic objectives, for instance, PV jewellery, art for public spaces, and indoor art like a PV-powered chandelier (see Figure 11). In this field, the imaginary world merges with the possibilities provided by the PV technology and its aesthetic appeal. The PV power and the location of use can vary considerably in this category.

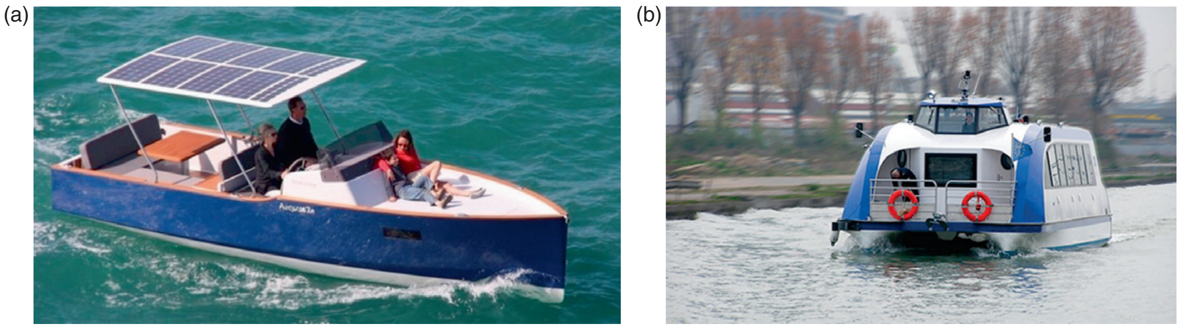


Figure 8 Examples of PIPV boats. (a) Recreational PV-powered boat, Aequus 7.0. (b) PV-powered ferry, Navette du Millenaire.

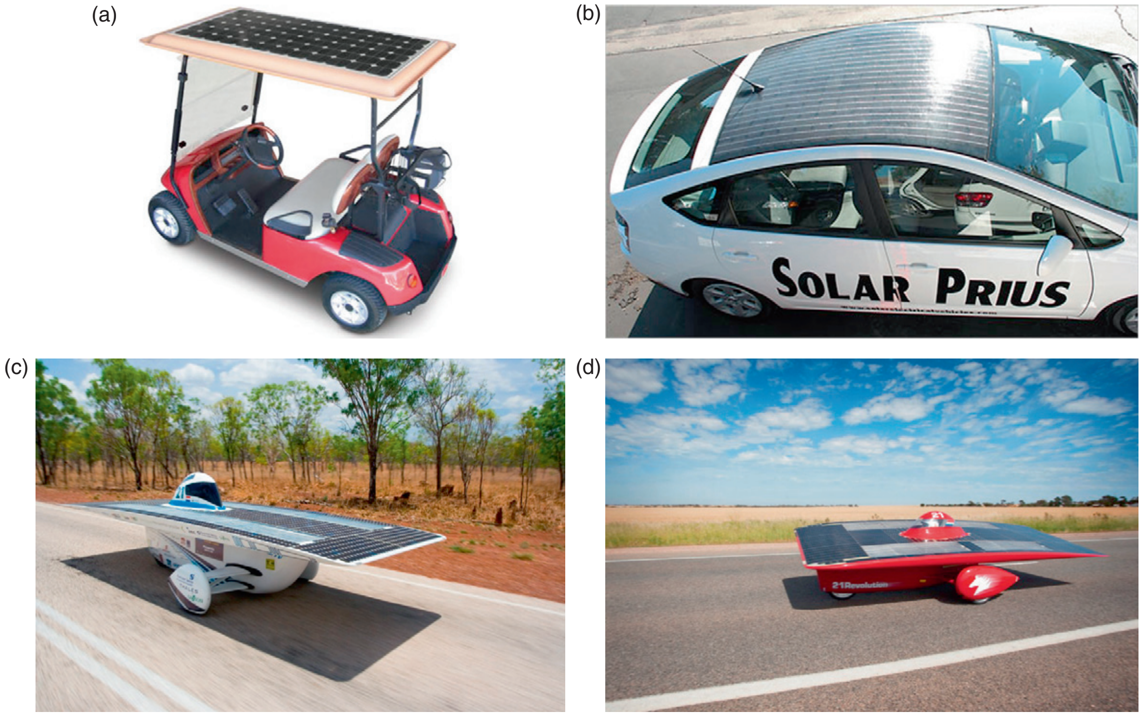


Figure 9 Examples of PIPV cars. (a) Golf cart. (b) Toyota Prius with PV roof. (c) Solar racing car of the Solar Team of University of Twente (2007). (d) Solar car of the Solar Team of University of Twente (2009). Courtesy: Solar Team (2010).

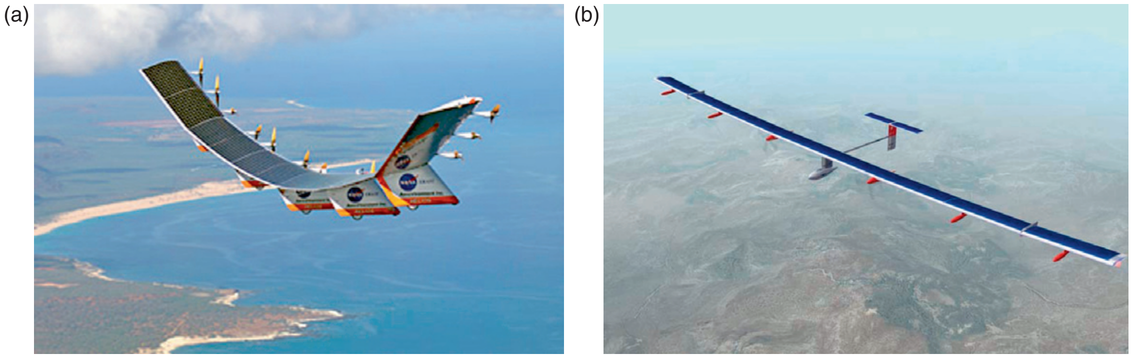


Figure 10 Examples of PIPV planes. (a) The Helios aircraft. Source: Helios. http://www.nasa.gov/centers/dryden/news/ResearchUpdate/Helios/index.html (accessed November 2010) [21]. (b) The solar impulse aircraft. Source: Impulse. http://www.solarimpulse.com/ (accessed November 2010) [22].

Figure 11 Examples of PIPV art. (a) The Brain in Graz (Austria). (b) The Sun Monument in Zahar (Kroatia) [25]. (c) A PV-powered chandelier [26], Photo: Bas Helbers, Virtue of Blue.

1.34.3 Designing Products with Integrated PV

1.34.3.1 Area Constraints in Design

A dominant factor in the design of PIPV is the required area on products surfaces that can be covered by solar cells. The typical area of solar cells in PIPV is determined by a trade-off of the internal power consumption of a product, its characteristic run time that results from the user behavior, the available area on the product, the PV technology applied, the storage capacity, and the irradiance conditions in the product's surrounding. For instance, in the case of PV-powered consumer products that are used indoors, area is constrained by the geometries of consumer products, which indirectly implies a very low internal power requirement of these products that can range from 0.005 mW up to a few Watts. Under indoor irradiance conditions of 10 W m^{-2}, c-Si PV cells perform with an efficiency of 10% or less. Assuming a run time similar to the charging time of batteries, an area of solar cells of 5×10^{-6} up to several square meters is required to meet the internal power requirement of these products (see **Figure 12**).

Under outdoor conditions, PV cells can generate power in the range of 120 W m^{-2} (using amorphous silicon) up to 270 W m^{-2} (using high-efficient III–V PV technologies) under STCs (which means standard test conditions that comprise an irradiance of 1000 W m^{-2}, an AM1.5 solar spectrum, and an ambient temperature of 25 °C). **Figure 12** gives an overview of the required solar cells area to meet the internal power consumption of products in the range from 0.005 mW up to 1000 W. It can be seen that an area of 5.4 m^2 of high-efficient solar cells is needed to meet a product's internal power consumption of 1000 W. PIPV that is used outdoors can meet the power requirements of outdoor lighting products, vehicles – such as cars, boats, and lightweight planes – portable accommodation – such as campers, caravans, and tents – and business-to-business applications – such as parking machines, traffic control, and public information displays.

1.34.3.2 Design Processes and PIPV

Only a few authors in the field of PIPV have discussed issues in the integration of PIPV from the perspective of designers and design processes. Here, we refer to studies by Randall [2], Kan *et al.* [68], Veefkind [80], Geelen *et al.* [27], and Reinders *et al.* (2009) [28, 29, 77]. To be able to successfully apply a technology in a product context, the following aspects should be included in the design process: (1) human factors such as ergonomics and customers' experiences with a product, (2) design and styling that fits to customers' lifestyles, (3) appropriate marketing of a product, and (4) societal aspects such as regulations and legislation. Product designers perceive each of these topics evenly decisive for the final success of a product. Hence, if these topics are required for a successful consumer product, they should be applied to products with integrated PV cells as well. As such, Randall [2] and Reinders *et al.* (2009) [28, 29, 77] agree on the applicability of generic engineering design processes [30] for the development of PIPV, represented as a linear sequence of tasks in **Figure 13**. The design process consists of four phases, namely, (1) clarification of the task, (2) conceptual design, (3) embodiment design, and (4) detail design. In the first three phases, product designers seek to optimize the working principle, that is, technology of a product. The last three phases involve optimizing the layout and form of a product. Thus, conceptual design and embodiment design form the connecting link between a technology – such as PV solar cells – and design and ergonomics, on the other hand [31].

Reinders and van Houten [31] mentioned that to foster innovation in PIPV during the design process, creativity and an integrated view are required. In this scope, innovation is not just a matter of implementing advanced technology in existing products but particularly a matter of sensing new opportunities that are created by new technology such as PV technology. To foster

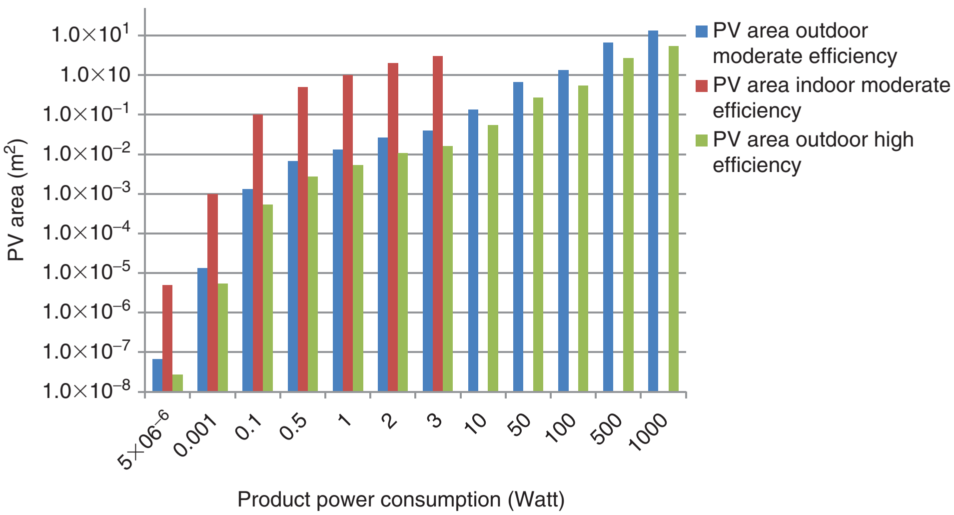


Figure 12 Area of PV solar cells required to meet the internal power consumption of products assuming an equal run time and charging time of batteries of 3 h under stationary conditions. Figures are based on an indoor irradiance of 10 W m^{-2} with 10% efficient c-Si cells (red bars), an outdoor irradiance of 500 W m^{-2} with 15% efficient c-Si cells (blue bars), and an outdoor irradiance of 800 W m^{-2} with 23% efficient III–V cells (green bars).

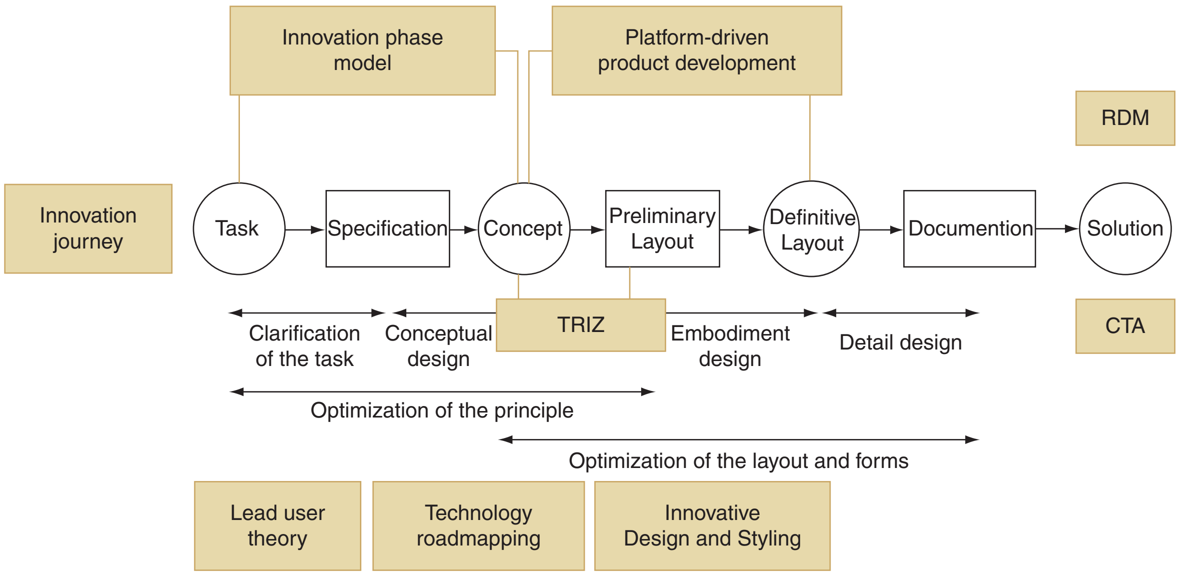


Figure 13 Linear design process in relation to innovation methods (brown boxes) that can be applied to innovate products in the field of PIPV.

innovation during a linear design process, several innovative design methods can be applied (indicated by brown boxes in Figure 13). These methods are the innovation phase model, lead user studies, platform-driven product development, risk diagnosing methodology (RDM), technology road mapping, TRIZ (a Russian acronym meaning 'theory of inventive problem solving'), innovative design and styling, innovation journey, and constructive technology assessment (CTA). From 2005 till 2010, Reinders conducted several case studies with the approach shown in Figure 13. A few resulting products are shown in Figure 14. The results show that the use of carefully chosen and applied industrial design methods can help to better integrate PV technology in products and can lead to surprising solutions.

1.34.4 Technical Aspects of PIPV

1.34.4.1 PV Cells

The efficiency of a PV solar cell is an important variable in the design of PIPV, because it determines the power that can be produced. The efficiency depends on the PV material and technology of the cell and the intensity of irradiance that impinges on a PV cell surface. In addition, the temperature of the PV cell and the spectral distribution of the light affect the efficiency.

If a solar cell is illuminated, a photocurrent I_{ph} is generated. This photocurrent is in most cases linearly related to the intensity of irradiance. Because of the semiconductor materials in the PV cell, the electric behavior of a PV cell can be represented by a current source in parallel with two diodes, D_1 and D_2. A series resistance, R_s, and a parallel resistance, R_{sh}, add to this electric circuit, as shown in Figure 15.

The electric behavior or current–voltage characteristic (I–V curve) of a PV cell is described by:

$$I = I_{ph} - I_{s1}\left(e^{\frac{q(V+IR_s)}{n_1 kT}} - 1\right) - I_{s2}\left(e^{\frac{q(V+IR_s)}{n_2 kT}} - 1\right) - \frac{V+IR_s}{R_{sh}} \qquad [1]$$

Here I_{s1} and I_{s2} are the saturation currents of the two diodes and n_1 and n_2 are the quality factors of the two diodes. In general, n_1 will not deviate much from 1, and usually $n_2 = 2$ if no imperfections occur. V is the voltage over the circuit, T is the temperature, and k is the Boltzmann constant. Figure 16 shows the I–V curve of a solar cell at a certain irradiation. It crosses the y-axis in the open-circuit voltage, V_{oc}, and the x-axis in the short-circuit current, I_{sc}.

In Figure 16, it is shown that the I–V curve of a PV cell has one point that delivers maximum power. This point is called maximum power point, P_{mpp}, and is characterized by V_{mpp} and I_{mpp}. This maximum power point is used to determine the efficiency, η:

$$\eta = \frac{I_{mp} V_{mp}}{AG} \qquad [2]$$

Here, AG is the optical power falling onto the solar cell, with A the solar cell area and G the irradiance. Please note that from the two-diode model it follows that if the operational voltage, V, of the cell deviates from the maximum power point settings, the efficiency will drop accordingly.

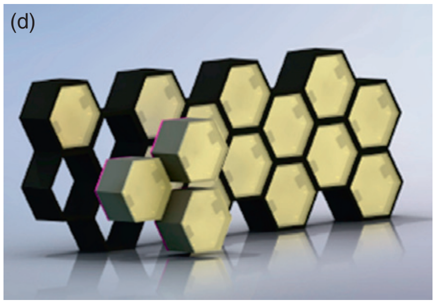
(a)

Artist's rendering of a PV-powered headphone with integrated FM radio and MP3. Design by Weeda and Prinsen.

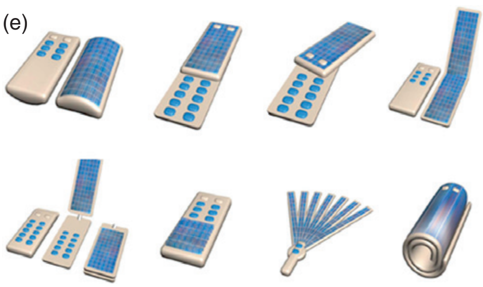
(b)

Artist's rendering of a PV-powered cooling unit for water sportsmen. Design by Doorn and Everlo.

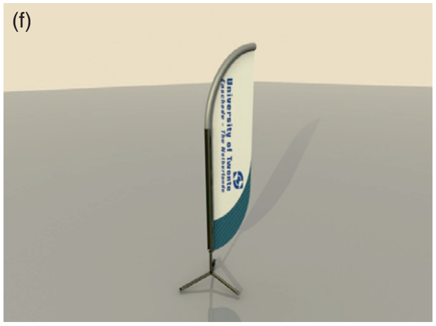
Artist's rendering of a sunshade made from flexible PV foil with integrated LEDs by Bos and Hartman. Artist impression of use during night.



Artist's rendering of PV-powered bricks that emit LED light, by Jong and de Beurs.



Geometric design variations of a PV-powered remote control by Heeres and Kerkhoffs.



Artist's rendering of a PV-powered beach flag by Groen and Verduijn.

Figure 14 Conceptual products with integrated PV systems resulting from case studies on innovative design of PIPV [28, 29].

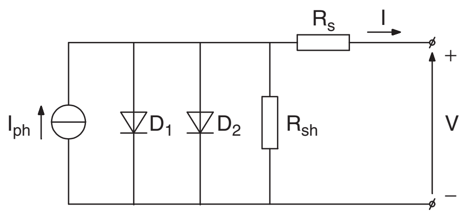


Figure 15 Equivalent circuit of a solar cell represented in the two-diode model.

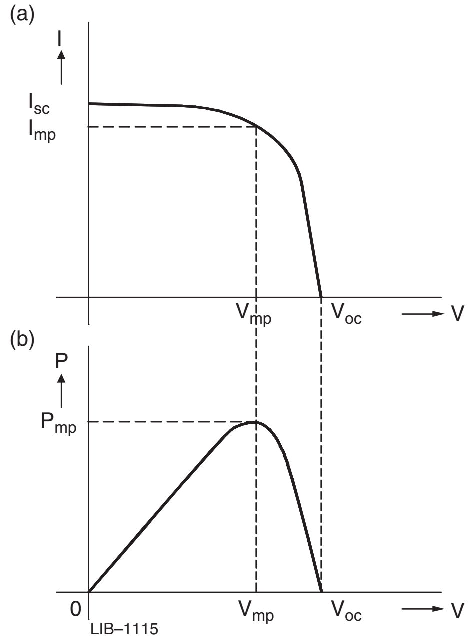


Figure 16 (a) The current–voltage characteristic of a solar cell. (b) The power–voltage characteristic of a solar cell.

Single values of efficiencies of solar cells are usually efficiencies at STC conditions, η_{STC}, which means that the value is measured at so-called STCs, which represent $1000\,W\,m^{-2}$ irradiance, AM1.5 spectrum, and 25 °C cell temperature.

PV cells are made from several different PV technologies based on semiconductor materials. These materials yield various efficiencies. The most well-known solar cell technology is the single-crystal silicon wafer-based solar cell, indicated by c-Si. It has improved significantly in the past 30 years, and today, it is the dominant solar cell technology. Crystalline silicon solar cell technology represents also multicrystalline silicon solar cells, indicated by m-Si. Both c-Si and m-Si are the so-called first-generation solar cells.

Besides this, second-generation solar cells have been developed with the intention to find a cheaper alternative for crystalline solar cell technology by using less material. For this reason, they are called thin-film solar cells. Several semiconductor materials allow for the production of thin films, namely, copper indium gallium diselenide ($CuInGaSe_2$), abbreviated to CIGS; cadmium telluride, CdTe; hydrogenated amorphous silicon (a-Si:H); and thin-film polycrystalline silicon (f-Si). Thin-film PV cells can also be made from organic materials. In the first place, dye-sensitized cells (DSCs) consist of titanium oxide nanocrystals covered with organic molecules. Second, polymer organic solar cells are made from conducting polymers. A third group of solar cells is made from compounds of the elements Ga, As, In, P, and Al. The entire group is called III–V technology, and the specific cells are named after their compounds, for instance, GaAs, GaInP, or InP. These PV cells have been developed for space applications because of their high efficiency. They are also increasingly being applied in terrestrial concentrator systems. **Table 1** shows typical efficiencies for the above-mentioned PV technologies.

Table 1 Characteristic efficiencies and spectral response range of several PV technologies

Type of PV cell	*Record lab cells, η_{STC} (%)*	*Commercially available, η_{STC} (%)*	*Spectral range (nm)*
c-Si	25	14–17 24.2	350–1200
m-Si	20.4	14–16	350–1200
a-Si	12.5	8–10	300–800
Nano-, micro- or poly-Si	16.5	11–13	300–800
CIGS	20.3	12–17	300–1200
CdTe	16.7	10.7	350–850
III–V three junction	43.5 (under 300 suns)	27–30	300–1250
III–V single junction, thin film	26	21–23	300–1000
DSC	11.1	8–10	300–800
Polymer	8	3–5	300–800

Adapted from Kan SY (2006) SYN-Energy in solar cell use for consumer products and indoor applications. Final Report 014-28-213, NWO/NOVEM. Delft, The Netherlands: Technical University of Delft [1], updated with Kazmerski L (2010) *Best Research Cell Efficiencies*. Golden, CO: NREL [32].

1.34.4.2 Irradiance and Solar Cell Performance

1.34.4.2.1 Outdoor irradiance in relation to solar cell performance

Irradiance, G, is the power density of light expressed in $W\,m^{-2}$. In daytime, outdoor irradiance is predominantly determined by sunlight. In **Figure 17**, the spectral distribution of the sunlight falling onto the earth surface is shown. This spectrum resembles the spectrum of a black body with a temperature of 5700K and is determined by the path length of the sunlight through the atmosphere (the air mass, AM): AM0 is the extraterrestrial spectrum. The various 'dips' in the spectra arise because of absorption in the atmosphere, among others by water vapor. In addition, the spectrum is being influenced by scattering taking place in the atmosphere.

The efficiency of a solar cell depends on the spectral composition of the light. Therefore, the efficiency is being defined at a standard spectrum. This is the AM1.5 standard spectrum for terrestrial applications and the AM0 standard spectrum for space travel applications. For terrestrial PV solar cells, STCs represent an irradiance of $1000\,W\,m^{-2}$, a spectrum AM1.5, and a cell temperature of 25 °C.

Figure 18 shows the measured efficiency curves in the maximum power point for c-Si and m-Si solar cells [33]. It can be seen that the efficiency steeply drops with respect to the STC efficiency with decreasing irradiance, which is confirmed by the two-diode model.

The sensitivity of each solar cell strongly depends on the wavelength of the light falling onto the solar cell. The sensitivity as a function of wavelength is called the spectral response (expressed in $((A\,m^{-2})/W\,m^{-2}))$ or in $(A\,W^{-1}))$ and is quantified by measuring the short-circuit current occurring at illumination with a monochromatic light beam. **Table 1** shows a range of spectral response of different cell technologies, which is determined by the band gap of the semiconductor material and the charge generation and recombination processes that internally take place in a solar cell. **Figure 19** shows the spectral response curves of samples of a-Si and c-Si under an AM1.5 spectrum by Reich *et al.* [34, 40].

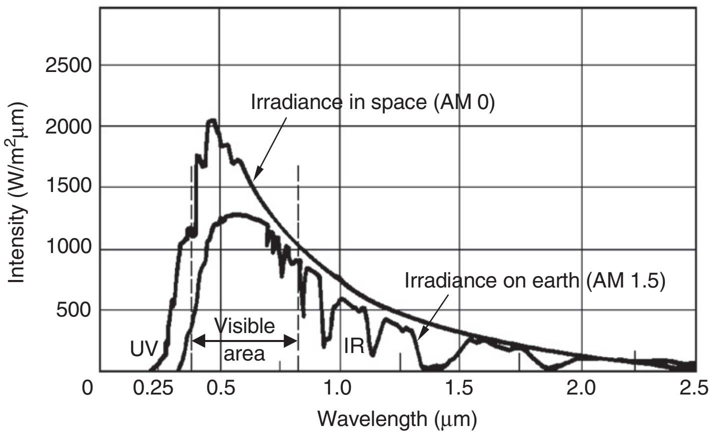


Figure 17 The wavelength-dependent AM0 and AM1.5 spectra of sunlight.

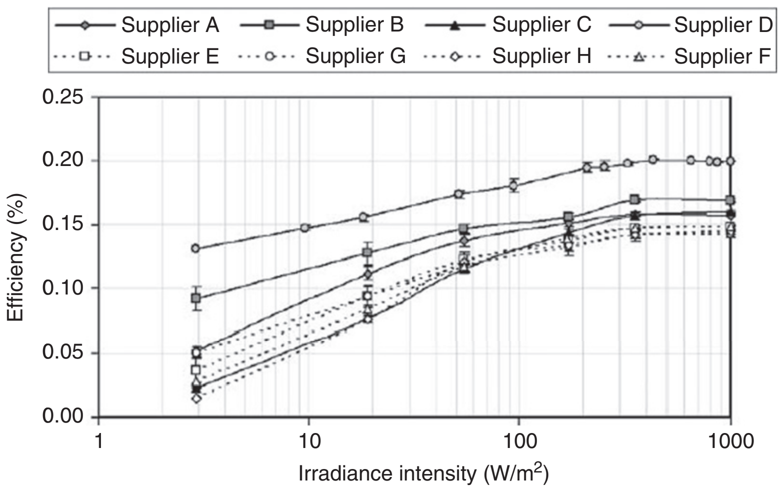


Figure 18 Measured irradiance intensity-dependent efficiencies of various Si solar cells by Reich *et al.* [15]. Measurements at $1000\,W\,m^{-2}$ reflect STCs below $1000\,W\,m^{-2}$, the intensity of the AM1.5 is linearly reduced.

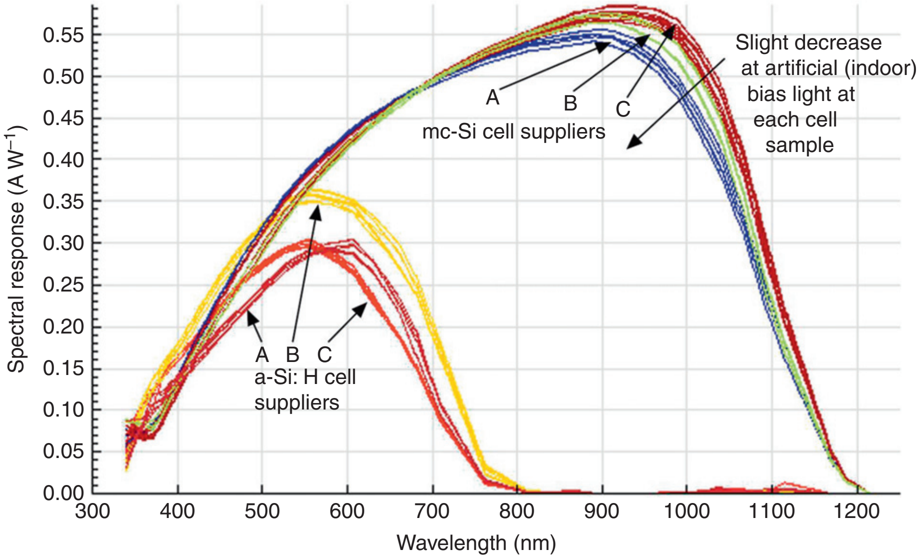


Figure 19 Spectral response of a-Si samples and m-Si samples from Reich *et al.* [40].

1.34.4.2.2 Indoor irradiance

Indoor irradiance usually consists of a mixture of sunlight that enters a building through windows and skylights, and artificial light originating from different light sources, such as incandescent lamps, fluorescent lamps, and LEDs.

Müller [35] has conducted an extensive research on the measurement of indoor irradiance. She reports that though indoor irradiance can exceed $500\,\mathrm{W\,m^{-2}}$, the basic orders of magnitude typically are about 1–$10\,\mathrm{W\,m^{-2}}$ with worst-case scenarios in the winter without the use of artificial light in the range of $0.1\,\mathrm{W\,m^{-2}}$. For surfaces orientated to the window, the solar radiation will contribute most, and for surfaces orientated to the electric light, the latter will contribute most of the radiation. These features can be important concerning the dominating spectral distribution of irradiance that can be converted to electricity by PV solar cells. Namely, the spectral range of irradiance from sunlight is from 300 up to 4000 nm, whereas the spectral distributions of artificial light are more narrow. For instance, artificial light emitted by incandescent lamps has a spectral range of 350 up to 2500 nm, by LEDs from 400 up to 800 nm, and by fluorescent lamps from 300 up to 750 nm [37]. In **Figure 20**, measured spectra of incandescent light sources and fluorescent lamps are shown.

1.34.4.2.3 Solar cell performance at indoor irradiance

Several studies have been devoted to solar cell performance under weak light or indoor irradiance conditions. These studies were conducted by Randall [2], Randall and Jacot [14], Reich *et al.* [34], Girish [38], Gong *et al.* [39], and Reich *et al.* [40].

Here we would like to refer to the most recent study in this field by Müller [35, 71–73], who has simulated and measured the performance of different PV materials for different spectral distributions in order to identify maximum efficiencies and the optimum technology under the specific light spectra (**Figure 21**) [35].

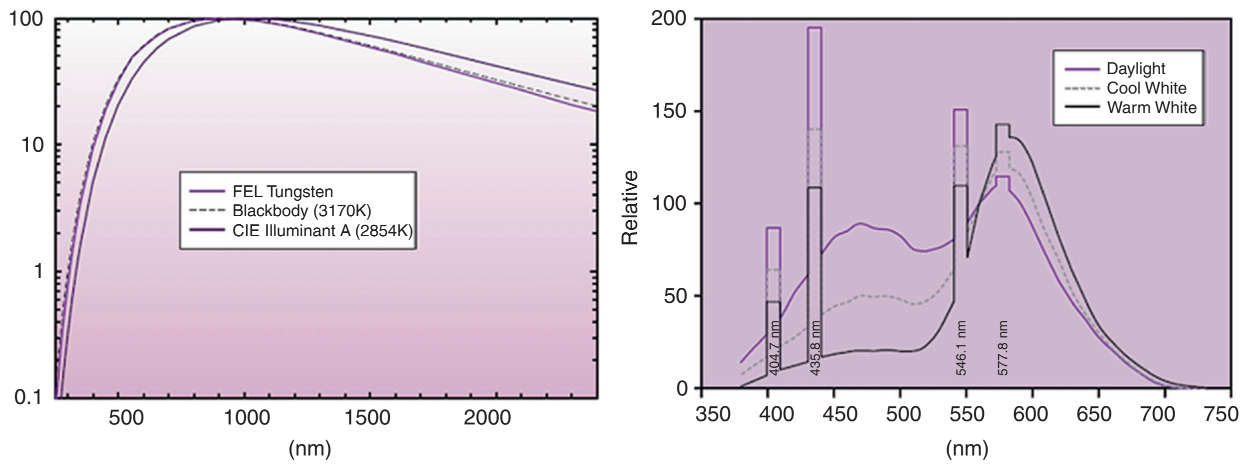


Figure 20 Spectra of incandescent lamps and typical fluorescent lamps from Ryer [37].

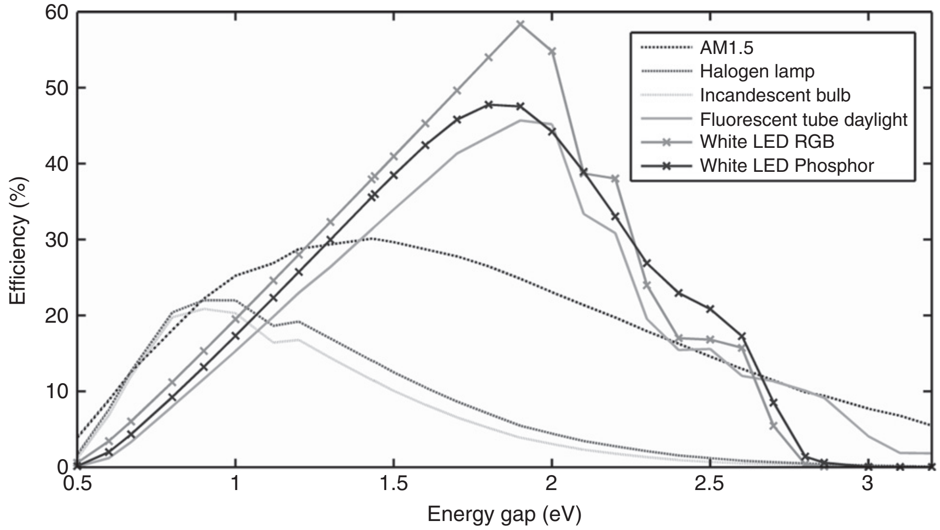


Figure 21 Calculated efficiencies for PV cells as a function of their band gaps for different radiation sources [35].

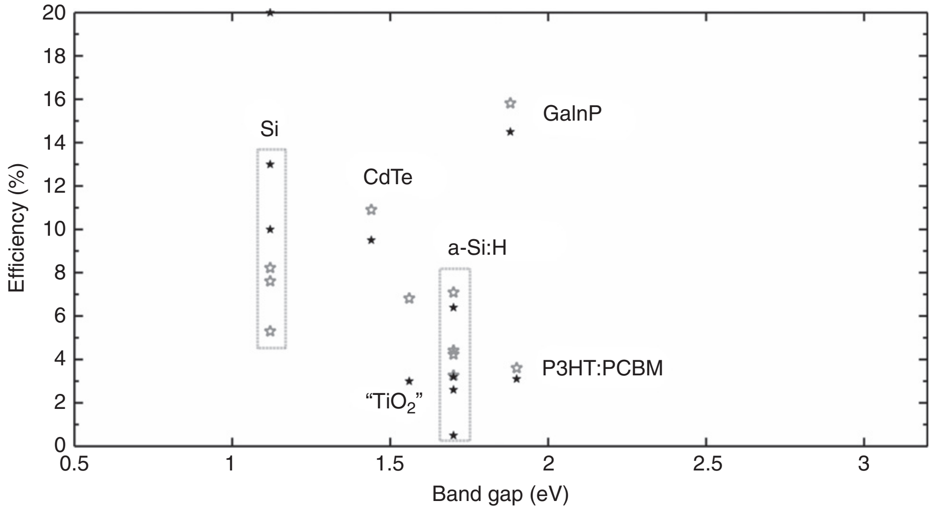


Figure 22 Measured efficiencies of a series of measurements of different sample groups at STC (solid symbol) and at 9.1 W m^{-2} OSRAM Lumilux 840 W fluorescent tube daylight lamps, 25 ± 2 °C (open symbol). Here TiO_2 stands for DSCs and P3HT:PCBM for polymer solar cells [35].

Although the measured devices were far from their ideal efficiency, all devices were within the theoretical predictions. **Figure 22** compares measurement results from STCs (black stars) to the results from measurements at 9.1 W m^{-2} OSRAM Lumilux 840 W fluorescent tube daylight lamps, 25 ± 2 °C. The results are average values from a series of measurements of one to six samples. In conclusion, the narrow band indoor light sources optimized for the human visibility function allow the use of higher band gap materials and a higher photon yield, thus enabling theoretical efficiencies close to 60% for white LED light (see **Figure 21**). The ideal band gap for these application ranges between 1.9 and 2 eV [35]. For different PV technologies, an efficiency of 4% up to 16% is found under conditions of artificial light (**Figure 22**). Surprisingly, polymer solar cells' efficiency is only slightly decreased with respect to their STC efficiency. Crystalline silicon solar cells in general perform better than a-Si solar cells in this experiment.

1.34.4.3 Rechargeable Batteries

A PIPV product that is powered by solar cells needs an energy storage device. This could be a capacitor that can be used for very short periods of storage [41] or a battery that can be used for longer periods of energy storage. In this section, we will focus on batteries, in particular on secondary batteries that can be recharged. In principle, a battery is a device that converts chemical energy contained in its active materials directly into electrical energy by means of an electrochemical oxidation–reduction (redox) reaction. A battery cell consists of three components: (1) the anode or negative electrode, (2) the cathode or positive electrode, and (3) the electrolyte or ion conductor. The combination of electrode materials defines the cell voltage and capacity of the battery cell. The name of the batteries is given by the anode and cathode materials, that is, nickel metal hydride (anode MH, cathode NiOOH). The capacity of a battery is determined by the amount of active materials in the cell and is expressed as the total quantity of electricity involved in the electrochemical reaction in terms of coulombs or ampere-hours. In **Table 2**, characteristic specifications are given for cells of different rechargeable batteries that are applied in PIPV.

Table 2 Practical specifications of cells of different rechargeable batteries that can be applied in PIPV

Battery type	*Nominal cell voltage (V)*	*Specific energy (Wh kg^{-1})*	*Energy density (Wh l^{-1})*	*Cycle life, 20% fading (cycles)*	*Efficiency (%)*
Sulfuric lead–acid	2.0	30–50	80–90	200–500	85
Nickel–cadmium	1.2	35–80	100	1500	80–95
Nickel metal hydride	1.2	75–120	240	300–500	
Lithium ion	4.1	110–160	400–500	500–1000	95–98
Lithium/manganese dioxide	3.0	100–135	265–350	300–500	
				2000	

Part of data adopted from Flipsen SFJ [42] and Kan [36].

1.34.5 System Design and Energy Balance

PV system design in a product context is a rather complex task because of the interdisciplinary character of product development, as discussed in Section 1.34.3. System design not only concerns an appropriate energy balance of the system components but also addresses issues related to manufacturability, costs, safety, operating temperatures, and environmental aspects.

Finally, the integration of PV systems in products should result in customer benefits like

1. a better functionality, increased comfort, or autonomy of a product
2. less dependency from the electricity grid
3. smaller batteries
4. fewer user interaction for recharging batteries [3].

Figure 23 aims to represents system design during product development of PIPV, by showing the relationships between the user, the product, and the integrated PV system and indicators that might be relevant for the decision making in the conceptual design stage.

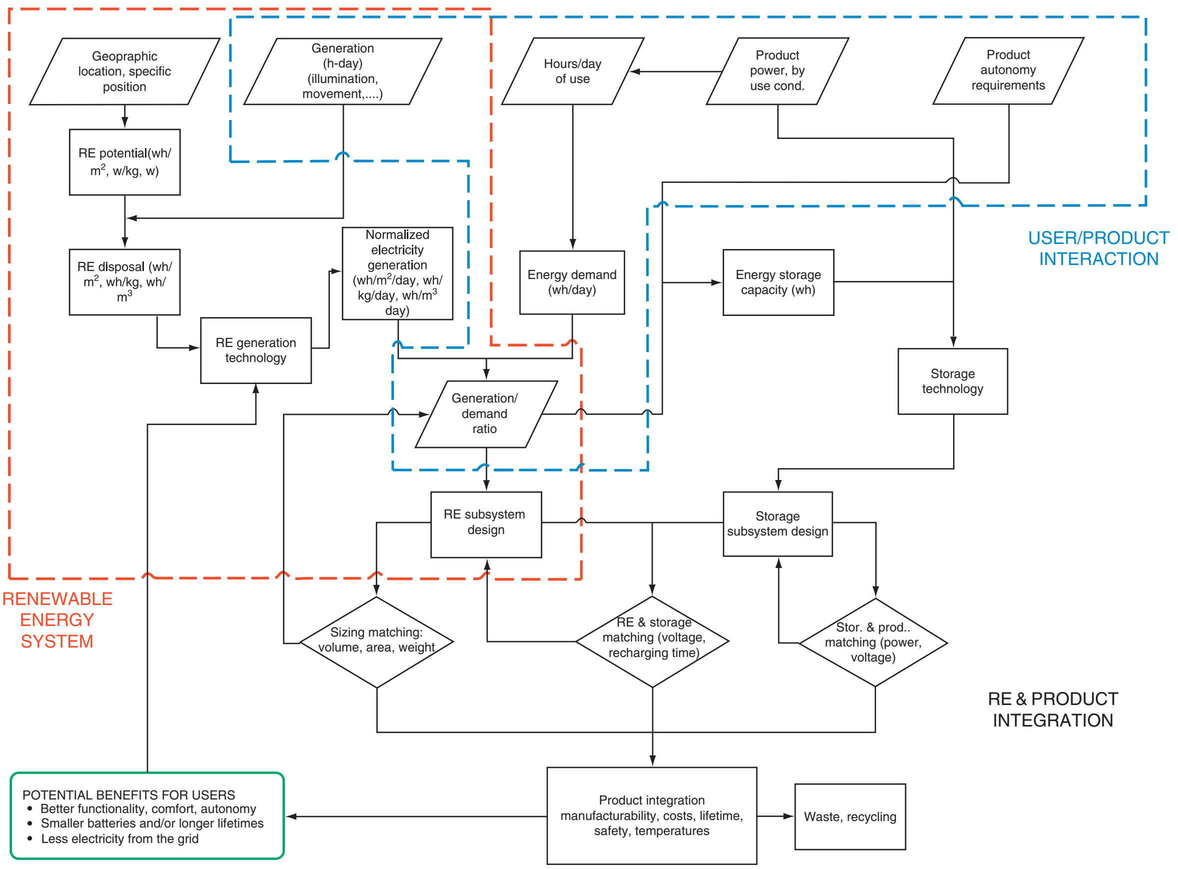


Figure 23 Issues involved in the integration of renewable energy sources, in particular PV technologies, in a product context.

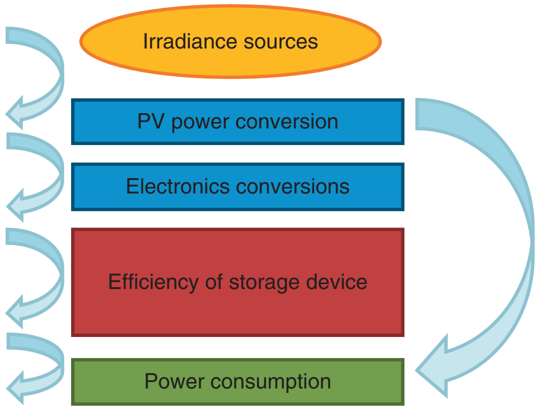


Figure 24 Flow scheme showing the energy chain of PIPV.

These indicators will be related to energy matching, final weight of the product, area required, volume, customer benefits, costs of the product, and safety and environmental indicators. Apart from this, it should be possible to produce a product with existing manufacturing technologies.

Within this vast context, the energy balance of a certain combination of PV system components, product, and user can be estimated, using the flow scheme shown in Figure 24. Next, we will give some guidelines for estimations of the energy balance of a PIPV.

1.34.5.1 Irradiance

Irradiance can be measured on locations of expected use of a PIPV. On the other hand, it might be convenient to simulate irradiance during the design process: Reinders [43], Reich *et al.* [15, 44, 75], and Tiwari and Reinders [45] developed different methods to determine irradiance in CAD tools. Moreover, at present the widely used design environment 3D Studio Max comprises a module with the established Perez model for irradiance simulation.

1.34.5.2 PV Power Conversion

The conversion of irradiance, G, should – at least – include the irradiance dependency of the efficiency, η_{PV}, of solar cells. In a certain period of time, the energy E_{PV} that can be produced by the solar cells is given by

$$E_{PV} = \int G(t) \times \eta_{PV}(G)dt \qquad [3]$$

1.34.5.3 Electronic Conversions

Power electronics in the device have a certain conversion efficiency that should be taken along in the estimates of the energy balance, in particular in low-power devices.

1.34.5.4 Efficiency of the Storage Device

The efficiency of a battery in a PIPV is affected by the charging patterns of the PV cells [69, 70]. Therefore, Gibson and Kelly [46] recommend determining the solar energy to charge conversion efficiency and to optimize it. This efficiency is given by

$$\eta_{PV-CC}(\%) = \frac{\text{average voltage (V)} \times \text{charge increase (Ah)}}{G(\text{W m}^{-2}) \times \text{PV area (m}^2) \times \text{time interval (s)}} \qquad [4]$$

1.34.5.5 Power Consumption

A reliable estimate of the power consumption of future users of PIPVs can be based on questionnaires and a quantitative insight of the power required for the different functions of a PIPV. The variability between user behavior can be used to set a minimum and maximum value for the area of PV cells needed to fulfill the energy demand of the future users, as indicated in Figure 23.

1.34.6 Costs of PIPV

Studies on the costs of PIPV that are publicly available are rare. Since electricity produced by solar cells is internally consumed in the product, common cost indicators in the field of solar energy such as 'levelized costs of electricity' (LCOE) do not apply to PIPV. However, cost calculations of PIPV should comply with generally acceptable approaches toward cost estimates of product manufacturing, purchase costs, and costs of ownership. Costs of PIPV should also refer to the functions provided by the product.

One study [18] regards costs of ownership of PV-powered LED lamp and compares these findings with different options for lighting in a BOP market in Cambodia [76]. (In economics, the BOP is the largest, but poorest socioeconomic consumer group. In global terms, this is the 2.5 billion people who live on less than $2.50 per day.) It is shown here as an illustration for cost calculations of PIPV that refer to the products' function, namely, providing light.

A PV-LED product consists of one or more LEDs, a rechargeable battery, and a small PV module. The LED lamp itself is embedded in a luminaire, which often has an aesthetically pleasing appearance. A small PV panel of typical 1 Wp could provide enough electricity for 3–4 h of lighting by a 1 W LED in most of the developing countries. The retail price of a small PV-powered LED lamp, including a rechargeable battery of up to 10 Wh, would be in the order of $12 up to $16. Compared with PV lanterns with compact fluorescent lamps (CFLs) – which cost about $60–80 – an LED lamp is reasonably cheap. However, compared with a kerosene lamp of $1, it is still a relatively high investment for poor families. After purchase, operating costs determine the costs of ownership of a certain option for lighting. Costs of operation comprise replacements of spare parts and costs of energy to power light, such as electricity for grid-connected (GC) lighting and fuel for kerosene lamps. Figure 25 presents for several lighting options the costs of ownership. It shows that grid-connected lighting is the cheapest option with $0.04 per 1000 lux-hours, but because access to the electricity often lacks, autonomous options for lighting have to be used. Figure 25 shows that kerosene lamps have very high costs of ownership of $12.00 per 1000 lux-hours, mainly due to fuel consumption. Halogen flashlights with costs of $3.40 per 1000 lux-hours require frequent replacement of primary batteries. The costs of ownership of a rental lamp (called Proseed) comprising a 1 W LED and a rechargeable battery are mainly due to the rental costs. A 1 W PV-LED lamp is the cheapest option of two PV-powered lamps, as shown in Figure 25. With costs of ownership of $0.22 per 1000 lux-hours, it is the cheapest option for autonomous lighting available.

1.34.7 Environmental Aspects of PIPV

Environmental aspects of products with integrated PV cells have not been evaluated extensively so far. As such, information about characteristic environmental indicators such as the embodied energy, the energy payback time, and CO_2 emissions of PiPV is not available. These environmental aspects can be determined by a life-cycle analysis (LCA). LCA is the process of evaluating the potential effects that a product, process, or service has on the environment over the entire period of its life cycle. The International Organization for Standardization (ISO) has defined LCA as "a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its lifecycle" [47]. The technical framework for LCA is illustrated in Figure 26.

PV lighting products can deliver a high quality of service in developing countries according to recent studies [19]. In general, it is assumed that PV lighting products have a better environmental profile than alternative lighting services. Though LCA data for PV cells seem to converge [48], still many uncertainties exist regarding the modeling of batteries in LCA studies [49, 50] due to variable charging regimes, lack of accurate data of materials used in batteries, and difficulties to estimate the energy required for several production processes for batteries. Maybe for this reason, LCAs of PIPV have not been widely explored [51–53]. Even the number of life-cycle analyses of a product that resembles PIPV, for instance, stand-alone PV systems, is rather limited. In 2000, three studies

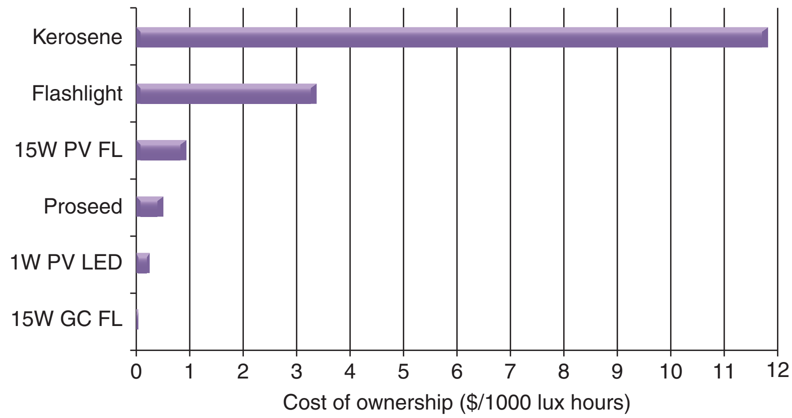


Figure 25 The costs of ownership of different options for rural lighting in $ per 1000 lux-hours assuming 3 h of lighting each day. Data are taken from Cambodia [18].

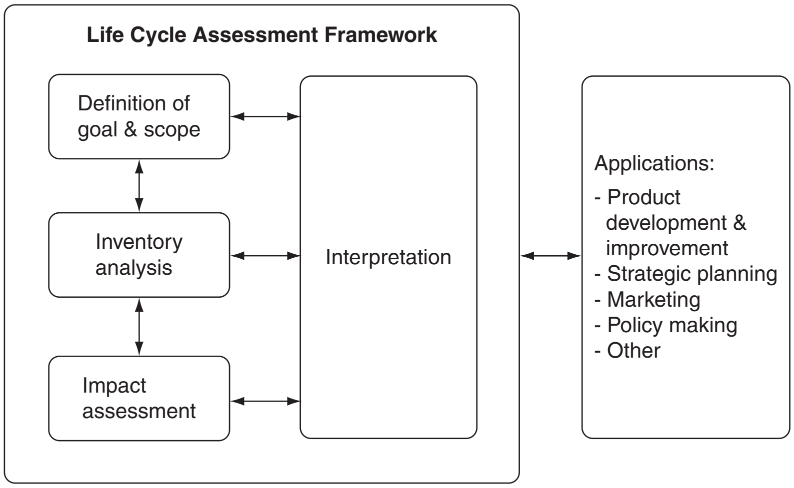


Figure 26 Framework for LCA from ISO [47].

have been executed [54–56] on small stand-alone PV systems leading to characteristic values for the CO_2 emissions and energy payback time of solar home systems (SHSs) of 49 Wp in Indonesia. The studies also covered a critical assessment of the selection of functional units of autonomous PV systems in developing countries. Relatively, recently, Celik *et al.* [57], Garcia-Valverde *et al.* [58], and Kaldellis *et al.* [59] published results of life-cycle assessments of stand-alone PV systems of, respectively, 12 kWp in Turkey, a 4.2 kWp stand-alone PV system in Spain, and stand-alone and grid-connected PV systems in Greece. All LCA studies about autonomous PV systems agree upon the fact that PV modules and batteries both contribute significantly to the environmental profile and the embodied energy of these systems.

To learn more about the potential environmental impact of small PV lighting products in South East Asia, Durlinger *et al.* [51, 52] executed a comparative LCA on these products. The results are shown in this section as an illustration of the application of LCA on PIPV. The LCA study was executed using software of Simapro with the EcoInvent v2.0 database [60] and the ReCiPe method [61, 62].

One of the products that was evaluated was a small PV lighting product powered by a 0.7 Wp a-Si solar panel. The product comprises two NiCd 2000 mAh AA-type batteries. Light is generated by six LEDs, delivering 42 lumens. It is assumed that the LEDs have a lifetime of 20 000 h of operation. The maximum daily operation time is 3.5 h and the lifetime of the entire product is considered to be 10 years.

For this product, most of the environmental impacts, as shown in Figure 27, can be attributed to production of the components, due to electricity used for the manufacturing of the PV panel and the printed wiring board, or materials used in the battery. In this case, the batteries contribute 23%, the solar panel 24%, and the printed circuit board with the LEDs 33% to damage to human health in the manufacturing phase. During the use phase, no processes take place; therefore, this phase has hardly any impact. An important contributor to impacts during the disposal phase is the disposal of the batteries.

The small PV lighting product was compared with an SHS. It was found that, in particular, the lead from the lead–acid battery in the SHS contributes significantly to the impacts on human health and ecosystems quality.

An important conclusion of the study of Durlinger is that solar PV lighting products have a lower environmental impact than conventional lighting solutions in developing countries, such as lighting services from kerosene lamps and powered by car batteries

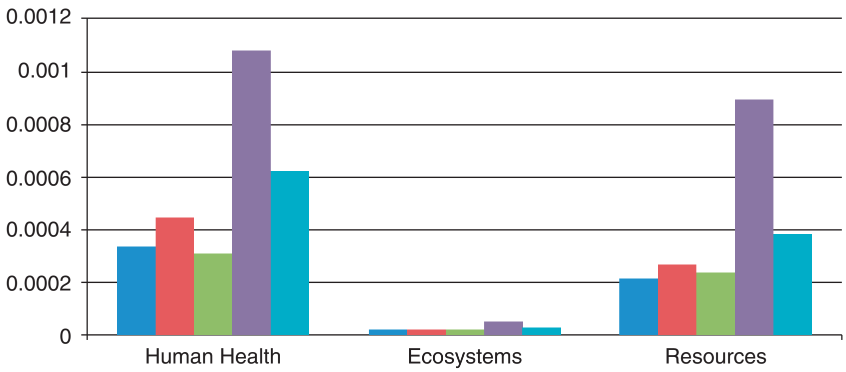


Figure 27 Normalized results per functional unit in endpoint impact categories, excluding the kerosene lamp, linear scale (World normalization). Small PV lighting system 1 (blue bars), small PV lighting system 2 (red bars), SHS (green bars), battery charged at station and CFL (purple bars), and grid connection and CFL (turquoise bars).

(see Figure 27). The environmental profile of small-size PV lighting products can be improved by 10% up to 50% by recycling of the batteries. From an evaluation of the accuracy of an LCA of PV lighting products, it can be concluded that impacts of these PV lighting products are lower or comparable to those of lighting by compact fluorescent lights powered by electricity from the grid in the South East Asian context. As such, they offer an environmentally beneficial lighting service for off-grid households. Although the results seem optimistic, there are some uncertainties in certain aspects of the inventory due to the relatively large impact of the battery (in relation to its disposal scenario) and the printed circuit board. An important conclusion of the study is that the environmental profile of solar lighting products can be improved by adequate battery waste management.

1.34.8 Human Factors of PIPV

Users' perception and users' experiences with PIPV are decisive in the adoption process toward these new innovative products. User perception refers not only to the perception of the real functioning of PIPV but also to more qualitative aspects such as the visual appeal of PIPV and the emotional reactions to PIPV. Despite this, only limited information is available about user studies regarding PIPV. We assume that for user studies on PIPV, existing methods such as interview techniques, observation, and participatory evaluations could be appropriate means to get insight in the user's reactions toward PIPV. The stage in which users should become involved should be as early as possible, preferably before or during the product development process to be able to implement the users' wishes as effectively as possible in the list of requirements of the product design. In the end, this will lead to a better acceptation of the final PV-powered product.

In this section, one of the few user studies available [44], which focused on an evaluation of a prototype of a PC computer mouse, will be presented as an illustration of the assessment of users' perspectives.

User tests with the PC computer mouse Sole Mio, as shown in Figure 28, were carried out during the period September–December 2007 at Delft University of Technology, University of Twente, Utrecht University, as well as at the KNMI by Reich *et al.* [44]. In total, 14 people used the mouse for several weeks in their daily practice, some doing a short test (5–6 weeks), others a longer test (10–12 weeks).

Users received instructions regarding the use of the mouse in advance. Each user kept a log to provide insight into their behavior and experiences. Halfway through the test and at the end, the logs served as a basis for an interview with each user to extract further relevant information. At the end of the test, a collective interview was held with all users at one location to extract further information regarding the interaction between the users themselves. The results of the user tests are listed as follows [44].

1. User assessment of the overall design

   Almost all users found the mouse rather big and poorly ergonomically adapted to the shape of the hand. The shape of the mouse (especially the width and height) clearly needs redesign.

   About half of the users liked the transparent cover as it gave a clear view of the solar cell. Some users liked to give advices about technical improvements of the mouse. A few users considered the PV-powered mouse as an ideal means to create awareness about sustainable energy.

2. Overall user expectations

   Most users did not have a clear idea about what to expect when they started the test. Everybody participated enthusiastically and pursued their own charging tactics.

   Across the whole test population, the varied performance of the mice clearly had a negative impact on the overall valuation of the concept. Still, the majority of users had faith in the product and believed that the problems related to the prototype stage of the Sole Mio device could be solved.

Figure 28 The prototype of the Sole Mio PV computer mouse that has been evaluated.

3. Sunbathing

   The test period happened to be in the darker part of the year: a real challenge for the mice's performance. Therefore, to charge the batteries of the Sole Mio, it was necessary to expose the solar cell in the product to a higher irradiance. This was done by so-called sunbathing, which actually implies the positioning of the mouse in the window sill. Positive judgments regarding sunbathing were especially related to the fact that the mouse performed well when treated well. However, users differed in their tolerance. A charging tactic followed by virtually all users (independently from each other and without having been instructed to do so) was to place the mouse in the window at the end of each working day. When left there over the weekend, this led to flawless operation of the mouse for quite sometime.

   Negative judgments regarding sunbathing were particularly related to the unreliability of the mouse after sunbathing. In some cases, the mouse was insufficiently charged, even after placing it on a brightly illuminated window sill for entire weekends.
4. User feedback on charging signal

   Two users indicated that it was unclear to them whether the signal indicated that charging was taking place or that charging was required. The LED signal functioned quite differently across the test mice, ranging from almost continuously blinking (and still being able to use the mouse for days) to hardly ever blinking (and flawless operation as well).

   Most users preferred the indicator to be as simple and energy-efficient as possible. One user would also like to have seen the impact charging had on the battery status.
5. User willingness to buy a Sole Mio

   Based on this test and on interviews held earlier in the project to identify user needs, two relevant types of customers were distinguished:
   - A group appreciating a PV mouse but preferring reliable, wired mice that are as cheap as possible
   - A group that seriously considers buying a PV mouse that would cost about €10 extra.

   Many users indicated to be willing to spend a total of approximately €50 for a Sole Mio mouse. Whether test users would actually purchase the Sole Mio, if it was available, could not be tested.

1.34.9 Design and Manufacturing of PIPV

Opportunities of the integration of PV technology in the final design of a product that can be manufactured partly depend, on the one hand, on the visual appearance of PV cells in the context of the product design and, on the other hand, on the possibility to shape and form PV cells and to attach them to the product. Roth and Steinhueser [20], Gorter *et al*. [24], Kan [36], Reinders and Akkerman [63], and researchers in the Europen PV-Accept project [64] have addressed these issues.

For PV cells characteristic, visual features of different PV technologies and possibilities to shape and form them have been shown in **Table 3**. It can be found that visual appeal, flexibility, and the number of possible operations vary considerably among the different technologies. Coloring is possible for c-Si and m-Si technologies, although it will affect the efficiency. For other solar cells, the use of colored glass sheets or colored plastics as a cover could bring in more variations with respect to their dark brown and grayish colors. a-Si and CIGS can be produced with customized patterns, and c-Si and m-Si can be decorated by grid designs that are different from the common H-pattern. Newly developed back-contact cells may be more appealing from a visual perspective.

PV cells or series of PV cells can be attached on product surfaces in the following ways:

1. Attachment on a surface and covering with a glass sheet or a plastic sheet
2. Attachment on a surface and covering with resin, for instance, epoxy resin
3. Lamination in between plastic sheets and next attachment on a surface
4. Encapsulation in fiber-reinforced plastic and next attachment on a surface.

The fourth option has the advantage of preshaping a series of PV cells into a mold that is injected with the fluid plastic, the so-called injection molding.

The selection of glass or plastics – such as epoxies, fluorides, polyolefins, and silcons – that could be applied for the protection of solar cells in products is based on variables like transparency, transmittance, service temperature, thermal expansion coefficient, glass temperature costs, weight, and expected lifetime in relation to the product's expected lifetime. Due to the last reason, we assume that for PIPV in consumer products, less stringent criteria are set to UV stability and impact resistance compared with PIPV in business-to-business products that must be able to endure harsh outdoor environments for many years.

Though less visible, the selection of a battery influences considerably the final design of a product regarding shaping, flexibility, costs, maintenance, and operating temperatures of the product. **Table 4** lists these design variables for a number of battery technologies that are frequently applied in PIPV.

Table 3 Design aspects of different PV technologies

Type of PV cell	*Maturity*	*Color/surface/other*	*Typical area (mm)*	*Typical thickness (μm)*	*Flexibility of cell*	*Operations on cells during design and manufacturing*
c-Si	Highly commercially available	Blue, dark-gray, or black/smooth surface with silver grid patterns on top/cells can be colored (gold, orange, pink, red, green, silver) by variable Si_3N_4 layer/decorative grid patterns possible	156×156	>180 to 220	Low	Bending only to a limited extent; laser cutting; heating; injection transfer molding in plastics; lamination in plastics
m-Si	Highly commercially available	Shiny blue, dark blue/shiny grains, smooth surface with silver grid patterns on top/cells can be colored (gold, orange, pink, red, green, silver) by variable Si_3N_4 layer/decorative grid patterns possible	156×156	>180 to 220	Low	Bending only to a limited extent; laser cutting; heating; injection transfer molding in plastics; lamination in plastics
a-Si	Commercially available	Dark brown or black/smooth surface with light lines/cell interconnects/patterned deposition is possible	Customizable from 10×10 to 1000×2000	<1	High	Bending; lamination in plastics; deposition on curved surfaces; cutting not possible
CIGS	Commercially available	Gray or black/smooth surface with light lines/cell interconnects/patterned screen printing is possible	Customizable from 10×10 to 1000×2000	1–3	High	Bending; lamination in plastics; deposition on curved surfaces; cutting not possible
CdTe	Highly commercially available	Brownish/smooth	Customizable from 10×10 to 1000×2000	1–3	Low	Heating
III–V three junction	Mainly available for space applications, concentrators	Black/smooth	40×80 80×80	140–200	Low	Connection to ceramics
III–V single junction, thin film	Commercially available for terrestrial applications	Black/smooth	40×80 80×80	5	High	Bending; heating; injection transfer molding in plastics; lamination in plastics
DSC	Available	Red or brown/transparent and smooth/cells can be colored by dye molecules	Customizable	1–10	High	Bending; lamination in plastics
Polymer	Limitedly available	Orange, red, or brown/smooth	Long strips, customizable	<1	High	Bending; lamination in plastics

Part of data adapted from Kan [36] and extended with manufacturing data.

Table 4 Design aspects of different battery technologies

Battery type	*Shape*	*Flexible*	*Safety/ environmental*	*Operating temperature (°C)*	*Maintenance*	*Specific costs (€ Wh^{-1})*
Sulfuric lead–acid	Cubic	Fluid	Hazard of shock/ release of gas	−20 to 60	3–6 months	0.50
Nickel–cadmium	Cylindrical	No	Toxic	−40 to 60	30–60 days	3.00
Nickel metal hydride	Cylindrical	No		−20 to 60	60–90 days	3.80
Lithium ion	Cylindrical, prismatic and pouch cells	Yes	Flammable	−20 to 45	Not necessary	9.50
Lithium/ manganese dioxide	Cylindrical, prismatic, and pouch cells	Yes		0–45	Not necessary	19.00

Part of data adapted from Kan [36] and Flipsen [42].

1.34.10 Outlook on PIPV and Conclusions

Because of the fact that the research field on PIPV has emerged only recently, it can be understood that from the review of the existing literature on PIPV, it follows that still many relevant issues regarding PIPV have not been addressed thoroughly. To foster innovation in PIPV, the following information should become available through research:

- Energy-efficient management of PIPV–battery systems
- Methodologies for cost calculations of PV technology in a product context
- Environmental aspects of PV technology in products
- Manufacturing of integrated PV in products
- The application of PIPV in combination with other renewable energy sources
- Users' experiences with PIPV in different product categories.

All the examples of PIPV products shown in Section 1.34.2 show that PIPV can be applied well in different product categories and various markets. With the steep decrease of prices of conventional PV technologies, such as c-Si, the emergence of low-cost PV technologies such as polymer solar cells and a slight decrease of the power demand of products induced by technological advances, PIPV might become a respectable widely applied energy source. For instance, PIPV might become common in public lighting products and other urban furniture in public spaces. We also expect that the market of PV-powered LED lamps in BOP markets might grow in the forthcoming years. In this chapter, it was shown that PIPV can offer energy to products with a wide range of power demand. Therefore, we believe that PIPV will be further developed in the field of microenergy harvesting, that is, for sensors and security, and that it will be applied more often in boats and cars.

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