1

State of the Art

1.1 INTRODUCTION

This chapter is structured in two parts. Firstly, the available knowledge with regard to low-power energy sources is examined (section 1.2). This review indicates that solar (photovoltaic) cells have a number of advantages within this group. For the example of indoor photovoltaic (IPV) products, therefore, the intellectual property (section 1.3) and IPV taxonomies (section 1.4) are investigated. These are presented with respect to their generic parameters. The links between the different taxonomies are summarised in Table 1.3 and show the wealth of information that may be available at the beginning of an IPV design project.

In the second part of this chapter, the areas where information is less complete are considered as well as how this book proposes to fill these gaps (see section 1.5).

1.2 LOW-POWER ENERGY SOURCES

The trend of the number of electronic devices per person, in the first world at least, has been steadily increasing for decades. From ostensibly electronic products, such as the mobile phone, to the more imperceptible, such as embedded systems, the issue of providing sufficient energy is ubiquitous. In some cases it is relatively simply resolved by the use of exisiting infrastructure: for example, automotive products have their own power supply and this is usually already fed throughout the vehicle. However, for each incremental device, the extra wires must be balanced against their extra cost and weight. Providing each electronic device with an independent power supply may therefore be an attractive option in order to avoid cost, weight or design complication. Unfortunately, existing technologies generally require recharging or refuelling (see the lower part of Table 1.1). An example of this is the power source for a mobile telelphone, which users are accustomed to recharging with the inconvenience of reduced flexibility of use during this period.

Designing Indoor Solar Products – Photovoltaic Technologies for AES J. F. Randall
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Table 1.1 Energy comparison of low-power (<1W) energy sources

Low-power technology	Typical power density ($\mu W/cm^3$)	Typical annual energy density (J/cm^3)	References
Ambient energy sources			
Solar (indoor – near window)	1 000	10 510	Table 3.3
Solar (indoor – electrical source)	100	1 050	Table 3.3
Shoe insert	300	200	[232]
Vibrations (mechanical)	45	120	[215]
Push button	300	80	[119]
Acoustic noise (100 dB)	1	32	[215]
Peltier thermoelectric (10 °C gradient)	15	20	[218]
Low-power energy sources requiring refuelling			
Wind up clockwork generator	210 000	27 600	[119]
Hand squeeze generator	120 000	15 700	[119]
Microheat engine (unlimited fuel)	400	12 700	[215]
Fuel cell (PEMFC) (unlimited fuel)	400	12 700	[215]
Fuel cell (PEFC) (unlimited fuel)	70	2 210	[174]
Electrochemical (single-use lithium)	45	1 420	[215]
Microbial fuel cell (unlimited input)	15	470	[192]
Electrochemical (rechargeable lithium)	7	220	[215]
Low-power energy sources without refuelling			
Nuclear	15	470	[133]
Radio frequency	10	130	[209]

Another trend that has persisted much longer than the use of electronic devices is the tendency of humans to spend a greater proportion of time in protected environments, especially buildings. The confluence of these two trends is the automation of the built space.

An approach that avoids the need for user intervention and extra wiring and, in principle, assures that the product is available whenever required is the collection and use of ambient energy in the environment. The word ambient means ‘encompassing on all sides’ and energy is the ‘capacity for performing work’ [264]; therefore, ambient energy systems seek to collect, in their immediate environment, those energetic flows that have the potential to be put to use. Both this energy (and this potential!) may or may not be perceptible to humans. This definition can be embellished by other aspects of ambient energy. For some it may mean the convenience of reduced maintainance while for others it may be the elegance of being self-sufficient from resources that will not be depleted.

A number of ambient energy technologies exist, compared in the top part of Table 1.1. One of the main reasons that they are not more widely used is that their energy density is generally relatively low (less than 200 J/cm^3 per annum). Also, no single technology can be applied in all environments [217].

One exception nevertheless stands out – the solar (or in the jargon ‘photovoltaic’ cell). As can be seen, the annual energy densities of solar technology under different indoor conditions have the same orders of magnitude as those of other technologies that require regular recharging. In the next sections, solar technology is therefore explored.

1.3 INTELLECTUAL PROPERTY RIGHTS

Patents may serve the product designer at two stages of a project. At the outset, the general technological area can be checked. Once the definition of the product is clarified, a more focused search ensures that no prior art is contravened. Both of these stages often provide a wealth of indirect knowledge and ideas which serve to inspire the designer. They also allow the designer to form an opinion on the extent of protection that their work will require.

1.3.1 Methodology

In this section, the first stage (technological area) is assessed. This area was considered with regard to four criteria that form the basis of an indoor photovoltaic (IPV) sensor product. Charge storage was included as this indicates a higher-power product than with solar alone. However, a ceiling of 100 mW was set on the consumption of the application. Each criterion was associated with keywords that were used as the basis of the search (Table 1.2) [59].

1.3.2 Results

The prior art analysis returned a total of 137 abstracts. Of these, 74 were obtained in hard copy. These, prioritised by relevance to the IPV concept, showed that 59 (80%) made reference to a photovoltaic system and, within these 59, the largest four groups of patents satisfied the following criteria:

1. Photovoltaic (PV), low light, low power, storage.
2. Photovoltaic (PV), low power, storage.
3. Photovoltaic (PV), low power.
4. Photovoltaic (PV), storage, mid power (<100 mW).

The same results are presented graphically in Figure 1.1. The patents that could present the main challenge to the further implementation of the IPV concept are in group 1 (PV, low

Table 1.2 Basis for author's intellectual property rights research

Criteria	Condition	Keywords
Photovoltaic	Is technology mentioned?	Photovoltaic, photoelectric, solar, photocatalytic, photoinduce
Indoor light	Is 200 lux specified or implied?	Domestic, indoor, low light, low intensity, lux
Charge storage	Is any mentioned?	Portable, battery
Application	Is power less than 100 mW?	Low power

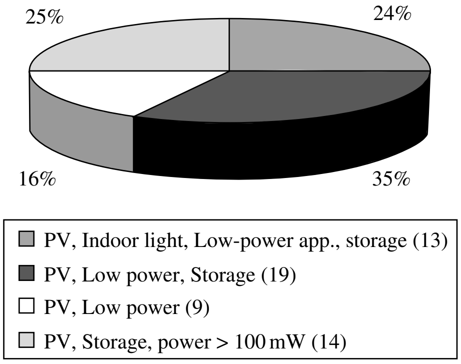

Figure 1.1 Proportion of the 55 most appropriate patents read and the criteria that they satisfied

light, low power, with storage) on the basis that all other patents reviewed were lacking one or more criteria. Of the 13 patents in group 1, the patents could be further sorted by relevance to storage technology, for example (i.e. the nine accumulator-based and four capacitor-based solutions protected).

Taking the nine accumulator-based patents, the following comments can be made:

FR 2 618 242: Dispositif émetteur à cellule photovoltaïque – may be important for sensor and communication application.
FR 2 606 912: Dispositif formant émetteur à cellule photovoltaïque – may be important for sensor and communication application.
EP 0 681 549: System for identifying, searching for and locating objects – may be important for specific application.
JP 03015168: Photo energy storage device – makes no mention of application in the abstract.
GB 2320 356: Combined liquid crystal display and photovoltaic converter – may be important for specific application.
WO 99/34337: Chip card for paying freeway tolls – may be important for specific application.
EP 0 856 738: Extern gespeiste Anordnung mit einer elektronischen Anzeige und/oder einer Kommunikations-Schnittstelle – may be important for specific sensor and communication application.
EP 0 918 212: Verfahren zur Erfassung und Auswertung von temperaturabhängigen Verbrauchswerten oder Messwerten anderer physikalischer Grössen – may be important for specific sensor application.
EP 0 935 099: Elektrisches Haushaltgerät mit Solarzelle – may be important for upgrading household equipment applications.

The four capacitor-based design patents are as follows:

EP 0 871 018: Electrically isolated interface for fluid meter – may be important for such fluid meters, but does not stock the energy.
JP 08036070: Solar cell timekeeper – may be important for horological applications.

FR 2 694 109: Ticket réutilisable d'affichage de données temporaires, notamment ticket de parking – may be important for display applications.
US 5 208 578: Light powered chime – may be important for such applications.

1.3.3 Conclusion

Based on the above research, it can be concluded that the IPV concept has been protected to some extent, but in an application-specific way. This implies that, for extending the use of the IPV concept in other applications, no intellectual property protection is in place. Furthermore, even if applications of the same kind as those found in the patents were to be targeted, this does not imply that the above patents would be automatically contravened. Once the targeted IPV concept product(s) has been specified, it would then be possible to perform a more focused prior art investigation.

1.4 IPV TAXONOMIES

As the product design of just one type of application is considered, expected requirements and typical characteristics may be predicted. The latter form the basis of the following classifications which may serve to *guide* the designer as they come at the price of some subjectivity and simplification. The purpose of such taxonomies for the designer is to appreciate the implications of their initial assumptions and decisions which, as will be seen in Section 2.3, may have a significant impact on the final design.

1.4.1 Product Use Taxonomy

IPV product or application descriptions may be sorted into three groups: ***toys***, ***tools*** and ***sensors***. Each of these has typical design priorities and useful life:

1. *Toys* are for amusement, especially of the young. These are typically low-cost and are not expected to last more than one or two years.
2. Solar ***tools*** include the pocket light, the calculator, the watch and the automatic stapler. They are expected to be available for use at all times, even if their use phase is relatively short compared with product life. As the customer benefits from not needing to change or actively recharge the battery, they may be more expensive than their battery-powered equivalents. Typical product life will be between two and five years.
3. ***Sensors*** measure one or more variables and communicate these, increasingly by wireless. For sensors in the security or comfort market sectors, reliability can be expected to have priority over cost. Typical expected life is between three and ten years, despite the fact that the useful life of the building in which they are installed is at least 20 years.

1.4.2 Function (or Circuit) Taxonomy

While the product use taxonomy may be useful at a relatively high level, the application functionality required forms a basis for product specification, such as the typical electronic circuit required. Functional categories ranked in roughly increasing energy consumption include ***respond to light***, ***display***, ***light***, ***move***, ***compute***, ***amplify*** and ***communicate*** (in this case understood as wireless communication).

The ***respond to light*** function is typical of the simplest solar-powered products: toys, mobiles, moving shop window presenters and simple light meters. It is associated with an electronic circuit with no charge storage between the solar cell and the application, R_A (see Figure 1.2).

Sense and display products often use a (non-backlit) liquid crystal display (LCD); such applications, R_A, include calculators, temperature gauges or electronic weighing scales. Given that LCDs require a certain amount of light to be read implies that only a small amount of charge storage is required. This is often achieved with a capacitance (see Figure 1.3).

Light, ***move***, ***compute*** or ***amplify*** functions are required of pocket torches, some toys, microcomputers and hand-held televisions respectively. The charge storage associated with these for solar-powered systems is generaly a rechargeable battery, such as Figure 1.4. In this diagram, the Zener diode is used as an overcharge protection for the battery. The Zener diode may be used in the same way and for the same purpose in other circuits with charge storage, such as Figure 1.5.

Wireless communication even for short-range devices (SRD) with a range of a few hundred metres may not be possible using the power of battery alone. This is because storage system high-current responsiveness and low-storage self-discharge are generally mutually exclusive.

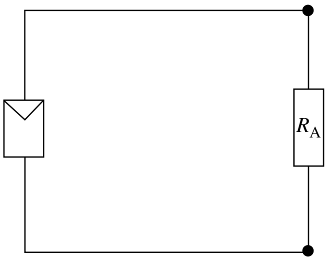

Figure 1.2 Typical circuit diagram for respond to light functionality

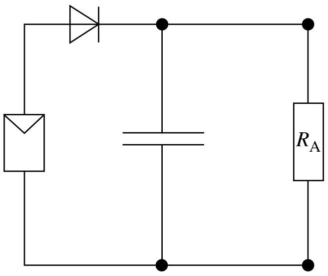

Figure 1.3 Typical circuit diagram for sense and display functionality

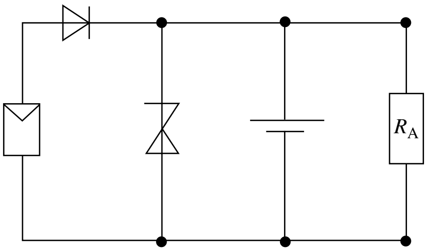

Figure 1.4 Typical circuit diagram for light or movement functionality

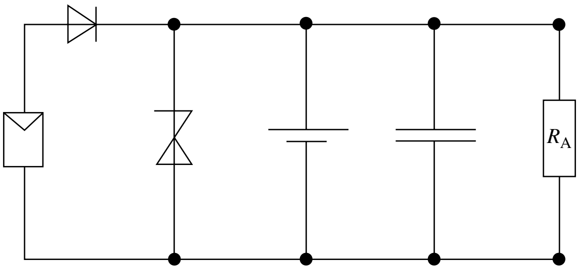

Figure 1.5 Typical circuit diagram for wireless functionality (R_A represents the application)

To compensate for this, a hybrid solution (see subsection 6.6.2) may be used, e.g. a capacitor and a rechargeable battey, such as the circuit in Figure 1.5.

1.4.3 Radiant Energy Application Taxonomy

By considering where and how the product will be used within the built space, it may be possible to determine the amount of radiant energy it will receive.

The typical ***location*** of the product within the built environment will determine the prevalent spectral type of radiant energy as well as typical intensity. In many cases there will either be a majority of daylight or electric light, see the ‘crossover point’ in subsection 3.4.3.

Another classification can be made as to the solar module ***orientation*** with respect to the prevalent radiant energy. In the case of a mobile device (e.g. a wristwatch), it may be impossible to determine this fully [36]. However, for those products that have a relatively fixed orientation such as by being wall mounted or set in a holster against the window, a typical solar module orientation with respect to the prevalent energy source may be specified.

Given typical radiant energy (see Chapter 3), the mean electrical energy that will be available to the application may be estimated. As an example, assume that a proposed product has a solar module active surface of 10 cm^2 which on average converts 5% of the incoming radiant energy into electrical charge; let the mean ratio of charge used by the application to charge available be 50%. From the figures in Table 3.4, the electrical energy that may be used by the application in an average month from a typical fluorescent source might be 7 mW h/month; daylight might deliver 125 m W h/month.

Table 1.3 Typical energy consumption of indoor consumer electronic devices as measured by the author

Application description [Reference]	Product use taxonomy	Main function (or circuit) taxonomy	Voltage (V)	Running power (mW)	Mean use per day (min)	Mean energy per day (mWh)	Mean energy per month (mWh)
Suited to fluorescent source in example							
Basic arithmetic calculator	Tool	Display	1.4	0.01	20	0.005	0.14
Wristwatch	Tool	Display	1.5	0.0005	720	0.01	0.21
Weighing scales (Maul tronic) [210]	Tool	Display	3.0	0.05	1	0.1	2
Wireless security key	Tool	Wireless	12.0	56	0.2	0.2	6
Suited to daylight source in example							
Wireless door movement detector	Sensor	Wireless	10.3	52	1	1	33
Alarm clock	Tool	Display	1.5	8	5	2	62
Fire sensor	Sensor	Amplify	9.0	58	0	2	65
Desktop automatic stapler	Tool	Move	3.4	578	0.3	2	72
TV/Video remote control	Tool	Wireless	3.0	27	5	3	80
PDA Casio PV S250 [229]	Tool	Compute	3.2	15	20	5	150
Wireless presence detector	Sensor	Wireless	9.6	36	1	8	230
Door lock remote controller	Tool	Wireless	3.0	60	10	10	300
Hand-held radio	Tool	Amplify	1.2	18	30	12	260
PDA Palm Pilot Series 1	Tool	Compute	3.0	75	10	13	400
Laser pointer	Tool	Light	3.0	66	15	17	500

Table 1.3 (Continued)

Application description [Reference]	Product use taxonomy	Main function (or circuit) taxonomy	Voltage (V)	Running power (mW)	Mean use per day (min)	Mean energy per day (mWh)	Mean energy per month (mWh)
Pacemaker	Tool	Amplify	6.0	0.7	1440	17	520
PC mouse (wired)	Tool	Amplify	5.0	75	15	19	560
Pager	Tool	Wireless	1.5	0.9	15	22	650
White LED hand torch [159]	Tool	Light	3.6	72	20	25	750
Bicycle lamp (5 LEDs)	Tool	Light	3.0	60	30	30	900
Alice microrobot	Tool	Move	3.0	7.5	120	35	1 040
Hearing aid	Tool	Amplify	1.3	1.8	1440	43	1 296
Wireless mouse (Logitech) [32]	Sensor	Wireless	3.2	19	5	45	1 360
PDA Palm III xe [229]	Tool	Compute	3.2	42	20	53	1 600
Solar torch	Tool	Light	1.0	130	30	65	1 950
Light sensor (bluetooth)	Sensor	Wireless	2.4	96	48	77	2 320
PDA Psion Revo [229]	Tool	Compute	3.2	109	20	89	2 680
Hand lamp	Tool	Light	2.0	400	30	200	6 000
Portable radio	Tool	Amplify	3.0	150	240	600	18 000
Furby (toy)	Toy	Move	6.0	600	60	601	18 030
Translator	Tool	Compute	3.0	1800	30	900	27 000
Mobile phone	Tool	Wireless	3.6	720	45	1210	36 300
Khepera mobile robot	Tool	Move	5.0	1250	60	1262	37 900
Portable personal computer (laptop)	Tool	Compute	4.0	960	120	1929	57 900
Hand-held television	Tool	Amplify	4.5	2385	60	2395	71 900

1.4.4 Mean Energy Taxonomy

While there are those for whom power and energy can be considered synonymous, e.g. [34], for IPV design this might be a serious oversight. This is because, to achieve the low energy consumption described in subsection 1.4.3, the application should be on standby (not running) for the majority of the time. With this in mind, applications must be considered with regard to their mean energy consumption and not their power rating when running. The typical actual consumption of potential applications is shown in Table 1.3. These are sorted by increasing mean energy consumption.

It is noteworthy that many applications that users may intuitively think would have potential to be powered from ambient energy consume, in their present designs, orders of magnitude more energy than is available. A good example of this is the mobile telephone. The latter suffers from the further disadvantage that its outer surface may be covered for the majority of its useful life. The energy consumption values in Table 1.3 are indicative and may be reduced by improved design. Other techniques for designing applications with improved energy feasibility are considered in the ensuing chapters, especially Chapter 7.

Table 1.3 forms the basis for comparisons between the various taxonomies. For the examples shown, no overriding trend can be seen between energy consumption and product use (subsection 1.4.1) or main function (subsection 1.4.2) taxonomies. However, for the example mentioned in subsection 1.4.3, it can be seen that the ‘display’ function may be powered by fluorescent sources; also, wireless applications may be powered by a daylight source. Those applications for the example mentioned above that might be powered by daylight sourced energy but not by electrically sourced energy are indicated.

In reviewing the mean use per day, it can be seen that the majority of applications function for less than one hour per day. This implies that they are on standby for the rest of the time and underlines the importance of standby power or current.

1.5 IPV GAPS IN KNOWLEDGE

While the importance of information gleaned at the outset of a design project cannot be too highly emphasised (see also subsection 2.3), some will inevitably be lacking. These gaps in designer knowledge form the directions of this work.

1.5.1 Radiant Energy Available

Many professionals are involved with the radiant energy found in the built space, but few are interested in the wavelength range collected by solar cells. The most common assessments are made in the units of a standard human eye (photometric or lux). Other analyses cover the thermal radiation range, for human comfort, for example. Radiant energy in the built space to which solar cells are sensitive is therefore characterised in Chapter 3.

1.5.2 PV Solar Cells

The literature supporting the technical understanding of how PV solar cells work is usually couched in the terms of physics. This may discourage some designers from exploring the parameters used to characterise PV and ultimately appreciating what opportunities of performance improvement are possible, especially for indoor products. Both of these issues are addressed in Chapter 4.

When collecting information on solar modules from suppliers, there is a noticeable dearth of comparable data of performance at indoor light intensities and spectra. This is therefore investigated in Chapter 5. A corollary of the lack of industrial information is that there is little research interest in characterising photovoltaics within the ranges of intensity and spectra found indoors. This is reflected in the lack of modelling in this area. Models are therefore developed in Chapter 5 that match the measured performance of 21 solar cells representing eight different photovoltaic technologies.

1.5.3 Charge Storage

Most renewable energy systems are not practical without some storage of the energy. In IPV this is in the form of charge storage. Given that this element may be the most expensive, voluminous and heavy within the IPV energy system, in Chapter 6 a number of ways of ensuring that it is correctly specified are presented, including a model of the relationship between storage cost and capacity required.

1.5.4 Energy Source Guidelines

Finally, in Chapter 7, the lack of a practical guide to ambient energy source design is addressed.

1.5.5 Applications

Although nanowatt standby applications are technically feasible, such as regulators and microcontrollers (e.g. [162]), their emergence on the market is limited.

1.6 CONCLUSION

This chapter opened by considering the low-power energy systems that are available, with special focus on ambient energy systems (see section 1.2). This section shows the advantages of indoor photovoltaic solar cells for powering such systems. The next section (section 1.3) therefore assesses what intellectual property already exists in the area of indoor photovoltaics and concludes that in general there is little protection. However, for the specific cases mentioned, more patent research would be necessary once the details of the proposed product were known.

With this is mind, in section 1.4, the available photovoltaic products are investigated and catagorised into a number of taxonomies. These focus chiefly on the product with respect to its function, use pattern and consumption. The product environment is also considered in terms of the ambient energy that will be available to power the device.

In the final section (section 1.5) the boundaries of available information to the engineering designer are set. The way in which the following chapters contribute to filling these gaps is summarised.