To my grandparents: Eileen, Frank, Madeleine and Xavier

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Grand St. Bernard pass, 2469m 4th April 2003

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Col du Grand St. Bernard, 2469m, 4 avril 2003

Abstract

Abstract The use of ambient energy systems (AES) for indoor applications is often limited to products of low power (microWatts, μW). This thesis defends the case that, under certain conditions, AES based on photovoltaic solar cells may be used for higher power devices (mW rating). Such devices, which are expected [Cha98], would allow fully autonomous sensor nodes which hold a number of advantages. One is that wiring, which may otherwise be the most capital expensive element of a sensor network installation, could be avoided. Alternatively, the sensor network battery maintenance could be prevented.

The motivation for the thesis is both financial and ecological, as two examples for the United States show: it has been estimated that a source energy saving of 55 billion US$ per annum, or the equivalent of 35 million metric tonnes of carbon emissions, could be made with building automation based on AES sensors [Sil01]. Another example supports the case that using AES to extend battery life would reduce toxic waste as batteries represent "less than one per cent of total municipal solid waste generated" but "accounted for nearly two-thirds of the lead, ninety percent of the mercury, and over half of the cadmium found in the waste" [McM98]. A further motivation is the trend towards more energy efficient and comfortable builings reflected in the Swiss Minergie standard [AMI02]; the latter would be furthered by the use of building sensors.

The main avenues of this engineering design research are:

i) power management: ensuring that the application and AES consume minimal energy

ii) characterising the influence of the environment on the ambient energy available

iii) technological selection: with respect the conversion of ambient energy into charge and the storage of this charge

iv) design methodologies that should be applied during all design process phases

Following these avenues, the case of solar (photovoltaic) cells is considered. The main contributions are:

a) two forms of a phenomenological model of solar cell response under indoor radiant energy conditions

b) the validation of a) with extensive experimental results which are necessary to the engineering designer but were hitherto unavailable

c) a model for application functionality confidence with respect to charge storage device capacity

d) a characterisation of the radiant energy indoors that solar cell collect

e) a range of design guidelines and heuristics that provides the designer with a complement to existing product design methodologies for indoor AES

Overall, this work identifies the technological barriers which at present hinder the further use of ambient energy sources. The

results obtained, however prove that solutions can be found by following the proposed design guidelines; hence further achievements can be expected.

Version abrégée

L'usage de systèmes d'alimentation utilisant l'énergie ambiante (SAES) pour des applications d'intérieur se limite souvent aux produits de basse puissance (microwatts, mW). Ce travail défend la thèse que, sous certaines conditions, les SAES basés sur des photopiles (solaires) pourraient être employés pour des dispositifs de puissance plus élevée (milliWatt, mW). De tels dispositifs, qui seront bientôt disponibles [Cha98], permettraient, par exemple, la mise sur pied de réseaux de capteurs entièrement autonomes, évitant ainsi le câblage, qui est souvent l'élément le plus cher de telles installations. Dans le cas de réseaux de capteurs alimentés par des batteries, c'est la maintenance de ces dernières qui s'en trouverait réduite.

Cette thèse est motivée par des considérations tant économiques qu'écologiques, comme l'illustrent deux exemples provenant des États-Unis. Dans le premier exemple [Sil01], il est estimé qu'une réduction de la consommation d'énergie équivalente à 55 milliards US$ par année, c'est-à-dire l'équivalent de 35 millions de tonnes d'émissions à base de carbone, serait envisageable en utilisant systématiquement des capteurs SAES dans les bâtiments. Le deuxième exemple [McM98] démontre que l'augmentation de la durée de vie des batteries qu'apporterait l'usage des SAES réduirait sensiblement la quantité de certains déchets toxiques. En effet, bien que les piles ne représentent que moins d'un pour-cent des déchets solides municipaux, elles représentent à elles seules presque les deux-tiers du plomb, les quatre-vingt-dix pour cent du mercure, et plus de la moitié du cadmium trouvé dans les déchets. Une motivation supplémentaire est la tendance vers des bâtiments plus confortables qui se reflète dans la norme suisse Minergie [AMI02]; le succès de ce dernier pourrait-être amélioré en utilisant des capteurs.

Les principaux axes de cette recherche sont:

i) la gestion de la puissance: visant à assurer une consommation minuscule d'énergie des SAES.

ii) la caractérisation de l'influence de l'environnement sur l'énergie ambiante disponible.

iii) le choix des technologies en tenant compte du rendement de la conversion de l'énergie ambiante en charge ainsi que des performances du stockage de charge.

iv) des méthodologies qui s'appliquent à toutes les phases de la conception.

L'étude des cellules (photovoltaïques) solaires selon cette approche (d'axes) à donné les principales contributions suivantes:

a) deux formes d'un modèle phénoménologique de la réponse à l'énergie radiative de photopiles à l'intérieur de bâtiments.

b) la validation de a) par d'amples résultats expérimentaux, indispensable à la conception d'équipements SAES mais qui n'étaient jusqu'à présent pas disponibles

c) un modèle du taux de service du SAES en fonction de la capacité de stockage de charge

d) une caractérisation de l'énergie radiative captée par les photopiles solaires à l'intérieur de bâtiment.

e) une gamme de directives et d'heuristiques de conception de SAES, qui fournissent un complément aux méthodologies existantes.

De façon générale, ce travail identifie les barrières technologiques qui entravent actuellement l'utilisation des sources d'énergies ambiantes. Les résultats obtenus prouvent toutefois que des solutions existent si on suit les directives de conception proposées; il en découle que de futurs réalisations seront bientôt sur le marché.

Introduction

A man may write at any time, if he will set himself doggedly to it

Boswell J. “Journal of a Tour to the Hebrides with Samuel Johnson, LL.D.”

Motivation and objectives

It has been estimated that a source energy saving of 55 billion US$/an in the US alone or the equivalent of 35 million metric tonnes of carbon emissions could be made with improved building automation [Sil01]. Wireless sensors would provide the data to a control centre.

Whilst sensors in buildings are not new, a major barrier remains: that of powering the devices. The commonly accepted solutions are to either hard wire the sensor or change the batteries on a regular basis. These have the disadvantage that installation (e.g. wiring) and maintenance (e.g. batteries) costs are likely to rival or exceed those of the sensor being installed. In order to offset this cost, especially for sensors that communicate without wires, the power could be drawn from ambient energy. Each sensor node could therefore function autonomously and cost significantly less than today.

Autonomous wireless sensors offer the potential for saving global sensor system cost. With lower costs, greater implementation can be expected with associated benefits including a reduction in the use of fossil fuels. Another advantage of the low cost of such sensors is that they could be integrated into building materials, such as ceiling and floor tiles, and installed by non-specialists.

As the example of sensors shows, using ambient energy systems can be advantageous both from the economical and ecological point of view. Against this background, the present thesis argues that ambient energy systems could and ought to be more widely applied for powering electronic devices within the built space than at present. The case for this is made taking the example of solar (photovoltaic) technologies; some of the findings may be transferred to other ambient energy technologies.

Contributions

The basis for the case for ambient energy systems in the built space rests on their technical feasibilty. Important factors which are investigated include the available energy, the ambient energy system performance under such conditions and the performance of the charge storage required. Taking the example of solar cell technology, the main contributions of this thesis are:

a) two forms of a phenomenologically based model for solar cell response; these models simulate PV response across a range of radiant energy intensities from 1000W/m^2 down to 1W/m^2, for both daylight and electrically sourced spectra.

b) further experimental results which are not available elsewhere such as the characterisation of radiant energy and PV performance indoors

c) a model for capacity specification confidence for charge storage, which describes the relationship between charge storage and the probability that the application will have sufficient charge to function

d) a range of design guidelines covering all design process phases that support the implementation of the report findings in practice

It is thereby shown under which circumstances such devices would be feasible. By providing models validated with experimental results, this work supports future product design efforts.

Report structure

The topics covered by the chapters of this thesis are sequentially organized to gather the knowledge required for an overall understanding of the problems related to IPV and AES product design.

Chapter 1 gives a state of the art in low power energies and in particular solar (photovoltaic) cells, identifies the areas where information is less complete and presents how this thesis proposes to fill these gaps.

Chapter 2 examines the IPV product engineering design process, highlighting the importance of reliable initial guidance and the influence of environmental concerns on the final design.

Chapter 3 takes the example of photovoltaic solar cells indoors, and presents a characterisation of the radiant energy in the built space.

Chapter 4 addresses the lack of widely accessible information about photovoltaic (PV) solar cells, by giving a historical and technological overview of PV and the reasons why solar cell efficiency is relatively low.

Chapter 5 explores the correct design of IPV cells and modules and considers the characteristation of solar cells indoors based on the results of chapters 3 and 4.

Chapter 6 determines the ways in which ambient energy systems charge storage requirements may be met by balancing the many storage parameters.

Chapter 7 considers the many issues necessary for ambient energy system (AES) or indoor photovoltaic (IPV) product design from the practitioner perspective and takes the form of guidelines and where appropriate, heuristics.

Chapter 1 : State of the art

The engineer's first problem in any design situation is to discover what the problem really is - Anon

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 their generic parameters. The links between the different taxonomies is summarised in Table 1.3 and show the wealth of information that may be available at the beginning of the project.

In the second part of this chapter, the areas where information is less complete are considered as well as how this thesis 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 refueling, 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.

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 which avoids the need for user intervention, 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” [Web03]; therefore, ambient energy systems seek to collect, in their immediate enviornment, those energetic flows which 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 whilst 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 200J/cm^3/an). Also, no single technology can be applied in all environments [Rou03].

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

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/an.]	References
Solar (indoor - near window)	1000	10510	Table 3.3
Solar (indoor - electrical source)	100	1050	Table 3.3
Shoe insert	300	200	[She00]
Vibrations (mechanical)	45	120	[Rou01]
Push button	300	80	[Jan99]
Acoustic Noise (100dB)	1	32	[Rou01]
Peltier thermoelectric (10°C gradient)	15	20	[RWP02]
Wind up clockwork generator	210000	27600	[Jan99]
Hand squeeze generator	120000	15700	[Jan99]
Micro heat engine (unlimited fuel)	400	12700	[Rou01]
Fuel Cell (PEMFC) (unlimited fuel)	400	12700	[Rou01]
Fuel Cell (PEFC) (unlimited fuel)	70	2210	[Nec01]
Electrochemical (Single use Lithium)	45	1420	[Rou01]
Nuclear	15	470	[Lal01]
Microbial Fuel Cell (unlimited input)	15	470	[Par00]
Electrochemical (Rechargable Lithium)	7	220	[Rou01]
Radio Frequency	10	130	[Rei00]

Key

(dark grey)	Ambient energy sources
(light grey)	Low power energy sources requiring refueling
(white)	Low power energy sources without refueling

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 which 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 100mW was set on the consumption of the application. Each criteria was associated with key words that were used as the basis of the search [Der03].

Table 1.2: Basis for author's intellectual property rights research

Criteria	Condition	Key Words
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 100mW?	low power

1.3.2 Results

The prior art analysis returned a total of 137 abstracts. Of these, 74 were obtained in hardcopy. These, prioritised by relevance to the Indoor PV concept showed that 59 (80%) made reference to a photovoltaic system and within these 59, the largest 4 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 (<100mW)

The same results are presented graphically in Figure 1.1. The patents that could present the main challenge to the further implementation of the Indoor PV concept are in group 1 (PV, Low light, low power, with storage) on the basis that all other patents reviewed were lacking 1 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 and four capacitor based solutions protected).

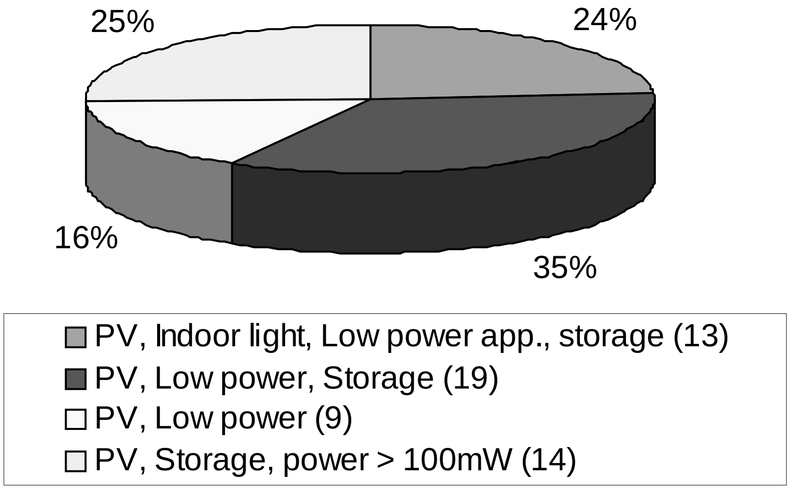


Figure 1.1: Proportion of the 55 most appropriate patents read and the criteria which they satisfied

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

FR 2 618 242: Dispositif émetteur à cellule photovoltaïque - maybe important for sensor and communication application

FR 2 606 912: Dispositif formant émetteur à cellule photovoltaïque - maybe important for sensor and communication application

EP 0 681 549: System for identifying, searching for and locating objects - maybe 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 convertor - maybe important for specific application

WO 99/34337: Chip card for paying freeway tolls - maybe important for specific application

EP 0 856 738: Extern gespeiste Anordnung mit einer elektronischen Anzeige und/oder einer Kommunikations-Schnittstelle - maybe important for specific sensor and communication application

EP 0 918 212: Verfahren zur Erfassung und Auswertung von temperaturabhängigen Verbrauchswerten oder Messwerten anderer physikalischer Grössen - maybe important for specific sensor application

EP 0 935 099: Elektrisches Haushaltgerät mit Solarzelle - maybe 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 - maybe important for horological applications

FR 2 694 109:Ticket réutilisable d'affichage de données temporaires, notamment ticket de parking - maybe important for display applications

US 5 208 578: Light powered chime - maybe important for such applications

1.3.3 Conclusion

Based on the above research, it can be concluded that the Indoor PV 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 were found in the patents were to be targeted, this does not imply that the above patents would be automatically contravened. Once the targeted Indoor PV concept product(s) has been specified, it would then be possible to perform a more focused patent research.

1.4 IPV Taxonomies

As the product design of just one type of applications 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:

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.

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 to 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 to five years.

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 to ten years, despite the fact that the useful life of the building in which they are installed is at least twenty years.

1.4.2 Function (or circuit) taxonomy

Whilst 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.

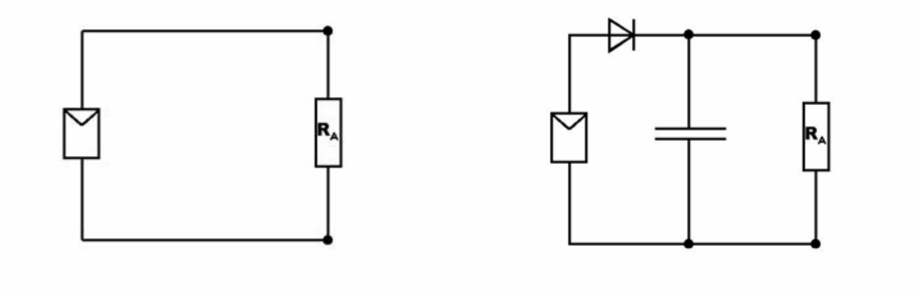


Figure 1.2: (left) Typical circuit diagram for respond to light functionality
Figure 1.3: (right) Typical circuit diagram for sense and display functionality

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 over-charge protection for the battery. The

Zener may be an used in the same way and for the same purpose in other circuits with charge storage such as Figure 1.5.

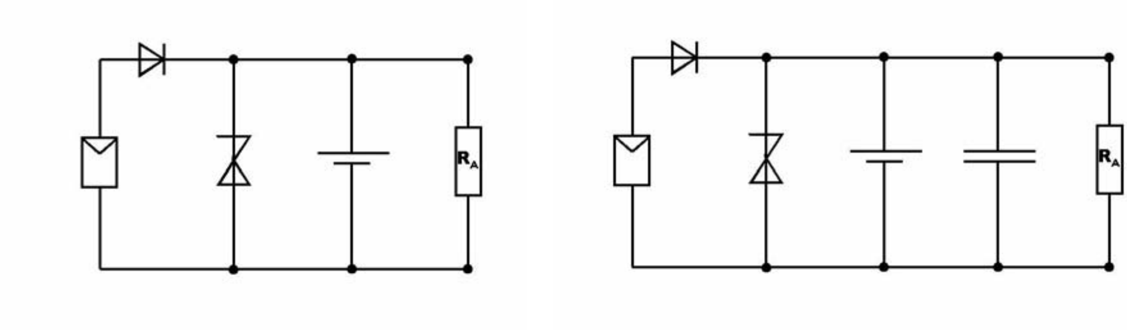


Figure 1.4: (left) Typical circuit diagram for Light or movement functionality
Figure 1.5: (right) Typical circuit diagram for Wireless functionality (R_A represents the application)

Wireless communication even for short range devices (SRD) with a range of a few hundred meters 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. To compensate for this, a hybrid solution (see sub-section 6.6.2) may be used such as 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 “cross-over point” in sub-section 3.4.3.

Another classification can be made as to the solar module *orientation* with respect the prevalent radiant energy. In the case of a mobile device (e.g. wrist-watch), it may be impossible to fully determine [Cal78]. However, for those products which 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 a proposed product has a solar module active surface of $10cm^2$ 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 7mWh/month; daylight might deliver 125mWh/month.

1.4.4 Mean energy taxonomy

Whilst there are those for whom power and energy can be considered synonymous, e.g. [Cag02], for IPV design this might be a serious oversight. This is because to achieve the low energy consumption described in sub-section 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 power rating when running. Typical actual consumption of potential applications shown in Table 1.3. These are sorted by energy consumption, lowest at the top and highest at the bottom of the table.

It is of note that many applications which 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 feasiblity 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 over-riding trend can be seen between energy consumption and product use (sub-section 1.4.1) or main function (sub-section 1.4.2) taxonomies. However, for the example mentioned in sub-section 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 sources energy are indicated with a grey background.

In reviewing the mean use/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.

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/day [mins]	Mean energy/day [mWh/day]	Mean Energy/month [mWh/month]
Basic arithmetic calculator	Tool	Display	1.4	0.01	20	0.005	0.14
Wrist-watch	Tool	Display	1.5	0.0005	720	0.01	0.21
Weighing scales (Maul tronic) [Rei99]	Tool	Display	3.0	0.05	1	0.1	2
Wireless security key	Tool	Wireless	12.0	56	0.2	0.2	6
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
Desk-top 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 [Sch01]	Tool	Compute	3.2	15	20	5	150
Wireless Presence detector	Sensor	Wireless	9.6	36	1	8	230
Door lock remote controler	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
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 [MiL01]	Tool	Light	3.6	72	20	25	750
Bicycle lamp (5 LEDs)	Tool	Light	3.0	60	30	30	900
Alice micro-robot	Tool	Move	3.0	7.5	120	35	1040
Hearing aid	Tool	Amplify	1.3	1.8	1440	43	1296
Wireless mouse (Logitech) [Bur01]	Sensor	Wireless	3.2	19	5	45	1360
PDA Palm III xe [Sch01]	Tool	Compute	3.2	42	20	53	1600
Solar Torch	Tool	Light	1.0	130	30	65	1950
Light sensor (bluetooth)	Sensor	Wireless	2.4	96	48	77	2320
PDA Psion Revo [Sch01]	Tool	Compute	3.2	109	20	89	2680
Hand lamp	Tool	Light	2.0	400	30	200	6000
Portable Radio	Tool	Amplify	3.0	150	240	600	18000
Furby (toy)	Toy	Move	6.0	600	60	601	18030
Translator	Tool	Compute	3.0	1800	30	900	27000
Mobile phone	Tool	Wireless	3.6	720	45	1210	36300
Khepera mobile robot	Tool	Move	5.0	1250	60	1262	37900
Portable personal computer (laptop)	Tool	Compute	4.0	960	120	1929	57900
Hand-held television	Tool	Amplify	4.5	2385	60	2395	71900

Key

Suited to fluorescent source in example
Suited to daylight source in example

1.5 IPV gaps in knowledge

Whilst the importance of information gleaned at the outset of a design project cannot be too highly emphasised (see also sub-section 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 which supports 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 modeling in this area. Models are therefore developed in chapter 5 that match the measured performance of 21 solar cells representing 8 different photovoltaic technologies.

1.5.3 Charge storage

Most renewable energy systems are not practical without being in tandem with some storage of the energy. In IPV this is in the form of charge storage. Given that this element may be the most expensive within the IPV energy system, in chapter 6 a number of ways of ensuring that it is correct specified are presented including a model of the relationship between storage cost and capactity 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 nW standby applications are technically feasible, such as regulators and microcontrollers e.g. [Mic03], their emergence on the market is limited.

1.6 Conclusion

This chapter opens by considering the low power energy systems that are available, with special interest for ambient energy systems (see section 1.2). This section shows that advantages of photovoltaic solar cells indoors 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 research would be necessary once the details of the 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.

Chapter 2 : Indoor sensor design in context

The ideal engineer is a composite ... He is not a scientist, he is not a mathematician, he is not a sociologist or a writer; but he may use the knowledge and techniques of any or all of these disciplines in solving engineering problems.

Dougherty N. W. , 1955

(Author's note: he may be replaced by she)

2.1 Introduction

The majority of this thesis is given over to ensuring the IPV product will conform with technical requirements. But these tasks are not performed in abstracto; the success of a product development project is unlikely to rest solely on technical issues. Many other aspects can cause failure and some of these are reviewed in this chapter.

The overview of the essentials of design (section 2.2) shows the breadth of definitions associated with the word, as well as how it is used in this case. The generic components of the thus defined design process are then presented, followed by a more detailed and therefore more satisfying representation of the engineering design process.

Within this context, the importance of the early stages of the design process are identified with respect to typical trends in design, see section 2.3. This indicates the contribution that may be brought to an indoor photovoltaic (IPV) product designer by providing guidance, ideally from the outset.

One design trend is that of increasing consumer concern with the environment. It may be that this will motivate the further use of ambient energy sources. A useful way to deal with this issue from the designer perspective is to use some form of Life Cycle Analysis (LCA). In section 2.4, LCA is defined and those aspects which may support the designer are explained.

2.2 Defining design

The word *design* is virtually indefinable without reference to the context in which it is used or the “product” which is envisaged. Take an artist, an architect, an engineer and a policy maker and probably the only consensus that will be found amongst them is that all consider themselves to be designers (of a kind!). One of the reasons for this is that human beings have been resolving problems which form part of the design process for millennia.

The French translation for engineering design is “conception”. This word comes from the Latin “capere” to catch and “con” meaning together - one might say to gather. Design is therefore a fusion of a number of elements. But what this definition lacks is that the elements may be abstract (mental) and the resulting concretisation is new.

One solution is to be more specific by the juxtaposition of an adjective such as “engineering” in front of the word design. In this thesis, the word design is understood to mean engineering design.

Another way to think of design is as a number of interconnected problem-resolution cycles, such as the simplified process in Figure 2.1.

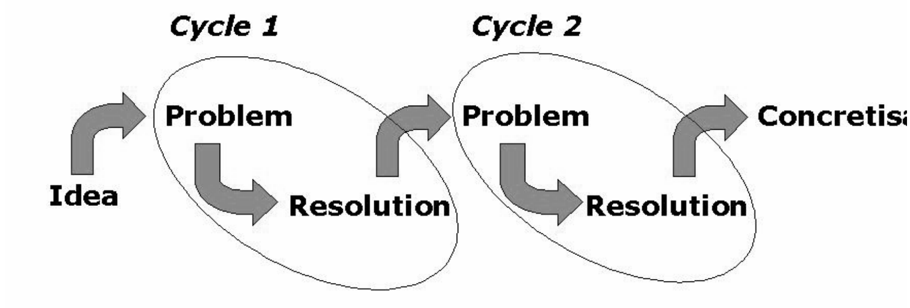


Figure 2.1: Simplified schema of a mono-linear design process showing two problem-resolution modules or cycles

A generally recognised categorisation [Pah01] [Fre98] of such cycles for engineering design finds four phases which may be referred to as analysis of the problem, conceptual design, embodiment and detailing. A brief description of a design project might read as follows:

Analysis of the problem is the step which takes a recognised need and converts it into a formal definition of the problem including boundaries and goals of the possible solution(s). This is followed by *conceptual design* in which broad solutions or schemes are prepared. At the *embodiment* stage, the schemes are further developed and may result in prototyping or some other result which will allow selection of the ideal candidate. The latter then undergoes *detailing* which includes the many but essential points that must be decided for production for example.

What this description fails to sufficiently highlight is that design never follows such a simple sequence without some (and usually much!) iteration. This is because not all problems encountered can be resolved without reviewing and possibly changing the work of a previous stage. For this reason and for its greater completeness, the description of engineering design proposed by VDI directive 2221 [VDI93] (see

Figure 2.2) is more comprehensive. This diagram includes the above mentioned phases on the left hand column.

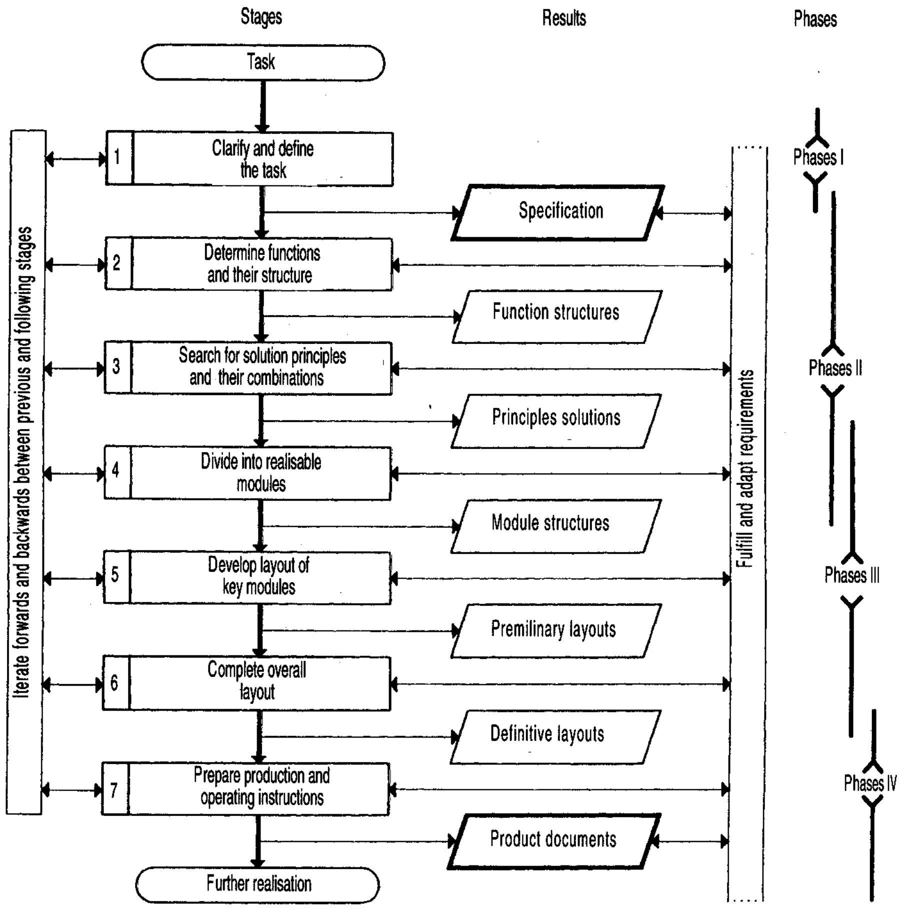


Figure 2.2: Generic engineering design process [BIB02]. English translation available in [Pah01]

This diagram brings out both the iterative nature of design (the "forward and backward" through the stages mentioned in the left most box) and the dynamic nature of design (the "fulfil and adapt requirements" (mentioned in the right most box). It also includes certain stages (boxes numbered 1 to 7) which in practice are often neglected. One of these is box 2 (determine functions and their structure).

A function in this context can be defined by answering the question "What does it do?" with one or more couples of an action verb plus a substantive. Examples of such couples include "collect energy" or "store charge".

Such functions for products will exhibit both usable and aesthetic functions. Usable functions satisfy requirements such as ease of use, effectiveness and product longevity. Aesthetic functions relate to appearance and the impression a product gives. Depending on the kind of product being designed, the share of these two kinds of function varies from capital investment (which are usable function intensive) to jewellery (aesthetic function intensive) as shown in Figure 2.3.

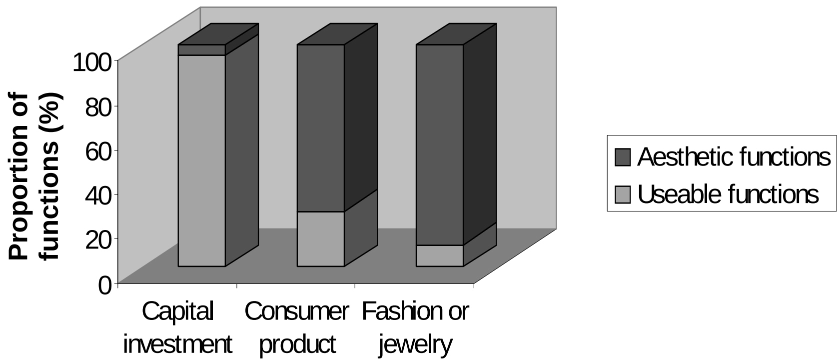


Figure 2.3: Examples of product share of usable and aesthetic functions, adapted from [Rys01]

For a designer, functional analysis is a necessary precursor for a cost-function analysis both of the design alternatives and competitor products where these exist. This is based on comparing the cost of each design component with the functions that it can perform. This goal of such an analysis is to satisfy the required functionality with least cost.

2.3 Trends in engineering design

Few authors when discussing the product development process do not make reference to the disproportionate amount of project costs, say 60-85%, which are fixed in the first stage(s) of the engineering design process. They will also recognise the miserly proportion of costs incurred in these first stages, maybe 5% (see Figure 2.6). They therefore argue that the earlier problems can be prevented, the less projects will cost. Whilst this explanation is correct, it is incomplete. A further trend is the cost of failure which grows exponentially as the product development unfolds (see Figure 2.4).

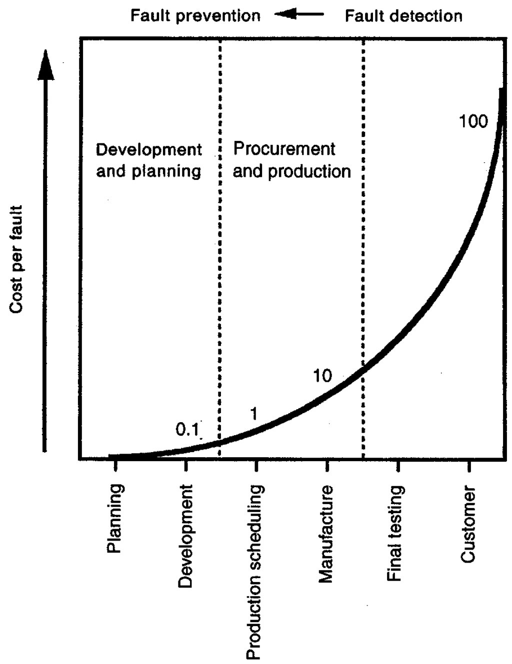


Figure 2.4: Failure cost with product development progress [DTI92]

Such costs clearly damage profits and may become business fatal due to ever growing product liability. The latter, although prevalent principally in the US, is also increasing in Europe (see the case in the UK Figure 2.5).

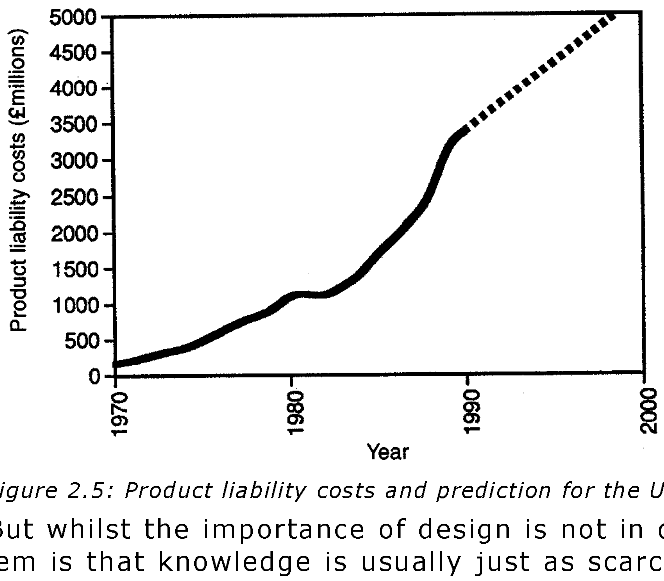


Figure 2.5: Product liability costs and prediction for the UK [Stu92]

But whilst the importance of design is not in doubt, the problem is that knowledge is usually just as scarce as is it necessary at the start of new product cycle, thus leaving the designer to deal with what Fabrycky [Fab94] refers to as the "knowledge gap" (see Figure 2.6).

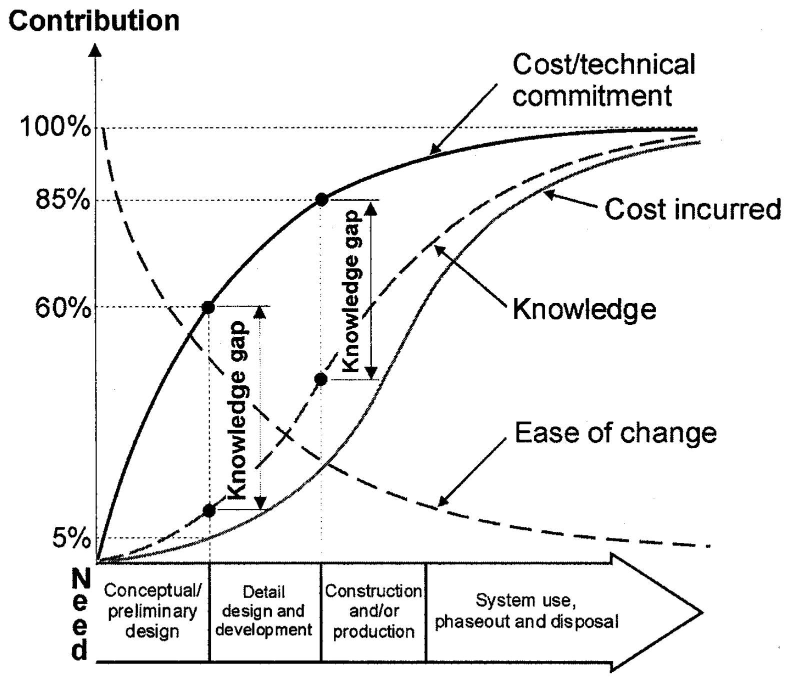


Figure 2.6: The knowledge gap and other trends of the product development process [Boo01]

This is made up of both lack of vision as to what the real issues are, as well as salient data. This thesis contributes to bridging this gap for a specific product type: that of autonomous (self recharging) energy supplies based on ambient energy. The example taken focuses on the use of photovoltaic solar cells to convert indoor radiant energy into charge which is then typically stored for later use. The proposed system would typically replace one or more single use batteries.

2.4 Life Cycle Methods

2.4.1 Introduction

This section briefly explains what life cycle assessment (LCA) is and how it may be used to support the practising IPV product designer; associated suggestions for product improvements are also provided.

Evidence from a number of LCA studies is presented that coincide in indicating that the main environmental issue of small electronic devices is the battery, in particular single use (or primary) batteries. This lends support to the case for ambient energy, the principles of which seek to aid designers to avoid primary batteries by the use limited secondary (rechargeable) storage. Other design enhancements that can accrue from LCA are also mentioned.

2.4.2 A definition

LCA is also referred to as *eco-balancing* or *cradle to grave assessment*. It is the assessment of environmental performance of a product or activity. This performance is based on an **inventory** of the product or activity inputs and outputs within a defined **system boundary**, such as the example in Figure 2.7. For IPV products, this will lie between their conception and eradication, although more limited time frame studies may also be considered.

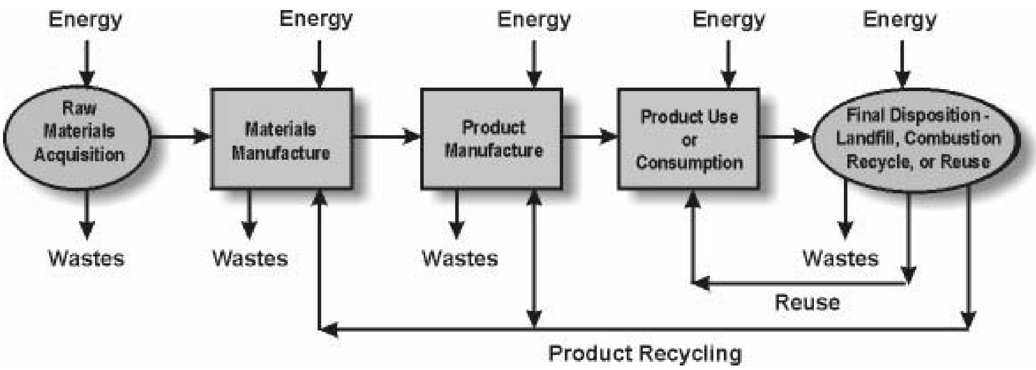


Figure 2.7: Simplified Product Life flowchart [Fra93]

The **impact assessment** is based on the inventory. For example the energy required for product manufacture may be calculated by integrating for each product component the weight [kg] and the related effect energy (e.g. [MJ/kg]). The result may be taken as being proportional to part of the environmental impact. Values for these effects and others may be found in databases such as those mentioned in the UNEP world review [Nor02]. The carbon dioxide emissions, ozone layer damage and so on can thus be estimated.

The fourth stage of an LCA is **interpretation** (previously improvement analysis). The four phases are summarised by the flowchart in Figure 2.8. Note the resemblance with the design process in Figure 1.2, especially with regard to the iterations.

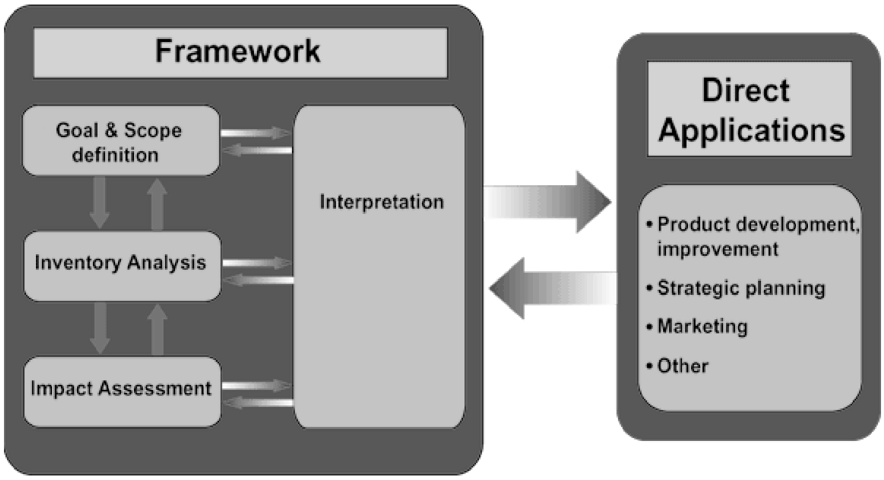


Figure 2.8: Phases of an LCA, based on ISO 14040 [CEN97]; diagram [CIT02]

2.4.3 LCA for IPV designers

The effort required for complex LCA implies that it is "not a solution for the busy product designer, who has many other design considerations to deal with. There are, however, important lessons to be learned" [MTM00]. The process of understanding an LCA *builds awareness* of the complexity of the environmental issues at stake. Whilst LCA helps the product designer to appreciate that there are no simple answers, LCA can contribute to the decision making process by indicating where the major issues lie.

Further limitations of LCA are enumerated in ISO 14040 [CEN97] including difficulties with:

- determining the boundaries and assumptions
- transferability of LCAs between domains and geographies
- statistical issues related to the variety of input data

Given the concerns with full LCA for the product designer, more limited approaches have been proposed such as ALCA (Abridged LCA) used by Motorola. Research in the area of simplified LCA is on-going [Reb02]. Such methods allow more usable information to be available earlier in the design process which it recognised increases the information value, see section 1.3.

Benefits of the LCA perspective can "boost creativity" [Bre97] and alert the designer to other concerns, such as legal issues. An example of the latter is that primary and secondary batteries are regulated differently depending on the country. For example, in the US "Alkaline (primary) batteries are not listed as hazardous waste under the Resource Conservation and Recovery Act (RCRA)" [EPA02] whilst NiCd (secondary) batteries are [Lan99]. On the other hand, Switzerland collects over 60% [BUW01] of her primary and secondary batteries on a voluntary basis, and recycles both kinds of battery [BAT02].

A further benefit is that LCA can provide *formal methodologies* in which to compare different design solutions, with the proviso that the absolute figures should be treated with caution.

LCA may therefore support the European Commission goal of "more environmentally friendly product design" as mentioned in the framework description of the Integrated Product Policy [CEC01].

2.4.4 LCA in IPV design

In practice, despite the variety of products which an IPV designer may work on, consideration may be given to a weight assessment, limited effects assessment for energy and emissions, the use cycle and a number of ways to make improvements.

Product weight assessment

For IPV products, as for most mobile electronic devices, the charge storage device typically represents a significant fraction of the global weight (e.g. 1/3) and is therefore important if waste minimisation is a goal. Batteries contribute 1% of the weight of US refuse and significant toxic waste, see sub-section 6.2.2. Therefore, the designer should include the battery in environmental impact calculations of such products, despite the fact that some reports do not e.g. [Oiv00].

Energy and Emissions

Given detailed weight data, the energy and emissions of different scenarios may be compared. The boundaries of the assessment should be defined such as considering for IPV only the production energy of the batteries. It has been shown that the production energy of single use (Zn-Alkaline) is around 5MJ and for a similar sized rechargeable R6 or AA (NiCd) cell is 6MJ [StM00].

Typically LCA of IPV products will show that battery storage is a major contributor with regard to most energy and emissions metrics [Ful00].

Battery impact can be confirmed indirectly with respect to another main component of the IPV power solution: the solar module. Making the reasonable hypothesis that a thin film technology (see section 4.6) will be used, this will represent only a small weight increase of the total product. Also the PV module will not have a significant impact on energies as the bulk of its weight (around 90%) is made up of glass which has a low (primary) energy of 14 MJ/kg compared with the photovoltaic material who's (primary) energy is around 100 MJ/kg [Wys00]. Therefore, a typical IPV solar module of 20g has a primary energy of around 0.4 MJ i.e. an order of magnitude less than the batteries. Polymer or organic substrate solar modules (as produced by VHF Technologies, Switzerland) are lighter, and therefore represent even less waste.

Use phase

It was seen above that the primary or production energy of rechargeable cell power solution is higher than a single-use cell. This is to be expected because such an LCA excludes the product use cycle and therefore the advantages of rechargeable storage. As Lankey puts it "We find that materials use, energy use, and emissions can be quantified over the entire product life cycle to quantitatively show that resource use and emissions are substantially lower if a rechargeable battery can be substituted for a primary battery. However, consumer use patterns will affect the relative environmental benefits of rechargeable batteries" [Lan00]. An example of "bad" consumer use patterns is leaving the battery recharger plugged into the mains when not in use: even though no charging is occurring, the charge transformer draws current which is wasted. If such "bad habits" could be avoided, daily energy consumption savings of 25% for mobile telephones and 80% for wireless telephones would accrue [Fin98].

A further life cycle comparison of batteries (both primary or secondary and fuel cells) indicates that the best alternative would be rechargeable Polymer exchange membrane fuel cells [Fli00]. However, as mentioned in sub-section 6.3.7, such cells, especially at the scale of IPV applications, are not market-available.

The finding that over 40% of (financial) life cycle costs of another kind of stand-alone PV system (outdoor) are due to the batteries [Bop95] is understandable. Battery manufacturers can contribute by producing products whose life cycle costs are lower.

Improving IPV product LCA

The Eco-design guide [Eco02] recognises eight ways of improving a products eco-performance which are:

- Selection of low-impact materials
- Reduction in materials usage
- Optimisation of production techniques
- Optimisation of logistics system
- Reduction of impact during use
- Optimisation of the initial life stage - design for upgrade and reuse
- Optimisation of end-of-life system
- New concept development

Some of the ways that the IPV designer can make improvements have been mentioned in the paragraphs above. Further approaches include labelling the application to encourage recycling and proper disposal, using labels of material content to aid battery sorting, designing products so that batteries can easily be removed and taking into account the level of recycling available for certain materials such as Lithium [McM98].

Consumer choice may also be influenced pre-purchase with eco-labels becoming more commonplace as seen for example in electricity supply [Rou02], to "promote products which have a reduced environmental impact compared with other products in the same product group" in Europe with the use of the "daisy" label [ECR00] (see Figure 2.9), the American Energy Star label used at present for electrical and electronic goods [Web98] and lastly in construction [Mak99].

Figure 2.9: Examples of "Eco labels". (left) European "daisy" label, (right) US Energy star

2.4.5 Designer responsibility

The importance of product design is reflected in the fact that the equivalent of "about 1.5% of Germany's total carbon dioxide emissions in 1995" were necessary to power consumer electronic devices which the user had ostensibly turned off [Ger02]. For example a PC and peripherals consume 20W when turned off but are connected to the mains [Mag02]. Given that the same equipment consumes around 300W in function [DoE02], then it must run for over 1.5 hours/day in order for the energy consumed in function to exceed that consumed daily in standby. This problem may be associated with "user" bad habits, as mentioned in sub-section 2.4.4, but the designer should also accept partial responsibility for the typical use of their products. This is for three reasons: firstly, only a minority of users are fully aware of their environmental impact; secondly, a number of technical solutions exist such as putting the transformer on reduced current mode when it is not in use. Thirdly, legislation can be parlously sluggish. The transformer standby current issue was recognised by the European Commission in 1991 [Off91] yet the code of conduct [DG-00] which sets the "no-load power consumption" target of 1W by 1st January 2001 took almost a decade. So far, 15 companies have signed this agreement [EU_02]. Motorola has a (mobile phone) charger which now runs at 0.12W in standby [PDE02].

2.4.6 Conclusion

LCA is a tool which can serve the IPV designer by indicating the environmental burden of different choices. A typical example is to check whether the energy saved in the use phase and at end of life exceeds the extra environmental cost during the production phase. In general this can be expected to be the case for IPV products when compared with a similar product that uses primary batteries.

2.5 Conclusion

In this chapter, the product engineering design process is explained. It is shown that what is known at the early stages has a significant influence on the final design.

Another influence on the designer, for ambient energy sources not the least, are environmental concerns. Ways in which these can be handled are presented in sub-section 2.4.

Chapter 3 : Radiant energy in the built environment

L'essentiel est invisible pour les yeux
de Sainte-Exupery A. Le Petit Prince, Harcourt Brace, 1943

3.1 Introduction

One of the first logical steps in ambient energy system design is to establish the available energy resources. This chapter takes the example of photovoltaic solar cells indoors, and aims to characterise the energy whose wavelength lies between the ultraviolet and infrared on the electro-magnetic spectrum that solar cells can collect. This energy is governed by the building physics parameters presented in section 3.2.

Such a characterisation is necessary due to the inability of the human eye to fully perceive the radiant energy that a solar cell collects. Much of the previous indoor environment work cannot be applied directly as it is in the photometric domain (sensitivity of the human eye), not the radiometric domain. Photometric findings nevertheless provide qualitative information which is investigated in section 3.3.

To allow a quantitative assessment, a number of radiometric experiments were carried out. These consider the obstacles and window transmissivity as well as the PV product orientation and location (see section 3.4).

Radiant energy is affected by many more variables including time and geographical location for example. A simulation can be used to confirm calculations, but few such programs are applicable to the radiometric characterisation of the built space. A ray-tracing approach that adheres to the laws of Physics is therefore presented in section 3.5.

A summary of the various parameters and their importance is covered in the Discussion (section 3.6). The ways in which IPV design can be optimised are also covered in this section.

As product applications may be permanently fixed to the walls or ceiling, particular attention will be given to these areas of the indoor space. It will nevertheless be possible to infer the overall energy distribution from what follows.

3.2 Physics of buildings

Whilst a great deal of variables can be used to characterise radiant energy, those associated with irradiance (see sub-section 3.2.1) are usually the most significant for indoor photovoltaic purposes, as this parameter can be expected to vary over the greatest range. The radiant energy spectra (see sub-section 3.2.2) in comparison usually has a smaller impact. These parameters whilst absolute in theory, interact in practice with the built space, in particular with respect to optical parameters such as those described in sub-section 3.2.3.

3.2.1 Radiant Energy

The fundamental unit of radiant energy in the spectral range of interest for IPV is the photon. Energy and frequency are related by the Planck equation:

$$E_Q = h_c f \qquad \text{Equation (3.1)}$$

where:
E_Q = Quantum energy [J]
h_c = Planck's constant = 6.63×10^{-34} [Js]
f = frequency [Hz]

and:

$$f = \frac{c}{w} \ (Hz) \qquad \text{Equation (3.2)}$$

c = speed of a photon in a vacuum = 2.99×10^{8} [ms^{-1}]
w = wavelength [m]

Taking a wavelength range between 0.4 to 0.8 microns on the electromagnetic spectrum (see Figure 3.1) gives an energy range for the quantum between 5×10^{-19}J (blue) and 2×10^{-19}J (red). Such an infinitesimal amount of energy is required in significant quantities for IPV applications. It is also evident that an ultra-violet photon may carry three times the energy of an infra-red photon.

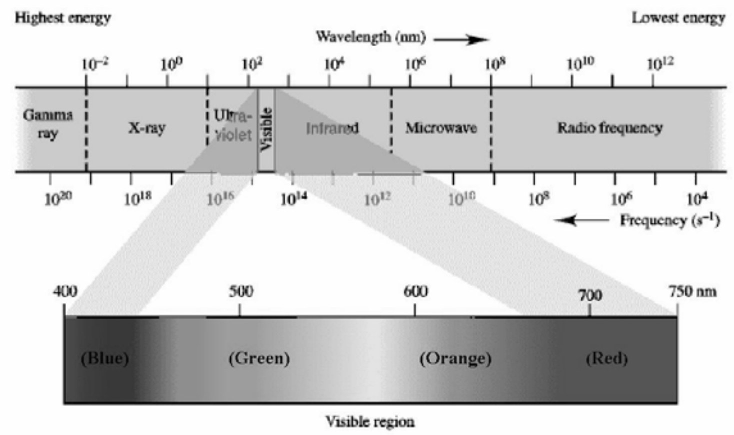


Figure 3.1: Electromagnetic Spectra (energy, wavelength and frequency) based on [Car02]

Once large quantities of photons are available, they can be described with relation to a number of "processes". Following a typical photon path for ease of understanding, four such processes can be identified:

"Light Creation"

The rate at which radiant energy is output from a point source is called the *Radiant Intensity* in Watts per steradian [W/sr]. Many radiant energy source volumes can be modelled as point sources at sufficient distance; for example, for a spherical source such as the sun, the Earth orbit (1.50×10^{11}m) is three orders of magnitude greater than the solar radius (6.96×10^8m).

A common IPV case is the window of a room. From the indoors, this may be considered as a planar radiant intensity source made up of many point sources.

"Translation" The resulting field formed by the radiant intensity is called the *Radiant Flux* or (radiant) power and is measured in W (or J/s). Such flux can be associated with emission or transmission.

"Incidence" If the radiant flux reaches an object, then the total received radiant flux (or power) per unit area is the *Irradiance* in W/m^2. For a flat surface, this is analogous to the radiant flux in a particular direction. In the jargon, irradiance may be referred to as radiant flux density.

"Reflection" If this object reflects, the resulting radiant flux per steradian is referred to as *Radiance* in W/(m^2.sr). For the special case of a uniform radiant flux surface, radiance is constant independent of the distance from it. This is because the angle of a sphere subtended by a steradian is constant.

These four processes are summarised in simplified form in Figure 3.2.

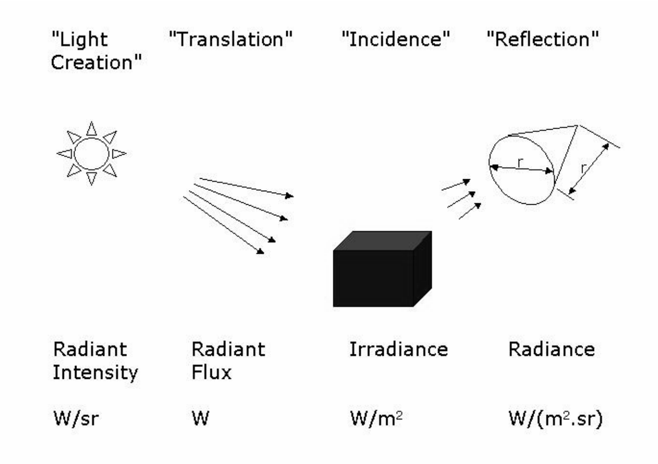


Figure 3.2: Schema of radiant energy "processes"

Further physical concepts such as reflection, absorption and transmission are presented in sub-section 3.2.3.

IPV Irradiance For IPV, we are interested in the irradiance on solar cells from radiant energy sources whose volume can be approximated to a point (e.g. the sun), a line (e.g. a fluorescent tube) or a surface (e.g. the window on a cloudy day).

Generally, as the distance between the emitter and receiver changes, so does the irradiance (received). Such irradiance,

I_{rps} from a point source emitting radiant energy with intensity I_{ps} at a distance r is related by the inverse square law:

$$I_{rps} = \frac{(constant) \bullet I_{ps}}{r^2}$$ Equation (3.3)

However, if the radiant energy source volume can be approximated to a line source of infinite length and of intensity I_{ls}, then the irradiance I_{rls} will vary with the reciprocal of the distance, not the inverse square:

$$I_{rls} = \frac{(constant) \bullet I_{ls}}{r}$$ Equation (3.4)

By corollary, if a further spatial dimension is added to the radiant energy source such that it has a surface of infinite size and constant intensity, the irradiance is then independent of the distance from the surface. A window is a good example so long as the solar module is suitably close and oriented towards the window.

Another mechanism with which irradiance varies is the cosine law (equation 3.5):

$$I_{rpa} = I_{pa}\cos\phi$$ Equation (3.5)

This is presented in Figure 3.3, which shows the following: when radiant energy is incident on a surface with a non-zero angle, ϕ to the normal, the irradiance, I_{rpa} is spread over larger surface, and therefore intensity at a point on the surface is lessened by the cosine of ϕ.

The incident radiant flux in this case is assumed to be a parallel beam, identified as I_{pa}. Such an assumption becomes valid once the distance between the source and surface is much greater than the source radius (for the case of a spherically shaped source). For IPV, a minimum distance:radius ratio of 10 is usually appropriate.

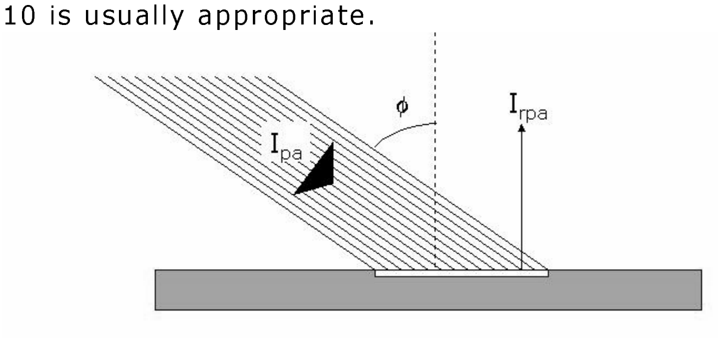


Figure 3.3: Cosine Law

Daylight

The most significant source of radiant energy for planet Earth is the Sun. Outside the atmosphere, the average intensity received in recent decades has been 1366 (+/-1.5) W/m^2, see

Figure 3.4. The slight variation in annual average has a period of approximately 11 years [Yor02]. A standard for such solar radiation is AM0 described in [AST03].

Due to the relative rotation of the Earth and the Sun, the irradiance on Earth is variable in both diurnal-nocturnal and annual cycles. This results in a preferential orientation of the irradiance both with respect the azimuth angle (or compass bearing) and the elevation (angle above the horizon). Poor orientation about the vertical can reduce annual irradiance by approximately 75% of the ideal [vdB01].

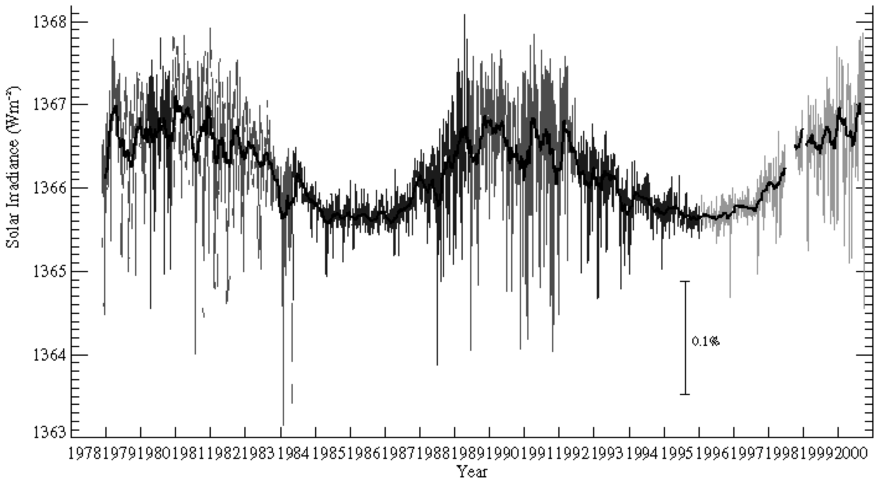


Figure 3.4: Total solar irradiance data measured by a number of satellites; on-line [Frö02], published [Frö00]

The atmosphere absorbs a part of the global (synonymous with total) radiant energy so that the vector received on Earth is made up of two components: the direct and indirect radiations. For a cloudless sky, the direct instantaneous radiation measured vertically up will reach a maximum of around 1000W/m^2, whilst as the weather worsens, the radiation will be more indirect. In European locations, daytime terrestrial instantaneous irradiance measured vertically up in the range 200-600 W/m^2 in Switzerland can be expected.

Considering this radiation in cumulative terms, an ideally positioned outdoor application in a European location facing due South (0° azimuth for architects) and having a 45° elevation will receive a cumulative daily irradiance in the range 1000-5000 Wh/m^2/day [Tri78].

In practice, a more complete set of values for a particular location and orientation can be obtained from a local meteorological station (see Figure 3.5) or an interpolation model of solar radiation can be used [Met00]. Also, a number of standard skies [CIE97] have been specified which allow laboratory comparisons to be made [Mic99]. Typical standard skies include overcast conditions (deep stratus clouds and sun disk is invisible from the ground) and clear (cloudless) conditions.

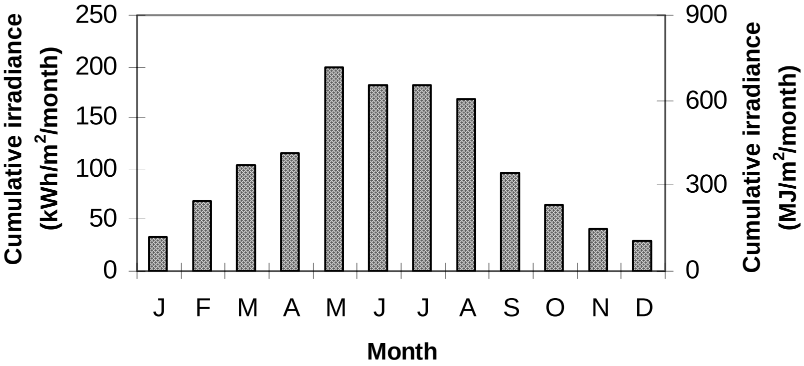


Figure 3.5: Cumulative irradiance measured vertically up at Payerne, CH 1998 (courtesy of World Radiation Center, Davos)

3.2.2 Radiant Energy spectra

Light occurs both naturally (e.g. sunlight, lightning, bioluminescence and pyroluminescence) and artificially (e.g. incandescence and luminescence). Light energy in the IPV environment can be categorised in the same way. Artificial light can be considered in the majority of IPV cases as synonymous with electrically powered light.

Thermal radiation

Each source can be identified by its spectral signature. Figure 3.6 shows how (natural) sunlight reaching the earths atmosphere (AM0) is then filtered by Rayleigh scattering at some wavelengths more than others before reaching sea-level (AM1). The resulting absorption troughs are associated with particular molecules which attenuate mostly above 700nm (red). This explains why sunlight varies in colour with latitude, as the light must pass through a greater distance of atmosphere to reach the ground at the poles than at the equator.

Areas North of the fortieth parallel at midday therefore receive a bluer sunlight than at the equator.

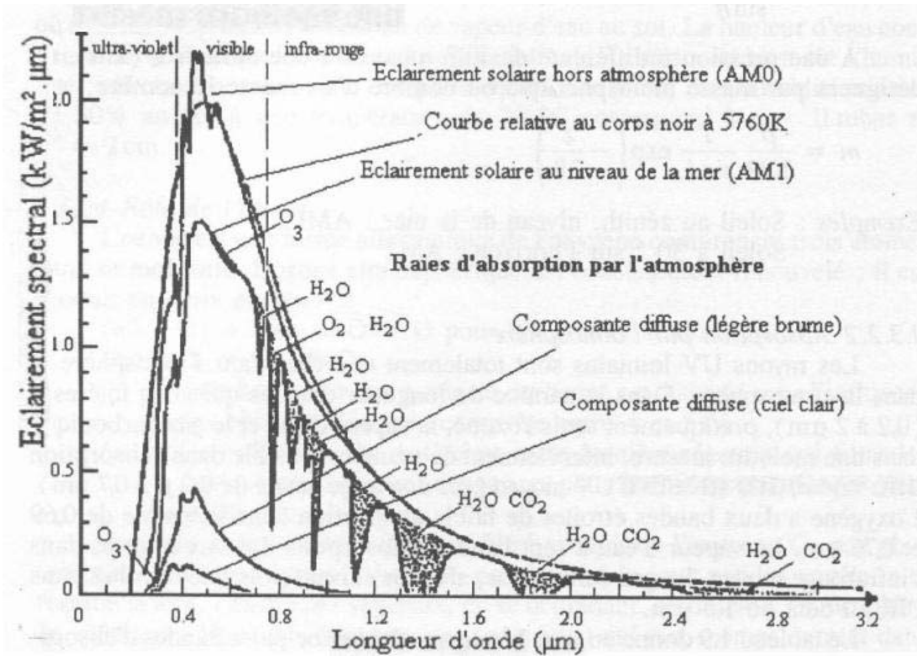


Figure 3.6: Spectra of natural light with wavelength in microns [Pal78]

From Figure 3.6, it can be seen that a surface just outside the Earth's atmosphere (AM0) receives an irradiance similar to that produced by a black body at 5760K (noted on the graph as "corps noir à 5760K") in spectrum. An ideal black body absorbs all radiation in the electro-magnetic spectrum incident on it without reflecting or transmitting this energy. This typically raises its temperature with respect to the non-illuminated surroundings. To return to equilibrium, it radiates energy at a power P_r (Watts) with a spectral distribution that Planck found to be fixed (see Figure 3.7). Stefan discovered that this distribution is related to temperature as follows:

$$P_r = sAeT^4$$ Equation (3.6)

where

s is the Stefan-Boltzmann's constant [$5.67 \times 10^{-8} Wm^{-2}K^4$]

A is the surface area of the object [m^2]

e is the emissivity constant

and T is the temperature [K]

The radiant energy sources of interest to IPV which can be approximated by a black body theoretically require a temperature of at least 3000K, such as daylight and incandescent light sources (see Figure 3.7), in order to emit with a peak in the spectral response of PV, see Figure 4.23 (Typical spectral response for solar cell technologies [Fie97 p2] where GaInP = gallium indium phosphide, a-Si = amorphous silicon, CdTe = cadmium telluride, GaAs = gallium arsenide, InP = Indium phosphide, multi-Si = multicrystalline silicon, mono-Si =

monocrystalline silicon, ZnO = Zinc Oxide, CIGS = copper indium gallium diselenide).

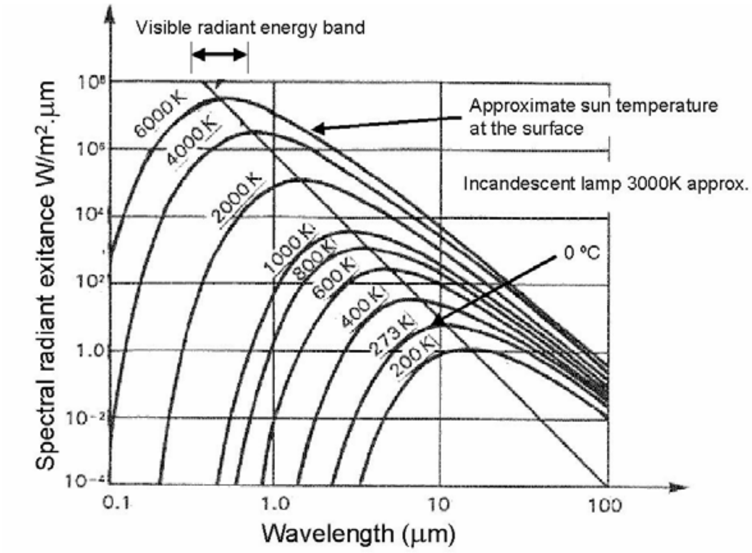


Figure 3.7: Spectral distribution of energy radiated from black-bodies for a range of temperatures, based on [Wat97]

Given that indoor lit objects will absorb radiant energy, their resulting temperature can be used to approximate the wavelengths at which they re-emit. As can be seen in Figure 3.7 for objects at room temperature (300K), peak emission is around 10µm which is much longer than typical PV spectral response. The process of absorption and re-emission equates to a wavelength (lengthening) shift of the radiant energy. Fortunately for IPV purposes, as will be seen in sub-section 3.2.3, objects located indoors that receive radiant energy do not only re-emit, but also reflect and transmit.

Other radiation spectra types

Not all indoor light sources have black body type characteristics. Another common spectra type is fluorescent (see Figure 3.8). Similarly to shop sign "neon" lamps, such sources function by the ionisation of mercury in an inert gas (such as argon) at low pressure. The mercury re-emits this energy in the form of ultra-violet light that in turn excites phosphor on the inner surface of the lamp tube. As a result, the phosphor fluoresces in the visible range with a spectrum that is generally bluer than incandescent bulbs.

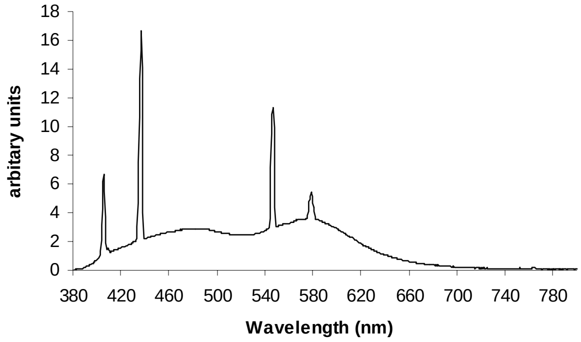


Figure 3.8: Typical spectrum of an indoor fluorescent tube (author's measurements)

It is of note for IPV that fluorescent sources lose from 9 to 30% of their luminous flux in the first 10,000 hours of use [Osr00].

Many other artificial light source types exist that are not dealt with here as they are less common in the indoor environment. These include discharge lamps (high-intensity sources, carbon arc, flash), semiconductor light emitting diodes (LED) and coherent sources (laser). It is likely that LEDs will be increasingly used in buildings of the future as they have relatively low volume and voltage, higher energy efficiency and a wide choice of intrinsic colours.

3.2.3 Basic Optical parameters

Quantum models as mentioned in sub-section 3.2.1 are one way to describe radiant energy. Another relatively older approach based on wave theory is also useful for understanding material properties indoors. A simple example which summarises a number of effects is shown in Figure 3.9 in which radiated energy passes from a transparent medium (e.g. air) through a second transparent medium (e.g. glass) and back out to the first transparent medium. An example of this is glass in air, such as for window applications. The arrows in the diagram are drawn with different thicknesses to indicate typical intensity.

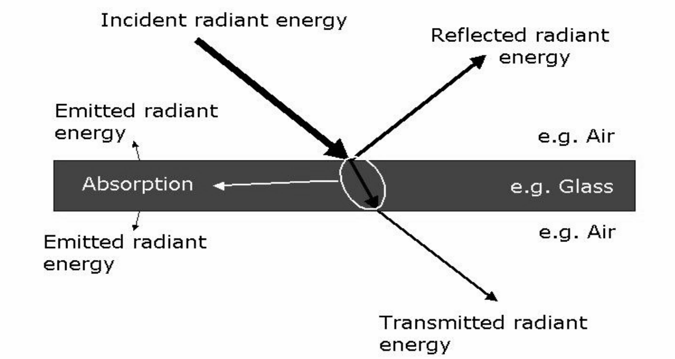


Figure 3.9: Light passing through transparent materials

As can be seen, the incident radiant energy (IRE) undergoes reflection, absorption and transmission. For a point on the top surface of the second material in Figure 3.9, the IRE is either reflected or penetrates the layer. The IRE which penetrates is refracted which indicates a change in refractive index described by Snell as:

$$i_1 \sin\vartheta_1 = i_2 \sin\vartheta_2 \qquad \text{Equation (3.7)}$$

where
i is the index of refraction of the materials
ϑ is the angle of the radiant energy to the normal of the surface
1 and 2 indicate the first and second materials respectively (e.g. air and glass)

A glass of increased refractive index maybe synonymous with increased reflection and loss of energy.

The third property is absorption, usually in the form of heat to the material bulk. Such absorbed radiant energy can be re-emitted. However, for the temperatures (300K) and materials (glass, air) of the applications considered in this work, the emitted energy is both slight and has a spectral distribution well away from the visible (see Figure 3.7).

That radiant energy which exits the bottom surface of the second material in Figure 3.9 does so with a reduced energy to the IRE. The ratio of transmitted radiant energy (TRE) to the IRE is called transmissivity ratio, R_T:

$$R_T = \frac{TRE}{IRE} \qquad \text{Equation (3.8)}$$

Similar ratios can be found for absorption and reflection.

Table 3.1: Typical fenestration transmissivity values

Glass window type	Single plate glass	Double glazing
Transmissivity ⊥ to surface	0.8-0.9	0.5-0.7

Assuming the surface is specular, IRE at an angle to the normal is reflected at the same angle to the normal (see top left of Figure 3.10). However, the proportion of light reflected is proportional to the angle of incidence, see Figure 3.11. In practice, the majority of surfaces are not specular and exhibit further reflection types such as are shown in Figure 3.10. The most common type in practice is the “mixed”.

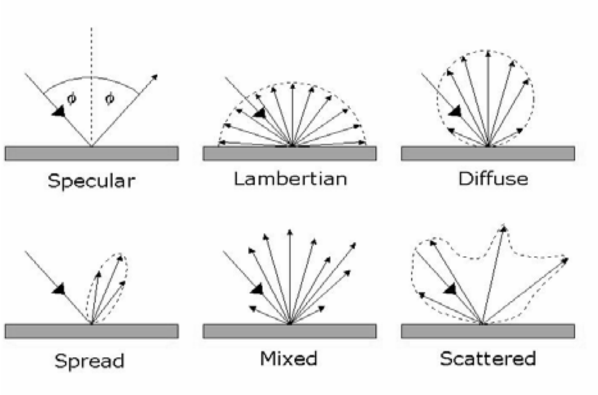


Figure 3.10: (left) Reflection types

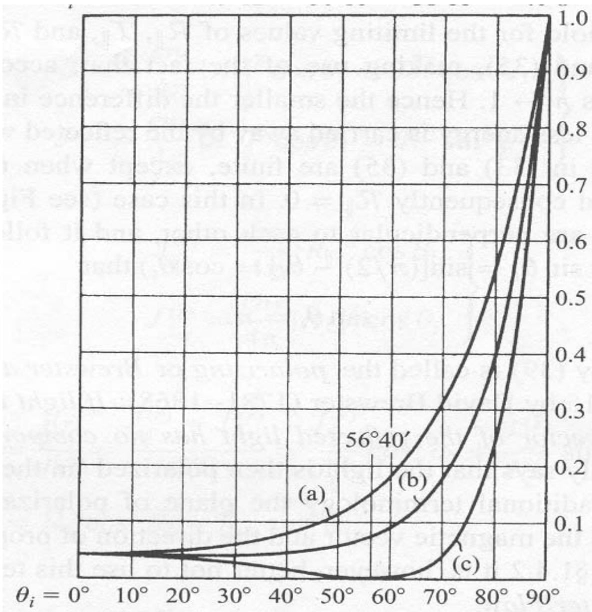


Figure 3.11: (right) Intensity of reflected light as a function of the angle of incidence on glass [Bor59] where a) = $R_{\perp}$, c) = $R_{||}$ and b) is an equal mix of perpendicular and parallel light

The range of reflectivity values that can be expected for IPV are shown in Table 3.2.

Table 3.2: Typical reflectivity values found indoors [Mah93][CIE08]

Room surface	Walls	Floor	Ceiling	Working planes
Reflectivity, R	0.3-0.6	0.2-0.5	0.5-0.8	0.2-0.6

3.3 Photometric characterisation

Most indoor light characterisations are photometric (synonymous for IPV purposes with photopic) i.e. they measure only that portion of the electromagnetic spectrum to which the human eye is sensitive (Visible Spectrum 380 nm - 750 nm or 400 GHz - 789 GHz) and have the unit Lux. As this falls within the spectrum of sensitivity of photovoltaic cells (see Figure 3.12), for qualitative purposes the photometric measure may be used as a representative sample of the spectrum of interest for radiant energy characterisation, see section 3.4, in which the unit of radiant energy is Watts/m^2 [W/m^2].

The CIE (Commission Internationale d'Eclairage) have standardised an average human eye response to daylight with respect to wavelength as shown in Figure 3.12 with a peak at 555nm (green). Real human eyes cannot be applied as reliable optical sensors since they do not respect this curve exactly. The 19th century physicist and physiologist Hermann von Helmholtz put it categorically: “If anyone offered me an optical device with such serious flaws, I would reject it in no uncertain terms.” [Hat00].

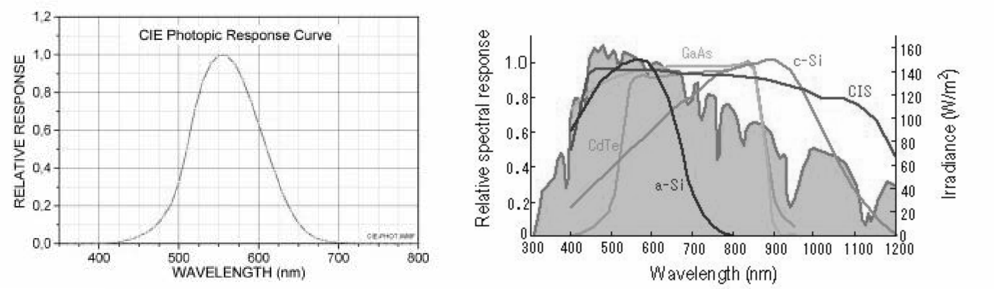


Figure 3.12: CIE standard photometric response (left) [Sol02] and some typical solar cell spectral responses (right) [Ned02]. For abbreviations of the latter, see Figure 4.18

3.3.1 Characterisation methodology issues

A number of approaches for assessing indoor radiant energy can be applied, some developed by architects and lighting designers. These which include simplified methods, in situ measurements, scale modelling and computer simulation are described with their advantages and disadvantages elsewhere [Mic99]. Key parameters for IPV needs are daylight factor (sub-section 3.3.2), aspect ratio (sub-section 3.3.3) and Glazing/floor ratio (sub-section 3.3.4).

Each of the methods has specific issues with respect to the characterisation of indoor radiant energy. For example, **simplified methods** are applicable to the mass of photometric calculations required in lighting installations; no such method was found for radiometric measurements, due to the lesser general need in this area.

The **in situ** approach has the disadvantage of being specific to location, room design and orientation, weather, time of year and the many other variables that must be taken into account in such global assessments. This approach was therefore applied for specific relative comparisons only.

The convenience of a **scale model** is attractive and is used by architects [Sca94]. For radiant energy simulations for IPV it has a key disadvantage with respect to finding sensors of the right scale. Taking a conservative 1:10 ratio for the reduction in room size implies that the measurement devices require a surface area of a few square millimeters. This is at least an order of magnitude below that of commonly available photo-voltaic mini-modules. Such modules could be scanned for data collection over each surface using an x-y table. The scanning method would alter the wall reflectivity (and therefore the results) less than positioning multiple sensors on each wall surface.

Lastly, **computer simulation** (see section 3.5) cannot exactly reproduce reality but has the advantage of being able to simultaneously deal with sufficient variables. It also offers the benefit of averaging significant quantities of data (i.e. years of meteorological data), making the final result more robust and understandable.

3.3.2 Daylight Factor

Many great architects (including Frank Lloyd Wright and Louis I. Kahn) have described the importance of natural light in the built environment. Architects and building physicists describe the effectiveness with which a particular built space transmits natural light indoors by a parameter called the daylight factor, D (see Figure 3.13). This is the ratio between the light level inside a building, L_{int} compared with the light level outside the building, L_{ext}, measured vertically up in both cases. "Indirect component" is light which has undergone reflection.

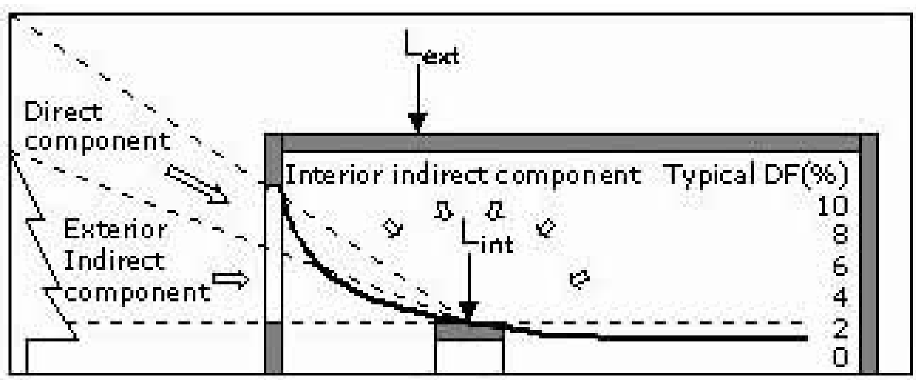


Figure 3.13: Components of the daylight factor, based on [Pau93][Rot88]

D is therefore:

$$D = \frac{L_{int}}{L_{ext}} \quad \text{Equation (3.9)}$$

where L_{int} is measured at workplane height, taken as 0.85m above the floor in Europe.

As Figure 3.13 shows, the reduction in light intensity follows a curve quite similar to the inverse square law (equation 3.3) as the distance from the window increases. In this case, the window can be considered as a multitude of point sources, but the points do not all have equal intensity.

Despite its limitations, D provides a useful indication of how little outdoor light is typically found indoors. Figure 3.14 which compares a number of different window techniques shows that peak D is around 15% with an average around 5% or below. As shall be seen in section 3.4, similar values can be found for radiant energy. This is significant for IPV because the majority of photovoltaic products are designed for outdoor use where light levels at least an order of magnitude higher than indoors can be expected.

From Figure 3.14, it is clear that D peaks in the vicinity of the window. It is also of note that light penetration is greater for the same surface of glass with a taller window; this is indicated by the increased D of the top right diagram compared with the case in the top left.

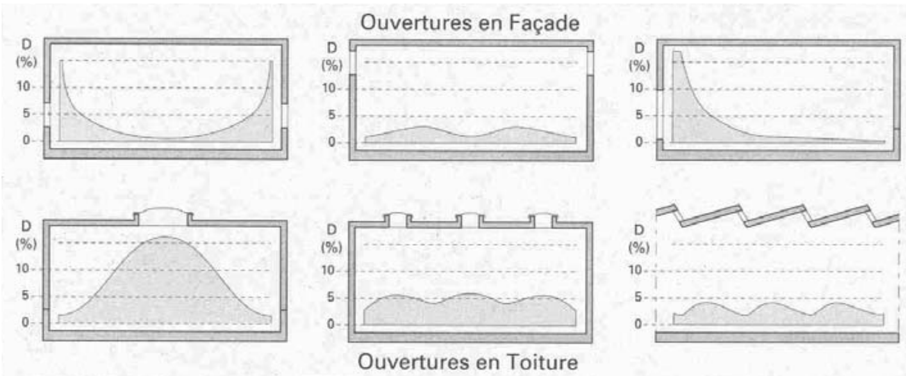


Figure 3.14: Typical Daylight Factor values for a number of window configurations in the facade or roof (toiture) [Pau93]

3.3.3 Nearby obstacle aspect ratio

Architects are also concerned with the impact of neighbouring structures, to which they refer to in terms of the aspect ratio, A_r of a particular “valley” created by buildings on two sides of a street for example (see Figure 3.15). The aspect ratio in this case is the height of the buildings, H divided by the distance between two facades, B.

$$A_r = \frac{H}{B}$$ Equation (3.10)

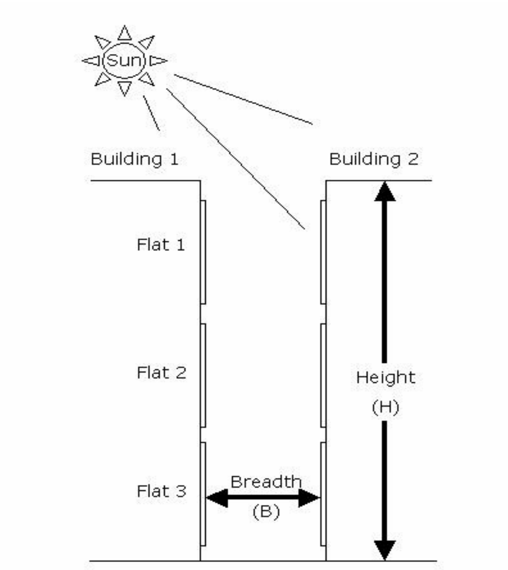


Figure 3.15: Aspect ratio parameters for the case of two facing buildings

The impact of this is examined experimentally in sub-section 3.4.1. Further data on the relationship between DF with aspect ratio and office layout can be found elsewhere [Mor97].

3.3.4 Glazing/floor ratio

The amount of daylight entering a room is related to the surface area of its windows. By dividing the window surface by the floor surface, the glazing/floor ratio is found, which can be useful for IPV design both for comparing absolute radiant energy available in a room and for assessing the opportunity of positioning the application close to a window.

3.3.5 Lighting recommendations

A related approach which provides insight on the *relative* radiant energy may be based on a reference such as the proposed international standard "Lighting of indoor work places" [CIE08]. This standard provides recommendations for minimum lighting levels (in Lux) for over 30 kinds of industries by type of interior, task or activity. The applicability of these values was confirmed experimentally (but not published) in July 2002 by the author in two types of buildings (educational and medical) by comparing measured data with the above standard. In the majority of cases (over 2/3), values measured exceeded those recommended by the standard, suggesting that values from the standard may be taken as a minimum for indoor lighting intensity estimation.

Other surveys in the area of lighting exist, but usually consider fewer kinds of interior than are covered by the above standard [e.g. Ekl96].

3.4 Radiometric characterisations

Whilst previous work in IPV design [Rot97] [Pet00] have mentioned many of the issues above, the analysis of some parameters can be improved upon, either because the whole IPV radiant energy spectral range is not included or because the specific case of wall mounted devices is not investigated. The complementary parameters covered in this section relate to obstacles (sub-section 3.4.1), windows (sub-section 3.4.2), IPV location (sub-section 3.4.3), IPV orientation (sub-section 3.4.4) and various profiles (sub-section 3.4.5). These are considered within the 400nm-1000nm range with relatively constant radiant energy sensitivity. As shown in Figure 4.18, this is the spectral response range of many photovoltaic technologies.

3.4.1 Obstacles

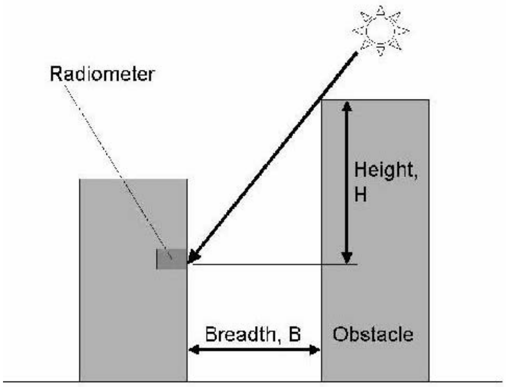
For IPV, an obstacle is any object which hinders radiant energy reaching the IPV application. The case of a direct light obstacle is familiar because it creates distinct shadows in the photometric domain.

Outdoor obstacles

Some basic theory of nearby obstacle aspect ratio has been presented in sub-section 3.3.3 but is too limited to predict the radiant energy reaching an obstructed window, especially in the horizontal plane which is perpendicular to the PV module of a wall mounted IPV application. The issue of predicting the radiant energy available is further complicated by the proportion of direct to indirect light available and the reflectivity of the obstruction for example.

In order to investigate the impact of nearby buildings on the total irradiance normal to the window of a number of rooms of the same building was measured. The rooms all faced East but had different distances to the nearest buildings; these buildings had the same exterior material and were designed similarly. The measurements in 9 rooms were taken within 33 minutes under constantly overcast conditions (diffuse light).

As Figure 3.17 shows, radiant energy intensity suffers rapid decline as nearby obstacle aspect ratio increases. From the unobstructed case (aspect ratio of 0) to a point where the inclination from the measurement point to the top edge of the obstacle is 45° (aspect ratio of 1), a relative intensity drop over 75% is measured.



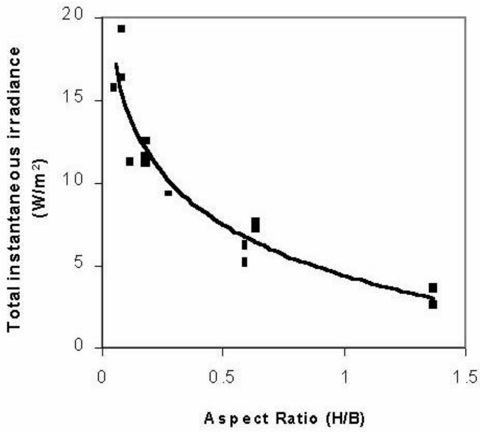


Figure 3.16: (left) Schema of irradiance measurement

Figure 3.17: (right) Total instantaneous irradiance normal to the window with respect to the aspect ratio between the measurement point and the top edge of the building directly opposite (author's measurements)

Architects typically position buildings with an aspect ratio of no more than one, i.e. building height is a guide to the minimum distance to the next building. An example for IPV of such an "obstacle" might be caused by either trees and buildings outside or by descending a few floors of the building. Typical aspect ratio ranges for homes and offices maybe 0.5-2 whilst for industrial sites the range is greater (e.g. 0.5-6), given the imperatives of contiguous processes for example.

One of the ways to compensate for the aspect ratio effect with regard to daylighting is to include an ever increasing surface of window per floor from the top to the bottom of the building.

An example of this technique in Fribourg is shown in Figure 3.18.

Figure 3.18: House on the Pont de Berne, Fribourg with greatest window surface on the ground floor (author's photograph)

Evidently it will be beneficial to improve the accuracy of the design if the expected building (aspect ratio) type is known. As not all IPV applications will be positioned on the ground floor (worst case) it can therefore be expected that the typical obstacle aspect ratio will be below one.

In the fortunate case of having more detailed building layout data, a more complete radiant energy scenario can be achieved by preparing a Waldram diagram such as Figure 3.19.

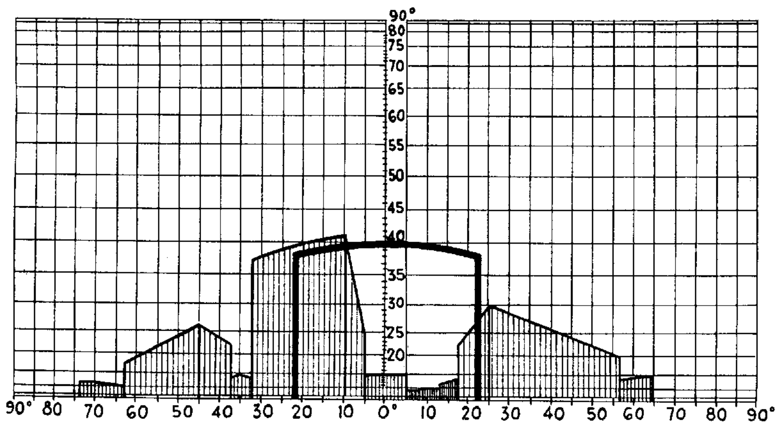


Figure 3.19: Waldram diagram from the perspective of a room showing the surrounding obstacles [Hop63]

The diagram above is a graphical representation of the view from a particular point; the bold line may represent a new building or a window opening. As the diagrams variable scale shows, it allocates different weights to the sky depending on elevation, i.e. more weight to the mid-range elevations than the highest and lowest elevations as the extreme elevations contribute the least light to the viewer. This allows total light entering the building through a known surface to be calculated.

Indoor obstacles

Obstacles indoors are objects which create shading for the IPV application within the built space. These include furniture and plants in the office or home, but may also be formed by more permanent elements such as screens and pillars. The built space is dynamic. Therefore, "rogue" obstacles that shade the IPV can also be expected. An example of malicious behaviour might be the positioning of duct tape on the solar cell, whilst an equally pernicious effect can be produced quite unwittingly by the thoughtless positioning of a new bunch of flowers. For the case of wall-mounted IPV application, the impact of indoor obstacles can in large part be mitigated by careful installation, for instance at a suitable height above the floor.

3.4.2 Window transmission

The transmissivity of the interface between the outdoors and indoors is determinant in finding the daylight radiant energy available for IPV. As will be seen below, the effects of the elements around the window can have an impact as great as the glass properties.

Furnishings

One class of IPV radiant energy obstacle that may be positioned either just in front or just outside of the window, are window furnishings. It includes (venetian) blinds, curtains and shutters. Each furnishing, although designed with visual comfort in mind, inevitably has an impact on the radiant energy available.

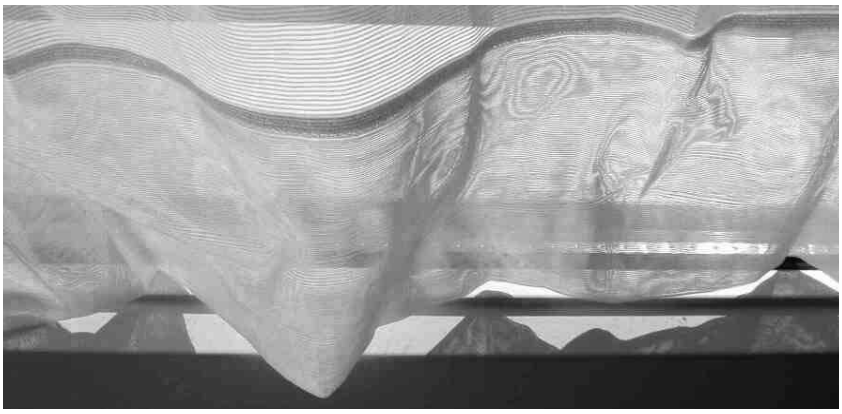


Figure 3.20: Net curtain (author's photograph)

Take for example the common (home) net curtain. To the naked eye, it appears to filter little, but as can be seen in Figure 3.21, even a single layer of net curtains transmits only 56% (+/- 2%) over the 450-700nm band. For the case of 2 layers, transmittance over the same range decreases to 32% and for 4 layers reaches 16% (+/-2% in both cases).

In practice, the true impact of a net curtain can be expected to be the equivalent of more than 1 layer as the folds of the material imply that some photons will travel through 2 or more layers. Equally the values presented in Figure 3.21 were measured perpendicular to the netting, while in practice photons are usually incident with a non-zero angle to the normal of the netting. They must therefore cross a greater amount of material, with the corollary of reduced transmission.

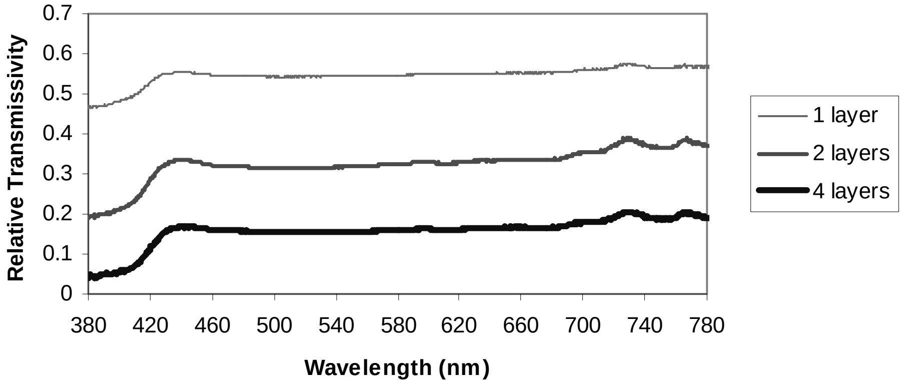


Figure 3.21: Transmissivity of the net curtain shown in Figure 3.20 (author's measurements)

In comparison, consider then a venetian blind. For the outdoor model measured in Figure 3.22, one can see that when the slats are angled so as to touch each other (slats closed) the transmissivity maybe reduced as low as 0.06, whilst with the slats "open", only down to 0.38. One can deduce that closed shutters will have a similarly low transmissivity.

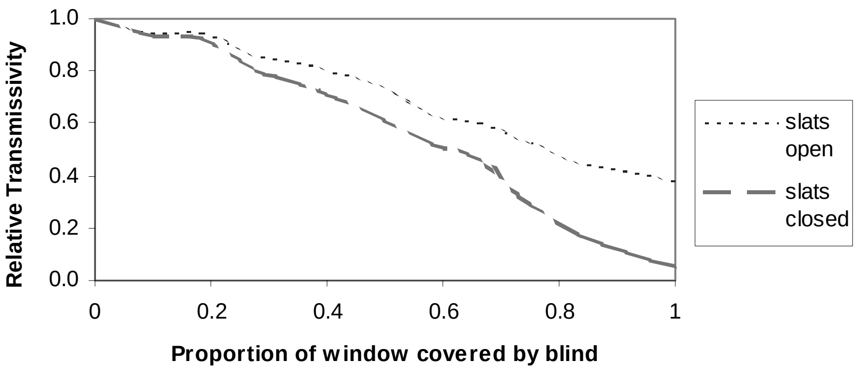


Figure 3.22: Relative transmissivity with proportion of blind surface deployed. Measurements taken at 2m from the window (facing it) at a height of 1.5m (window sill height 1.10m) with sensor at 30° from vertical (author's measurements)

Glass properties

Glass has been used for making windows for centuries [PPG02] as the stained glass in churches suggest [Mic02]. The subject has fascinated many authors [Moy01]. The importance of glass in modern architecture goes well beyond traditional window requirements. Glass today may have a safety remit (anti-fire and anti-ballistic), a structural contribution to the building as well as noise abatement role. In terms of transmissivity of radiant energy properties, a compromise between the two often contradictory needs of visual and thermal comfort is sought. Visual comfort requires sufficient photopic transmissivity whilst thermal comfort is required in two cases: firstly when the outdoors is colder than the indoors as an insulating layer; secondly, when the aim is to keep the indoors cool by preventing the ingress of invisible radiation (UV and IR range photons) and hot air. The different designs use one or more sheets of glass. The relatively linear reduction of radiant energy transmissivity for the example of a few sheets of plate glass perpendicular to the surface can be seen in Figure 3.23 to be around 0.83 per sheet.

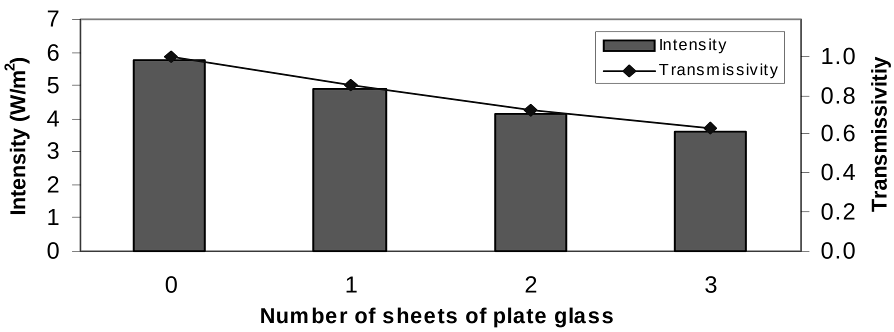


Figure 3.23: Measured intensity and transmissivity of a number of sheets of plane glass (author's measurements)

Such plate glass radiant energy transmissivity loss is also a component of the loss mechanism of thin film solar modules, see sub-section 4.5.1. It varies with the difference between the spectral response of the particular photovoltaic technology and the spectrum transmitted by the glass, see Figure 3.24.

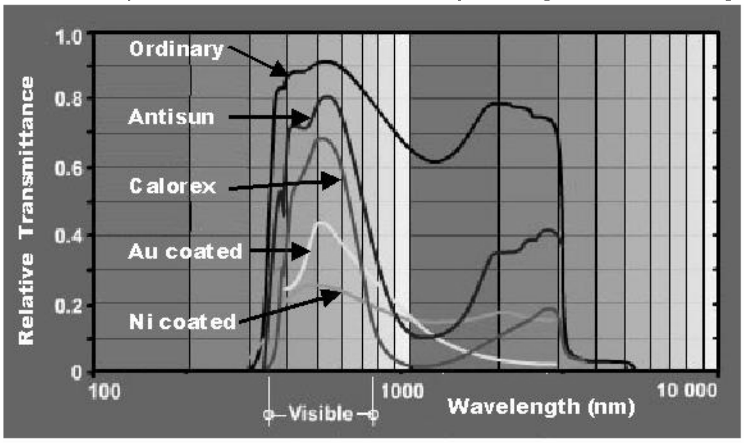


Figure 3.24: Transmission spectra for 5 kinds of glass (Au = Gold, Ni = Nickel) based on [Mar03]

This complex and developing area of window design has already produced a number of solutions such as the "sun protection" designs shown in Table 3.3. As can be seen, the ratio of thermal energy transmissivity to photopic transmissivity varies over a considerable range. Other factors (such as conductivity) being equal, glass with a ratio above one can be considered to provide less thermal insulation than the visual transparency may suggest. Modelling such properties in more detail can be involved [Rub97].

Table 3.3: Comparing the energetic and photometric transmissivity of a number of examples of solar protective glass; based on [Pau93]

Glass type	Thermal transmissivity (%)	Photoptic transmissivity (%)	Thermal Trans. / Photopic Trans. Ratio
Normal transparent	77	81	0.95
Infrastop silver	48	48	1.00
Infrastop neutral	39	51	0.76
Parélio clair	50	43	1.16
Calorex A1	42	38	1.11
Stopray Blue	36	50	0.72
Antisun Green	48	66	0.73

A short "gedankenexperiment" is useful: imagine you are standing before a roaring fire in a cold room. Think what you see and feel. If you then hold a large sheet of colourless glass up between you and the fire what do you now see and feel? You should now *see* the fire as it is, but it will *feel* much cooler behind the glass. This is because the transmissivity of glass, although high for visible wavelengths, drops markedly for wavelengths above the near infra-red band (in the 2.5-3μm range) which we can sense with our skin. These properties of glass (and polycarbonate material [Har01]) are basic for the greenhouse effect.

The greenhouse effect is based on 4 steps. Taking the example of the built environment, they are as follows: first (solar) irradiation in the visible to near infra-red range incident on a window is largely transmitted indoors. Second, the indoor objects are warmed by absorbing this energy. In the third step, they re-emit with a much longer wavelength than the incident radiation (see Figure 3.7). This long wave infra-red cannot be collected by PV solar cell, see Figure 4.23 (Typical spectral response for solar cell technologies [Fie97 p2] where GaInP = gallium indium phosphide, a-Si = amorphous silicon, CdTe = cadmium telluride, GaAs = gallium arsenide, InP = Indium phosphide, multi-Si = multicrystalline silicon, mono-Si = monocrystalline silicon, ZnO = Zinc Oxide, CIGS = copper indium gallium diselenide). This wavelength shift is described in more detail in sub-section 3.2.2. In the fourth and final step, the glass both physically blocks the warm air from escaping and reflects the long wave infra-red back into the room. The resulting indoor temperature rises so long as the radiative heat gain is not balanced by conduction and convection (i.e. heat loss).

3.4.3 IPV location

The ideal position for an IPV application will depend on a number of factors including the availability of artificial radiant energy sources such as Figure 3.8 (Typical spectrum of an indoor fluorescent tube (author's measurements)). The case of a classroom was characterised for irradiance on the walls. The windows were fitted with blinds making it possible to seal out the majority of the daylight. As can be seen in Figure 3.25, measurements were taken on two sections of the wall which it was hypothesised were representative of the other parts of the walls. This is due to the fact that the position pattern of the light sources was repeated in both the length and breadth of the room.

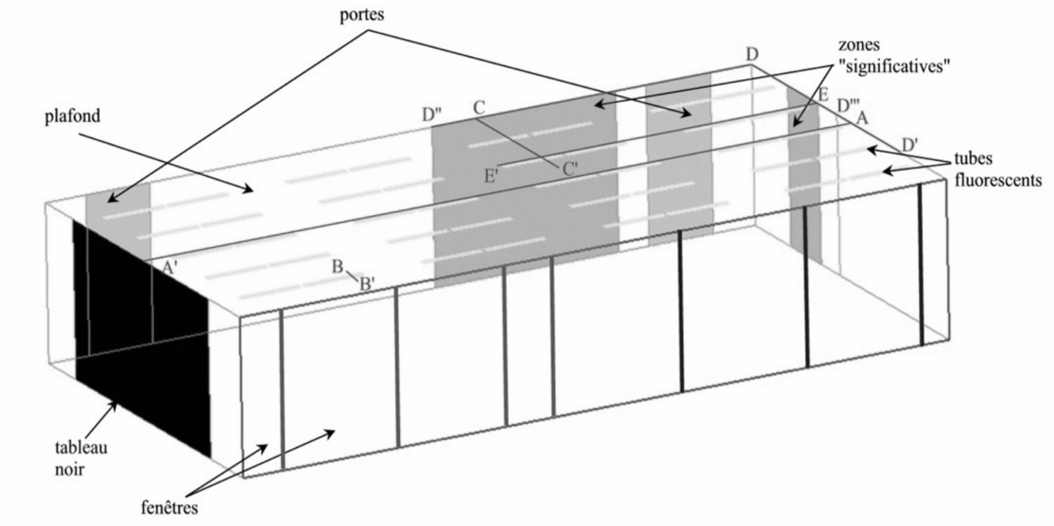


Figure 3.25: Diagram of the room characterised showing the areas where the measurements were taken (zones "significatives"), the doors (portes), the light sources (tubes fluorescents) and windows with blinds fully deployed (fenêtres) [Ba202]

The light sources can be seen to form discontinuous lines down the length of the room. For this reason it was not expected to find inverse square law behaviour (equation 3.3), but rather intensity variation with the reciprocal of distance (equation 3.4).

As the graphs in Figure 3.26 show, the irradiance on the wall parallel to the tubes was found to be generally less than that found along the wall to which the tubes are perpendicular.

This is to be expected as the parallel tubes are installed further from the wall than the perpendicular tubes.

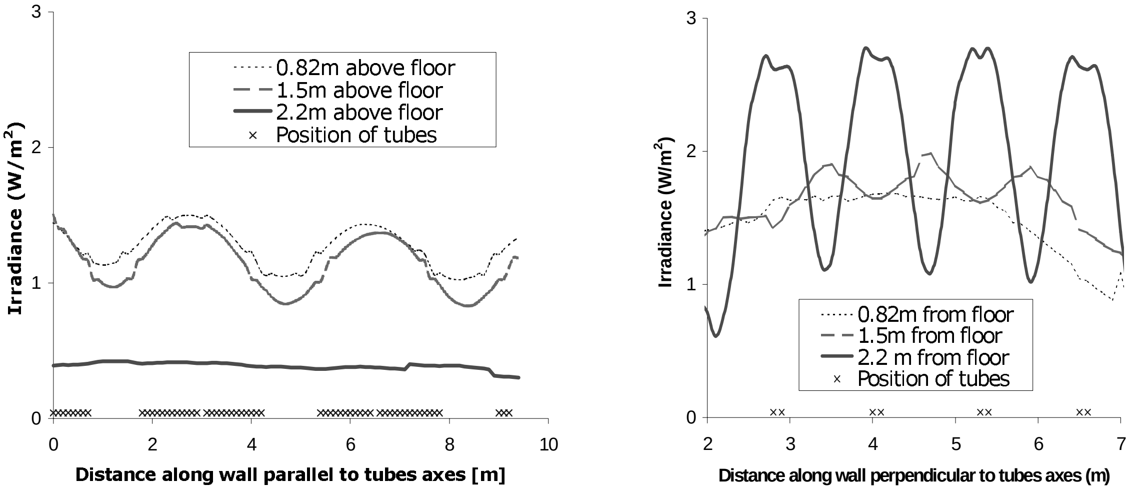


Figure 3.26: Irradiance along wall parallel with tubes (left graph) and perpendicular to tubes (right graph) at three heights above the floor (author's measurements in collaboration with [Ba102])

Super-position

The relationship between tube position and intensity can also be seen. The position of the maxima indicates that there is super-position between adjacent light sources at 1.5m from the floor on both graphs whilst no such super-position is found at 2.2m from the floor. The general case is schematised in Figure 3.27 which indicates the importance of vertical position on the wall for an IPV application. If the vertical position is specified and the light sources are suitably close together, then a related ideal horizontal position with respect the light sources is evident: i.e. in the case of a vertical position in the "super-position" area, this would be equidistant between two sources, and for a vertical position in the "no super-position" zone, directly below one of the light sources.

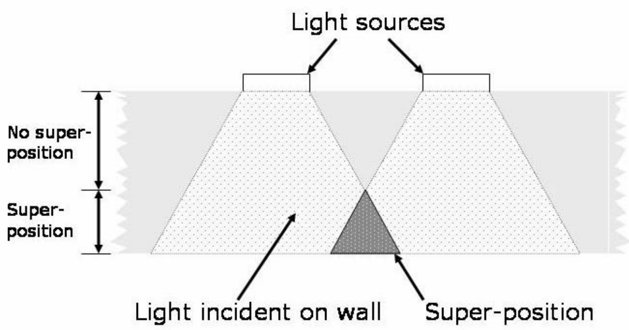


Figure 3.27: Super-position of two adjacent light sources

Cross-over point

The various sources of irradiance have so far been reviewed individually. In practice of course, they overlap. Given the artificial light source irradiance distribution mentioned and combining it with the daylight data (sub-section 3.3.2) allows a comparison of the two, see the general case in Figure 3.28.

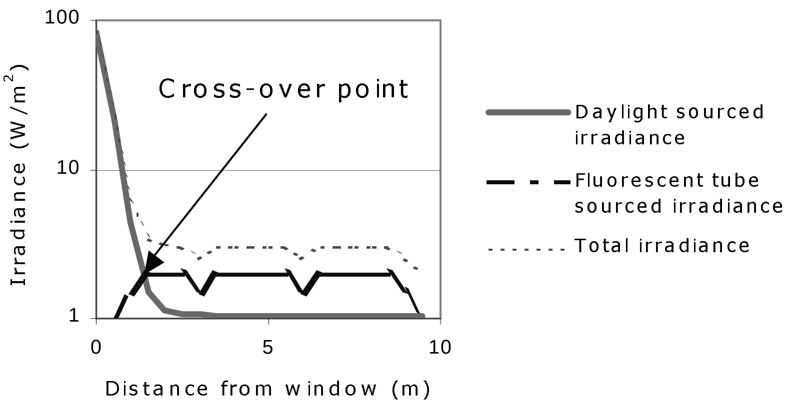


Figure 3.28: Cross-over point of daylight and artificially sourced irradiance (author's measurements)

As can be seen, the greatest irradiance is usually found at the window (see Figure 3.32) and is independent of weather conditions during daylight hours. This irradiance rapidly attenuates with distance from the window so that it's intensity equals that of the electrically sourced light at a "cross-over point" (see Figure 3.28). The reason for such attenuation can be explained by separating the direct and indirect daylight vectors. The strongest direct light will come from a direction overhead and will have a relatively shallow angle to the plane of the window. Some of the indirect light will have a more ideal angle for penetration into the built space but at an intensity of around an order of magnitude less than the direct light. The remaining indirect light will also have a vector with a relatively shallow angle to the plane of the window and can therefore not penetrate deeply into the room either, thus also contributing to the intensity near the window. Only when the sun is low in the sky can direct light penetrate into the room, but with an intensity below the maximum for direct light.

This point is usually around 2m from the window, although due to the dynamic nature of all radiant energy sources, will vary over the day. The rapid reduction of daylight is due to a similar as one moves away from the window is due to the fact that the direct light from the does not penetrate

Therefore, so long as an IPV design can cope with the reduced intensity available from artificially sourced irradiance, it can be located in a much larger range of positions within the room. On the other hand, if it cannot be adapted, then the position must be within a short distance (less than 2m) from the window.

3.4.4 IPV cell orientation

The importance of cell orientation with respect to the irradiance has been presented (equation 3.5). However, only one wall mounted IPV application has been found (Migros Indoor/Outdoor temperature gauge) that has an orientation of the solar cells other than parallel with the wall. Consider the irradiance maps in Figure 3.29; these were measured in the room shown in Figure 3.25 with the sensor parallel to the wall. The irradiance is generally below 1W/m^2.

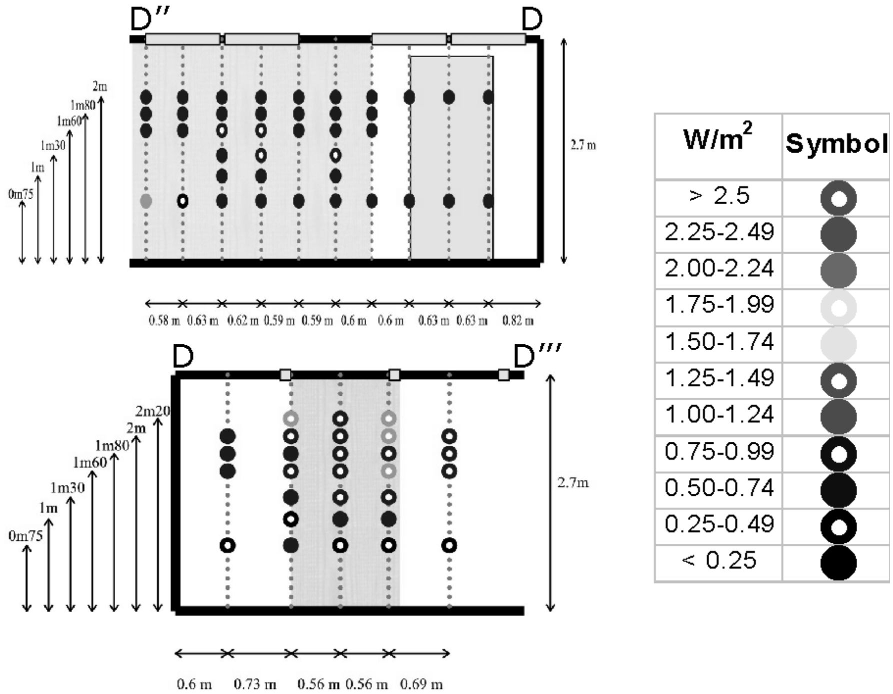


Figure 3.29: Irradiance maps for both areas measured with the sensor parallel to the wall (author's measurements in collaboration with [Ba202])

If the sensor is then incrementally oriented over the range shown in Figure 3.30, then a maximum value can be found, see Figure 3.31. These values are generally over double those found in Figure 3.29, such as those measured on the wall perpendicular to the tube axis of 1.5-3W/m^2. This is evidently an important parameter in IPV design as it can translate into reduced solar cell surface or battery size.

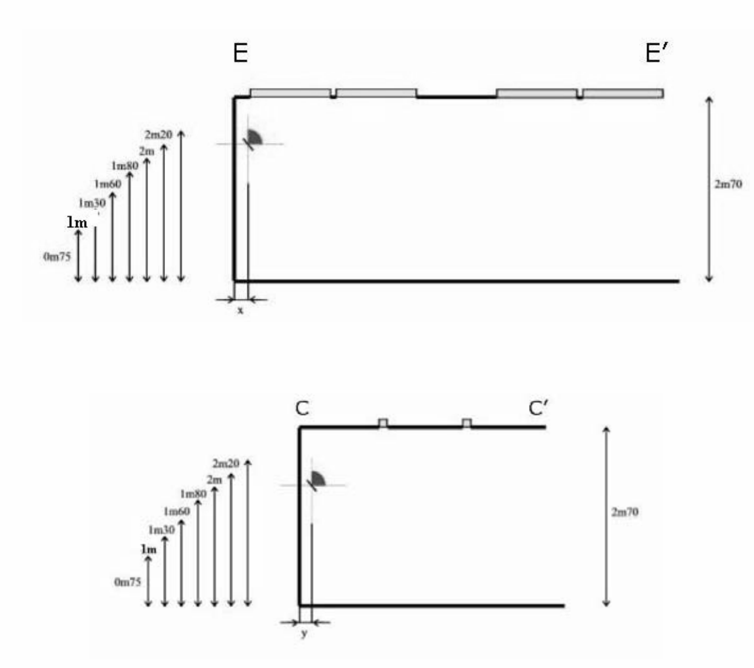


Figure 3.30: Orientation range of sensor [Ba202]

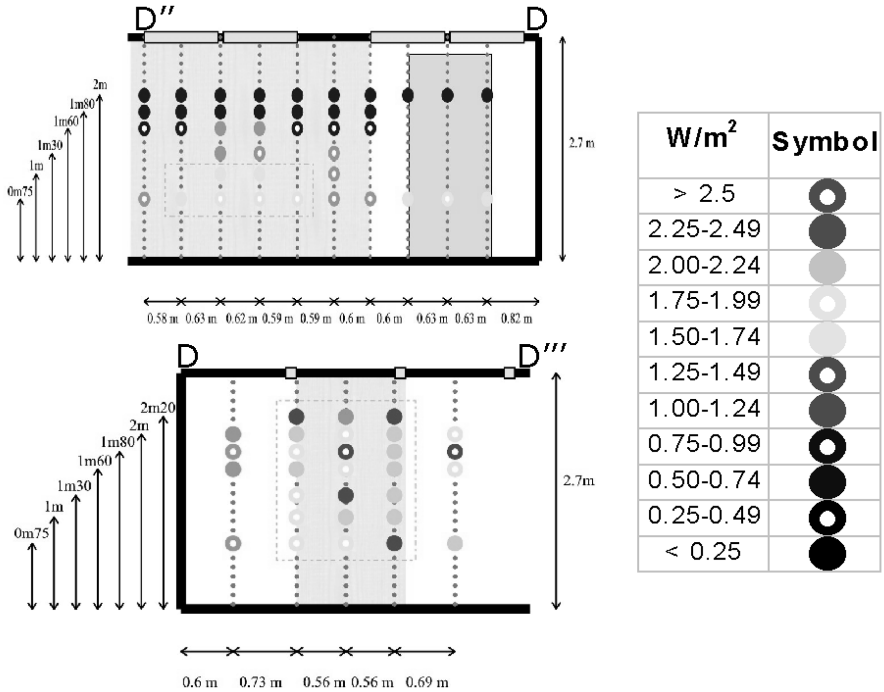


Figure 3.31: Irradiance maps for both areas showing the maximum value found with the sensor oriented across the range shown in Figure 3.30 (author's measurements in collaboration with [Ba202])

The angle chosen will depend on typical installation height and the extent to which the product (in the case of a retrofit) can be modified to allow the solar cells to be more ideally oriented. In the study on which the results are based [Ba202], the ideal angle was found to be in the range 35-70° from the vertical.

3.4.5 Further profiles: Buildings, Users and applications

When one specifies an IPV product, a number of parameters cannot be specified exactly and are therefore treated with profiles. Profiling can allow a complex problem to be converted into a small number of simplified representative cases which can provide input to the overall analysis.

The importance of building profile for example is evident when comparing the typical distribution of artificial light sources. In US surveys [Lat93], 98% of households used incandescent lighting whilst commercial floor space was lit in 77% of cases by fluorescent sources [Joh95]. This affects IPV as solar cell technologies have different response to spectra (see Figure 5.4). A trend today is the growing acceptance of long-life compact fluorescent lamps (CFL). As these are lower rated power than the incandescent bulbs they replace, this implies that less emitted power or radiant energy is available to IPV.

Equally, the building users do not necessarily have predictable lighting use behaviour. This might be due to a number of reasons including climate, culture, typical hours worked and whether extra light is required for performing the task.

Further profiles (e.g. product use pattern) are covered in sub-section 7.2.2.

3.5 Computer simulation

The attraction of simulation software in the area of lighting design can be gauged by the number of products available (23 are mentioned for Switzerland in [Pau94]). But these have issues, chief of which for IPV design is their low physical accuracy. Typically, in order to maximise computational speed, the models used little respect the laws of Physics over the range that they are applied. This naturally compromises the results produced. Further pros and cons of simulation in the area of lighting are covered in [Com94].

The software which to the author’s knowledge best respects the physical laws is the UNIX based “Radiance” by Ward [War88] [GRC88]. It has the disadvantage of being one of the least accessible to an unskilled user, requiring of the order of 3 months for proficiency. However, as can be seen in the Figure 3.32 a scene can be fully modelled and characterised.

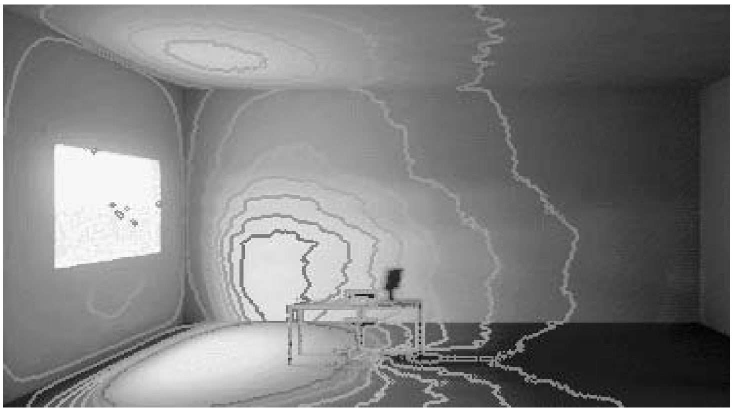


Figure 3.32: Rendering of a simple office augmented with iso-intensity lines (red=high, blue=low) [Com02]

Such a representation of a an indoor environment is typically made for a single time. It is also interesting to IPV designers to have cumulative data over a year for example. "Radiance" studies of cumulative solar energy for photovoltaics have already considered outdoor locations with simulated [Com00, Com01] and real data [per01] skies. The application of either kind of sky to indoor studies has to the author's knowledge not been previously described.

Ideally such daylight data will be combined with appropriate electrically powered light irradiance data so that the total energy reaching an IPV product can be computed.

3.6 Discussion

Reports dealing with the irradiance available for solar cells exist, but are incomplete for IPV purposes as for instance they deal only with outdoor radiant energy [vdB01] [Kri00]. Another reference is the ISO standard "Lighting of indoor work places" [CIE08] which suggests appropriate lighting levels for a large variety of indoor locations. Experiments to validate this standard in a number of location types (e.g. schools, hospitals and homes) indicate that the lighting levels mentioned in the standard are generally exceeded. This means that the designer may use them as an expected minimum light level.

3.6.1 Summary of parameters

In order to provide an overview of this chapter, the radiant energy that can be expected outdoors and indoors is set out in the top two lines of Table 3.4. The lines below show the radiant energy parameter ranges that can be expected inside built spaces. For a particular product case, this would be augmented by the (statistical) distribution of each parameter. The tighter these parameter tolerances can be specified by the designer, the more likely it is that the resulting product will perform as required.

Table 3.4: Built space radiant energy parameter range (based on author's findings)

Parameter	Typical IPV range	Sub-section reference
Radiant energy: daylight outdoors	0-1000W/m^2 33-200kWh/m^2/month	"5.1" "3.2.1"
Radiant energy indoors: electrical (fluorescent) daylight (worst month)	0-3W/m^2 0-700Wh/m^2/month 0-10kWh/m^2/month	"3.4.4"
Distance from effective radiant energy source (including windows) to IPV application	0-100m	"3.2.1"
Horizontal orientation	-180-180° 0.25-1.0	"3.2.1"
Orientation above horizontal	0-90° 0.5-1.0	"3.4.4"
Spectra	Daylight, Fluorescent, Incandescent.	"3.2.2"
Built space daylight factor	0-15%	"3.3.2"
Obstacle aspect ratio	0-6	"3.3.3"
Glazing/floor ratio	0-0.5	"3.3.4"
Window transmissivity	0.5-0.9	"3.2.3"
Surface reflectivity	0.2-0.8	"3.2.3"
Window furnishings transmissivity	0.06-1	"3.4.3"

3.6.2 IPV designer recommendations

A parameter which in IPV applications is often ill-implemented is the orientation of the solar module, see sub-section 3.4.4. This parameter is often overlooked and could save both PV surface and battery size. In practice for a wall mounted device, this saving can be achieved by designing the product casing to accommodate an elevation of the module (see Figure 7.9).

With respect to the IPV location, it seems worthwhile to recommend better installation of wall mounted applications with respect IPV location see sub-section 3.4.3. For those that the user installs, brief instructions could be included with the product. For the installer, only limited training would ensure more reliable performance.

3.7 Conclusion

An easy mistake for designers to make in assessing the applicability of a location for IPV is to rely too heavily on what they see. The human visual systems suffer two disadvantages when determining the radiant energy capital of a location: they are relative light meters and they do not have the same spectral sensitivity as solar cells. The results presented here may therefore seem counter-intuitive at first. This chapter should enable the designer to overcome their human (photometric) perception and appreciate the radiant energy resources available in a built space.

The new perception is based on the many parameters that affect indoor radiant energy. These may be qualitative (photometrics in section 3.3) or quantitative (radiometric experiments section 3.4). Considered together, such as in section 3.6, they may serve the IPV product designer at a number of levels such as providing the range of values of the radiant energy found indoors. As can be seen in Table 3.4, a well oriented and located product may receive of the order of a kWh/m^2/month of radiant energy. At least ten times this value may also be achieved, on the window ledge for example.

This chapter also provides an appreciation of which are the most significant parameters that are found along the “photon chain” between the light source and the PV device. A number of recommendations are provided in order to allow the designer to achieve the best performance from a proposed IPV application. Further recommendation for the practitioner can be found in chapter 7.

3.8 Future work

Ambient energy in the built environment is available at other frequencies than the radiant energy chiefly considered here. These include (“mechanical”) vibrations in the 50-200Hz range [Rou01]. It would be interesting to perform a similar study of the built space for such frequencies. Figures for twelve vibration source examples are presented in [RWR02]. By combining the results of the present chapter and this future study, a more general mapping of the ideal locations for ambient energy products could be developed.

The well known mathematical non-diffusive billiard ball model could be applied to IPV photon modelling if the energy diffusion created by the imperfect reflectivity of the walls were included. At present, whilst the billiard ball model has attracted hundreds of journals contributions, none deal with diffusion.

3.9 Further reading

For more detail on many aspects of building physics, especially light distribution in the built space, see [Hop63].

Chapter 4 : Fundamentals of Photovoltaics

Pour nous, les s'miconducteurs, c'est des gens qu'ont qu' le permis provisoire!

Rotzetter N., Chamonix, 29th March 2002

4.1 Introduction

Understanding the way photovoltaic (PV) solar cells work is non-trivial. Therefore designers without prior training are likely to find understanding the concepts on which solar cells rely uninviting. One reason is that the quality texts on semi-conductors generally require Physics understanding.

It is the aim of this chapter to address the lack of widely accessible information about photovoltaic solar cells. In tandem with the radiant energy information (chapter 3), the foundations are thus lain for the following chapter (chapter 5) that considers the characterisation of solar cells indoors.

An appreciation of how solar cells work is essential to the designer as it forms the basis for the improvement of solar cell performance (treated in section 4.7 and section 5.5).

This chapter may serve a broad spectrum of readers, from the scientifically inclined novice up to the photovoltaics specialist. For those who are relatively new to the area of solar cells, the first two sections set PV in its historical (section 4.2) and technological context (section 4.3). The more experienced may prefer to skip to section 4.4, where the fundamental solar cell parameters are briefly explained. In section 4.5, the reasons why solar cell efficiency is relatively low are reviewed. The most common PV materials available are reviewed in section 4.6 with special consideration to IPV applications.

In summary, this chapter aims to answer these questions:

a) how was PV developed? (section 4.2)

b) how does PV work? (section 4.3 and section 4.4)

c) what are the weaknesses of PV? (section 4.5)

c) what PV solar cells are available? (section 4.6)

d) how may indoor PV modules be improved (section 4.7)

To the author’s knowledge, no other single published document combines all these elements, especially as succinctly and with reference to indoor ambient energy systems.

4.2 A brief history of solar collectors and PV

All inhabitants of planet Earth have been collecting solar energy since the beginning of their existence. Evolution (and more recently civilisation) can be considered as a progression of ever more efficient means of collecting and converting this energy which is both bountiful - delivering 1.5 Z[1]Wh/an - and consistent, having been burning for an estimated 4.6 billion years. Relative to such time scales, the discovery that solids

1. Zeta (Z) is the SI unit for 10^{21}

can convert solar energy directly to produce that most flexible of energy medium, electricity, is a very recent one. In its infancy, however, photovoltaic technology was based on a solid-liquid system.

4.2.1 The "Selenium years"

The first event of note in the history of solar cells was the discovery of selenium made by Berzelius in 1817 [Wol72]. Incidentally, he was also the first to prepare elemental silicon a few years later. However it was over two decades before Alexandre-Edmond Becquerel (1820-91), a French physicist, observed the photovoltaic effect in 1839. The nineteen year old made this discovery by immersing two metal plates in a conductive fluid and observing a small voltage across them on exposing the apparatus to the sun. It is a twist of fate that his son, Antoine-Henri (1852-1908), shared the 1903 Nobel Prize in Physics for the discovery of spontaneous radioactivity, a competing technology to solar energy in modern power production!

34 years after the discovery of the photovoltaic effect, Willoughby Smith (born Great Yarmouth, UK, 1828, died Eastbourne, UK, 1891) made another significant discovery. Already a pioneer in the installation of submarine telegraphic cables, he reported the photoconductivity of selenium in 1873 [Smi73]. This was to inspire W.G.Adams and R.E. Day to make the first selenium cell in 1877.

One of the first to envisage that such cells could be applied to power production was an American, Charles Fritts. Having produced his own selenium solar cells, which were verified by Werner Siemens [Sie85], he predicted their use in what are today called Building Integrated PV (BIPV). He wrote in 1886 that the sun "is both without limit and without cost and will continue to stream down on earth after we exhaust our supplies of fossil fuels" [Per02]. How familiar such arguments for renewable energy sound even today! Yet as today, the reason for the lack of expansion of photovoltaic cells was affordable efficiency. Typical cell efficiency was less than 1%, and therefore unrealistic for large-scale power production.

This remained the case for over half a century, but did not stop further discoveries in photovoltaics. New materials were found to be photosensitive, such as the combination of copper with cuprous oxide, discovered by Hallwachs in 1904. The science of photovoltaics also evolved with Milikan's experimental proof of the photovoltaic effect in 1916 and Albert Einstein's Nobel Prize of 1921 for his contribution to explaining this effect [Arr21].

4.2.2 The "Silicon years"

It was to be another material on which the progress of photovoltaics was to rely: silicon. The first solar cell of silicon was reported in 1941 by R. Ohl. Thirteen years later, the efficiency of such cells had reached 6%, as reported by D.M. Chapin, G.L. Pearson, and C.S. Fuller [Cha54] from Bell Telephone Laboratories.

Figure 4.1: (left) Chapin, Pearson and Fuller [Per99]

Figure 4.2: (right) Hoffman scientist indicates a PV cell on Vanguard 1 [Per99]

Such cells were applied to space applications within 4 years aboard America’s second satellite, Vanguard 1 [Wil99] which continued to transmit until 1964! Indeed, the then space industry culture of “performance at any cost” contributed to the development of solar cell technology which was to favour terrestrial applications. The Club of Rome report, “The Limits to Growth” [Mea72] and the 1973 oil crisis also raised awareness of the importance of renewable energies in general and photovoltaics in particular, but as can be seen from Figure 4.3, the most significant market growth for PV has only come since 1995.

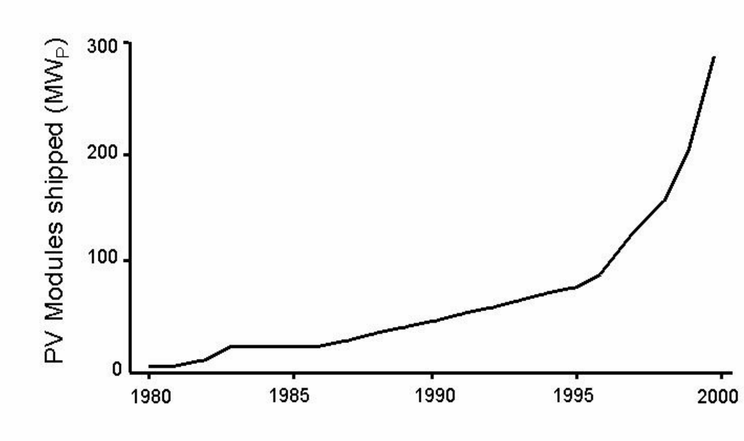


Figure 4.3: Global production of PV 1980-2000 based on [U.S02]

This is reflected in the present PV production rate of the order of 400MW/an [Fig98] and a consistent growth rate of the order of 30% per annum in recent years, which is far superior to a typical business cycle.

These impressive figures should be taken in context. The majority of outdoor use PV applications benefit from subsidies; also, at the global scale, PV is still a minority power source i.e. 400MW represents 0.004% of the global power *installed capacity* of around 10TW[1]. This is due to the much larger contributions of other technologies indicated by global energy *supplied* in 2000 (see Figure 4.4).

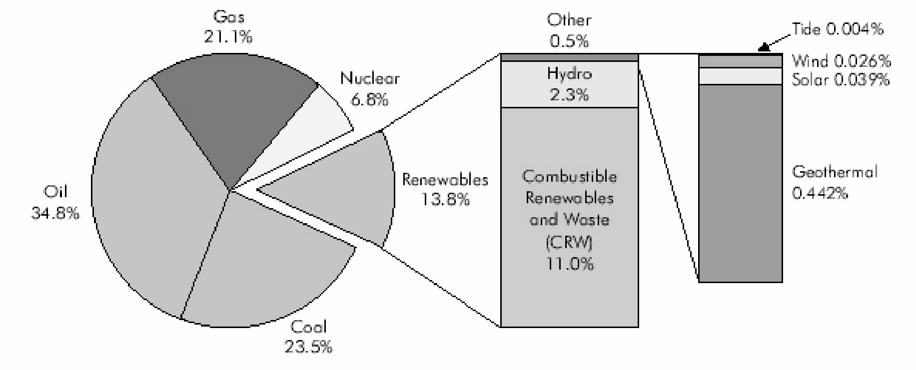


Figure 4.4: Global Total Primary Energy Supply (9958 Mtoe) in 2000 by fuel (Nb Solar includes solar thermal) [IEA02]

PV will remain a minor power source even if such an ambitious target as those set by the European Commission [Com97] of 3GW of PV production by 2010 are met. The latter target represents 100 times the 1995 value - the most aggressive relative growth of all the renewable energies considered in this White Paper [Com97 Table 1A 4.8]

Exceptional progress has also been achieved in the cost of PV. In 1970, modules cost $100 per rated Watt whilst now one would expect to pay less than $4 for the same power rating [Gir98]. However the true cost of producing electricity using PV includes the installation and maintenance cost (collectively, balance of system or BOS costs). When comparing power producing technologies from the perspective of installed cost, see

1. 1 TW (or $1x10^{12}$ W) is equivalent to 1 billion kW; therefore assuming 7 billion ($7x10^9$) inhabitants of the Earth, average installed capacity is around 1.4kW/ inhabitant

Figure 4.5, we see that PV is uncompetitive with respect to existing centralised power technologies and price structures.

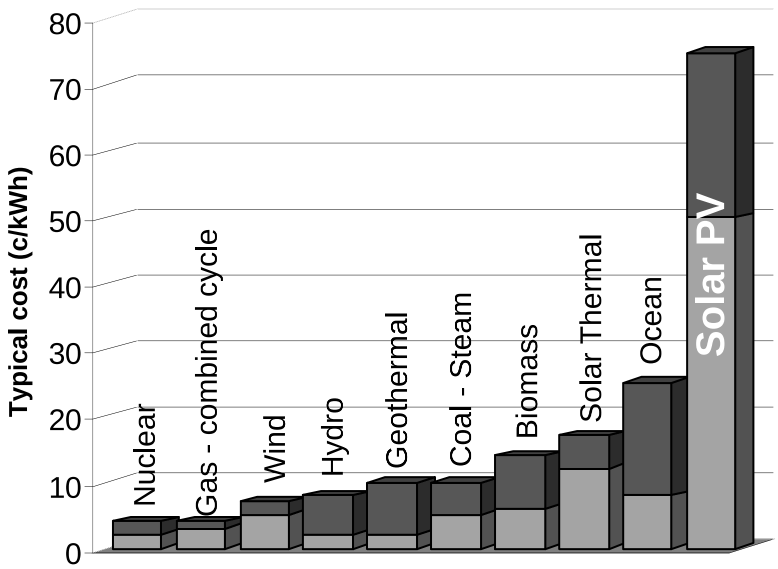


Figure 4.5: Typical minimum and maximum electricity generation cost for a number of power generation technologies [ABB98]

An exception to this is for locations that are outside the electrical power distribution network (in the jargon "off-grid"), where the cost of installing power cabling may be prohibitive. For the moment, such decentralised PV applications represent only a minor fraction of the PV installed base.

Decentralised energy production is conceptually equivalent to the target applications of this project. Whilst the majority of research in PV is aimed at making power production applications economically viable, the following chapters focus on indoor applications, an area which is already economic and, as is submitted here, can be further developed.

4.2.3 History of IPV

IPV (or Indoor PV) has been successful despite much less governmental support. One of the first applications of solar cells to indoor devices came in the mid-1960s in the form of table-clock with the solar panel on the dome, see Figure 4.6.

Figure 4.6: Cheveaux table-clock courtesy of Patek Philippe Museum

Watches followed in the mid-1970s, such as the Ragen Synchronar® 2100 (Figure 4.7) below and calculators, for example those produced by Royal (Solar 1), Teal (LC812) and Sharp (EL-8026).

Figure 4.7: The Ragen Synchronar, an early solar watch [Ste02]

Calculators have been the most successful IPV application to date, seeing the strongest growth in sales during the 1980s and reaching sales of 10M pieces/an by 1990 [Hil95] thus avoiding millions of single-use batteries. This volume of solar cell sales would produce 4MW under 1 sun, which at the time (see Figure 4.3) represented approximately 10% of the global PV shipments. Since then, the latter market has grown significantly whilst the solar calculator market has saturated. Therefore, in order for the IPV sector to grow, other applications such as are considered herein (e.g. Figure 4.8) are necessary.

4.2.4 IPV today

The present day situation is one of relatively ubiquitous application of amorphous silicon for many calculators and some watches. An ever growing range of indoor use solar products are now available such as those shown in Figure 4.8 including from left to right calculators, watches, alarm clocks, scales (e.g. Maul®), meters, moving shop window presenters (e.g. Dual Promoter®), decorations (e.g. Solar Seerose with lid removed to show LED), office staplers (e.g. Skrebba®), torches and a kitchen whisk (e.g. SoLait®) not to mention radios (not shown).

Figure 4.8: Present day IPV products (author's photograph)

Given the lower radiant energy intensities indoors, and therefore reduced voltage (see section 5.2.2), it is all the more important to create series connected modules. For such applications, thin film technologies are appropriate as they can be monolithically series interconnected (see sub-section 4.6.6). Indoor applications therefore contributed to the production growth of such technologies as amorphous silicon, which today represent 12% of solar cells manufactured, see Figure 4.9.

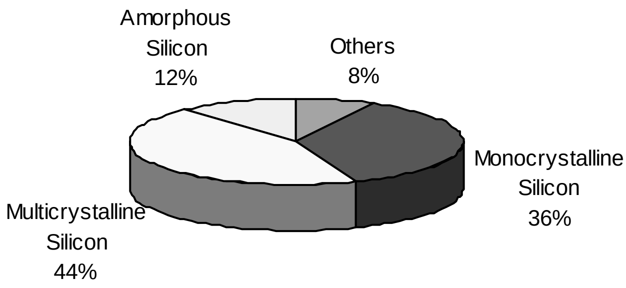


Figure 4.9: Photovoltaic cell production by technology in 1999 [Eur00]

4.3 Photonic semiconductors

All solar cells are based on semiconductors, more specifically the class of photonic semiconductors. A general description of semiconductors is therefore provided in sub-section 4.3.1; the fundamentals of photonic semiconductors may be found in sub-section 4.3.2. These may be categorised in at least four different way, see the "Solar cell categories" described in sub-section 4.3.3.

4.3.1 What is a semiconductor?

A simplified approach to material conductivity categorisation is to graph the available energy levels that electrons can occupy for each material. These are in bands, unlike the case for atoms which have discrete energy levels. Each material can then be sorted into one of the three categories shown in Figure 4.10

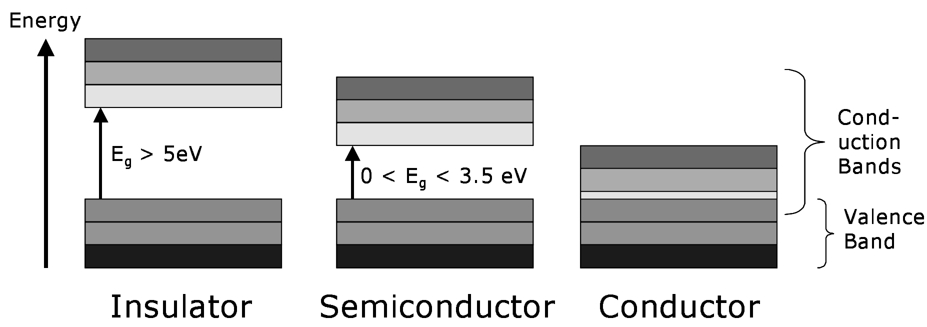


Figure 4.10: Band-gap diagrams for a typical insulator, semiconductor and conductor showing approximate excitation energy (E_g)

These bands can be further summarised on the Energy (E) scale into the valence band (VB) and the conduction band (CB). Materials with a greater than 5eV energy gap between the VB and the CB are called insulators; those with a gap in the range 0 to 3.5eV are referred to as semiconductors. If the CB overlaps the VB, the material is said to be a conductor.

Conduction requires electrons to be available in the CB. Semiconductor materials can fulfil this criterion with controlled variation of heat, light, magnetic field or impurities (doping). Their resistance may therefore be adjusted across many orders of magnitude, for example roughly within the range $1\text{m}\Omega\text{–}1\text{M}\Omega$.

4.3.2 Photonic semiconductor properties

Semiconductors can be used to convert light into charge and vice-versa; such semiconductors are called Photonic (devices). A few examples are shown in Table 4.1, "Examples of Photonic Devices".

Table 4.1: Examples of Photonic Devices

Conversion Process	Light -> Charge	Charge -> Light
Examples	Photodiode, Solar cells	LED, OLED, LASER

The p-n junction

Solar cells therefore convert light into charge. They achieve this across a junction (see Figure 4.11), which is an interface between an appropriately p-doped (positive) and an n-doped (negative) area. This doping is characterised as being fixed in the material lattice and having a different amount of electrons in the outer orbit than the bulk material. It can therefore be ionised to either provide an electron or a hole (an effective positive charge due to the absence of electron). In Physics, such dopants are called (electron) donors and (electron) acceptors respectively.

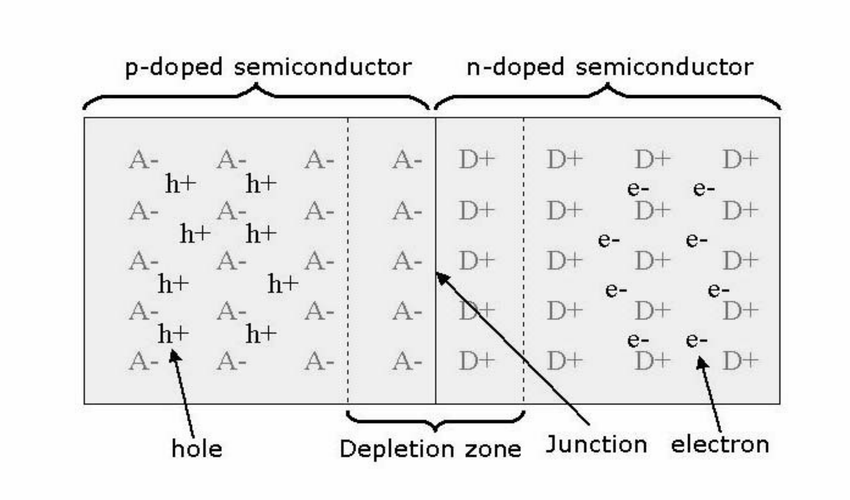


Figure 4.11: Simplified schema of p-n junction inspired by [Zal01]. A- is an ionised acceptor, D+ is an ionised donor.

On formation of the junction, the mobile charge carriers (electrons and holes) next to the junction jump across it, being attracted by the opposite charge on the other side, and then recombine. In so doing, the electrons from the n-doped area leave (positively) ionised donors behind. Equally, holes expose ionised acceptors. This leaves a net negative charge on the p-doped side and net positive charge on the n-doped side thus creating an electric field which separates the remaining mobile charge carriers. The area where this occurs is called the depletion zone (see the middle vertical stripe in Figure 4.11)

Such a p-n junction can be used as a diode and therefore Figure 4.11 can be summarised with the standard symbol for a diode as shown in Figure 4.12 which maintains the same p-n orientation. When a voltage is applied across the junction in forward bias (left hand diode), the depletion zone is reduced in width allowing current to pass. In reverse bias (right hand diode), the electrons are drawn apart, the depletion zone is widened and it is thus much more difficult for electrons to pass the junction.

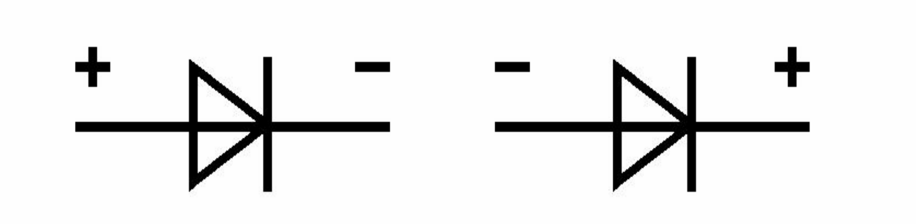


Figure 4.12: Forward bias (left hand diode) and reverse bias (right hand diode)

When the junction is made of photovoltaic material and illuminated, the arriving photons can excite electrons from the valence band into the conduction band, leaving a "hole". Each electron-hole "pair" may be separated under the influence of the electric field at the junction and contribute to the photocurrent.

Light absorption modes

The absorption process is material dependent and may be *direct* or *indirect*. As a result, semiconductor materials are said to have a *direct band gap* or an *indirect band gap* respectively. The simpler (first order) process of direct band gap absorption is so called because the maximum valence band energy (band edge) has the same crystal momentum as the minimum of the conduction band. This means that absorption of the photon can occur without a change of momentum, see Figure 4.13. A material that exhibits such properties is GaAs.

Indirect band gap semiconductors have a conduction band edge that has a different crystal momentum (or wave vector) to the valence band edge, see Figure 4.14. The process of absorption is therefore second order requiring a phonon to be absorbed and emitted to allow the absorption to take place.

A phonon is simply put the fundamental (quantum) particle corresponding to the crystal structure vibration. Just as light can be considered as a wave or a quantum (fundamental particle) which is the photon, sound can also be treated as a wave or a phonon. The two quanta differ in that the photon has high energy and low momentum, whilst the phonon has low energy but high momentum. This may be understood more intuitively when one considers the large difference in the velocity of light and sound through a material.

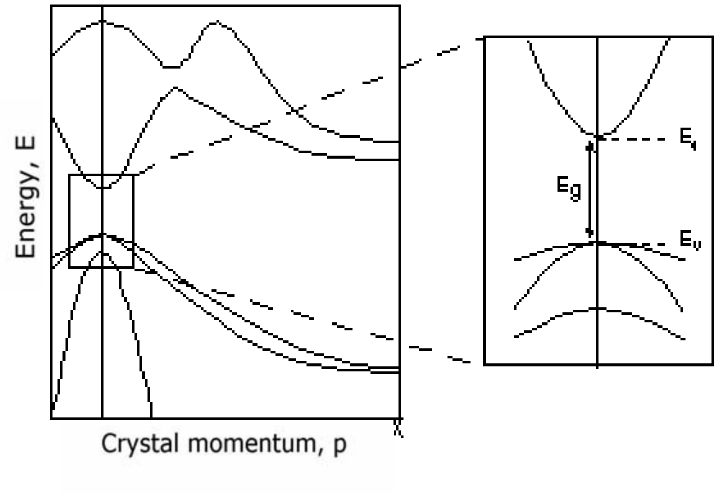


Figure 4.13: Energy-wave vector graph for a direct band gap semiconductor [Hes02]

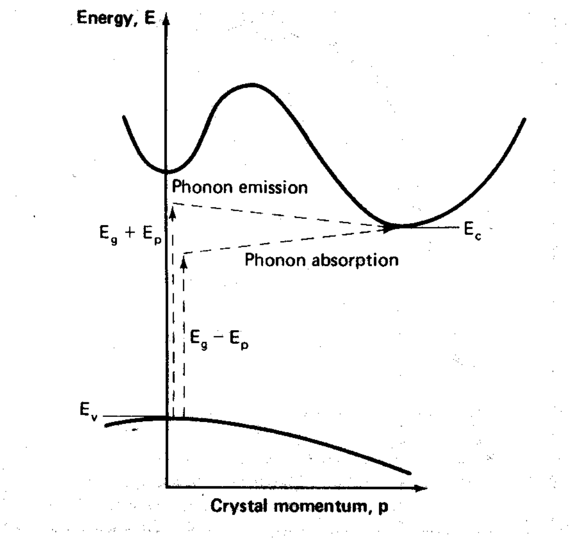


Figure 4.14: Energy-wave vector graph for indirect band gap semiconductor from [Gre98] p46

Electrical contacts

Post absorption, the current is collected via front and back contacts. The rear contact typically covers the entire surface whilst the front contact must have low surface area for non-transparent materials (achieved by the use of a fine grid of metal) to allow the photons access to the PV material. Semi-transparent contacts are commonly produced using a conductive oxide.

4.3.3 Solar cell categories

Solar cells can be categorised in a number of ways:

i) by thickness of semiconductor material

ii) by group number(s) in the Periodic Table

iii) by specific compound

iv) by being based on plastics (organic polymer compounds)

i) Semiconductor thickness

The solar cells most used at present are technologically based on the silicon wafers of the microchip industry. They have a thickness of approximately 300-400µm and include crystalline (single crystal), polycrystalline and multicrystalline silicon cells. They are manufactured in blocks and sawn in to wafers except in the case of EFG (edge-defined film-fed growth), in which wafers are drawn directly out of the melt by capillary action.

The other principal category with respect to thickness is called the Thin Film solar cells, so called because the typical photo-sensitive semiconductor material thickness is of the order of 3-5µm. These are produced by deposition of the photovoltaic material on to a substrate such as glass, metal and relatively recently, polymers.

ii) Periodic Table Group number(s)

Semiconductors can be made from single element materials or compounds. Group IV elements such as silicon (Si), germanium (Ge) and tin (Sn) are used to produce elemental semiconductors. These elements can also be combined (e.g. SiGe) to form compound semiconductors. More common compound semiconductors are made from combinations of Group III and V (e.g. GaAs) or Group II and VI (e.g. CdTe).

A simplification of the group number categorisation is to consider the chemical composition of the bulk material on either side of the junction. If it is the same, it is called a homojunction; if it is different, it is called a heterojunction.

It is of interest that Diamond (C), although a Group IV element, has non-ideal semiconductor properties for at least two reasons: it has a high band gap (around 5eV [Rob98]) and whilst it can be doped positively (B), it is more difficult to dope negatively (e.g. with N) which jeopardises the formation of p-n junctions. With present technology, such as Chemical Vapour deposition (CVD), this material cannot presently be used for solar cells. Research is nevertheless going ahead to make solar cells with diamond thin films for space applications [VAN02].

iii) Specific compounds

The Chalcogenides name (Group VI and in the future Group 16 when including the transition metals) is most often used to refer to various compounds containing at least one member of the group in the period range III-V (i.e. sulphur, selenium or tellurium). These therefore include the compounds $CuInSe_2$ (typically abbreviated to CIS) whose E_g, band gap is around

1.0 eV and its alloys with $CuInS_2$ (E_g of 1.5 eV) or $CuGaSe_2$ (E_g of 1.7 eV) for example. CdTe (E_g of 1.4eV) is one of the other common chalcogenides. Ternary chalcopyrites include compounds of the $(Cu,Ag)(Al,Ga,In)(S,Se,Te)_2$ form also [Bir01].

iv) Organic solar cells

The fact that certain organic materials have semiconductor properties has been known since the 70s [McG74] [Shi77] and led to the Nobel Prize in Chemistry of 2000 [Nob00]. Early examples include Melanins and Polyacetylene.

Whilst such electrically conductive plastics are already being applied to flat screens [For00], they could in principle be used in the "reverse direction" i.e. as solar cells [Fai02].

Photonic semiconductor research based on organics continues [SML01]; one of the Nobel laureates (Heeger) is involved in the development of photodetectors [Fai02] based on organics.

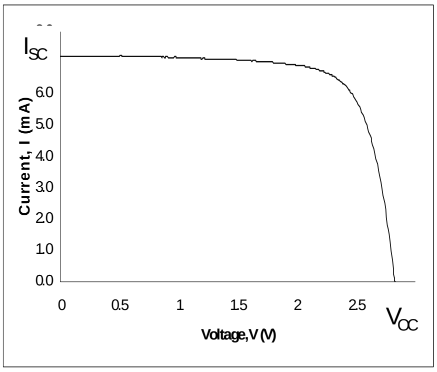
The production of organic semiconductor solar cells, however, is still at the research phase [Dya01]. These may be interesting for IPV applications as peak fill factor occurs at relatively low light intensities, in one case at $30W/m^2$ [Rie01].

4.4 Photovoltaic Technology

Solar cells can be characterised by a significant number of parameters, both common to the branch and specific to a particular material. It is not the aim of this thesis to investigate such details as a great deal of specialists are already occupied in this pursuit. However, in order to appreciate the following chapters, a basic understanding of the four common parameters is essential, especially in as much as they relate to IPV. These are presented one by one in the next four sub-sections.

4.4.1 Electrical efficiency calculation

The parameter which is of chief concern to researchers and practitioners alike is electrical efficiency, from here on referred to as *efficiency*. Although in principle this can be calculated by the ratio of output power P_O to input power P_I, in practice it is only calculated under the ideal condition that P_O is a maximum. To satisfy this condition, the resistance across the solar cell or module under test is varied across a wide enough range for the relationship of voltage against current to take the form of the curve in Figure 4.15.



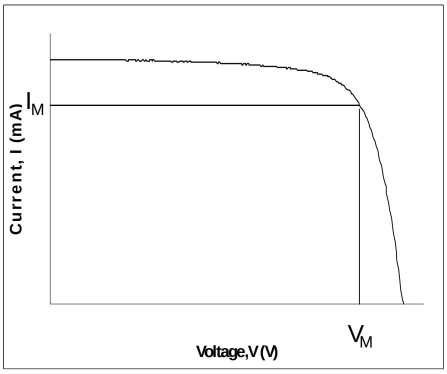


Figure 4.15: (left) Typical solar module I-V characteristics (author's measurements)

Figure 4.16: (right) I-V curve showing maximum power point current & voltage (author's measurements)

At zero resistance, therefore, the current is at its highest possible value, called the short circuit current (I_{SC}), whilst at maximum resistance, the voltage is at a maximum, referred to as the open circuit voltage (V_{OC}). Returning to I_{SC} and increasing the resistance above the impedance of the solar cell, the voltage increases quickly and the current decreases slowly until the "knee" of the curve. At this point, known as the maximum power point (MPP), the power (product of voltage and current) is at a maximum and the related values of voltage and current are referred to as V_M and I_M respectively (see Figure 4.16).

4.4.2 Fill Factor

The latter values can also be used to calculate the (electrical) efficiency by equation 4.1:

$$\eta = (V_M I_M)/P_I \qquad \text{Equation (4.1)}$$

but in practice a further parameter is used to summarise both V_M and I_M in one. This is the Fill Factor (FF), so called as it represents the ratio of how fully the area delimited by $V_M \bullet I_M$ covers the ideal power $V_{OC} \bullet I_{SC}$. It can be found graphically (Figure 4.17), but is more usually calculated from the equation:

$$FF = \frac{(V_M I_M)}{V_{OC} I_{SC}} \qquad \text{Equation (4.2)}$$

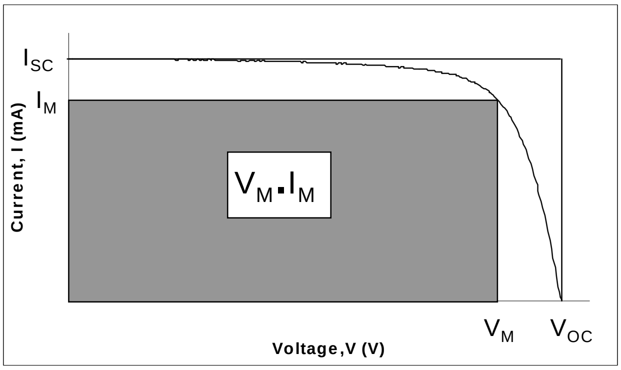


Figure 4.17: Graphical calculation of Fill Factor (author's measurements)

Substituting equation 4.2 into equation 4.1, efficiency can be found by:

$$\eta = \frac{V_{OC} I_{SC} FF}{P_I} \qquad \text{Equation (4.3)}$$

Efficiency is therefore related to the three parameters, V_{OC}, I_{SC} and FF, which are related to many more variables, see the next two sections. In practice, actual efficiency will always be less than or equal to the efficiency in equation 4.3, as the solar cell is not likely to be used at the maximum power point at all times. Actual voltage and current therefore determine the actual efficiency.

4.4.3 Short circuit current

For a range of incident radiant energy intensity well beyond that of IPV, the short circuit current is assumed to be directly proportional to radiant energy intensity. For IPV purposes, this is considered a given. Ideally, it is also equal to the light-generated current I_L.

I_L is calculated by integrating the product of the incident radiant energy spectrum and the solar cell spectral response. The latter is the ratio of charge carriers collected per incident photon. I_L therefore, can be seen to be for a unit bandwidth:

$$I_L(\lambda) = (1 - R(\lambda)) \bullet SD(\lambda) \bullet SR(\lambda) \qquad \text{Equation (4.4)}$$

where R is the portion of incident radiant energy reflected from the surface of the solar cell, SD is the spectral distribution of the incident radiant energy flux and SR is the spectral response. Integrating across the SD wavelength range gives the total light-generated current for a particular device.

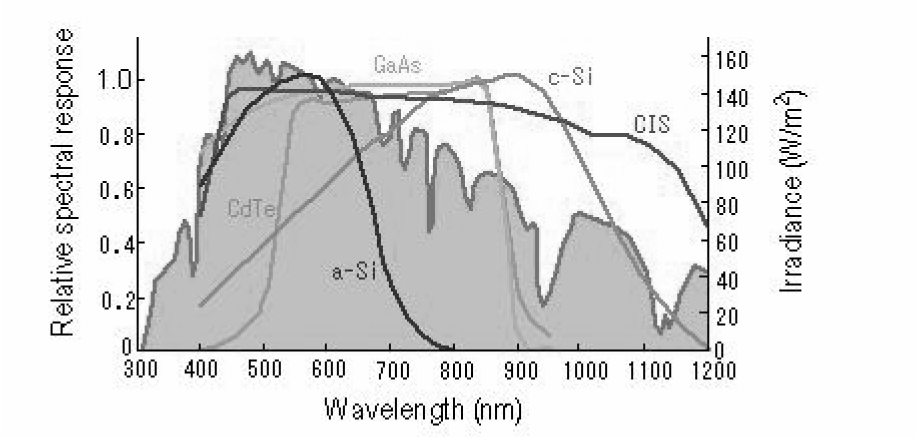


Figure 4.18: Spectra of daylight and spectral response of solar cells representing 5 PV technologies based on [Ned02]. CdTe = cadmium telluride, a-Si = amorphous silicon, GaAs = gallium arsenide, c-Si = crystalline silicon, CIS = copper indium diselenide

4.4.4 Open circuit voltage

The ideal diode law (in the dark for the junction region) has been shown to be [Gre98]:

$$I = I_S(e^{(qV)/(kT)} - 1) \qquad \text{Equation (4.5)}$$

where I is current, I_S is dark current, q is electronic charge, V is voltage and k is Boltzmann's constant. I_S is found by the same procedure as is used to collect I-V curves such as Figure 4.15 with the exception that illumination is kept as close to zero as possible. This produces a graph of the form shown in Figure 4.19.

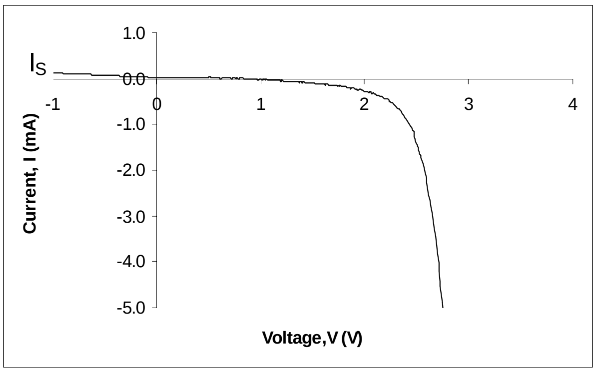


Figure 4.19: I-V characteristics of solar cell in the dark (author's measurements). As I_S is not strongly voltage dependent, it need not be measured at a specific V

Under illumination, equation 4.5 becomes [Gre98]:

$$I = I_S(e^{(qV)/(kT)} - 1) - I_L \qquad \text{Equation (4.6)}$$

where I_L is the light-generated current. Setting I to zero and resolving for V gives V_{OC} (for a "perfect" junction) as [Sze01]:

$$V_{OC} = \frac{kT}{q}\ln\left(\frac{I_L}{I_S} + 1\right) \qquad \text{Equation (4.7)}$$

Other than temperature, one of the principle influences on the dark current (I_S) is the material band gap. This represents the minimum energy required by an incoming photon to produce an electron-hole pair that is collected. Therefore, if the band gap is reduced, I_S will increase and from equation 4.7, V_{OC} will decrease.

4.4.5 Power curve

Whilst standard test conditions efficiency (see section 5.1) is important for comparing solar cells, real systems are more than likely not to be running at this ideal power, especially IPV ones without the benefit of a maximum power point tracker. This is not only because the intensity may be less than 1 sun but also because power is the product of voltage and current; PV cells have a single maximum power point, see the power-voltage graph below (Figure 4.20) for the same module and values as shown in Figure 4.15. For an IPV system charging a battery for example, the battery voltage will tend to control the PV voltage. In this case, there is no reason why this voltage will be either constant or ideal; as a result, some power will be lost.

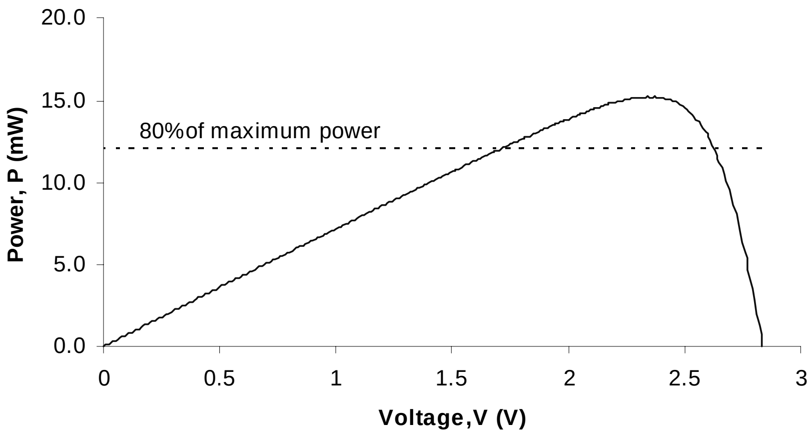


Figure 4.20: Power-voltage graph for the module in Figure 4.15 (author's measurements)

4.5 Suboptimal solar cell efficiency

The relatively low efficiencies of solar cells is a cause of surprise to those who know little about the technology and concern to PV specialists. Assuming constant temperature, which is reasonable for indoor applications, there are three important reasons for this:

a) the incompatibility of the solar module with the incident light which is associated with reduction of I_{SC} (see sub-section 4.5.1)

b) recombination of the charge carriers which is associated with reduction of V_{OC} (see sub-section 4.5.2) and

c) effects which are associated with deterioration of FF (as well as V_{OC} and I_{SC}) in sub-section 4.5.3

4.5.1 Optical issues

The principle cause of low efficiency in solar cells is due to the *spectral mismatch*, or proportion of overlap between the incident light spectrum and the spectral response. An example of typical spectra can be seen in Figure 4.18. The mismatch is due to two energetic modes. Firstly, incident photons that have an energy, $h\upsilon$ below the solar cell band gap, E_g cannot contribute directly to the photocurrent. Secondly, whilst all photons having more energy than the solar cell band gap contribute to the photocurrent, the excess energy (greater than the band gap) is typically not collected. The dissipation mechanism in this case is to heat the solar cell (*thermalisation* in the jargon). The combined effect of these two spectral mismatches account for energy conversion losses of the order of 50% in the 400-1000nm range.

Another source of loss is the *electrical contact* on the front (light facing) surface of the cell or module. This is especially evident for conventional (silicon) solar cells, as contacting is achieved using a metal grid. Whilst this grid is necessary for appropriately low resistance current collection of these relatively high current cells, by its presence it creates a shadow on the solar cell, blocking light from the cell. Losses due to such coverage are around 5% using conventional techniques. For devices that use alternative front contacts, such as transparent conductive oxide (TCO), which have a higher resistance than a grid, the current must therefore be lower. The lower current is achieved using a monolithic series connection. This also implies coverage loss as the series interconnections take the place of active solar material. A further implied loss of TCO solutions is that the incident photons pass through a sheet of glass which will have a non-unity transmissivity.

As already indicated in sub-section 4.4.3, the calculation of I_{sc} takes into account the reflectivity of the front (facing incident light) surface. From Optics the reflection of normal incident light is related to the refractive index by the complex refraction index $n_c = n - i\kappa$ as follows:

$$R = \frac{(n-1)^2 + \kappa^2}{(n+1)^2 + \kappa^2} \qquad \text{Equation (4.8)}$$

Using this equation with the appropriate values for silicon for example, gives a reflectivity of around 30% [Gre98 p41]. In practice this can be reduced by anti-reflection coating to about 10%, or light trapping to about 3% (by preferential chemical etched texturing), or a combination of both to around 2%.

That radiant energy which is transmitted into the semiconductor material then suffers exponential attenuation of the form:

$$S(x, \upsilon) = S(\upsilon)\exp(-\alpha_c x) \quad \text{Equation (4.9)}$$

with the absorption coefficient:

$$\alpha_c(\upsilon) = \frac{4\Pi\kappa\upsilon}{c} \quad \text{Equation (4.10)}$$

where:

$S(\upsilon)$ is the number of incident photons (per unit time, area and energy)

x is the distance from the semiconductor surface (m)

υ is the frequency of the incoming radiant energy and

α_c is the absorption coefficient.

In theory therefore, there is an optimal minimum thickness of material required to collect all the transmitted light. For direct band gap material, it is of the order of 1-3μm whilst for indirect band gap material it is from 20-50μm. An example for the latter is conventional cells whose 300-400μm material thickness is not a limiting factor. However, for thin film solar cells, the typical thicknesses of a few μm are much more critical, especially for indirect band gap material. In the case of amorphous silicon, this is countered by the light trapping techniques mentioned above in this sub-section.

4.5.2 Material quality issues

The recombination of charge carriers (electrons and holes) is a normal and unavoidable aspect of solar cells, as it is the process by which an illuminated solar cell returns to thermal equilibrium when the light is turned off. This is another reason for the interest of making an I-V characterisation in the dark e.g. Figure 4.19. The dark current indicates junction characteristics which in turn determine how efficiently the solar cell will deliver the photocurrent to the terminals.

The process of recombination may be simply the reverse of the charge separation (radiative recombination) process shown in Figure 4.13 and Figure 4.14 or by other processes such as Auger recombination or recombination in traps. Traps can be thought of as being a deterioration of the ideal solar cell which only has energy bands (permitted states) in the valence and conduction bands, see Figure 4.10 and none in between (in the forbidden zone). Practical solar cells therefore, due for example to imperfections or impurities in the material lattice, have further allowed energy states (traps). When such states occur in the forbidden zone, they create further opportunities for electrons and holes to recombine. These effects can be located both at the junction (depletion zone) or surface and in the bulk of the semiconductor.

Such imperfections are therefore associated with reduced (charge) carrier lifetimes, or the average time from charge carrier creation to recombination. Material imperfections are especially important for conventional solar cells where material thickness implies that the charge carriers may have to pass through relatively more material to reach the junction.

4.5.3 Parasitic resistance

In the same way as electrical sources can be symbolised with internal resistance losses, solar cells suffer from two parasitic current losses (I_{SR} and I_{PR}) caused by series and parallel resistance respectively (see Figure 4.21). The series resistance (R_S) is due principally to bulk resistances of the semiconductor and its metallic contacts as well as the contact resistance between these two (materials). The parallel resistance (R_P) can be caused by leakage at the cell edge or extended defects in the depletion zone. Extended defects associated with low cost solar cells include grain boundaries, dislocations and large precipitates. These sites become areas likely to suffer (doping) diffusion or fine metallic bridges from the contact metalisation.

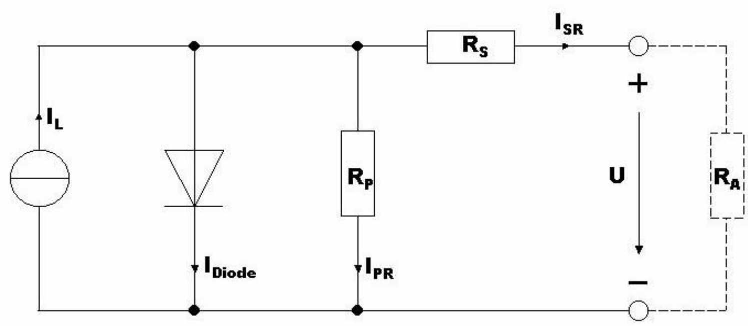


Figure 4.21: Solar cell equivalent circuit and load (R_L) based on [Cou81 p307]

When a resistance is connected to a solar cell, such as an application of resistance R_A (represented by the dashed lines in Figure 4.21), two parasitic effects are found: current is deteriorated the higher the R_S whilst voltage is deteriorated the lower the R_P. Both these detrimental cases reduce FF as I_M and V_M (see Figure 4.17) respectively are shifted towards the origin on an I-V graph.

4.5.4 Efficiency losses summary

It is easier to appreciate the previous section by summarising the different efficiency losses in a single chart such as the example below.

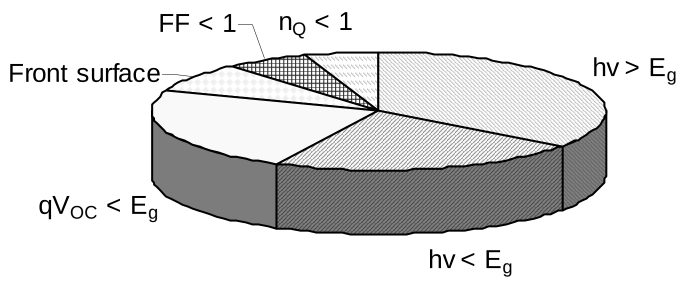


Figure 4.22: Efficiency loss summary for a conventional silicon cell at AM1.5 [based on Fah83 p242-3]

As can be seen in Figure 4.22, the principal effects are the incident photon spectral mismatch having either more or less energy than the band gap ($h\upsilon > E_g$ or $h\upsilon < E_g$ respectively). A third significant power loss is due to the collection efficiency of photogenerated charge carriers being less than unity. This implies that the V_{OC} is less than ideal ($qV_{OC} < E_g$).

Less significant power losses include front surface losses (such as reflection or area loss) as well as non-unity quantum efficiency ($n_Q < 1$) and FF ($FF < 1$).

4.6 IPV Material Technologies

Solar cells can be produced in a large number of ways as presented in sub-section 4.3.3 and elsewhere [Gre98 Chapter 9]. The aim of this section is to provide a more detailed review of those technologies which have been or could be applied to IPV.

IPV solar cell technologies in common use today are therefore reviewed individually in sub-section 4.6.2 to sub-section 4.6.4. Other technologies which can be considered but are not presently in use for IPV are covered in sub-section 4.6.5.

Few IPV applications have a voltage requirement of less than a few volts, whilst cells deliver less than a volt each; the series connection of cells to form modules is therefore briefly described in sub-section 4.6.6. This is followed by a section on efficiency improvements (section 4.7) that apply to the majority of solar cells.

4.6.1 Spectral response

Given that spectral mismatch is the most significant loss of efficiency in sub-section 4.5.4, it is worthwhile to compare the spectral response of a number of technologies (Figure 4.23) with the spectra encountered indoors (Figure 4.24). Naturally it should be remembered that those photons with the highest energy (UV) are on the left of the graphs and the lowest energy photons, therefore of less relative interest, are on the right.

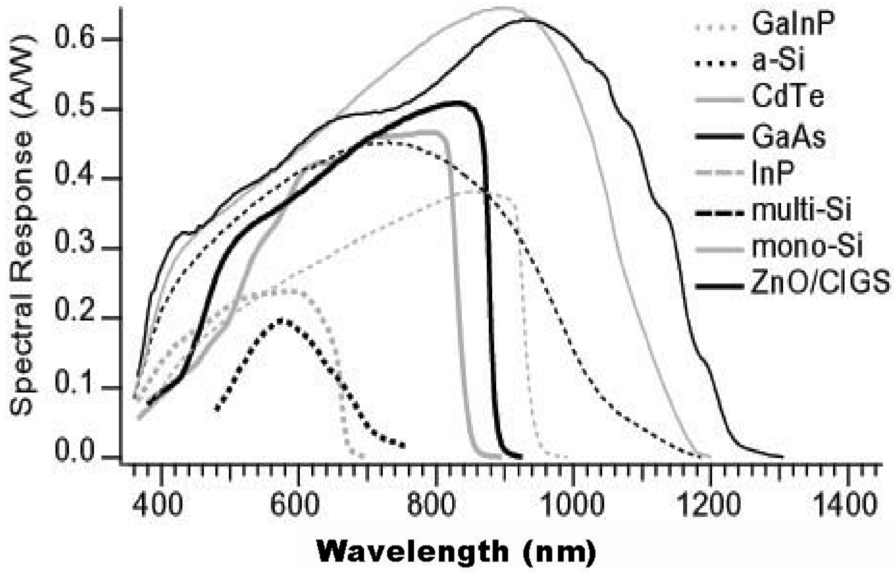


Figure 4.23: Typical spectral response for solar cell technologies [Fie97 p2] where GaInP = gallium indium phosphide, a-Si = amorphous silicon, CdTe = cadmium telluride, GaAs = gallium arsenide, InP = Indium phosphide, multi-Si = multicrystalline silicon, mono-Si = monocrystalline silicon, ZnO = Zinc Oxide, CIGS = copper indium gallium diselenide

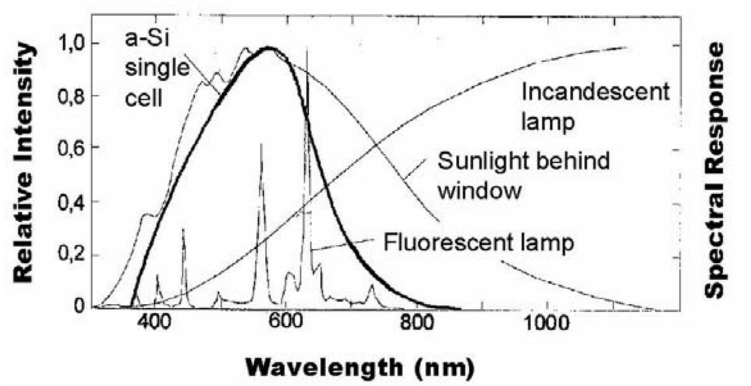


Figure 4.24: Qualitative comparison of light source spectra and an amorphous silicon (a-Si) single cell, based on [Rot97 p167]

The better match between the fluorescent source and amorphous silicon (a-Si) than the other samples can be seen in Figure 4.24, which helps to explain why this technology is well adapted to IPV. However, the technology of choice for indoor applications depends on many other factors such as cell cost, application location in the room, colour of cell restrictions and application use pattern.

4.6.2 Amorphous silicon Thin Film

This thin film technology has been applied to IPV for decades and is still the most significant today. It has a material structure without long range order and a band gap, E_g of 1.7eV, which is much higher than crystalline silicon. Deposition of the successive layers of silicon requires silane gas (SiH_4) mixed with around 10% Hydrogen in the presence of a plasma in a vacuum. The hydrogen passifies the amorphous material structure, reduces its resistivity and allows it to be doped.

The 2 doped areas need only be very thin (order of 10-20 nm) for charge separation but as silicon is an indirect band gap material, greater material thickness is required. The latter is achieved by depositing an undoped (intrinsic) layer between the p-layer and n-layer. Typical i-layer thickness is in the 1μm range. The result is a p-i-n structure.

This i-layer deteriorates with illumination of the solar cell reducing initial module efficiencies of around 6% by as much as a third after extended outdoor illumination (called Staebler Wronski effect [Sta77]). Given the much lower radiant energy intensity found indoors, it is known that such a loss of efficiency will usually be negligible.

For outdoor applications, a partial solution to the degradation problem has been found by depositing successive p-i-n junctions one on top of the other; these are known as tandem modules. Apart from the higher resulting voltage, this solution has the advantage of enabling the E_g of each layer to be preferentially adjusted to a different spectral response. This increases efficiency (8-10%). Moreover, such cells degrade less (around a sixth).

4.6.3 Polycrystalline Thin Film

There are two main compounds of interest in this group: the II-IV CdTe [Omu96] and the I-III-VI $CuInSe_2$ (or CIS) [Tiw00]. These cells are both produced as heterojunctions with cadmium sulphide (CdS). As CdS absorbs light, it is deposited thinly (around 50nm).

Where the two compounds differ is in band-gap. CIS has an E_g of 1eV which is relatively low for solar cells. It is usual to alloy the indium with gallium to increase the gap. Such cells are called CIGS (CuIn $GaSe_2$). CdTe on the other hand has a near ideal band gap for outdoor application of 1.4eV.

One of the "bug bears" of these technologies is the cadmium content, which are frequently claimed to be a risk to health or the environment. Such statements are rarely supported by evidence and seem to be motivated by fear and uncertainty.

Risk is defined as the product of hazard and the probability of occurrence. With regard to the hazard, whilst it has been shown that the elements cadmium and tellurium can be toxic, cadmium telluride is relatively inoffensive [MnF95 p223]. The highest hazard found is occupational (to production staff) [Fth95], whose working environment should be controlled by good housekeeping for example. The potential hazard to the public is related to the production method used (some imply less toxic waste than others) and accidental combustion of the modules in a fire.

Both these hazards should be considered in the context of their likelihood of occurrence; there is natural pressure on manufacturers to use material efficient processes, as much for regulatory as economic reasons. The options for achieving this exist [Mos95]; therefore manufacturers are motivated to keep waste and pollution to a minimum.

Fire related hazards would require temperatures above the CdTe melting point of 1041°C. Such a situation is unlikely for a large installation (>100 kW_P such as a PV farm). For a smaller domestic system (e.g. 5kW_P), those in the immediate vicinity of the fire would be at risk for a few minutes and there would be no hazardous ground level contamination [MnF95 p226].

As another report [Als96] states "the risks from cadmium or selenium use in CdTe respectively CIS modules seem acceptable in comparison with some existing products or services like NiCd batteries or coal-fired electricity production".

4.6.4 Conventional silicon cell

Although for the last half century the technology most applied for outdoor applications, such cells are rarely used for IPV applications. This is both due to the relatively low band gap of 1.1eV which offsets the spectral response towards the infra-red range, but also the inconvenience of creating series connections between relatively small (<1cm^2) cells. Furthermore, such cells are typically too expensive for the low currents found indoors.

Conventional cells are mainly based on an ingot of silicon which can be produced in a number of ways. This ingot is then cut into wafers. Usually it is pre-doped p-type (e.g. with boron). The outside of the wafer is then thinly n-doped (e.g. phosphorous $POCl_3$); this layer is then removed from one side and the edges of the wafer to leave a p-n junction.

4.6.5 Other PV technologies

A number of other PV technologies have been considered in this report but because they are relatively new on the market cannot be recommended for IPV applications at present.

i) Dye Solar cells

This liquid state technology (as was Becquerel's first solar cell, see section 4.2) is based on a semiconductor (titanium dioxide, TiO_2) layer impregnated with a photosensitive dye. This layer along with a liquid electrolyte is "sandwiched" between two conducting glass electrodes.

As the semiconductor band gap of TiO_2 of 3.2eV is too high for light collection, the dye acts as to promote electrons into the TiO_2 conduction band. These may then make their way to the electrodes under the influence of an electric field inside the bulk material.

The electrolyte (redox solution, typically of I^-/I_3^-) maybe based on a molten salt, butyrolactone or acetonitrile. Due to its liquid and reactive nature, one of the challenges of bringing dye products to market is sufficiently long lasting sealing. It is believed that LCD technology might be an interesting avenue of research at this level [St200].

It would be of interest to designers of IPV applications if dye cells were more widespread, as they seem well adapted to indoor light conditions [Bur00]; further references can be found in [Pet01].

ii) Thin Film crystalline Si

Other thin films of silicon, not to be confused with amorphous silicon, are microcrystalline [Kep99] and polycrystalline thin films. These can be deposited by chemical vapour deposition (CVD) or from solution onto low cost substrates. These cells are especially thin (1μm for polycrystalline, 3μm for microcrystalline) and therefore like amorphous cells, require optical trapping of the light. Theoretically, these cells could achieve better efficiencies than conventional cells, due in part to the reduced bulk carrier recombination. The bulk refers in this case to the semiconductor material apart from the junction through which the charge carriers must pass to reach the electrodes. Due to its non-ideal conductivity, this area is a cause of electrical losses.

iii) Space cells

A number of material alloys are generally considered only for space applications due to their cost. These include amorphous Silicon with Germanium [Guh98] and Gallium based [Kar98] alloys. A special case for "deep space" (low irradiation) exploration is "Low intensity/low temperature" (LILT) solar cells. Given that typical temperatures of -135°C (much lower than IPV) and irradiances of 50W/m^2 (relatively high for IPV) are considered [Str95], little can be concluded here from such work. Should their price reduce, these cells would also be of greater interest to the IPV designer.

4.6.6 Thin Film Modules

The commercial thin film technologies described in section 4.6 are only available on the market as "monolithically" (literally "one stone", in practice "one piece") series interconnected modules. Such an approach is scalable from high volume manufacturing of high surface area (order of 1m^2) products down to mini-modules (around 100cm^2) [Kel00] and miniature products (less than 1cm^2) [Kro00] [Ruf01].

The processing begins with cleaning of the substrate sheet (typically glass), followed by deposition of the TCO (transparent conductive oxide) if this is not already present. The TCO is then scribed into long straight bands of around 1cm in width (typically by laser) before the deposition of the solar cell material over the entire surface. A second scribing then follows which matches the first except for a small (<1mm) offset in a direction perpendicular to the strips. Lastly, the back contact is deposited, often by sputtering if it is metallic. It is scribed in the same way as the second scribing step. This results in a solar module where the top of each cell (one of the strips) is electrically connected with the bottom of the adjacent cell forming a series connected module such as Figure 4.25. This has the advantage that each module has much higher voltage than would have been the case without series connection; however, if the cells do not deliver similar current, the lowest performing cell will lower the current of the entire module.

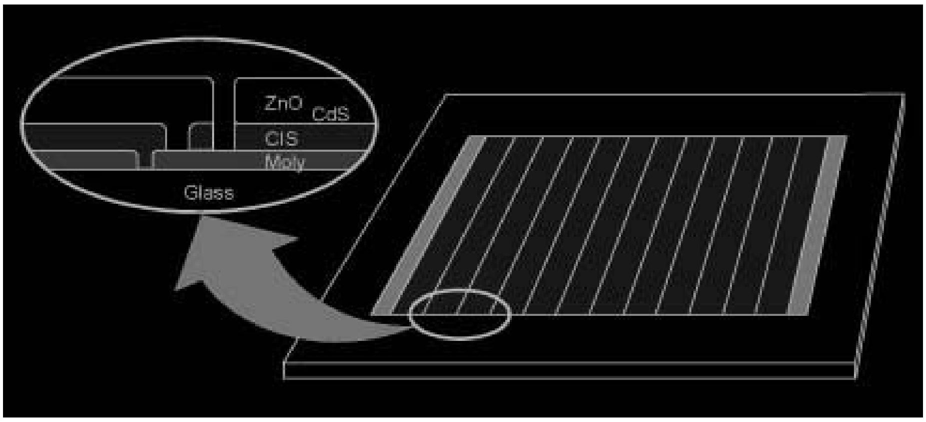


Figure 4.25: Example of series interconnected Thin Film technology solar module from [Tar00]. In this case each CdS/CIS PV cell has a molybdenum (Moly) back contact and a zinc oxide (ZnO) transparent front contact

During the remainder of the manufacturing process, ribbon and wire contacts are added, the entire module is sealed by lamination (typically with epoxy and often with a second sheet of glass) and the necessary quality tests are performed.

Thin Film modules have several advantages for IPV use over conventional cell modules as they can be deposited with the required voltage and surface area design. IPV products also benefit from the progress made for outdoor cells with respect to the series interconnection. As mentioned above, outdoor modules require uniform deposition over areas of the order of m^2. As IPV products have surface areas measured in cm^2, it can be expected that current matching issues due to deposition variation can be ignored.

A further benefit of thin films is that they can be deposited on flexible substrates. These, although not usually transparent (like glass) have the promise of both continuous (roll-to-roll) manufacturing and new applications liberated of the constraint of using a flat glass surface module. This may well be important to IPV as it may be advantageous to have the solar cell better respect the shape of the product; also, the flexible substrate is usually thinner than a glass solution, which may be beneficial where space is limited.

4.7 Efficiency improvements

Efficiency can be altered both at the design stage and during manufacturing of PV. At the first design stage it is still reasonable to proceed with respect to the scientific principles and ideals mentioned above that PV can aspire to. These are hard to maintain on the production line where further imperatives such as units produced per unit time and low cost compete for limited resources.

When considering the improvements possible from the scientific perspective, each of the heading level parameters in section 4.4 namely V_{OC}, I_{SC} and FF can be reviewed. Efficiency is related to the product of all three (equation 4.3), so an improvement in anyone without detriment to another is beneficial to overall efficiency.

Current and I_{SC}

Just as the principal loss area for outdoor PV is optical ("4.5.1"), this can be expected to be the more so for IPV given that the indoors are characterised by an increased variety of light sources (i.e. fluorescent, incandescent, window filtered daylight). An avenue for improving efficiency via the current would be to review the PV spectral response at the radiant energy intensities and spectra found indoors. Reduced spectral mismatch would improve I_{SC} and might be possible by an adjustment of band gap (E_g) by changed material chemical composition for example. This application specific approach would be hindered by the mix of spectral signatures that IPV applications may receive.

With regard to the parasitic resistance, at IPV radiant energy intensities it can be assumed that series resistance is relatively unimportant as the current flow is relatively low.

Other technical solutions for the improvement of current performance are also of interest e.g. tandem (stacking) of cells, anti-reflection coating (sub-section 4.5.1), improved light trapping, improved TCO, but these need to be balanced against how cost effective they are for the specific application.

Voltage and V_{OC}

Whilst current is proportional to intensity, and therefore directly related to IPV radiant energy intensities, voltage is less affected, i.e. it varies with the log of intensity (see equation 4.7). At such intensities, improvements of the voltage can be achieved by maximising the parallel resistance, as the related leakage current may otherwise be comparable to the photocurrent.

Improvements are also possible by improving the photocell ideality. The case of an ideal junction is described mathematically in equation 4.7. In practice equation 4.11 can be used [Hov75]. The A represents how "ideal" the junction is and takes a value between zero and one:

$$V_{OC} = A\left[\frac{kT}{q}\ln\left(\frac{I_L}{I_0}+1\right)\right] \quad \text{Equation (4.11)}$$

Therefore, maximising ideality (A), or "junction perfection" will also benefit V_{OC}.

FF The Fill Factor is also dependent on parasitic resistance (subsection 4.5.3). Like the voltage, at low radiant energy intensities, it is more affected by low parallel resistance.

Concentration A technique for efficiency improvement which has been tried outdoors is concentration. This is the PV jargon for the use of mirrors or lenses, such as to focus the radiant energy onto a smaller surface [Yam99][Nos00]. The main disadvantage is that the resulting device is "directional" i.e. it mainly collects direct light [Luq01]. This is mitigated outdoors with a "sun-tracking" devices which ensures that the solar cell is facing as close to the sun as possible. Clearly, such tracking devices are hard to conceive indoors. However some focusing of the radiant flux can be imagined in the case of a majority of direct radiation.

4.8 Conclusion

"Do not re-invent the wheel" summarises the message of this chapter to IPV designers. The idea that they should be familiar with a technology such as PV is much more than an academic nicety. The aspects considered in this chapter support this as follows:

Firstly, the history of PV technology (see section 4.2) provides the designer with an impression of what has been achieved. Equally, what remains to be done can be inferred. For example, no wireless (communicating) PV powered indoor products are as yet available on the market. The rest of this thesis shows what would be required for such products to see the light of day.

Secondly, a grounding in the science of a technology is essential. It may help the designer to understand how solar cells work (section 4.3 and section 4.4), the advantages and limitations of PV (section 4.6) and to see the improvements that can be achieved (section 4.7).

The main limitation to PV performance is related to a mismatch between the spectrum of the incident radiant energy and the spectral response of the solar cell. Other issues include the recombination of charge carriers and effects which are associated with the deterioration of fill factor (FF). Ways of improving solar cells for indoor use therefore aim principally to reduce the spectral mismatch and increase the parallel resistance.

To what extent the improvements mentioned in section 4.7 will be beneficial in practice will depend on designers' success in inducing the PV manufacturer to make the necessary modifications. Manufacturing structures appropriate for the production of outdoor use modules may hinder changes that would serve indoor products. Reading section 4.3 to section 4.7 will help to equip the designer for facing this challenge.

4.9 Further reading

For those wishing to further their understanding of PV, the two references from this chapter which will prove most useful are by Green [Gre98] and Hovel [Hov75]. For more history see Perlin [Per99] and [Per02].

Chapter 5 : Photovoltaics for indoor use

But, soft! what light through yonder window breaks?
It is the east, and Juliet is the sun
Shakespeare W., Romeo and Juliet, Act II Scene 1

5.1 Introduction

This chapter explores the correct design of indoor Photovoltaic (IPV) cells and modules. Firstly, existing solar cells under indoor conditions are investigated (see section 5.2), modelled (see section 5.3) and discussed (see section 5.4). Then in section 5.5, the ways in which future IPV modules may be improved are considered.

As has been seen in chapter 3 (see Table 3.4), the parameter which may vary the most in the built space is radiant energy intensity. So having characterised a particular environment, the IPV product designer will then wish to establish how the various solar modules will respond under these conditions.

Some reports on the use of PV indoors have been published including [Rot97] [Pet00] [Nak79] [Gem01]. In comparison with these, this chapter provides the IPV designer with a more complete appreciation of PV module performance indoors, especially with respect to technology choice. This work is both novel and important for the same reason: solar cell comparison is generally based on an arbitrary maximum terrestrial intensity and spectra (of 1 sun or 1000W/m^2) at 25°C perpendicular to the cell plane. In practice, no solar cell experiences such (STC) [IEC89] conditions that “combine the irradiation level of a clear summer day, the module temperature of a clear winter day and the spectrum of a clear spring day” [Büc95], yet few alternative bases for comparison exist [Büc97].

One way is to compare real modules outdoors [CCC98] [Eik00] [And00] [Chi00], but these conditions, when compared with those indoors, are characterised by much higher radiant energy intensities (a factor of 10 or more), less spectra types (such as the various electrical light sources) and more temperature variation. Further issues for solar cells used outdoors are covered in [Kin99].

IPV products generally receive both daylight and electrically sourced spectra. Given the lack of comparable data in existing reports of PV indoors, it was elected to test a wide range of possible technologies under both these spectra types and a range of radiant intensities from AM1.5 (1000W/m^2) down to those found indoors (1W/m^2).

The models presented in section 5.2.2 simulate PV response across a range of intensities and under both spectra. This is complemented by a heuristic model which shows greater accuracy still. These may permit the designer to infer properties based on more freely available AM1.5 data.

As a complement to the above information and section 4.7, certain potential performance improvements of photovoltaic modules are described in section 5.5.

The reader is assumed to be familiar with photovoltaic technology in this chapter. For a more basic introduction, see chapter 4.

5.2 Technology performance at indoor light levels

5.2.1 Experimental Procedure

"Standard test condition" STC [IEC89] similar to 1 sun directly overhead on a cloudless day at 25°C were reproduced with a Wacom solar simulator connected to a Keithley 238 High Current Source, a Keithley 705 Scanner and a PC running I/V measurement software. Before testing began, the lamps of the solar simulator (a Xenon XBO 1000W and a Halogen Osram CP/72 2000W) were switched on and allowed to stabilise for 20 minutes. The room temperature was controlled to 22°C (+/- 3) with air conditioning. The light intensity was controlled with one or more wire mesh filters between the light source and the sample (see Figure 5.1). Three samples from each line in "Table 5.1" were measured individually with 4 point contacts (2 positive and 2 negative contacts) except for the samples from Edmund Scientific due to lack of contact space. Current/voltage (I/V) measurements were made for the following percentages of 1 sun: 100%, 58.2%, 39.7%, 19.1%, 11.0%, 4.1%, 1.1%, 0.439%, 0.211%, 0.08%. As precautions, the filters were positioned on the support in the same orientation and by only allowing the light source shutter (which otherwise prevented light reaching the sample) to be open during the time that a measurement was being made. The latter contributed to minimising the heat transfer from the light source to the sample. Furthermore, the sample area temperature was homogenised with a small fan.

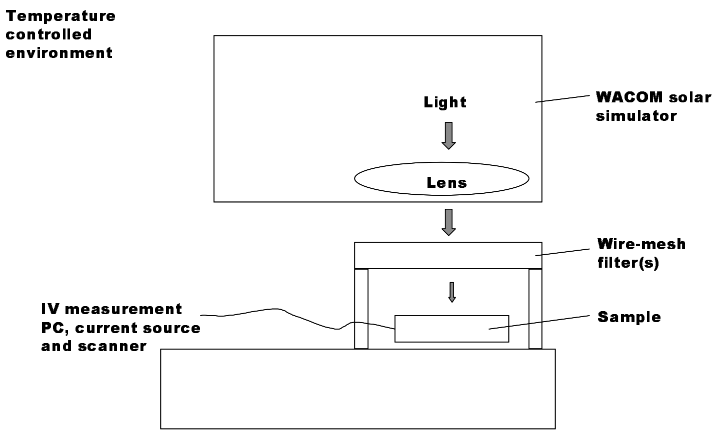


Figure 5.1: Experimental apparatus

Some samples were also tested under a separate artificial E_{rad} source (the fluorescent Philips Ecotone PL-L, 830/4P HF, 40W) over a smaller range of intensities (1-5W/m^2). The intensity from this artificial light source on the solar cell was varied by controlling the distance (>1m) between the source and the solar cell under test.

Solar cell temperature outdoors is a factor of both the surrounding climate and the fact that solar cells thermalise a significant proportion of the incoming radiant energy (see section 4.5). The indoor environment is characterised by a smaller temperature range and much lower radiant energy intensity which might warm the module. Therefore, these experiments were performed at a temperature of (22°C +/-3). This contributed to reducing the uncertainty related to changing more than one variable at the same time, often the case in outdoor comparative testing.

Table 5.1: Technologies and sources of the 21 types of solar cell/ module that the author collected and tested showing whether the manufacturer was a laboratory or industry, the active area and number of cells in the module

Technological Classification	Supplier or Laboratory name	Cell Code	Indu. = I Labo = L	Active Area (cm^2)	No. of cells in module
Silicon (crystalline)	BP Solar (via IWS)	xSi-BP	I	9.36	1
Silicon (crystalline LGBC)	BP Solar, UK	xSi-LGBC	I	0.90	1
Silicon (crystalline)	Spacecells, Edmund Scientifc, US	xSi-EdSi	I	0.38	1
Silicon (crystalline)	Unknown (via Distributor)	xSi-Dist	I	10.95	1
Silicon (polycrystalline)	MAIN, TESSAG, D	pSi-MAIN	I	12.47	1
Silicon (polycrystalline)	EFG, TESSAG, D	pSi-EFG	I	10.25	1
Silicon (polycrystalline)	Unknown (via Distributor)	pSi-Dist	I	2.88	1
III-V cells (GaAs)	NREL, Golden, CO, US	3-5-NREL	L	0.25	1
Polycrystalline thin film (CdTe)	Matsushita / Panasonic, J	CdTe-Mats	I	5.80	5
Polycrystalline thin film (CdTe)	Parma University, I	CdTe-Parm	L	0.79	1
Polycrystalline thin film (CIGS)	ZSW, Stuttgart University, D	CIGS-ZSW	L	0.46	1
Other (GaInP)	NREL, Golden, CO, US	GIP-NREL	L	0.25	1
Amorphous Silicon	TESSAG, Putzbrunn, D	aSi-Tess	I	4.95	5
Amorphous Silicon	Sanyo Electric, Hyogo, J	aSi-Sany	I	3.71	4
Amorphous Silicon	Solems, Paris, F	aSi-Sole	I	1.76	3
Amorphous Silicon	VHF Technologies, Le Locle, CH	aSi-VHF	L	3.36	4
Amorphous Silicon	Sinonar Corporation, Taipei, TW	aSi-Sino	I	1.26	4
Amorphous Silicon	Millenium, BP Solar	aSi-BP	I	0.20	1
Photochemical (Nanocrystalline dye)	Greatcell SA, Yverdon, CH	PC-GCSA	L	1.00	1
Photochemical (Nanocrystalline dye)	EPFL ICP2, Lausanne, CH	PC-ICP2	L	0.90	1
Multijunction cell (GaAs-GaInP tandem)	NREL, Golden, CO, US	MJ-NREL	L	0.25	1

Samples were selected by the author to be representative chiefly of those cells which the IPV designer would be likely to use at present (e.g. amorphous and crystalline silicon). Some samples of more "exotic" technologies (e.g. based on Gallium) were also included for comparison purposes. Sample whose active area exceeded 5cmx5cm (25cm^2) were not considered as this is typical size of IPV product modules.

5.2.2 Results

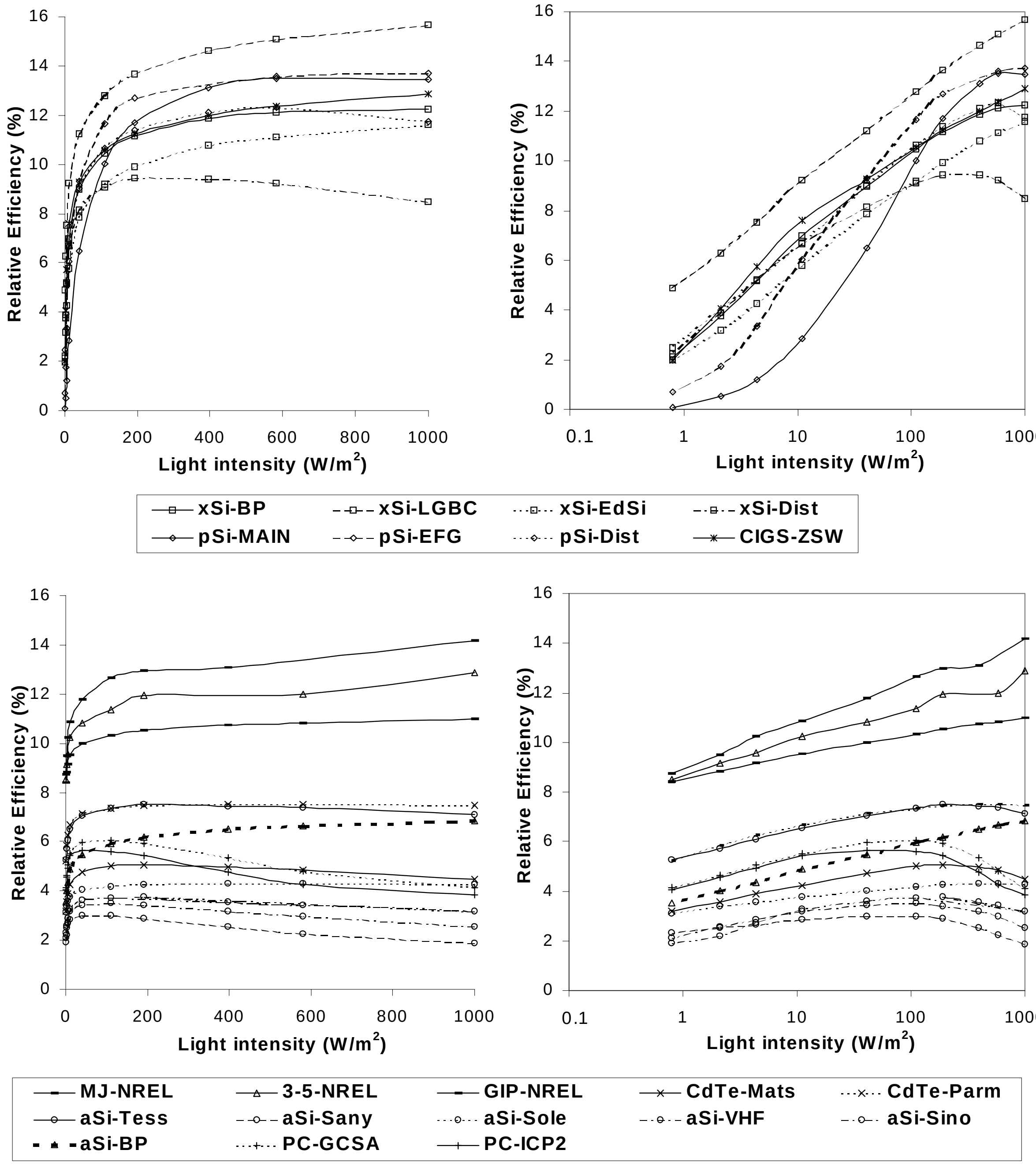


Figure 5.2: Author's measurements of efficiency of all samples under wire-mesh filtered AM1.5 source at 1000W/m^2 showing the same results against intensity on the base 10 scale (left) and natural logarithm (right). The log scale slope has been used to sort the results between the top and bottom graphs (see phenomenological model).

5.2.3 Efficiency with intensity

The two graphs on the left of Figure 5.2 show that solar cell efficiency in the highest intensity decade, 100-1000W/m^2, varies less than in the lower decades. The ranking by 1 sun efficiency is almost completely maintained down to 200W/m^2 as has been found elsewhere [BKB97]. For intensities below 100W/m^2 (see Figure 5.2 right graphs), which are typical of indoor conditions, a much more marked change is found and the ranking by technology is altered when one reaches the lowest intensities so that some of the highest performing cells at 1 sun were the weakest at 1W/m^2.

For cells of some technologies (including amorphous silicon) the loss of efficiency from 1000-1W/m^2 was less than 50%, whilst for other technologies (such as mono- and poly-crystalline silicon samples) the drop was greater than 65%.

Open circuit voltage with intensity

The effect of intensity change on V_{OC} has already been presented [Ran00]. V_{OC} over the range tested is relatively linear on the logarithmic scale with a negative gradient. In Figure 5.3 open circuit voltage has been normalised to one cell for ease of comparison.

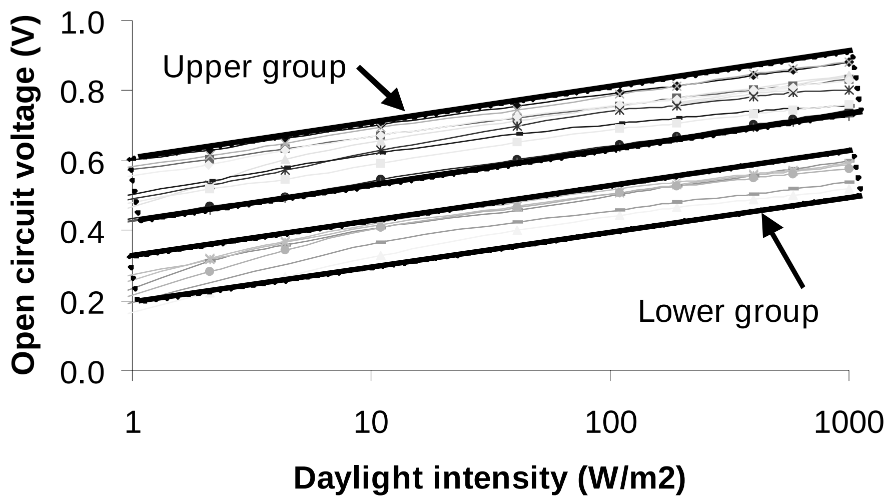


Figure 5.3: Open circuit voltage per cell with respect to daylight spectrum intensity for 16 of the samples from Table 5.1 (author's measurements)

It is noteworthy that the samples appear to form two distinct groups. The "upper group", with open circuit voltage in the 0.7-0.9V range at 1000W/m^2, is formed exclusively of amorphous silicon, cadmium telluride and dye cell samples. The "lower group" members are all of crystalline, polycrystalline or CIGS technologies and have an open circuit voltage at 1000W/m^2 in the 0.5-0.6V range.

5.2.4 Spectral response

The graphs in Figure 5.4 compare the efficiencies under filtered AM1.5 with those found under the fluorescent source for selected samples representing 3 technologies. These indicate, for the samples tested, an increase of efficiency for the amorphous silicon, slight change for the dye cells and a decrease of efficiency for the crystalline silicon samples. The result for the crystalline silicon samples is suggested elsewhere [Nak79],

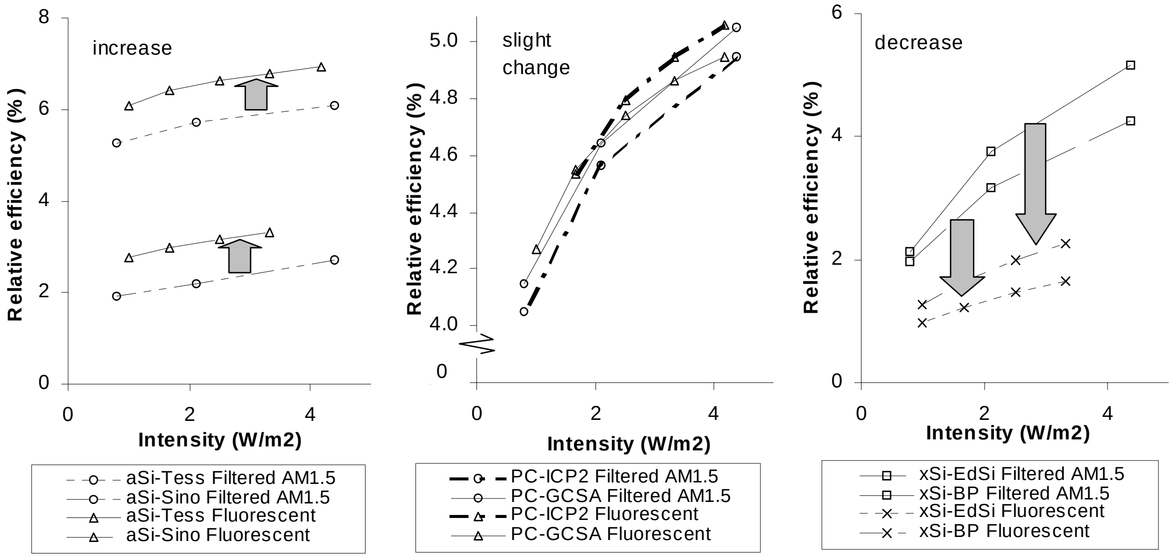


Figure 5.4: Author's measurements of efficiency difference going from filtered AM1.5 to the fluorescent spectrum for 2 samples of amorphous silicon cells (left) and dye cells (middle) and crystalline silicon (bottom)

The fluorescent intensity was measured using a Lux meter and then converted to W/m^2 using the (simplified) relationship:

$$\frac{E_{rad}(Lux)}{120000} = \frac{E_{rad}(Wm^{-2})}{1000} \qquad \text{Equation (5.1)}$$

or:

$$E_{rad}(Wm^{-2}) = \frac{E_{rad}(Lux)}{120} \qquad \text{Equation (5.2)}$$

5.3 Indoor light level model presentation

5.3.1 Phenomenological model

The modelling of the maximum power point on the I-V curve under the influence of either R_S or R_P has been modelled [Gov81]. However, neither of these factors nor which of the respective parasitic currents (see section 4.5.3) will be prevalent is known in advance. A model is therefore proposed below which requires none of this information, and focuses on the efficiency rather than maximum power.

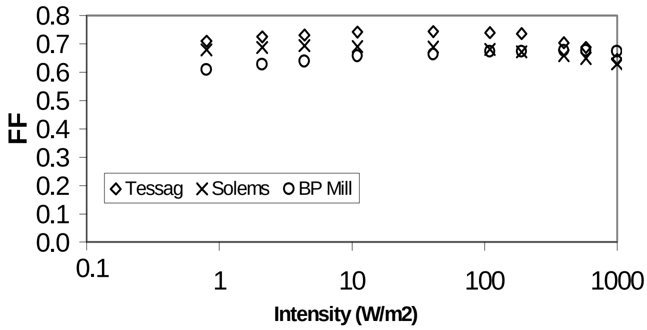


Figure 5.5: Fill Factor (FF) with respect to Intensity on base 10 log. scale for selected amorphous silicon samples (author's measurements)

For the samples in Figure 5.5 it can be seen that FF is approximately constant in the range 1-100W/m^2. This was found to be relatively valid for some samples; for example the FF maximum - FF minimum for the range 8-100W/m^2 was 2% for CdTe, 5% for a-Si and dye cells. Poly-crystalline silicon and mono-crystalline silicon varied over the same intensity range by 22-23%.

It is also well accepted that I_{SC} is directly proportional to G over a range wider than we consider here; in this case $\alpha_f G$ is used instead of I_{SC} where α_f is a constant:

$$I_{SC} = \alpha_f G \qquad \text{Equation (5.3)}$$

Solving the ideal diode (equation 4.5) for V_{OC} has been shown to be [Sze01]:

$$V_{OC} \cong \frac{kT}{q} \bullet \ln\left(\frac{I_{SC}}{I_S}\right) \qquad \text{Equation (5.4)}$$

where I_S is the saturation current and kT/q is the thermal voltage. If $I_L/I_S >> 1$ then a term for R_P is not required, such as proposed elsewhere [Mey01]. Substituting equation 5.4 and equation 5.5 into equation 4.3, we find that:

$$\eta \cong FF \bullet \alpha_f \bullet \frac{kT}{q} \bullet (\ln(G) + \ln(\alpha_f) - \ln(I_S)) \qquad \text{Equation (5.5)}$$

I_S can be found [Möl93 p29] [Gre98] using the approximate formula:

$$I_S \cong \beta_f \bullet \exp\left(\frac{-E_g}{kT}\right) \qquad \text{Equation (5.6)}$$

where E_g is the band gap, β_f is relatively constant and temperature, T [°K] is held constant for the experiments. β_f is of the form:

$$\beta_f = eA_{CS}N_CN_V\left\{\frac{D_nF_p}{L_nN_A} + \frac{D_pF_n}{L_pN_D}\right\}$$ Equation (5.7)

where
A_{CS} is cross-sectional area
N_C and N_V are effective densities of states in conduction and valence bands
D_n and D_p are diffusion coefficients
L_n and L_p are diffusion lengths
N_A and N_D are densities of acceptors and donors

For non-research purposes, it will suffice to know that β_f has been estimated [Gre98 p88] as having a value of 10^5A/cm^2 for crystalline Silicon. Substituting equation 5.6 into equation 5.5 gives:

$$\eta \cong FF \bullet \alpha_f \bullet \frac{kT}{q} \bullet \left(\ln(G) + \ln(\alpha_f) - \ln(\beta_f) + \frac{E_g}{kT}\right)$$ Equation (5.8)

which in the form:

$$\eta = a\ln(G) + b$$ Equation (5.9)

has:

$$a = FF \bullet \alpha_f \bullet \frac{kT}{q}$$ Equation (5.10)

and:

$$b = \left(\ln\alpha_f + \ln\beta_f + \frac{E_g}{kT}\right)$$ Equation (5.11)

From the right hand graphs of Figure 5.2, it can be seen that the overall trend is a straight line on a logarithmic scale and therefore a good fit with an equation of the form of equation 5.9. This is particularly the case in the range 1-100W/m^2 and for the lower right hand graph.

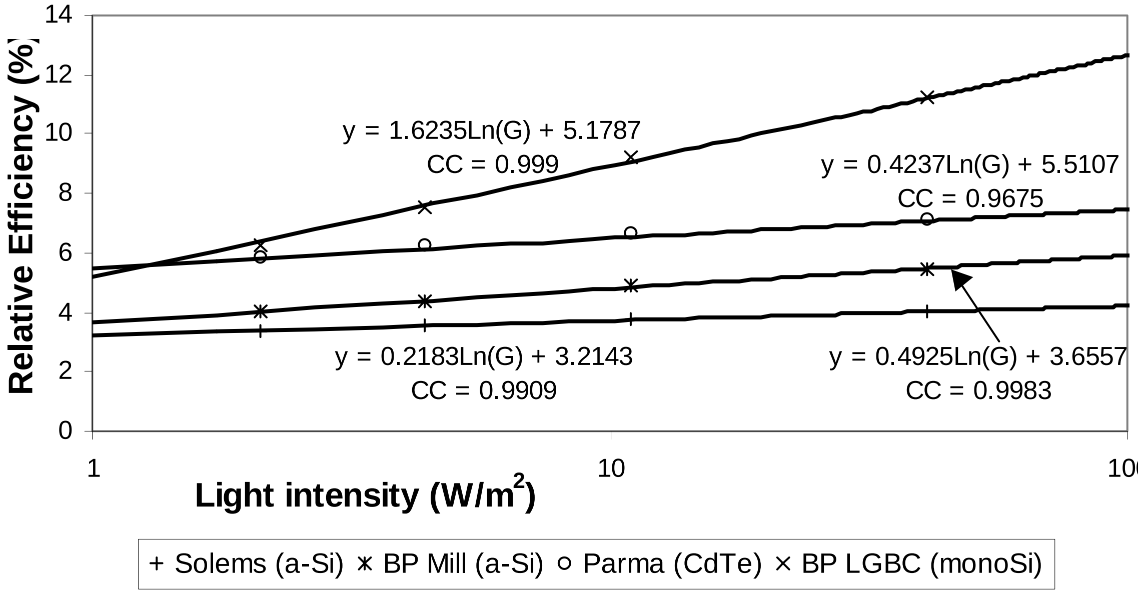


Figure 5.6: Fit of author's measurements for selected samples from Figure 5.2

In Figure 5.6 we magnify the efficiency range 1-100W/m^2 and compare it with a line whose equation is of the same form as equation . This latter relationship was applied to the data for all samples in the range 0.8-100W/m^2 and the results shown in "Table 5.2" suggest a good fit (linear correlation coefficient CC over 0.98).

Table 5.2: The parameters of the author's phenomenological model (equation 5.9) in the 1-100W/m2 range for all samples tested by the author under AM1.5

Cell code	a_{AM}	b_{AM}	CC	a_{AM}/b_{AM}	~Eg
pSi-EFG	2.33	0.48	0.99	4.87	1.10
pSi-MAIN	2.05	(-)0.84	0.92	2.43	1.10
xSi-EdSi	1.50	2.16	1.00	0.69	1.10
xSi-BP	1.71	2.58	1.00	0.66	1.10
CIGS-ZSW	1.73	2.83	0.98	0.61	0.90
pSi-Dist	1.67	2.80	1.00	0.60	1.10
xSi-Dist	1.40	2.88	0.99	0.48	1.10
xSi-LGBC	1.62	5.18	1.00	0.31	1.10

Cell code	a_{AM}	b_{AM}	CC	a_{AM}/b_{AM}	~Eg
aSi-Sino	0.40	2.06	0.95	0.19	1.70
aSi-VHF	0.33	2.30	0.96	0.14	1.70
aSi-BP	0.49	3.66	1.00	0.13	1.70
CdTe-Mats	0.38	3.30	1.00	0.11	1.40
PC-IPC2	0.42	4.25	0.95	0.10	-
PC-GCSA	0.40	4.37	0.96	0.09	-
MJ-NREL	0.74	9.02	0.99	0.08	-
aSi-Tess	0.43	5.41	0.99	0.08	1.70
CdTe-Parm	0.42	5.51	0.97	0.08	1.40
aSi-Sany	0.17	2.39	0.98	0.07	1.40
aSi-Sole	0.22	3.21	0.99	0.07	1.40
3-5-NREL	0.57	8.72	0.98	0.07	1.50
GIP-NREL	0.36	8.59	1.00	0.04	1.40

Nb:

a_{AM} & b_{AM} are values of a & b under AM1.5 source

Cell codes are defined in Table 5.1

Average CC for all 21 samples 0.98

An ideal cell for IPV use therefore has as low *a* (gradient on the logarithm graph) and high *b* (intersect of the efficiency axis). Such ideal characteristics are displayed by those samples that perform best in these experiments under indoor light conditions (e.g. Ga compounds).

For convenience, the parameters *a* and *b* can be combined to form a single parameter which is equal to *a*/*b* by an adjustment of equation as follows:

$$\eta = b\left(\left(\frac{a}{b}\right)\ln(G) + 1\right)$$ Equation (5.12)

where:

$$\frac{a}{b} = \frac{1}{\ln\alpha_f - \ln\beta_f + \frac{E_g}{kT}}$$ Equation (5.13)

As can be seen from equation 5.13, with α_f, β_f and T constant, *a*/*b* is inversely related to band gap. In Table 5.2, the values of *a*/*b* are shown for all samples tested. They are ranked by *a*/*b*, and although this relationship to band gap is not found, it can be seen on the left hand side that for *a*/*b* greater than 0.3, the approximate material band gap is less than or equal to 1.1. On the right hand side, where *a*/*b* is always less than 0.2, approximate band gap (where known) is greater than 1.4. It can only be inferred that the latter values of *a*/*b* and band gap may be appropriate for IPV; in general, the lowest *a*/*b* is recommendable for IPV design.

Two distinct technological groups are also found when ranking the results with respect to *a*. Those cells with a value of *a* greater than 1.4 (left-hand side of Table 5.2, including monocrystalline silicon, polycrystalline silicon and CIGS) and *a* in the range 0.17 - 0.74 (on the right hand side, amorphous silicon, CdTe, gallium compounds and dye cells). These two modes have already been identified [Ran00]. However, this is the first time that numerical variables have been associated with them.

Neither *a* nor *a*/*b* therefore have been shown to be related to band gap. This can be explained not only due to the comparison of both cells and modules in the same experiment, but also to the variety of processes and methods used to produce the samples.

Table 5.3: Author's phenomenological model (equation 5.9) parameters over the 1-100W/m^2 range for samples tested by the author under fluorescent source

Cell code	a_F	b_F	CC	a_F/b_F
xSi-BP	0.82	1.26	1.00	0.65
xSi-EdSi	0.57	0.95	1.00	0.60
aSi-Sino	0.46	2.76	1.00	0.17
aSi-Tess	0.57	6.11	1.00	0.09
PC-IPC2	0.57	4.26	1.00	0.13
PC-GCSA	0.48	4.29	0.99	0.11

Nb: a_F & b_F are values of a & b under fluo. source

Average CC for all 6 samples 1.00

Table 5.4: The ratio of fluorescent parameters (Table 5.3) to AM1.5 parameters (Table 5.2)

Cell code	a_F/a_{AM}	b_F/b_{AM}
xSi-BP	0.48	0.49
xSi-EdSi	0.41	0.33
aSi-Sino	1.15	1.34
aSi-Tess	1.32	1.13
PC-IPC2	1.36	1.00
PC-GCSA	1.18	0.98

Table 5.3 shows the parameters of equation for the results in Figure 5.4. These are then compared in Table 5.4 with the values under AM1.5 (Table 5.2); as can be seen, the amorphous silicon parameters increase by 13-34%. The dye cell samples parameter b changes little and have an 18-36% increase in parameter a. The crystalline silicon samples parameters decrease from 51-62%. This indicates that the latter samples are affected more by spectral mismatch (product of the incident spectrum and the spectral response of the cell integrated over the response range) than the amorphous and dye cells.

5.3.2 Heuristic model

Another equation from [Dur02] that for the moment remains without complete explanation is nevertheless noteworthy given its good fit to the results presented here. The full equation is as follows:

$$\eta = p\left[q_s \bullet \frac{G_n}{G_{no}} + \left(\frac{G_n}{G_{no}}\right)^{m_s}\right] \bullet \left[1 + \frac{r_s\vartheta}{\vartheta_0} + \frac{s_s AM}{AM_0}\right] \qquad \text{Equation (5.14)}$$

where the following constants have the values G_{no}= 1000W/m^2, ϑ_o= 25°C and AM_o =1.5. The variables light intensity (G_n), temperature (ϑ) and spectrum (AM) are accounted for. p, q_s, m_s, r_s, and s_s are parameters. Given that for the present experiment temperature and spectrum were kept constant, the above equation may be simplified to:

$$\eta = a_s(b_s G_n + G_n^{\ h}) \qquad \text{Equation (5.15)}$$

However, a slightly improved fit is obtained with:

$$\eta = \alpha_s(\beta_s G_n^{\chi_s} + G_n^{\delta_s}) \qquad \text{Equation (5.16)}$$

As Table 5.5 shows, the fit of equation 5.16 is satisfying, and this over a range of intensity one order of magnitude greater than that applied to equation 5.9 i.e. 1-1000W/m^2. This is therefore of interest to IPV practitioners.

Table 5.5: The fit of equation 5.16 for all samples tested by the author over the range 1-1000W/m2 under AM1.5 spectrum

Cell Code	α_s	β_s	χ_s	δ_s	CC	Cell Code	α_s	β_s	χ_s	δ_s	CC
xSi-EdSi	19.605	-0.861	0.422	0.405	0.996	GIP-NREL	10.791	-0.210	0.152	0.069	0.999
xSi-Dist	5.130	-0.351	0.466	0.339	0.993	aSi-VHF	3.420	-0.322	0.342	0.206	0.998
xSi-LGBC	12.267	-0.554	0.342	0.285	0.999	aSi-Tess	5.558	-0.035	0.436	0.099	1.000
xSi-BP	9.012	-0.641	0.439	0.389	0.993	aSi-Sole	6.068	-0.474	0.194	0.134	1.000
pSi-Dist	6.867	-0.535	0.466	0.393	0.997	aSi-Sino	3.217	-0.352	0.365	0.243	0.983
pSi-MAIN	-14.324	-0.959	0.094	-0.033	0.986	aSi-Sany	2.648	-0.113	0.402	0.133	0.996
pSi-EFG	44.670	-0.956	0.563	0.558	0.990	aSi-BP	5.019	-0.267	0.257	0.156	0.999
3-5-NREL	11.855	-0.266	0.157	0.090	0.992	PC-GCSA	4.499	-0.052	0.514	0.140	1.000
CdTe-Mats	3.419	-0.044	0.484	0.136	1.000	PC-ICP2	11.473	-0.630	0.265	0.209	0.987
CdTe-Parm	7.257	-0.246	0.250	0.127	0.996	MJ-NREL	8.644	0.061	0.064	0.064	0.993
CIGS-ZSW	12.325	-0.798	-0.218	0.029	1.000						

5.3.3 Technology specific models

Whilst it is ideal for the IPV practitioner to have such pan-technological models of performance prediction, it is clear that each individual technology (e.g. amorphous silicon, cadmium telluride or dye cells) can and usually is modelled using mutually exclusive models. Equally, the modelling is at the level of a single and more fundamental parameter (e.g. V_{OC}) than a combined parameter such as efficiency. Fascinating though it would have been to investigate them further, such levels of detail are beyond the scope of this project.

Similar technologies can sometimes be modelled using similar approaches such as the Variable Illumination Method (VIM) for amorphous silicon [Me197, Me198, Me298] and microcrystalline silicon [Me297].

5.4 Discussion

The effect of series resistance (R_S) and parallel (shunt) resistance (R_P) on solar cell I/V curves is known [Gre98 pp 96-7], and is explained in sub-section 4.5.3 and can be modelled with 1 or more diodes [Ori00][Ori01][Bla02]. At high E_{rad} intensity, high R_S creates high series current I_S which reduces FF whilst at low E_{rad}, low R_P implies a high parallel current I_P which reduces FF. The effect of I_S and I_P on efficiency can be seen in the gradient of the curves in Figure 5.2. This is consistent with the hypothesis [Mey98] that where R_S is sufficiently high for the shunt current I_P to be negligible, the efficiency below 1 sun will first increase as radiant energy intensity is reduced. As can be seen, some samples in the intensity decade 100-

1000 W/m^2 indeed have such a negative gradient. Where the gradient approaches zero, the efficiency is maximised. For IPV products in particular, knowledge of these efficiency variations can improve product and cell design as well as help to explain variations in performance of ostensibly similar modules.

As I_P can be related to current paths through the solar cell or at its edges, the perimeter length was compared with the estimated R_P, but no clear relationship was found.

For IPV solar cell design, the low E_{rad} intensity implies that high R_S should not have a significant effect. This is fortunate as one of the contributions to R_S is the contact resistance, which can be thought of as a "leaky Schottky diode with non-linear characteristics" [Fah83 p229]. The relatively small effect of high R_S (and overly low R_P) for the present experiments is indicated by the "flatness" of the fill factor curves of certain samples such as shown in Figure 5.5; this suggests that these cells are in the range of radiant energy intensity in which they will best perform. Such an ideal range has also been described for outdoor conditions with respect to efficiency [BKB97].

The effect of incident radiant energy spectrum is of interest for the IPV practitioner. It has been demonstrated in Figure 5.4 that amorphous silicon sample efficiency was higher with fluorescent spectrum (up 14-34% at 2W/m^2) whilst the crystalline silicon samples efficiency deteriorated (down 51-57% at 2W/m^2) compared with filtered AM1.5. It would be interesting to test other samples as well as corroborate the results with comparison of the spectral response. The latter was not pursued, as the selection of samples did not include a single cell sample (a prerequisite for the spectral response equipment) for each technology.

5.5 Designing PV modules for indoor use

Given that certain thin film technology solar cells perform better at low radiant energy intensity, it is worthwhile to review other factors that can further improve the performance of such modules. These include the transparent conductive oxide (TCO) in section 5.5.1 and the dimensioning of the cells within the module, see section 5.5.2. Solar modules designed for a specific indoor use may be able to benefit from cost savings associated with the less stringent environment indoors compared with the outdoors. The benefits might be achieved by reducing the glass thickness; another way would be to use less or cheaper encapsulation.

5.5.1 Transparent conductive oxide

Thin film solar cells use a TCO as the front contact through which the light passes, see Figure 5.7. The design of this layer

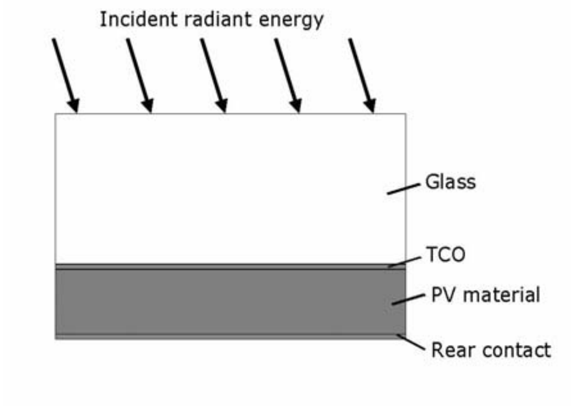


Figure 5.7: Position of TCO "front" electrical contact in typical thin film PV cell

is a trade-off between its thickness, which will filter incoming radiant energy, and its resistance (e.g. Asahi U-type SnO_2:F coated 1mm glass has a sheet resistance of 12.5Ω/cm2 and transmissivity of 82% for a TCO thickness of 1μm [Zha02]). At 1 sun, it maybe reasonable to take a (thicker) TCO with a lower resistance whilst accepting that it filters more radiant energy. However, for indoor purposes, with the current to be conveyed orders of magnitude lower, a thinner layer may well be sufficient and hold two further advantages. Firstly, it will transmit more light to the photovoltaic material and secondly, as TCO cost is usually proportional to thickness, allow some savings.

5.5.2 Dimensioning of the module

The width of the cells in a module (distance from one series connection to the next) has been modelled by Burgelman [Bur97] and combined with an outdoor climate model [Bur98]. This work suggests that efficiency at low intensity radiant energy is related to the cell width. An initial experiment made using indoor use cells from Tessag lends support to the hypothesis that wider cells are more appropriate for indoor use. Further test are required.

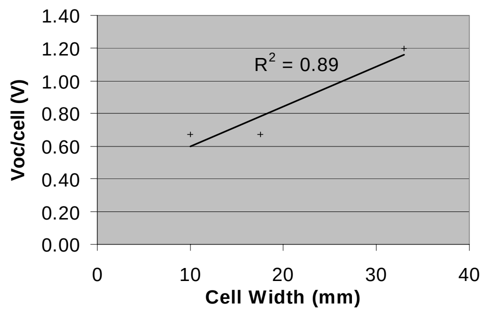


Figure 5.8: Relationship of V_{OC}/cell with cell width for RWE indoor solar cells

5.6 Conclusion

The lack of comparable low intensity solar cell data has been identified in sub-section 1.5.2 and section 5.1. Results for 21 samples representing 8 material technologies tested by the author under two spectra types and radiant energy in the range 1-1000W/m^2 have been presented. Thereby, it has been demonstrated that a 1 sun efficiency reference cannot be projected reliably down to indoor radiant energy intensities for all solar cells either because peak efficiency does not necessarily coincide with STC or the gradient of efficiency with intensity is non-zero. Also, efficiency varies markedly with intensity for many samples in the decades 1-100W/m^2 (see Figure 5.2), the limiting factor being the parallel current, I_P. Furthermore, the results confirm that efficiency is affected by spectra. This indicates the limitations of STC solar cell comparisons for indoor PV (IPV).

The lack of appropriate models has also been described and addressed; two models, one developed by the author, have been shown to correlate well to experimental results in the intensity and spectra ranges of interest for IPV design. These can be of service to IPV researchers and designers alike.

The above results form the basis for two relative classification criteria of the samples tested. The first classification is determined from the gradient for each sample on the logarithmic scale graphs (see right hand side of Figure 5.2). Two groups appear, based on photovoltaic technology:

Group 1: crystalline silicon, polycrystalline silicon and CIGS samples tested

Group 2: amorphous silicon, Cadmium Telluride, Gallium based and dye cell samples tested

For the 10-1000W/m^2 range, group 1 generally performs better than group 2. The opposite is the case for intensity between 1-10W/m^2. This shows the importance of knowing what radiant energy capital is available (see chapter 3). Based on radiant energy available, recommendations can be made as to which sample will have the best performance.

A second relative classification can be made with respect to spectra. The group 1 samples tested performed better (or efficiency was little affected) under a fluorescent spectrum whilst the group 2 samples performed noticeably less well in the same experiment. Given that fluorescent sources generally deliver radiant energy in the 1-10W/m^2 range implies that group 2 samples should be selected for such cases. The fact that they have lower STC efficiency may be a bonus to the designer as this will reduce the need for overcharge protection should the product be exposed to outdoor radiant energy intensity levels. Members of group 1 will be better suited to daylight spectra in the 10-1000W/m^2 range. This classification can be of service to the designer who will nevertheless take other factors into account such as cost, facility of series connection, surface area limitations and component availability. Cost for example will at present rule out the Gallium based samples for indoor use.

5.7 Further work

An ideal outcome from the IPV practitioner perspective would be a model based on easily accessible data (such as 1 sun efficiency) which would provide a prediction of cell performance over the full range of intensities tested here. The phenomenological model (equation 5.8) is valid for only some of the samples across the full range tested, 0.8-1000W/m^2, namely Solems, BP Millenium and Tessag. In order to extend the validity, more terms are required to model that part of the efficiency-intensity curve where the gradient becomes negative. It is also necessary to investigate the physical meaning of the control parameters a (equation 5.10) and b (equation 5.11).

Another area requiring further understanding is the physical mechanism which induces R_P. It is thought to be related to intrinsic leakage (junction resistance) and extrinsic leakage (perimeter). Assuming it is independent of light intensity, the R_P at low light intensities can be related to efficiency. R_P was estimated by the common technique of taking the gradient of the I-V curve at I_{SC} (see Figure 4.15) at a low E_{rad} (4.4W/m^2). The samples in Figure 5.9 suggest that there is a natural log relationship between R_P and efficiency per technology. Other techniques for measuring R_P exist such as [McM96].

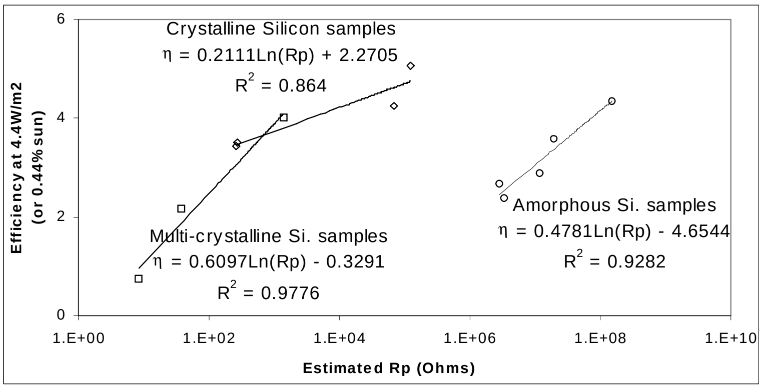


Figure 5.9: efficiency under low illumination (filtered AM1.5 with intensity of 4.4W/m^2) vs. R_{SC} (approx. R_P)

Chapter 6 : Indoor ambient energy charge storage

It has long been an axiom of mine that the little things are infinitely the most important
A Case of Identity (Sherlock Holmes), Doyle A.C., Strand Magazine, September 1891

6.1 Introduction

Many IPV systems require charge storage to fulfil their specified function. Storage is important for a number of reasons. Firstly it is often a determinant of application "lifetime". Secondly, it may be the costliest component of an autonomous power system (see Figure 7.18). Thirdly the trend of power and energy consumption of consumer electronic devices is far outstripping the advancement in (battery) storage technology [Sla02] despite significant scientific effort [Kin02].

The above three reasons focus attention on charge storage. However, finding the ideal storage solution for a particular application is made non-trivial by the many storage parameters that must be appreciated and balanced by the designer; these are mentioned in section 6.3 and section 6.4. In section 6.3 the general requirements of IPV charge storage are explained as well as the technologies at hand.

One of the determinant factors of charge storage cost and feasibility is the storage capacity [J]. In order to ensure this is correctly specified, a model of the relationship between charge storage and the probability that the application will have sufficient charge to function is developed. The relationship is composed of both deterministic (see sub-section 6.5.1) and non-deterministic elements (see sub-section 6.5.2). These are combined in sub-section 6.5.3 to form a global model.

The indoors is characterised by a less harsh environment (i.e. smaller temperature and humidity ranges) than outside. The ways in which such charge storage requirements may be met in practice are described in general in section 6.3. Of these, electrochemical charge storage (section 6.6) is the most likely to be applied to ambient energy systems.

This chapter however opens by setting the storage problem in its wider context, see section 6.2, in particular with respect to the trend of recent decades towards greater decentralisation of a number of associated fields.

6.2 Trends in charge storage

The last few decades have been witness to a general trend of decentralisation leading to distributed networks in various areas including data-processing, electrical power generation and electronic devices (e.g. mobile telephony). It is also recognised that this trend will continue for the coming decades, as can be inferred for electrical power generation from a forecase made in Osaka by the International Energy Agency. This stated that non-hydroelectric renewable energy "will grow faster than any other primary energy source, at an average rate of 3.3% per year for the next 30 years" [Int02].

One factor on which all these trends rely is *storage*, be it programs on the hard disk drive of a computer, water stored in a hydroelectric dam of an electricity network [Vou02] or the electrochemical potential of the battery in a personal digital assistant (PDA).

A related parallel can also be seen between the technical needs of distributed electrical networks and those of electronic products. Both must cost-effectively balance supply and demand of electrical energy - a non-trivial problem. A number of policies may be considered including reducing or smoothing global energy requirements (consumption) as well as storing energy for later use, such as with batteries for "peak-shaving" (e.g. the 40MWh NiCd in California [Col94]). Typical IPV storage technologies are considered in section 6.6, whilst Figure 6.1 shows the breadth of electrical power storage technologies currently available.

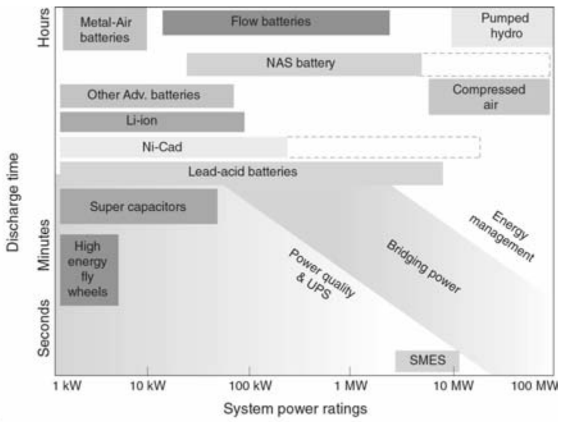


Figure 6.1: Simplified summary of electrical power storage technologies [Gma02] (SMES is Superconducting Magnetic Energy Storage, NAS is Sodium Sulphur, UPS is Uninterruptible Power System).

6.2.1 Electrical storage parameters

The conceptual graph in Figure 6.1 places discharge time on the y-axis. This is of interest not only because it indicates how long the storage medium will function (e.g. provide back-up), but also indicates the responsiveness of the medium. Given the variety of properties, no one technology can cover all requirements. As a result, another trend affecting both electrical and electronic storage technologies can be brought out: hybridisation of technologies. An example of this in electrical power production is cogeneration (simultaneous production of electricity and heat). A similar case for indoor electronic applications is the use of a battery and a capacitor.

Many other parameters must be considered by the system designer requiring such a storage device; these include energy density (the volume per unit charge stored), safety, maintenance, recycling, charge/discharge efficiency and cycle life and, in some cases, portability. However, under present economic conditions, capital cost is most often a priority.

Some reversible charge storage is essential for IPV applications. A reversible battery, for example, is one which can both deliver charge in one polarity and be recharged with the inverse polarity. This class of rechargeable (referred to from here on as secondary) storage should not be confused with refuelable secondary technologies such as the way in which Zinc-Air and fuel-cells are often used in practice. By corollary, primary storage is synonymous with devices which can be used only once, and are therefore neither rechargeable or refuelable.

Taking the example of electrical systems again, it can be seen from the conceptual graph in Figure 6.2 that Metal-Air batteries hold an apparently ideal position (and are infact often used for hearing aid applications e.g. Zinc-Air). An important reason why such storage has not replaced other technologies is that it is not used reversibly and can therefore be considered in practice only as a refuelable. Equally, the "fuel" is not cost-effective at the kW scale.

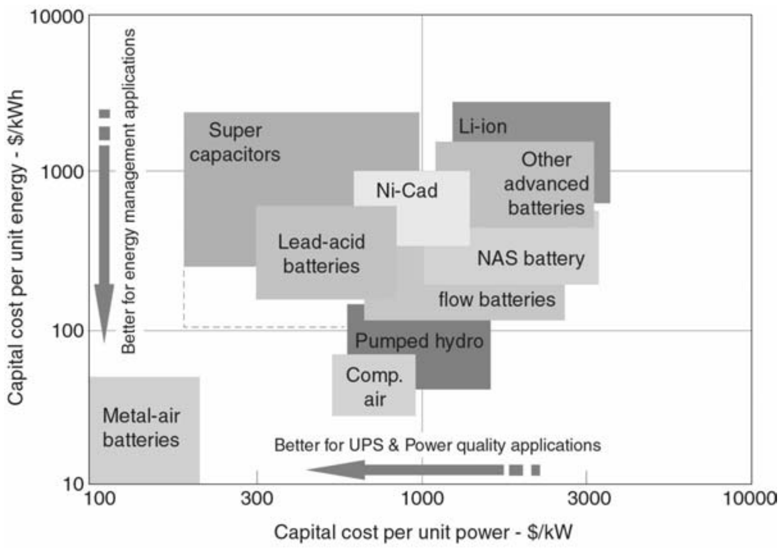


Figure 6.2: Simplified summary of capital cost of electrical storage media (NAS is Sodium Sulphur) [Gma02]

6.2.2 The market

The scale of the worldwide battery market is remarkable. Take the automotive sector (see Figure 6.3) alone which represents a demand of the order of G-units (10^9).

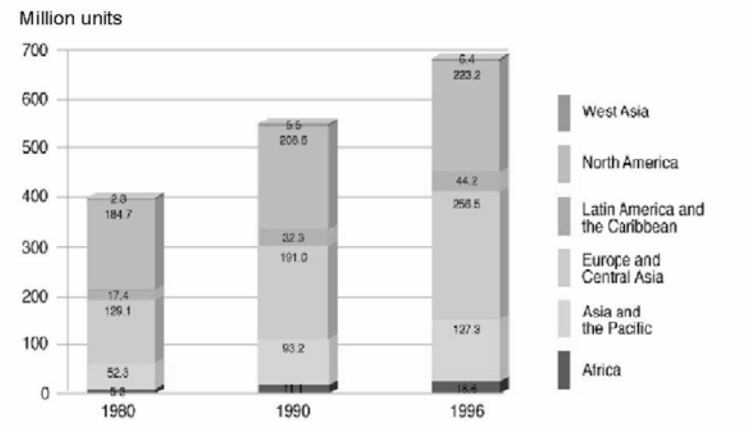


Figure 6.3: World car market growth [UNE97]

Given that most individuals buy a car less often than a consumer product, and that the latter often have a lower usable life, explains why the consumer electronic market (of which IPV products are part) represents much larger volumes (e.g. 1.6 G-units for the portable sector for Germany alone in 1996) [Hah00]. It is predicted that the *sales* of secondary batteries for the consumer sector will exceed those sold in the automotive sector in at least one European country - Germany - in 2003 [Hah00].

6.2.3 The waste

So what happens to all these batteries once used? In the US, batteries in general represent "less than one per cent of total municipal solid waste generated" **but** "accounted for nearly two-thirds of the lead, ninety percent of the mercury, and over half of the cadmium found in the waste" [McM98]. This supports the case for battery recycling structures as well as switching from primary to reversible secondary batteries where possible. Secondary batteries, when used correctly, contribute to reducing waste [Lan98] and therefore pollution.

Related pollution at the worldwide level comes from small consumer electronic products (such as IPV applications) which are disposed of still containing their batteries. This indicates the importance of ensuring minimal environmental impact of storage devices in general, be they primary or secondary. An ideal goal is to avoid electrochemical storage altogether, which is already technically feasible in low power electronics [Peg02], an area which may be ideal for IPV applications.

6.3 Charge storage technology

6.3.1 Introduction

The necessity for storage implies both significant investment and lifetime costs for outdoor stand alone PV systems [Bop95]. Significant investment costs for charge storage may equally be the case for IPV autonomous power systems (see Figure 7.18). It is therefore worth considering the various technologies available for fulfilling this role, both mechanical (sub-section 6.3.3) and electrochemical (sub-section 6.3.4).

Given that electrochemical technologies are used for the majority of applications, these are reviewed in turn, see sub-section 6.3.5 to sub-section 6.3.7.

All such storage technologies may be compared with respect to common units and properties which are presented first in (sub-section 6.3.2).

6.3.2 Technology characterisation

Storage technology comparisons may be based on many factors. One of these, the discharge time, has been mentioned above (see sub-section 6.2.1) and may be measured as a rate (e.g. per cent per unit time) or the time to reach a set level of discharge (see Figure 6.1).

This should not be confused with the inherent parasitic discharge of the majority of storage devices, usually referred to as the self-discharge. This is usually quoted as a rate. For sensor applications, with wireless communication requiring product life of some years, see section 1.4, it can be anticipated that self-discharge is one of the most important issues associated with ensuring satisfactory product life.

Four further factors that are often quoted with regard to storage technology relate energy and power to weight and volume, see Table 6.1, "Four inter-related storage technology comparison factors":

Table 6.1: Four inter-related storage technology comparison factors

Units	Volume (l)	Weight (kg)
Power (W)	Power density (W/l)	Specific power (W/kg)
Energy (Wh)	Energy density (Wh/l)	Specific energy (Wh/kg)

As can be expected, ideal storage technologies will have as much power and energy as possible with the least possible volume and weight. All of these values are for constant temperature, humidity and pressure. Although extremes of such parameters can be found in other environments, the indoors can be expected to be relatively less harsh for charge storage devices.

A weakness suffered by some battery technologies, such as Nickel Cadmium, for IPV applications is the charging “memory effect”. Such batteries are unable to accommodate pauses in the charging process that are typical of the intermittent nature of renewable energies. The consequence is that actual capacity is reduced, in the case of NiCd due to the formation of Ni_5Cd_{21} which renders the active material inaccessible [Lan98]. The resultant loss of storage capacity should be allowed for if using such a storage device for IPV.

The storage technologies considered here may be categorised into two classes: mechanical and electrochemical. In the following two sections, the principles on which these classes rely are explained. At present, electrochemical technology is usually used for IPV applications requiring charge storage. However, this assumes that they have sufficient usable calendar life. For building applications, use life might be of the order of decades, which is greater than the approximate ten years maximum life that electrochemical battery technologies can offer at present.

6.3.3 Mechanical storage technology

One solution for extending usable life of the storage device beyond ten years is mechanical storage. It is generally characterised by a store of potential energy linked to an electrical motor. The motor may be used both to convert the potential energy into charge as well as, when running in the opposite direction, recharge the potential energy. In principle, the fact that the motor is required is a disadvantage due to its volume, the added complexity and incumbent inefficiency.

Springs

Of the available mechanical storage technologies, springs have a long history of use for energy storage. Their use in horology (e.g. timekeeping) since the 15th century [Lan87] paved the way for both miniaturisation and portability. Their main advantage is having a virtually nil self discharge rate, making them appropriate for applications requiring autonomy greater than 10 years (roughly the limit of electrochemical technology life). This may be appropriate for building sensor applications where ideally the device would have a usable life in proportion to the expected life of the building (i.e. decades). The key disadvantage of using springs for storage is that their energy density is two orders of magnitude lower than batteries [Xua99].

Flywheels

Flywheels are in themselves not a new concept. They have long been used to reduce variations in engine operating speed. Their use for energy storage is being researched for spatial [Ian97], automotive [Hiv96], micropower distributed energy source [Cal01] and power quality [Kam02] applications. The orders of magnitude of capacity are for the moment much larger than IPV scale, even at the laboratory level, such as a 50Whr design [Kef99]. Also the typical practical time that a charge is held is of the order of hours [Heb02] indicating significant self-discharge. For IPV, if the necessary miniaturisation can be achieved, flywheels have the potential of higher power with rapid response. Another advantage is their relatively lower sensitivity to temperature and charge-discharge cycling, both often the bane of electrochemical technologies.

Shape memory alloys

An area with potential for storing small amounts of energy due to their limited expected efficiency [Bel99] are shape memory alloys (SMAs). They are sensitive to heat rather than electrical energy, so are typically associated with thermal cycle systems. Therefore use in an IPV system implies a hybrid solution such as a catch or a piston and spring.

6.3.4 Electrochemical storage technology

Electrochemical technology is characterised by at least 2 electrodes (i.e. anode and cathode) between which is a seperator and an electrolyte; the resulting cell is housed in a container. When the electrodes are connected to a suitable resistance, the cathode is (chemically) reduced releasing electrons and the anode is oxidised by receiving electrons. Such charge carriers pass through the electrolyte from one electrode to the other and through the exterior circuit. From the outside of the circuit, the positive electrode is therefore the anode, the negative electrode the cathode.

In principle, electrochemical devices have a number of properties in common including thermodynamics, electrode kinetics and transport phenomena [Ull98]. Temperature sensitivity of electrochemical devices can be an issue; however this is usually less the case indoors given the relatively lower expected temperature variance.

Electrochemical device capacity is directly related to the surface area of anode and cathode that overlaps and therefore their construction seeks to maximise this area. This is achieved via a spiral section or a stack of parallel layers leading to the cylindrical or prismatic shapes shown in Figure 6.4.

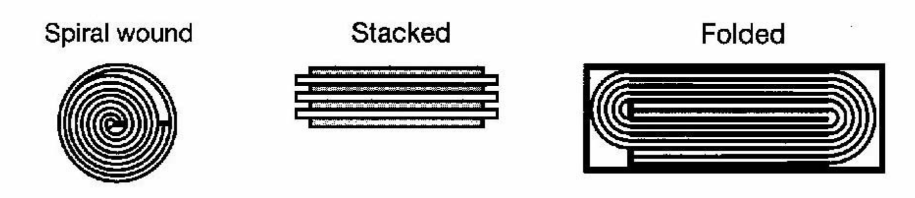


Figure 6.4: Electrochemical storage device configuration, based on [Oma99]

In the future, cells will also be available in sachets [Sla02]. Spiral (wound) cells are the most established technology; prismatic shapes are newer and whilst they offer the promise of tighter packing density, easier series connection and bipolar electrodes (which can act as both anode and cathode) they have the disadvantage of requiring the perimeter of each layer to be sealed. Compared with a spiral design, the latter is more demanding to manufacture and gas venting is also more complex.

Members of the electrochemical storage technology class include batteries (primary and secondary) see sub-section 6.3.5, capacitors (see sub-section 6.3.6) and fuel cells (sub-section 6.3.7). These are compared on the graph of specific power (y-axis) vs. specific energy (x-axis) in Figure 6.5.

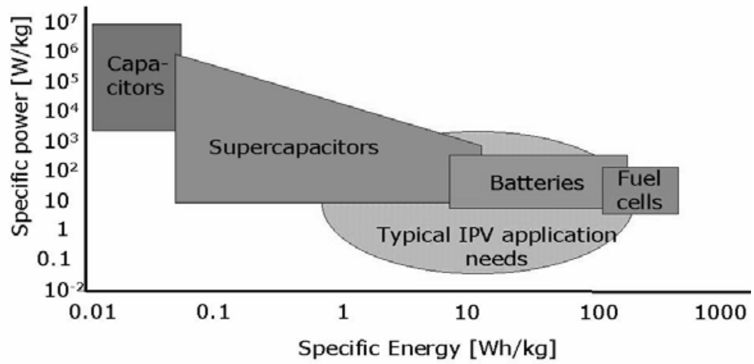


Figure 6.5: Simplified electrochemical storage technology comparison with IPV storage requirements (author graph based on [Ene00])

This shows how batteries are generally the most well matched technology to IPV applications. However, some specifications require a supercapacitor (or double-layer capacitor, DLC) or fuel cells. Combinations of technologies are also feasible, leading to hybrid storage solutions such as battery and DLC for increasing instantaneous power [Ruf99].

6.3.5 Batteries

Whilst electrochemical storage devices have certain aspects in common, a battery may usually be distinguished from a DLC by the fact that the battery anode and cathode are of different materials; these determine the battery electrochemical couple. Ideally the difference in (standard) electrode potential of the two materials should be as great as possible as they have a direct influence on output voltage [V]. Another determinant of voltage is the number of such cells in series.

Another difference of batteries, when compared with fuel cells or DLCs, is that with batteries the anode and cathode participate in the electrochemical reaction; for DLCs, the charge seperation is distributed through the volume of the electrodes. This means that the limiting factor determining battery capacity [mAh] is related to the amount of active electrode material available to react. This quantity of electrons which are available for discharge are delivered at a rate referred to as current [A].

Some battery chemistries are readily reversible which allows the battery to be electrically recharged. The range of currents output from a battery give an indication of what current range may be used for recharging. This range must also be compatible with the application current requirements.

The unit used to describe charging and discharging of a storage device is C (N.b. C in this context is not a coulomb). The measure is determined as the ratio of current to capacity, more specifically a current of 1C is required to fully "fill" (from 0% charge) or "empty" (from 100% full) the battery in one hour. Typical charging currents in IPV will be 0.1C or less.

A related battery technology parameter is the depth of discharge (DoD) sensitivity, usually measured as number of cycles that can be achieved for a certain specification. In the long term, repeated deep (>80% of rated capacity) discharge is known to have a deleterious effect on the capacity lifetime of some battery technologies such as Lead-Acid. Other technologies such as Nickel-Cadmium are better suited to a single continuous recharge from empty.

The designer may seek to ascertain how many such cycles are likely to occur and whether predicted capacity loss will reduce application functionality. For IPV applications positioned close to the window, a life cycle similar to outdoor applications can be expected, as shown in the left graph of Figure 6.6.

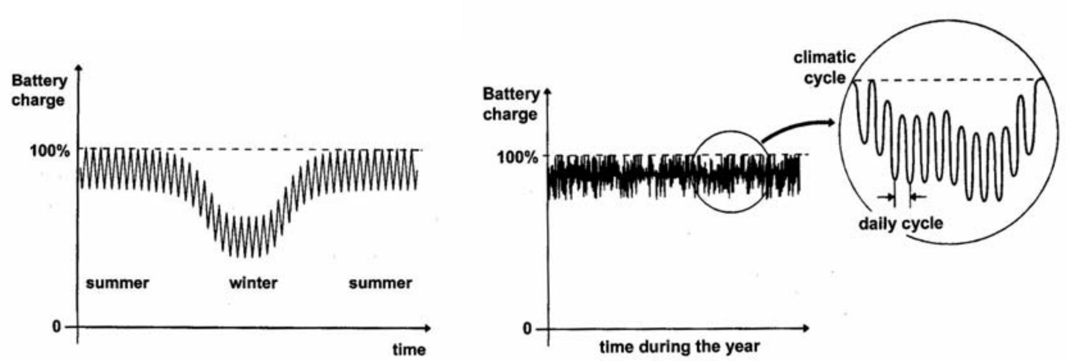


Figure 6.6: Typical storage charge cycles for a daylit (left) and electrically lit (right) IPV application with lead-acid technology storage

For those applications that collect electric light, the cycles may not show such a deep discharge in winter (see right graph of Figure 6.6), but are likely to suffer more frequent shallow cycles (e.g. an office or school lit in the week and unlit on the weekend).

For portable applications in particular, it is attractive if batteries have the lowest possible weight. This is covered further in sub-section 6.6.2.

6.3.6 Double-Layer Capacitors (DLC)

The devices of interest for IPV autonomous power sources may be described as a supercapacitor, ultracapacitor, electrochemical capacitor, gold capacitor or double-layer capacitor (DLC) [Pro03]. Such capacitive storage relies on opposite charges being seperated by an insulating medium. A basic example of this is two parallel conducting plates seperated by a dielectric. Such a device can be readily charged and discharged, and it is for this property that capacitors are applied in electronics (for power smoothing circuits [Ruf02] or blocking direct current). For IPV storage applications, they are used to support a battery by coping with peak energy demand or as storage devices in their own right, for example for solar calculators (see sub-section 4.2.4). A key parameter is the amount of electrostatic charge which is stored, F [Farads]:

$$C_F = \frac{KA_O}{d} \quad \text{Equation (6.1)}$$

where:
C_F = Capacitance [F]

A_O = surface area of the overlap between plates [m^2]
d = distance between the plates [m] and
K = the permittivity of the seperation material (at a fixed temperature)

It is of note for storage solutions using only capacitors that the actual voltage tends to vary over a wider range than batteries in normal charging or discharging; for this reason, such devices should be used for charge storage rather than as voltage source [Zub00].

For peak energy demand, it is rather the maximum power, P that can be delivered from a capacitor which is of interest; this is directly related to the square of the maximum voltage [Ruf99] as follows [Pan97]:

$$P_F = \frac{(V_{max})^2}{4 \bullet R_{es}} \quad \text{Equation (6.2)}$$

where:
V_{max} = maximum voltage deliverable from capacitor [V]
R_{es} = effective series resistance [Ω]

DLCs have greater energy density than traditional dielectric capacitors, although this density remains approximately one order of magnitude below that of batteries. Recent research has considered these devices combined with batteries [Bae00, Bas00] and as electrical energy storage solution in their own right e.g. [Bar02][Zub00]. In the latter article it is observed that DLCs have similar characteristics to a number of increasingly small capacitors connected in parallel. A simplified model of this is shown in Figure 6.7.

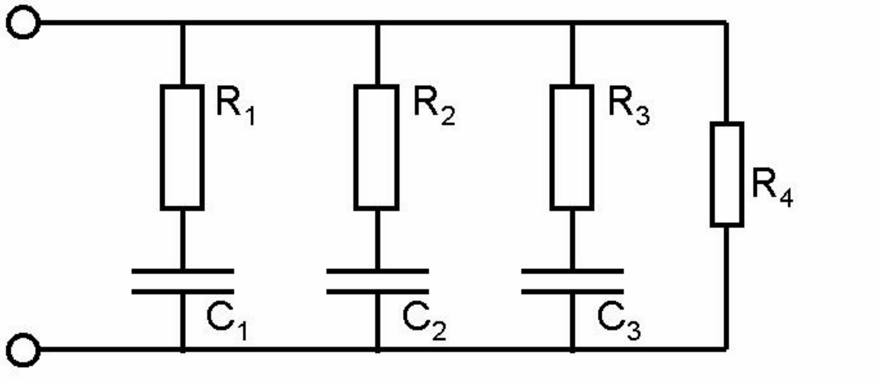


Figure 6.7: Simplified DLC model where $R_1>R_2>R_3$ and $C_1>C_2>C_3$

This is confirmed in a DLC catalogue [Tok01] which shows that more total charge can be extracted at low discharge currents (e.g. 0.1-0.001mA) than at high discharge currents (e.g. 1mA-1A). The rechargeable nature of all capacitors suggests that they would likewise store relatively more charge when trickle charged, a case typical of the energy delivered from PV under indoor electric light sources.

With regard to the useful life of a DLC, it was found that [Nec02] load life at 85°C is at least 1000 hours. Such conditions are expected to be extreme for IPV products, and therefore longer useful life can be expected.

Devices with a diameter of around 2cm (i.e. the size range of some IPV applications) with capacities of tens of Farads are available on the market indicating that they are likely to play an increasing role in consumer electronic charge storage; with this in mind, of the capacitive devices only DLCs are considered as storage devices below.

Pseudo capacitance

One way of increasing the charge storage compared with the simple parallel conducting plates example above is to encourage charge to intercalate in the plates. This charge comes from the electrolyte i.e. there is still no reaction with the electrodes. Whilst this idea is unlikely to improve the power characteristics, pseudo capacitance can be expected to give higher energy density [Mun00].

6.3.7 Fuel cells

Fuel cells might in the future be used as a solar rechargeable storage technology; however, for the moment, they are being mostly considered as “engines”, converting a fuel into charge. Given that once the fuel reservoir is spent, it needs to be recharged, such an approach therefore corresponds to a primary cell. Given the importance for IPV of having some electrically rechargeable storage, present day fuel cells cannot by envisaged for IPV charge storage. Their use for IPV in the future would depend not only on their reversible use, but also that the fuel reservoir would not be sufficient for the life of the product.

Of the six classes of fuel cell, only two have appropriate operating temperature for IPV (approximately 80°C [Fli00]). These are DMFCs (Direct Methanol Fuel Cell) which as the name suggests consume methanol and PEMFCs (Polymer Exchange Membrane Fuel Cell) which run on Hydrogen. DMFCs benefit from the fact that as methanol is a liquid, it is easier to contain than hydrogen, especially in the small quantities [ml] required. PEMFCs although considered safer and “closest to commercial production” [Mac02] suffer a price disadvantage. DMFCs are thus under development [Can00] for mobile phone applications [Cha01] although the latter will not reach the market before 2005 [Mor01]. PEMFC have also been announced on the market, but at over 7000 US$/unit (with three recharge packs) [Cor02] are out of proportion for expected IPV applications.

6.4 Charge storage parameters

Given the energy stored and the voltage of a storage device, the capacity may be determined, the units of which for IPV are generally mAh, 3.6 coulombs. Manufacturers quote the rated capacity which corresponds to the amount of energy that can be discharged at the rated current (at a set temperature which is usually close to indoor conditions). However practical applications do not constantly consume rated current, so for each application an actual capacity is also found. This may be greater or smaller than rated capacity.

Actual capacity will be a compromise between the many (and sometimes conflicting) properties that suitable devices and technologies should exhibit. Some of these are as follows:

6.4.1 In general

• be cheaper than the other components - rather than the most expensive element of the IPV system, as may often be the case

• be designed for lower life cycle costs than presently used solutions - this may include being a) readily produceable with low energy, b) recyclable, c) composed of non-toxic materials and d) in a structure of material reuse

• be lower volume with respect to power and capacity than existing solutions - given that the storage device may be the most voluminous IPV power source component

6.4.2 In charging

• be chargeable over the several orders of magnitude of current delivered by the IPV device - from slow/trickle charge to fast charge with constant charging efficiency and/or without damage to the internal structure. Not suffer loss of capacity due to inconsistent charging

• be sufficiently insensitive to overcharging - continuing to charge when a storage device is fully charged is associated, for some technologies, with the creation of heat and gas, both of which contribute to increased pressure in the storage device. This can cause damage and reduce useful life if the device is sealed. If it is not, the device may need the lost contents to be replaced, whether this is practical or not. The solution found for systems much larger than IPV where overcharge for extended periods is likely [Vel00] is a charge controller which amongst other functions might reduce current delivered to the storage device once it is fully charged.

6.4.3 In discharge

• have appropriately low self-discharge rate - this may be important for an IPV product if it should function immediately the customer receives it, and therefore the storage should "hold" charge from manufacturing to first use. The same parameter may be important once the product is in use for periods of low radiant energy intensity. The process of self-discharge can be related to an electrochemical reaction and the rates of all such reactions rises with temperature [Ber98]; therefore, if the IPV product is subject to temperatures outside typical average room temperature (e.g. 20°C +/-5) this may be an issue.

• be able to deliver sufficiently high and constant current without reduction of voltage or capacity (in discharge). With respect to the latter, batteries are known to suffer from the rate capacity effect which is observed if the current magnitude drawn is greater than the rated current. The result is that the ratio of delivered energy to stored charge is reduced. This may be compensated in idle periods by an increase of actual capacity, and therefore useful life; this is referred to as the recovery effect, which may be of interest for intermittent use IPV applications

• be insensitive to deep discharge (>80% capacity) and not suffer from being 100% discharged with respect to technical characteristics such as polarity reversal. IPV applications can expect such conditions at least annually (holiday weeks when windows are shuttered and no lights are used). Deep discharge may be important when more than one kind of storage device is used (i.e. in a hybrid system) as the most used device tends to suffer deepest cycling. Another similarly undesirable example may occur for cells connected in series when the weakest cell is discharged below 0V; this can have the consequence of side chemical reactions for the example of batteries

• not require maintenance - reliable and sufficient service life with respect to the required charge-discharge cycling for example

6.4.4 For portable devices

• have sufficiently low weight with respect to power and capacity - given that the storage device is often the heaviest IPV power source component

• be appropriately insensitive to temperature, which can induce premature ageing of the storage device

• be usable in any (three dimensional) orientation

• be sufficiently resistant to shocks and vibration and not leak if punctured or misused

These requirements maybe contradictory: for example, a design that can deliver high current implies relatively low internal resistance with the incumbent likelihood of increased self-discharge rate. Given the difficulty to satisfy all the functional needs of storage lends support to the case that storage should be minimised or, better still, eradicated [Peg02].

Usually this is not possible and the designer will prioritise the charge storage parameters. Two factors which are likely to be important to most ambient energy systems are low self-discharge and cost, treated in sub-section 6.5.1 and sub-section 7.4.3 respectively. This is because most batteries average self-discharge rivals the ambient power collected. Generally those storage devices which are used for standby (float-service duty) will be the most applicable for IPV.

6.5 To determine storage capacity

An essential consideration for the technical feasibility of an IPV system is that there is sufficient energy for the required functionality, see Figure 6.8. Evidently, the energy available may be sourced from either daylight and/or electrical sources (see chapter 3).

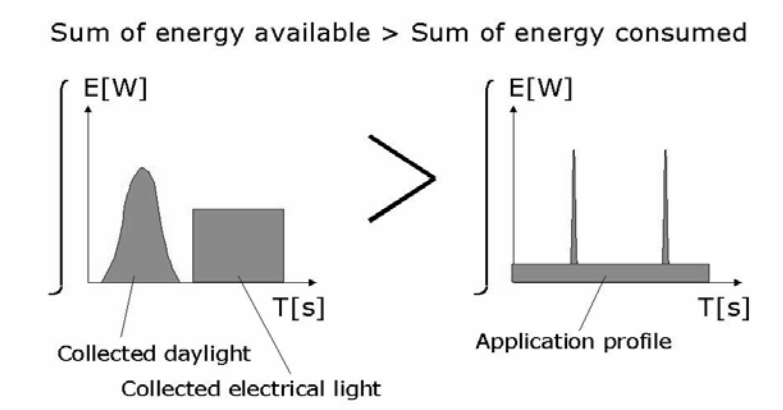


Figure 6.8: Schematic of energy constraint

Assuming that the inequality in Figure 6.8 is always satisfied, no storage may be necessary e.g. a solar toy which only functions with sufficient radiant energy. If the equality is only partially satisfied, two cases can be imagined:

a) the total available energy is insufficient for the application to function satisfactorily, in which case the present product configuration cannot be pursued, or

b) total available energy does exceed total application energy, but some charge storage will be required to compensate the phase difference between supply and demand

In the latter "energy buffer" case, a charge storage specification can be developed including capacity [Ah], voltage [V] and maximum discharge current [A]. It is assumed that the total energy available and the total energy consumed are similar.

The necessary capacity may be specified with respect to a number of parameters, some of which are relatively stable and may be considered deterministic, see sub-section 6.5.1 whilst others are stochastic and require more involved modelling, see sub-section 6.5.2.

6.5.1 Relatively stable factors

In this sub-section, the specification of storage size is considered with regard to those factors which are expected to be sufficiently stable to be modelled deterministically.

Application standby current

The application will typically have a constant standby current demand which requires a suitable storage capacity for standby consumption, h_{SBY}. It is of note that the global consumption due to the standby mode may be greater than the total energy consumed when "in-function".

Storage actual capacity

The storage device will also have issues. For example, it is rarely possible to extract all the charge at a fixed voltage, see Figure 6.9, and the application minimum voltage requirement will usually be reached before the storage device is fully discharged. A symptom of this problem is that around a third of batteries collected for recycling in Switzerland still contain 90% of their charge! [Kas02]. A typical "culprit" for such waste is a high current application (e.g. camera) which fortunately for the present case consume much more than typical IPV applications.

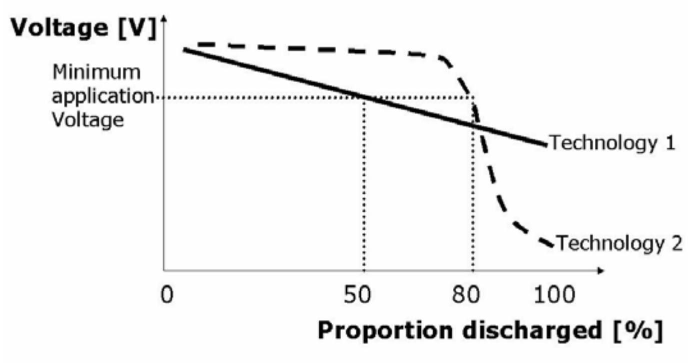


Figure 6.9: Examples of discharge profiles for two battery technologies

The two simple discharge examples in Figure 6.9 show that the minimum application voltage fixes the proportion of the storage capacity that may be discharged in practice. For technology 1, only 50% of the rated capacity can be used whilst for technology 2, 80% of the rated capacity may be extracted. An approximation of the extra storage capacity, h_{MAV} that will have to be specified to use a particular storage device is the reciprocal of the proportion discharged on reaching the minimum application voltage.

Storage self discharge

Equally, a certain self-discharge of the storage system is typical and should be catered for with storage capacity, h_{SD}. This rate can be modelled by a constant loss of charge with time. It is especially important for applications with occasional but large current demands or for applications that will receive reduced radiant energy for extended periods. Also, given that the self-discharge rate for many technologies is directly proportional to the storage capacity, it will become more of an issue as capacity is increased. The designer should therefore guard against excessive storage capacity as it is technically feasible that the self-discharge current can be greater than the average energy delivered from the photovoltaic module.

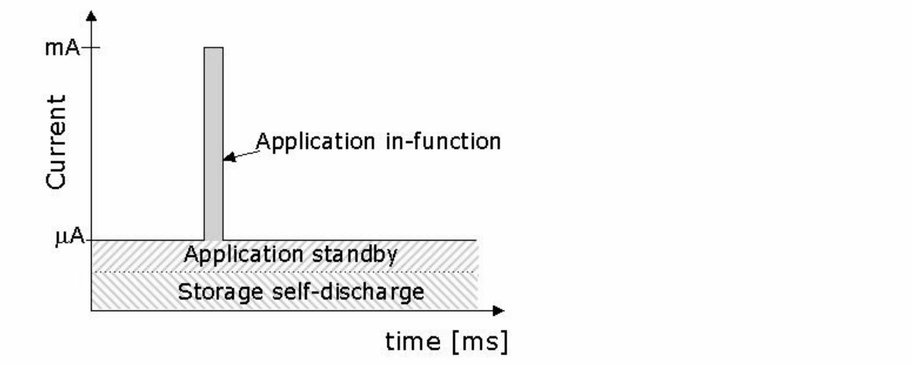


Figure 6.10: Global consumption of IPV system

Two of the above three parameters are schematised graphically in Figure 6.10. To summarise, all three (h_{SBY}, h_{MAV} and h_{SD}) losses may be considered deterministic and be modelled appropriately e.g. constant consumption with time. Assuming that these parameters have normal distributions, it can be expected that such values will suffice 50% of the time. In order to increase the confidence level, it is advisable to scale them up by a suitable heuristic constant. From manufacturing experience, a confidence level of 98% might be achieved with a safety factor of $(1+2\sigma)$ where σ is the standard deviation [Gra88].

The deterministic parameters can therefore be set aside until the total storage required is calculated in sub-section 6.5.3.

6.5.2 Non deterministic parameters

This leaves the fact that energy collected by the PV and the application "in-function" consumption of it, whilst usually exhibiting some periodicity, are not deterministic. Energy collected may be available by day and not by night for example, but to model using a diurnal cycle only is to ignore annual variation for example. Equally it may be assumed that the application will be "in-function" without a constant frequency and independently of the energy available at the time.

In order to specify the capacity required, more involved modelling is necessary. Four classes of modelling have been identified as analytical, electrical circuit, stochastic and electro-chemical in [Lah02]. The latter authors conclude that whilst electro-chemical models are desirable due to their increased accuracy, they tend to rely on proprietary data (which is rarely available to the designer) and be computationally intensive. More general models have the advantage of being applicable to a wider range of storage devices and be based on parameters set by the IPV system designer; for these reasons a general model is chosen here.

An IPV energy systems where the PV module (PV) and the IPV application (App) are connected by a charge storage device (St) is shown in Table 6.2, "Summary of IPV dipole compared with two storage models". Conceptually, this can be thought of as bath with a tap and a plug. When the tap (current from the PV) is opened the bath may fill; when the plug is lifted (or the application is used), the bath contents can flow out (the storage device "empties"). This analogy can be used to describe the functioning of water reservoirs [e.g. Kal77], production processes [e.g. Wij79], communication systems and electronic systems such as IPV.

Such analogies to storage systems all imply a flow, be it information, water, electricity or products. Such flows are made up of fundamental elements which, when in sufficient number, may be approximated by discretisation into packets for ease of modelling. An example of this might be the night and day cycle of energy available, see Figure 6.11. Equally, the application in-function mode may be likewise simplified for modelling purposes.

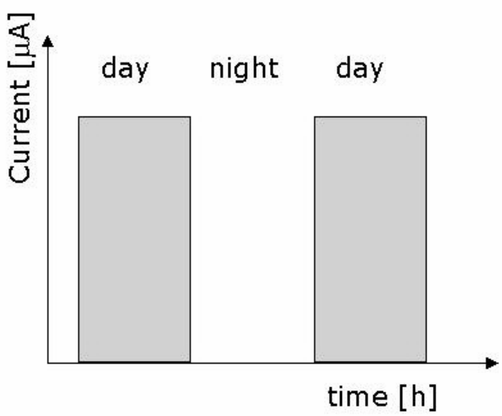


Figure 6.11: Example of discretisation of energy available

The discretisation allows the parameter to be considered as having binary mutually exclusive states and so a storage model from Queueing Theory may be applied, implying Markovian chain mathematics. An example of a well known queueing theory model is the simple single server queue referred to in the shorthand as the "M/G/1 queue", see Chapter 7 of [Nel95].

Another example from Queuing Theory based on [Dub81] is the manufacturing dipole consisting of two manufacturing processes (M_1 and M_2) separated by a buffer stock (B_{12}). It can be seen in Table 6.2, "Summary of IPV dipole compared with two storage models" that the radiant energy available (converted by the PV) may be represented as the throughput of a machine M_1, the IPV storage device may be thought of as buffer stock (B_{12}) and the application energy consumption may be considered to be a machine M_2 which consumes the "contents" of the buffer stock.

Table 6.2: Summary of IPV dipole compared with two storage models

Generic Terms	Input	Storage	Output
IPV Energy Key	Radiant Energy	Charge storage	Application consumption
IPV Energy Block Diagram	RE →	Sto →	Ap. Co.
Conceptual bath	"Tap"	Bath	"Plug hole"
Manufacturing Dipole Key	Machine 1	Buffer	Machine 2
Manufacturing Dipole Block Diagram	M_1 →	B_{12} →	M_2

The functioning of machine M_1 therefore represents the PV charging the storage (e.g. battery) and the functioning of M_2 represents the application in-function consuming the charge stored. Given this close comparability between these stochastic aspects of an IPV storage and this simple manufacturing system, and that the mathematical equations for the manufacturing dipole model exist [Hon00], the seven hypotheses (H1 to H7 respectively) on which the latter equations rest may be investigated in detail. Here we show that all of the latter may be respected by an IPV dipole and therefore the model may be applied.

H1 That the flow through the circuits in Table 6.2, "Summary of IPV dipole compared with two storage models" may be approximated by a hydrodynamic flow. This is better respected by an electronic circuit than a manufacturing process, as in electronics the fundamental unit is an electron, not for example a semi-assembled product. The number of fundamental units typically flowing through an electronic circuit is therefore significantly higher than a typical assembly process. This implies that either there is flow or there is not, which forms the basis of Markovian approximation. Further, by assuming a constant voltage throughout the dipole, current may be considered proportional to energy flow.

H2 That when B_{12} is empty and M_1 is not functioning, then M_2 is "starved". Likewise when B_{12} is full and M_2 is not functioning, then M_1 is "blocked". These two states are equivalent to zero flow at the corresponding machine-buffer interface. For the IPV system, the starved case represents the application failing due to lack of energy; the blocked case is analogous to energy being lost to overcharging the battery.

H3 That machine malfunctions are considered i.e. a blocked or starved machine cannot simultaneously malfunction. Whilst a manufacturing process may suffer a certain downtime due to malfunction, in IPV all components are expected to function throughout the life of the product. Therefore, whilst it is possible for the application or PV module to fail, irrespective of whether it is starved or blocked, designs considered will typically avoid blocked or starved states and the mean time between failures (MTBF) of the components is expected to be of the same order as the product life. Therefore any resulting reduction in the specified capacity of the storage will be insignificant.

H4 That the time for flow in the system is negligible; this is the case for IPV.

H5 That the in-function duration of machines M_1 and M_2 is random and exponentially distributed with parameters λ_1 and $\lambda_2=\alpha\lambda_1$. The probability density function is therefore $f_k(t)= \lambda_k \exp\{-\lambda_k t\}$ where $k=\{1,2\}$.

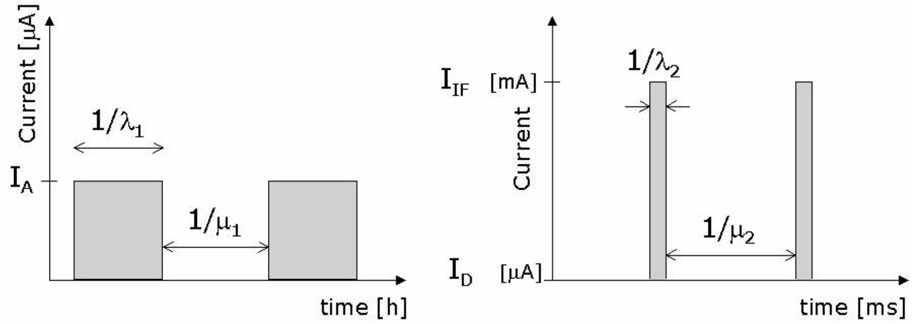


Figure 6.12: Energy delivered by photovoltaic and consumed by application where I_A is the average current available (equivalent to the M_1 nominal capacity), I_{IF} is in-function current and I_D is deterministic current consumption

Strictly speaking, a PV module "machine" is constantly in-function throughout its useful life. It is the radiant energy incident on the module which is the main factor in determining its output. For convenience, the approximation that the radiant energy intensity is constant for relatively long periods (e.g. $1/\lambda_1$ hours of the day) and otherwise zero (e.g. $1/\mu_1$ hours at night, explained further in H6) is permitted. The PV in-function state can therefore be modelled by a Markovian renewal process taking values $\{0, I_A\}$. The mean frequency of the in-function state is λ_1 (or the mean duration of one cycle is $1/\lambda_1$).

The application in-function mode can be modelled in the same way as for the PV in-function mode. The mean frequency of the in-function state is λ_2 (or the mean duration of one cycle is $1/\lambda_2$).

H6 That the non-functioning duration of machines M_1 and M_2 is random and exponentially distributed with parameters μ_1 and $\mu_2 = \beta\mu_1$ i.e. $f_k(t) = \mu_k \exp\{-\mu_k t\}$ where $k = \{1,2\}$. As in H5, these conditions are respected for IPV, with PV and application equivalent to M_1 and M_2 respectively (see Figure 6.12).

H7 That the average rate of production (U in parts/s) of both machines M_1 and M_2 (referred to as U_1 and U_2 respectively) is equal.

This hypothesis cannot be normally be assured for IPV, as the instantaneous current collected will generally be lower (e.g. µA) than the application in-function current (e.g. mA). To correct for this a normalisation may be applied as follows. Given that the non-availability, N, of a machine is the ratio between "mean time between two consecutive in-function phases" and the "mean time in function" this may be written:

$$N = \frac{\frac{1}{\mu}}{\frac{1}{\lambda}} = \frac{\lambda}{\mu} \qquad \text{Equation (6.3)}$$

then:

$$\frac{U_1}{1+N_1} = \frac{U_1}{1+\lambda_1/\mu_1} = \frac{U_2}{1+\tilde{\lambda}_1/\mu_1} = \frac{U_2}{1+\tilde{N}_1} \qquad \text{Equation (6.4)}$$

Therefore a machine M_1 defined by parameters $\{U_1, \lambda_1, \mu_1\}$ is transformed into an effective machine eM_1 with parameters $\{U_2, \tilde{\lambda}_1, \mu_1\}$. The two machines, M_1 and eM_1 have identical output but the instantaneous production of eM_1 is U_2.

If the above hypotheses are fulfilled, and as $N_2 = (\alpha/\beta)N_1$ the dipole non-availability N_{dip} with relation to the battery capacity, h, can be found using equation 6.5:

$$N_{dip}(h) = N_1 \left\{ \frac{\left(\frac{\alpha}{\beta}\right)^2 \bullet e^{\Gamma h} - 1}{\left(\frac{\alpha}{\beta}\right) \bullet e^{\Gamma h} - 1} \right\}$$ Equation (6.5)

where the non availability of M_1 and M_2 (referred to as N_1 and N_2 respectively) is not equal, α is not equal to β and where:

$$\Gamma = \frac{\alpha - \beta}{U} \left\{ \frac{\mu_1}{1 + \alpha} + \frac{\lambda_1}{1 + \beta} \right\}$$ Equation (6.6)

Whilst the non-availability is a useful concept, it cannot be applied directly to aid the designer determine the storage capacity required. The latter is usually based on the proportion of application requirements which should be satisfied, or in networking vocabulary, the quality of service. The latter is the ratio of "proportion of time the dipole runs" to "the proportion of time the application is in-function:

$$P_{DS} = \frac{P_2}{P_{dip}}$$ Equation (6.7)

where:

P_{DS} = probability that application demand will be satisfied

P_{dip} = proportion of time the dipole runs

P_2 = proportion of time the application is in-function

From Figure 6.12, the proportion of time that a machine is in-function, P [%] for the case where λ and μ are constant (reasonable for certain IPV dipoles) may be found as follows:

$$P = \frac{\frac{1}{\lambda}}{\frac{1}{\mu} + \frac{1}{\lambda}} = \frac{1}{\frac{\lambda}{\mu} + 1}$$ Equation (6.8)

Substituting equation 6.3 into equation 6.8 gives:

$$P = \frac{1}{N + 1}$$ Equation (6.9)

And therefore equation 6.7 becomes:

$$P_{DS} = \frac{N_{dip} + 1}{N_2 + 1}$$ Equation (6.10)

Or with respect to the storage capacity, h, by substituting equation 6.5 into equation 6.10:

$$P_{DS} = \frac{N_1\left\{\dfrac{\left(\dfrac{\alpha}{\beta}\right)^2 \bullet e^{\Gamma h} - 1}{\left(\dfrac{\alpha}{\beta}\right) \bullet e^{\Gamma h} - 1}\right\} + 1}{\dfrac{\alpha}{\beta}N_1\left\{\dfrac{\left(\dfrac{\alpha}{\beta}\right)^2 \bullet e^{\Gamma h} - 1}{\left(\dfrac{\alpha}{\beta}\right) \bullet e^{\Gamma h} - 1}\right\} + 1}$$ Equation (6.11)

As storage capacity, h tends to infinity (and is full), the probability that the demand will be satisfied, P_{DS}, tends to one, indicating that in IPV terms, the application will never be starved. This can be visualised in Figure 6.13 which shows equation 6.11 with some example values. In practice the designer will avoid excessive storage capacity as mentioned in sub-section 6.5.1.

In practice the designer cannot specify an infinite storage capacity, but will chose a suitable value, h_{IF} based on the trade-off between the probability that demand will be satisfied and storage capacity. In the example in Figure 6.13, it can be seen that a 97% probability corresponds to a storage capacity for the in-function demand of 200mAh.

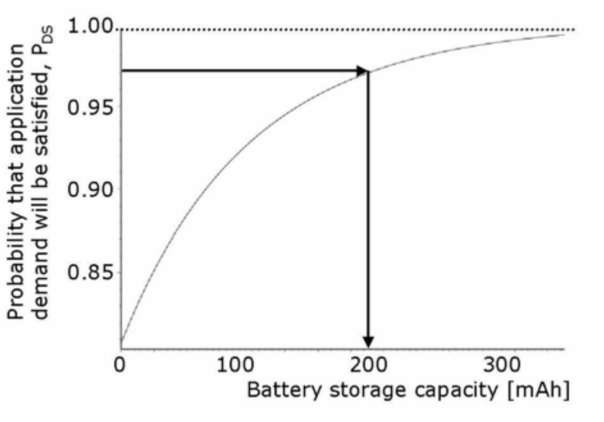


Figure 6.13: Example for dipole model in equation 6.11

A minor issue is that the model is not applicable for very small values of storage, as can be seen by the intercept on the P_{DS} axis. This is acceptable as such low capacity is unlikely in practice.

This model shows that the designer may make good use of meaningful frequency distributions as also noted by [Bop97].

6.5.3 Heuristic of total storage capacity

The total capacity given by the model can now be found by summing the energy collected/in-function capacity (covered in sub-section 6.5.2) with the function independent factors mentioned in sub-section 6.5.1. For a simple example based on the above mentioned factors, total theoretical capacity is therefore:

$$h_{TTC} = h_{IF} + h_{SBY} + h_{SD} + h_{MAV} \qquad \text{Equation (6.12)}$$

where:
h_{TTC} = Total theoretical storage capacity
h_{IF} = In-function storage capacity
h_{SBY} = Standby consumption storage capacity
h_{SD} = Storage self-discharge capacity required
h_{MAV} = Extra storage due to the minimum application voltage

In practice, the designer makes such a calculation before choosing an available product, as he/she must also take other factors into account (e.g. cost).

Based on the actual storage capacity, the system autonomy can be calculated [days]; it is the ratio of storage capacity to the average daily load. This is useful to the IPV designer with respect to periods of reduced charging due to "bad weather or failure in the system" [Spi94].

Differences with reality

It is of note that this model is a Markovian approximation and that other distributions may match real data more closely but are likely to yield more complex mathematics.

Another issue not treated by this model is the characteristic of electrochemical storage to require relatively tight voltage tolerances for charging e.g. accumulators [SAN99] and DLCs. It may be that some of the energy delivered by the photovoltaic device will be lost due to out of limit voltage. This will depend on the system design and the range of incident radiant energy intensity.

6.6 Electrochemical Storage Technologies

Whilst the storage function has been investigated above, it remains to consider the various technologies which may satisfy these needs. In this section, two classes of electrochemical storage technology are considered: DLCs and secondary batteries. The way these work can be found in sub-section 6.3.4. Here the individual chemistries and associated properties are described.

6.6.1 Double-layer capacitors (DLCs)

Capacitor technologies have seen three technological phases. In the first, symmetric (identical) carbon electrodes separated by an aqueous electrolyte were used (late 1970s). Secondly, non-aqueous electrolyte was used instead which increased the cell voltage (1980s). In the third phase, asymmetric electrodes (e.g. one of carbon and one of nickel oxyhydride) with an aqueous electrolyte (e.g. potassium hydroxide) have been applied [ESM02].

DLCs combined with certain batteries of low current range, such as those with low self discharge current, offer the benefit of reducing the response time of the resulting hybrid system.

6.6.2 Secondary batteries (accumulators)

Although many chemical pairs are suitable for electrochemical secondary storage, in IPV low power electronics three groups of technologies are most common: these are based on Nickel (with Cadmium or a metal-hydride), Lithium (Ion or Polymer) and reusable Alkaline (Manganese). Some of their half reactions are shown in Figure 6.3. The theoretical voltage of a cell is the difference between the potential for the anode and the cathode.

Table 6.3: Some IPV storage device anode and cathode half reactions

Name	Cell type	Electrode	Anode (-) / Cathode (+) Half-Reactions
Lith/Mang	Primary	Anode	$Li(s) \rightarrow Li^+(aq)+e^-$
Lith/Mang	Primary	Cathode	$MnO_2(s)+2H_2O(l)+e^- \rightarrow Mn(OH)^3(s)+OH^-(aq)$
Zn/Mn (Alkaline)	Primary	Anode	$Zn(s) + 2OH^-(aq) \rightarrow ZnO(s) + H_2O(l) + 2e^-$
Zn/Mn (Alkaline)	Primary	Cathode	$MnO_2(s) + H_2O(l) + e^- \rightarrow MnO(OH)(s) + OH^-(aq)$
Lead/Acid	Secondary	Anode	$Pb(s)+HSO_4^-(aq) \rightarrow PbSO_4(s)+H^+(aq)+2e^-$
Lead/Acid	Secondary	Cathode	$PbO_2(s)+3H^+(aq)+HSO_4^-(aq)+2e^- \rightarrow PbSO_4(s)+2H_2O(l)$
Nickel/Cad.	Secondary	Anode	$Cd(s)+2OH^-(aq) \rightarrow Cd(OH)_2(s)+2e^-$
Nickel/Cad.	Secondary	Cathode	$NiO(OH)(s)+H_2O(l)+e^- \rightarrow Ni(OH)_2(s)+OH^-(aq)$

Lithium sets itself apart by having a low relative atomic mass. It in fact has the lowest equivalent weight of any practical negative electrode [Mun00]. Similarly, the high atomic mass of Lead, and to a lesser extent Cadmium may be a disadvantage. But the usability of a storage device is not based on mass alone. With respect to the standard electric potential, Lithium is again notable having a high reduction potential [Ram99] (synonymous with being a strong reducing agent). The materials for typical IPV electrochemical batteries are shown in Table 6.4, "Secondary electrochemical battery materials":

Table 6.4: Secondary electrochemical battery materials

Name	Anode	Cathode	Electrolyte	Container
Lithium-polymer	Lithium (Li)	composite	solid polymer	Steel
Lithium-Ion	Lithiated carbon	LiX intercalation compound	non-aq., salt in organic solv.	Steel
Nickel Metal Hydride	Metal hydride alloy	Nickel (Ni)	Potassium Hydroxide (KOH)	Stainless Steel
Nickel Cadmium	Cadmium (Cd)	Nickel oxide	Potassium Hydroxide (KOH)	Ni-plated steel
Lead Acid	Lead (Pb)	Lead Dioxide	Sulphuric Acid	Plastic or metal

In general, the above details are not considered in the choice of technology, but rather the factors mentioned in Table 6.1, "Four inter-related storage technology comparison factors". Their values for the technologies of interest are shown in Table 6.5, "Comparison of secondary electrochemical storage technologies" ([Lah02], [Lan98], [Hoc00], [Ber02], [Hal98] and [NEC02]), although this serves only as a guide because the data has been compiled from a number of authors. To deal with differences between sources due to the diverging interests of these authors, a range rather than a specific value has been indicated. Wherever possible data applicable to consumer electronics is used.

Table 6.5: Comparison of secondary electrochemical storage technologies

Cell type	Name	Rated voltage [V]	Energy density [Wh/l]	Power density [W/l]	Specific Energy [Wh/kg]	Specific power [W/kg]	Self discharge [%/month]	Cycle Life [no. cyc.]
Electrochem. Second. Batt.	Lithium-polymer	3.0	150-385	>350	100-200	>200	1-2	200-1000
Electrochem. Second. Batt.	Lithium-Ion	3.6	165-300	400-500	60-127	200-250	5-10	500-1200
Electrochem. Second. Batt.	Reusable Alkaline Mang.	1.5			77-290		2	25
Electrochem. Second. Batt.	Nickel Metal Hydride	1.2	175-260	475	30-90	130	20-30	300-600
Electrochem. Second. Batt.	Nickel Cadmium	1.2	60-200	220-360	23-60	140-220	10-25	300-2000
Electrochem. Second. Batt.	Lead Acid	2.0	70-85	~400	25-35	~200	4-10	200-300
for comparison:								
Electrochem - Secondary	Supercapacitor	2.5	5	300	5	1800	20-200	>50000
Mechanical - Secondary	Flywheel		370		185			>10000
Electrochem - Primary	Alkaline	1.5	375	35	150	14	0.3	1
Electrochem - "Primary"	Zinc-Air	1.2	204	190	146-175	150	~5	~200
Electrochem - "Primary"	Fuel cell (DMFC)				300-767		0	

Technology choice cannot be made without reference to the application. In abstracto, however, the importance of the characteristics described in Table 6.5, "Comparison of secondary electrochemical storage technologies" can be discussed. For all IPV applications, the storage self-discharge is often of principal concern, see sub-section 6.5.1. The Nickel based batteries show the worst properties in this respect, and therefore cannot be recommended except for applications which have regular radiant energy or an alternative energy source (e.g. mains transformer).

Useful life The number of cycles may also be of importance. The figures shown in Table 6.5, "Comparison of secondary electrochemical storage technologies" are typically for an 80% depth of discharge (DoD), which for IPV applications is deeper than expected (see Figure 6.6). Therefore further tests are required to indicate what the DoD would be for the shallower but more frequent discharges typical of IPV. Nevertheless, the relative characteristics of the technologies can be expected to be maintained even in lower depth of discharge, and therefore care should be taken when using reusable alkaline manganese as, of the batteries considered here, these have the lowest cycle life.

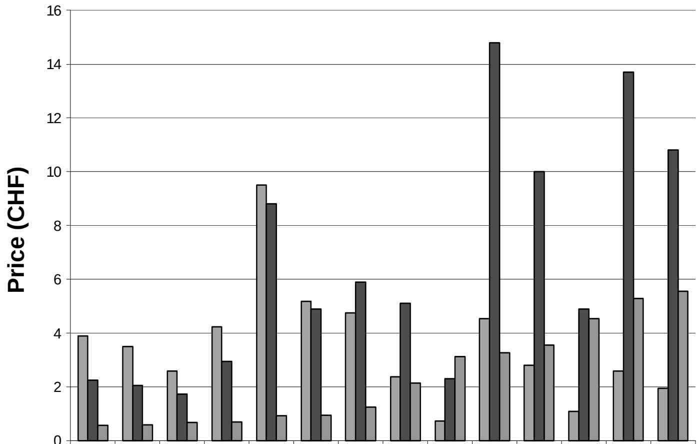
Weight For IPV building sensors in particular, which are usually wall mounted, it can be assumed that one may compromise on weight (i.e. specific power and energy). This is fortunate as some believe that with Li-Ion, the technical limits of specific energy are close to being reached [Blo02].

Volume Volume [l] is often more of an issue for IPV, although it is to be expected that a secondary storage volume will not be greater than the space required by primary batteries. As can be seen in Table 6.5, "Comparison of secondary electrochemical storage technologies", lead acid which is associated with automotive applications but is also available in suitable sizes for IPV applications suffers relatively low specific energy. On the other hand, overall the Lithium technologies have good characteristics.

Hybrid solutions Batteries are associated with relatively slow discharge (hours or more) with relatively constant voltage and current. Capacitors typically are used for a rapid discharge (e.g. minutes or less) but with higher power. Some storage system requirements may only be satisfied by a combination of both of these characteristics e.g. at least one battery and one capacitor. This is called hybrid storage.

Another conceivable hybrid solution is that of primary and secondary storage technologies being combined. Given that such an approach is exceptional, this section has dealt mostly with secondary storage technologies available to the IPV system designer.

Cost Last but by no means least, one must consider the cost of the storage. As can be seen in Figure 6.14, price per kJ capacity (and by corollary cost) can be seen to vary over an order of magnitude. This can be explained by the various sizes of batteries compared as well as the other functionality such as the parameters mentioned above that they may offer.



	NiCd AA	NiCd 3.6V	NiCd AA	NiMH AA	NiMH A	NiMH AA	NiCd A	NiMH AAA	NiCd bouton	NiCd 9V	NiMH Th650	NiCd AAA	NiMH 4.8V	NiMH 3.6V
Capacity [kJ]	3.89	3.50	2.59	4.23	9.50	5.18	4.75	2.38	0.73	4.54	2.81	1.08	2.59	1.94
Price [CHF]	2.24	2.05	1.73	2.95	8.8	4.9	5.9	5.1	2.3	14.8	10	4.9	13.7	10.8
Price per kJ [CHF/kJ]	0.576	0.586	0.667	0.697	0.926	0.945	1.242	2.146	3.132	3.263	3.561	4.537	5.285	5.556

Sorted by price per kJ

Figure 6.14: Price capacity comparison for Nickel based batteries [MiL01]

In a similar way to the data in Table 6.5, “Comparison of secondary electrochemical storage technologies”, the values in Figure 6.14 are worth less if the context is not mentioned. In this case, the data was collected for a report on the design of a solar (PV) powered LED hand torch, and is therefore relatively applicable to the IPV designer.

6.7 Conclusion

The importance of the storage function in ambient energy systems has been seen in this chapter at the economic level (e.g. cost of component in Figure 6.14), the technical level (e.g. balancing stochastic inputs and outputs in section 6.5) as well as the environmental level (see sub-section 6.2.3). Advantages of ambient energy systems have been shown at the economic and environmental levels. Further advantages of ambient energy devices may relate to greater safety and robustness. Safety is improved with less charge storage capacity as the risk of fire from accidental short circuit is reduced. Greater robustness can be expected in that if the product is left on by accident, so long as the product is not needed immediately, it will “recover” without further intervention.

Assuming that sufficient radiant energy is available for an IPV application, in the majority of cases correct functionality will depend on charge storage. The latter balances the availability of energy from the ambient radiant energy and the demand of energy from the application. A model has been developed in section 6.5 which determines the relationship between the storage capacity and the confidence level that the application will have sufficient energy to function. This treats the deterministic factors (sub-section 6.5.1) and the non-deterministic factors (sub-section 6.5.2) seperately; these factors are combined in sub-section 6.5.3. The non-deterministic factors are modelled using Queuing Theory (Markovian chain).

This model will typically be complemented in practice by many more parameters such as those in section 6.2 and section 6.4. The number of these parameters alone indicates the complexity of the charge storage problem and its importance to the IPV designer. The most important of these parameters is likely to be component cost.

Having calculated the storage required, the IPV designer must also find suitable components. These are treated globally in section 6.3 and with regard to typical components used today in section 6.6.

6.8 Future Work

The model presented in section 6.5 could be improved in a number of ways, some of which have already been mentioned. One approach, by which the model would be brought closer to the designer selection, would be to combine it with cost functions for the various IPV system components in order to optimise the surface of PV material and storage capacity with respect to cost and, by corollary, quality of service.

Ideally one would avoid batteries altogether, and some believe this may be possible in the future, especially for the low power range electronic applications such as IPV systems [Peg02]. However whilst reduced storage capacity for autonomous devices is an elegant concept, applications are rarely suitable from the outset today.

6.9 Further reading

More information about electrochemical technologies can be found on Nickel Cadmium batteries in [Lan98], Lithium batteries [Vi299]; rechargeable batteries are covered in [Hal98].

Chapter 7 : Ambient Energy Power Source Design

Hell, there are no rules here - we're trying to accomplish something.
Thomas Alva Edison

7.1 Introduction

7.1.1 Chapter goals

Whilst the design process by which any two products are developed will rarely be exactly the same, the designs of a product type generally do have commonality. For this reason and due to the prodigious general product design literature, this chapter is not an exhaustive methodology for all ambient energy power source design but rather a product specific complement to it. This takes the form of guidelines and where appropriate, heuristics; these are based on practical experience gleaned from experiments, research, and working with a number of companies on a variety of products.

As with the rest of the thesis, the main focus is indoor photovoltaic (IPV) products. However, the approach may be generalised to other ambient energy sources.

For brevity, cross references are made to the rest of the thesis as some of the principles are presented elsewhere. It is the authors intention that this chapter may serve the practitioner as a key to the rest of the work.

7.1.2 Chapter structure

Design guidelines can be categorised in a number of ways including by design process phase, design phase outcome, actor concerned, selection level or chronology. The first four of these are compared in Table 7.1 which indicates that these categorisations may be relatively equivalent. Given the general recognition [Pah01] [Fre98] [Gre01] of the *design process* phase categorisation, it is used in this case. The up and down arrows in the left hand column of Table 7.1 indicate that the phases are interdependent e.g. a result in one phase may alter the conclusion drawn in a previous phase.

Table 7.1: Design process after [Pah01]

Design process phase	Typical end of phase "go/no-go" conditions	Phase outcome	Actor(s) concerned	Selection level
Planning and clarification	Is energy equality (equation 7.3) satisfied?	Design Specification	Marketing Architect Designer	"Ball park"
Conceptual design	Have the options for maximising available energy and minimising application consumption been exhausted?	Concept	Designer	Application
Embodiment	Does customer find product visually attractive? Can producer make product?	Preliminary layout	Designer Producer	Component
Detailed design	Are user instructions well adapted?	Definitive Layout	Installer Customer	Final product

The *design process* phases cannot be defined exhaustively, as previously mentioned in section 2.2. They indicate different types of activity which are ideally consecutive and punctuated with evaluation against criteria (e.g. technical and economic criteria).

During the *clarification* of design (see section 7.2), product requirements are specified based largely on existing information. Companies may consider both internal aspects as well as the external (contextual) aspects such as market and legal factors. *Conceptual design* (see section 7.3) extracts from the resulting design specification those essential functions and problems on which the product specification of principle (or concept in “Table 7.1”) may be based. The *embodiment* phase (see section 7.4) is associated with first concretisation of this concept and may result in one or more functional prototypes. In *detailed design* (see section 7.5) the final product properties are specified for production. This typically includes material and dimensional specifications, documentation and cost estimates. Each of these phases is treated in this chapter and reviewed for two representative cases in section 7.6.

7.1.3 Guideline caveats

Design decisions are often associated with the optimisation of numerous variables. This is no less the case with these guidelines which may be partially contradictory. It is therefore in the hands of the product designer to apply them appropriately.

The design phases in Table 7.1 read from top to bottom are increasingly product specific. The guidelines below therefore aim to respect this categorisation. However, the author’s choice of design phase in which each guideline is found should not be considered prescriptive; the practitioner should use each guideline when it is deemed necessary.

7.2 Clarification

Clarification is the first phase of the design process (see Table 7.1) and considers the “ball-park” figures. The designer will want to ensure technical feasibility. To allow an application to function at all times, the electrical energy available to it and (optional) charge storage (E_A) must always exceed the energy it consumes (E_C). This may be summarised:

$$E_A \geq E_C \qquad \text{Equation (7.1)}$$

Both sides of this fundamental equation are covered in sub-section 7.2.1 and sub-section 7.2.2 respectively. Those legal considerations that are necessary at the start of an IPV design project are then covered in sub-section 7.2.3.

7.2.1 Realistic functions

For electronic functionality, a finite average power level will be consumed over a period of time. The product of these two variables determines the energy consumed (E_C). E_C is generally calculated with respect to both in-function power and standby power:

$$E_C = \left(\int_0^{t_{IF}} (P_{IF} \cdot dt_{IF}) + \int_0^{t_{SBY}} (P_{SBY} \cdot dt_{SBY}) \right) \qquad \text{Equation (7.2)}$$

where:

P_{IF} = power in-function [W]
t_{IF} = time in-function [t]
P_{SBY} = power on standby [W]
t_{SBY} = time on standby [t]

Therefore, the fundamental energy inequality (equation 7.1) may be re-written:

$$E_A \geq \left(\int_0^{t_{IF}} (P_{IF} \cdot dt_{IF}) + \int_0^{t_{SBY}} (P_{SBY} \cdot dt_{SBY}) \right) \qquad \text{Equation (7.3)}$$

Two categories of IPV products may thus be identified:

a) low storage capacity: those products that consume the majority of the energy available in-function. Therefore, to allow the fundamental energy inequality to be true, the in-function *power* must be less than or equal to the power converted from the radiant flux and available to the application (P_A). In IPV, this is commonly of the order of µW. Examples of products which function at such power levels are some electronic wrist watches and solar calculators. For an explanation of the radiant flux, see sub-section 3.2.1.

$$P_A \geq P_{IF} \qquad \text{Equation (7.4)}$$

b) high storage capacity: those products that consume the majority of the energy available in standby. Typically, such products consume intermittent "peaks" of energy when in-function at power ratings in excess of what the instantaneous radiant energy can deliver. In order for equation 7.3 to be true therefore, the ratio of in-function time to standby time will be suitably low. A heuristic for wireless communication products is a ratio of time in-function to time on standby of 1:300 or less. Furthermore, the average standby power must be lower than the average radiant energy available, i.e.:

$$E_A \geq \int_0^{t_{SBY}} (P_{SBY} \cdot dt_{SBY}) \qquad \text{Equation (7.5)}$$

Given that most applications that the IPV designer will consider are in category b), a general guideline is "at first, be less concerned with the product function than seeking products which need only function intermittently" such as Figure 7.1. For such products, which spend the majority of time on standby, the designer should then ensure that the standby consumption is suitably low, or can be reduced to respect equation 7.5. To enable the designer to recognise suitable applications for IPV, typical values for the parameters of equation 7.3 are as shown in Table 7.2.

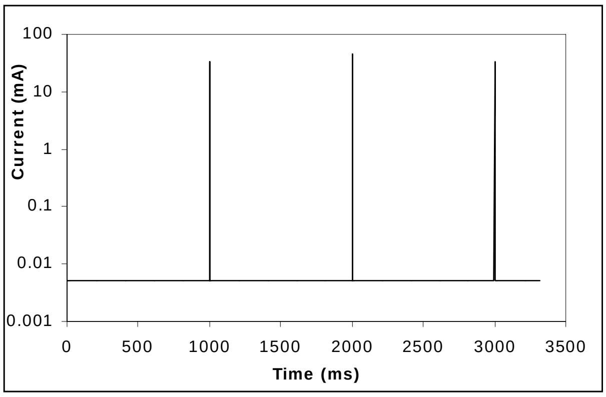


Figure 7.1: Typical charge consumption of datalogging or sensor device

Table 7.2: Parameter values for equation 7.3

Application description	Typical function	P_{sby} [μW]	P_{if} [mW]	t_{sby} [mins/day]	t_{if} [mins/day]	t_{sby}/t_{if}	Mean energy/day [mWh/d]	Mean En./month [mWh/mon.]
Fluorescent Source	Display	< 3	< 60	> 1439	< 1	> 1440	< 0.3	< 10
Daylight Source	Wireless	< 90	< 600	> 1435	< 5	> 300	< 3	< 100

Appropriate functions for IPV have been identified in sub-section 1.4.2. With regard to the (wireless) communication function, it is of note that mobile phones, whose in-function power range (0.5-2W) is acceptable for IPV, typically suffer too high a standby power (5-20mW). For short range devices (SRD) whose range is hundreds of meters or less, the values of in-function and standby power can be expected to be less and are therefore better adapted to IPV.

Examples of present day IPV products are shown in Figure 4.8. Within these examples are products that have relatively high in-function power (0.1-0.5W) such as the solar stapler (mechanical) and the Lily in the water (light) shown in Figure 7.2. These support the case that such high power functions may be achieved; naturally, standby energy consumption is kept to a minimum (a few μA). In the case of the stapler this is achieved by using a mechanical switch, triggered only when pages are to be stapled (see Figure 7.3). Despite this, the batteries will dissipate energy in self-discharge.

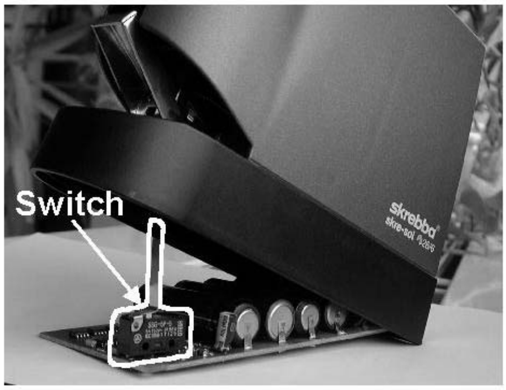


Figure 7.2: (left) Relatively high (in-function) power IPV products
Figure 7.3: (right) Mechanical switch on solar stapler

7.2.2 Realistic Use pattern

The fundamental energy equation (equation 7.1) cannot be satisfied unless sufficient radiant flux is collected. Whilst radiant energy in the built environment is characterised in Chapter 3, the designer should also consider how the product will be used. A typical question is "will the product be fixed or mobile?" The answer to this question will affect how deterministically it is possible to specify the radiant energy resource. This is important to the designer in that the more tightly the energy system tolerances may be set, the more precisely (and typically cost effectively) the product may be designed.

The energy available to fixed products is generally easier to specify than that available to mobile ones. Two examples of "fixed" product are the higher power products (stapler and Lily in Figure 7.2) which are not intended to be moved over more than 1m or so during use. Furthermore, such products may be assumed to be in areas of human activity where minimum incident radiant energy can be expected for hours at a time. Cases where this is more difficult are personal mobile products - e.g. watches [Cal78], phones, digital assistants and cameras, electronic keys - as in each case their outer surface is likely to be shielded from the available radiant energy e.g. up a sleeve, in a draw, pocket or holster. Futhermore, their economic value makes it unlikely that users will be prepared to leave them uncovered (let alone unattended) for hours at a time to collect radiant energy.

Further heuristics based on optimising radiant energy are as follows:

a) Seek products which will be positioned within 1m of an unobstructed window (ideally where the module can be oriented towards the window) see sub-section 3.4.3. In such a case, the PV will output around 50mWh/cm^2/month.

b) seek product locations in areas of frequent (daily) human activity, see sub-section 3.4.5; these are associated with PV output of 1.5 mWh/cm^2/month.

c) seek product locations with constant (24 hours/day) lighting (e.g. public multi-storey car parks). Whilst the radiant energy is of lower intensity than in the home or the office, as it is available all day, the PV will output around 2 mWh/cm^2/month.

d) seek to wall mount product; in any location, wall mounted products have the advantage that once installed, they require no user intervention. A well positioned PV cell can deliver 1 mWh/cm^2/month.

It is also possible to satisfy equation 7.1 by using charge storage. The use pattern will influence the charge storage capacity required.

7.2.3 Prior Art

Given that a number of PV technologies exist, the protection of one in particular has the disadvantage that it encourages the product designer to transfer to a competing technology, be it PV or otherwise. Furthermore, patents relating to the majority of established PV technologies can be expected to have been filed over twenty years ago, and will have therefore expired [TRI94]. This may not be the case for the intellectual property rights protecting specific IPV applications; these should always be checked, (see section 1.5).

7.3 Conceptual Design

Conceptual design is the second phase of the design process in Table 7.1, during which a product concept will be developed based on the required product functions. Considerations of importance during this phase are how to ensure the concepts are as energy efficient at all levels of application design. This may be at the level of the electronic device (sub-section 7.3.1), how the available energy may be maximised (sub-section 7.3.2) or optimised (sub-section 7.3.3), and how to optimise likely components (sub-section 7.3.4 and sub-section 7.3.5).

7.3.1 Energy efficient design and responsiveness

Low-power devices designers must often resolve one or more "standby dilemma". Whilst it is simpler from the functionality point of view to have a product in-function constantly, this will tend to drain the energy resources rapidly, in particular with batteries. A compromise is to put the product on standby (or quiescent mode). This reduces energy consumption, but comes at the "price" of reduced responsiveness. To power up a mobile phone, such a delay may be acceptable; however, it is unlikely to conform to the specifications required for security or safety critical systems. The "price paid" is therefore the loss to the supplier of a potential market.

The cost of not implementing multiple power modes can be seen in the example of the mains to DC transformer. The latter is used to provide energy to a host of consumer electronic products. As mentioned in sub-section 2.4.5, a significant amount of electricity is consumed in Europe by products that the user has ostensibly turned off [Mag02]. Taking the example of Germany, a study commissioned by the German Federal Environmental Agency and the Federal Ministry for the Environment reported in 1997 that "At least 11% of the electricity consumed in German households and offices is used by temporarily unused equipment running in stand-by mode" [Ger02]. They calculated that this amounted to 20.5TWh/annum which will have cost German users a total of 4×10^9CHF/an. One technical solution is to use burst-mode transformers. This shows the significant power consumption impact that low power device can have.

A good example of how to reduce consumption, which may be of service to the IPV designer, is to use multiple power modes such as with the ARM microprocessor [ARM03] shown in Figure 7.4. Both RUN and IDLE are two modes of in-function; SLEEP is otherwise referred to herein as standby (see bracketed words in Figure 7.4).

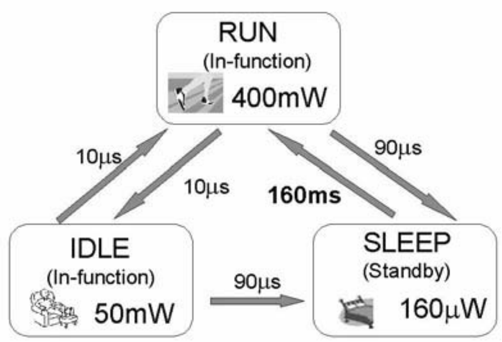


Figure 7.4: StrongARM [ARM03] SA1100 Microprocessor power-saving states. The designer can see from the standby current that this processor is not well suited to IPV

For the microprocessor (Figure 7.4), the approach taken implies a penalty for using the standby mode: the 160ms it takes to return to the in-function state is a time long enough in its own right to be noticeable to the user. In general, "waking" a microprocessor may coincide with a higher demand of current than average in-function consumption. Assuming that the energy saved by switching the chip on and then off standby exceeds leaving it in-function, the designer must decide whether the resulting reduction in "quality of service" is acceptable.

The power values in Figure 7.4 can be improved upon today with standby modes some three factors lower (100nW) than the SA1100 now available [Mic03]. Such low standby currents are achieved using multiple modes and are indicative of the trend towards consumption which coincides with what AES can deliver.

An aspect of energy efficient design related to wireless systems that the designer may consider at the conceptual design phase is where to position the processing ("intelligence"). This may be at the sensor and/or at the motherstation (central control unit). Assuming that the energy limitation is with the (distributed) sensors and not the motherstation, and that wireless communication is both required and is the most energy intensive activity, the designer will tend to decentralise some processing. An example of this for an indoor temperature control system is providing the distributed sensors with typical profiles for what the temperature should be in each location. Sensor communications then become only necessary for correcting those divergences which require action on the part of the motherstation to adjust the temperature). This can contribute to reducing the sensor energy requirements.

Such dilemmas, including the standby dilemma, are found not only at the system level as in the above examples, but at all levels of microprocessor design. The issue of hardware/software partitioning is conceptually reminiscent of the centralisation/distribution of processing in the above example. Essentially it may be more energy efficient to set some processes in hardware, potentially at the cost of reduced flexibility of the overall design, than rely entirely on the processor for all computations.

Further microprocessor level energy efficiency techniques can be categorised as hardware or software. An example with regard to hardware from which a number of energy saving techniques may be inferred is the power consumption of a CMOS gate:

$$P_T = P_{SW} + P_{SC} + P_{SBY} \qquad \text{Equation (7.6)}$$

where:
P_T = Total power [W]
P_{SW} = Switching power [W]
P_{SC} = Short circuit power [W]
P_{SBY} = Standby (or leakage) power [W]

Switching power has generally attracted the most attention in processor design and can be modelled for an individual CMOS gate as follows:

$$P_{SW} = 0.5(V_S^2 \cdot f_{CK} \cdot C_L \cdot E_{SW}) \qquad \text{Equation (7.7)}$$

where
V_S = Supply voltage [V]
f_{CK} = Clock frequency [Hz]
C_L = Output load capacitance [F]
E_{SW} = Switching activity factor [probability of switching]

From equation 7.7, power can be reduced most effectively by a reduction in voltage. This is apparent in the drop from 5V to around 1V in gate voltage that has come with the advent of process geometries below 0.5µm [EMa02]. However, as the switching power of general use microprocessors has decreased, the leakage power (P_{SBY}) has become increasingly important.

The other factors in equation 7.7 that can also contribute to reducing hardware energy consumption; techniques includes voltage scaling, reducing load capacitance and reducing switching activity [Ben02].

It is also possible to improve energy efficiency at the software level. A compelling approach is energy-aware compilation, in which the programmed code is analysed for the energy it demands. This allows specific lines or sub-routines to be modified to reduce overall consumption. Further software techniques to reduce energy consumption may be related to the choice of algorithm (e.g. MPEG-2), code compression, and operating system support [Mar02].

Overall, the designer should be aware that a wide range and significant number of techniques and methodologies exist for minimising the energy consumed by microprocessor technology. Literature in this area may (unscientifically) by entitled "Low Power" rather than "Low Energy".

The circuit of the energy system

Another important aspect of energy efficient design is selecting the appropriate IPV energy system circuit. Therefore the basic circuits mentioned in sub-section 1.4.2 are further analysed here to support the designer in circuit selection and specification. These are based on typical designs for the following functions "respond to light", "sense and display", "light, move, compute or amplify" and "communicate (wirelessly)" and are shown in Figure 7.5 to Figure 7.8 respectively.

The variables are as follows:

$PV_{1,\ 2,\ 3\ \text{or}\ 4}$ is the photovoltaic module, characterised in section 4.4 and a model of which is shown in Figure 4.21

$i_{1,\ 2,\ 3\ \text{or}\ 4}$ is the current at that point in the circuit

$R_{A1,\ A2,\ A3\ \text{or}\ A4}$ is the resistance of an application

R_{B4} is a battery internal resistance

$C_{2\ \text{or}\ 4}$ is a capacitance

$i_{R1,\ R2,\ R3\ \text{or}\ R4}$ is the current passing through a resistance

$i_{C2\ \text{or}\ C4}$ is the current passing through a capacitance

$i_{B3\ \text{or}\ B4}$ is the current passing through a battery

$i_{Z3\ \text{or}\ Z4}$ is the current passing through a Zener diode

$u_{1,\ 2,\ 3\ \text{or}\ 4}$ is the voltage across a resistance

u_{B4} is the voltage across a battery

u_{Z3} is the reverse breakdown voltage across an ideal Zener diode

From Kirchoff's first law, which states that all current flowing into a node is equal to all current flowing out of the node, the following relationships may be deduced.

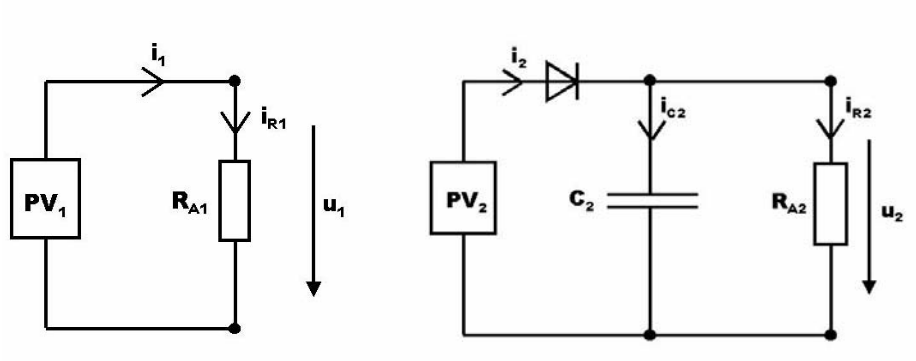


Figure 7.5: (left) Equivalent circuit diagram for Figure 1.2 (respond to light function)

Figure 7.6: (right) Equivalent circuit diagram for Figure 1.3 (sense and display function)

The general equation for Figure 7.5 is

$$i_1 = i_{R1} \qquad \text{Equation (7.8)}$$

and

$$i_{R1} = \frac{u_1}{R_{A1}} \qquad \text{Equation (7.9)}$$

For Figure 7.6

$$i_2 = i_{C2} + i_{R2} \qquad \text{Equation (7.10)}$$

and given

$$i_{C2} = C_2\frac{du_2}{dt} \qquad \text{Equation (7.11)}$$

and

$$i_{R2} = \frac{u_2}{R_{A2}} \qquad \text{Equation (7.12)}$$

therefore

$$i_2 = C_2\frac{du_2}{dt} + \frac{u_2}{R_{A2}} \qquad \text{Equation (7.13)}$$

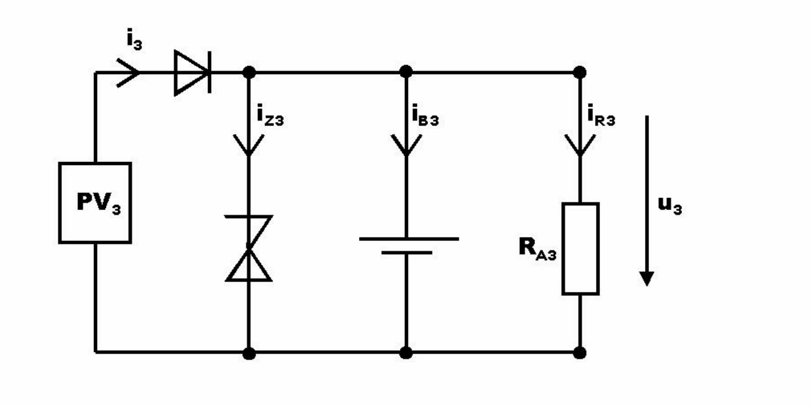


Figure 7.7: Equivalent circuit diagram for Figure 1.4 (light or movement function)

The general equations for Figure 7.7 are

$$i_3 = i_{Z3} + i_{B3} + i_{R3}$$ Equation (7.14)

and

$$i_3 = i_{Z3} + i_{B3} + \frac{u_3}{R_{A3}}$$ Equation (7.15)

Assuming an ideal Zener diode with reverse breakdown voltage of u_{Z3}, the battery is charged when

$$u_3 < u_{Z3}$$ Equation (7.16)

and in this case

$$i_{Z3} = 0$$ Equation (7.17)

in which case equation 7.15 simplifies to

$$i_3 = i_{B3} + \frac{u_3}{R_{A3}}$$ Equation (7.18)

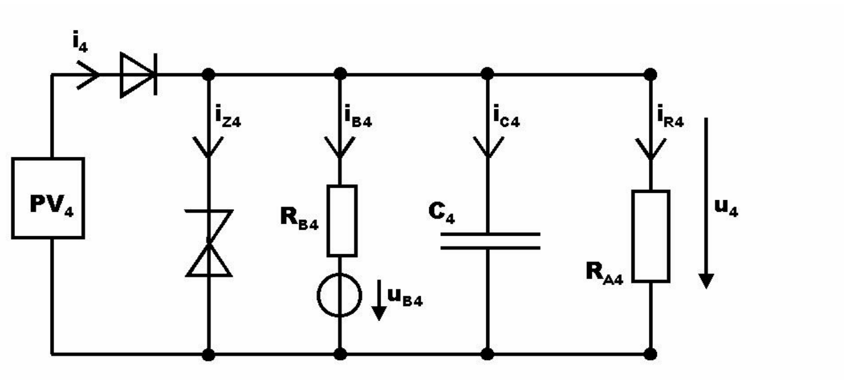


Figure 7.8: Equivalent circuit diagram of Figure 1.5 (wireless communication function)

The general equations for Figure 7.8 are

$$i_4 = i_{Z4} + i_{B4} + i_{C4} + i_{R4}$$ Equation (7.19)

$$i_4 = i_{Z4} + i_{B4} + C_4 \frac{du_4}{dt} + \frac{u_4}{R_{A4}}$$ Equation (7.20)

$$i_4 = i_{Z4} + \frac{u_4 - u_{B4}}{R_{B4}} + C_4 \frac{du_4}{dt} + \frac{u_4}{R_{A4}}$$ Equation (7.21)

Wireless system design

For wireless applications, the transceiver is likely to be the highest power component. Ensuring that this power is at the correct level and that the communications transmit effectively (e.g. no message repeating necessary) is therefore an important energy efficiency concern. The designer will benefit from having details of the buildings in which the products will be used such as layout and materials. However, these alone are unlikely to be usable as "radio signals are subject to attenuation, reflection, and the interference and time-dispersion effects of multipath propagation" [For95]. Therefore, a simulation may be recommendable, using techniques such as ray tracing [Mor99][Sei94].

7.3.2 Maximising available energy

At the conceptual design phase, without specifying the exact components, the designer should be aware of a number of guidelines that will support the collection of as much radiant energy as possible beyond those related to location mentioned in sub-section 7.2.2. These may regard Human interaction, PV technology selection and Obstacles.

Human interaction

The first of these is to consider human interactions with the product. Whether by accident, out of ambivalence or for deliberate reasons, product users may influence the amount of energy available to the product. Where possible, it is therefore advisable to include foolproofing such as is shown in Figure 7.9. This wall mounted device is designed so that the plane of the solar module is at an angle to the wall. Given that radiant energy in the built environment usually has a greater vertical component than horizontal component, by the cosine law (equation 3.5) this module will collect more energy than a module whose plane is vertical (i.e. parallel to the wall).

Figure 7.9: Foolproofing the inclination of the solar module of a solar powered thermometer. A typical value for such an angle would be 25°

Users may feel that it is in their interest to tamper with products, such as those that are monitoring their use of services e.g. hot water. Equally, applications that have home security functions might be tampered with by a potential intruder. The designer should therefore consider how to make products resilient to such behaviour. If using an IPV energy system for either of these examples, it may be necessary to dissimulate (sub-section 7.4.1) the module as well as add software that, for example, may recognise, signal and record incorrect product use.

PV technology selection

The results from the testing of the eight PV technologies tested in Chapter 5 indicate that IPV applications which receive the majority of radiant energy from daylight of over $10W/m^2$ should prioritise the use of crystalline silicon, polycrystalline silicon or CIGS solar cells. The results also suggest that amorphous silicon, Cadmium Telluride and dye cell technologies are better adapted for applications that generally receive radiant energy of an intensity less than $10W/m^2$ (see sub-section 5.2.3).

If a majority of this radiant energy is from fluorescent sources, for the examples tested in sub-section 5.2.4 amorphous silicon solar modules showed the greatest performance improvement compared with results under a daylight spectrum. The results also indicate that crystalline silicon is less well adapted to fluorescent sources as confirmed elsewhere [Nak79].

Thin film solar modules in general offer the advantage that the voltage required by the application can be achieved in a single module by adjusting the number of solar cells in series. Whilst this is electrically feasible using wafer-based technologies such as crystalline Silicon, thin film technology provides a more convenient single unit.

For applications requiring more than 3V, convenient voltage "tuning" may also avoid the necessity for a DC-DC converter, not to mention the associated conversion losses of such a device.

Open circuit voltage, shown graphically in Figure 4.15 and discussed further in sub-section 4.4.4, is another issue. Typical values at $1000W/m^2$ are 0.7V +/-0.1. Of the samples tested in Chapter 5, two groups by technology appear. Amorphous Silicon, Cadmium Telluride and dye cell (the "upper group" in Figure 5.3) had at least a 0.1V/cell higher open circuit voltage than the crystalline, polycrystalline and CIGS samples tested (the "lower group" in Figure 5.3).

Open circuit voltage is relatively linear with intensity on the logarithmic scale; a heuristic for all samples is 0.1V/cell/decade of intensity. This may be helpful when the designer only has data for one intensity level (e.g. $1000W/m^2$).

Obstacles

All non-transparent objects that lie in a straight line between the radiant energy source and the PV module may reduce the energy collected. In order to maximise the available energy, the designer should be aware of the impact of obstacles, be they indoors or outdoors. As has been seen in sub-section 3.4.1, an obstacle which has an aspect ratio of one, as viewed from the module, may reduce the local irradiance by four-fifths (see Figure 7.10).

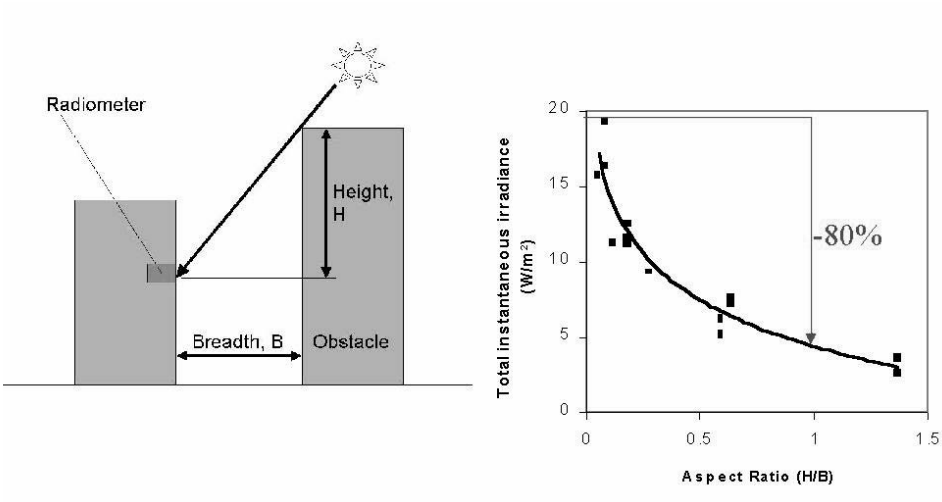


Figure 7.10: Effect of aspect ratio on instantaneous irradiance, based on Figure 3.16 and Figure 3.17

7.3.3 Variation in design

It is generally to the designer's advantage to reduce variation of the many product parameters that must be considered. For products that must function all year round and are storage-limited, despite the fact that daylight irradiance may have the highest absolute intensities at some times, it may be advisable therefore not to rely on daylight-sourced irradiance. This is because daylight radiant energy may vary by a factor of ten over the year (see Figure 7.11). Furthermore, even if the designer takes the "worst case" (e.g. December in Figure 7.11), some locations in certain "bad" years may receive much less than this amount of energy. The range of average radiant energy over 59 locations in Switzerland supports this. As Figure 7.12 shows, the very month of December which the designer might choose coincides with the widest range of average global irradiance! If this is an issue for a particular IPV design, it may be advisable to prioritise the collection of electrically sourced irradiance.

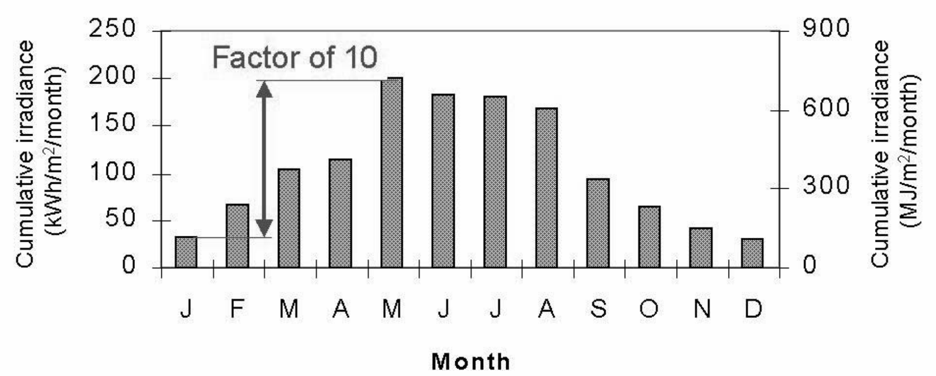


Figure 7.11: Factor of ten variation in cumulative outdoor irradiance in Payerne, CH 1998 (courtesy of World Radiation Center, Davos)

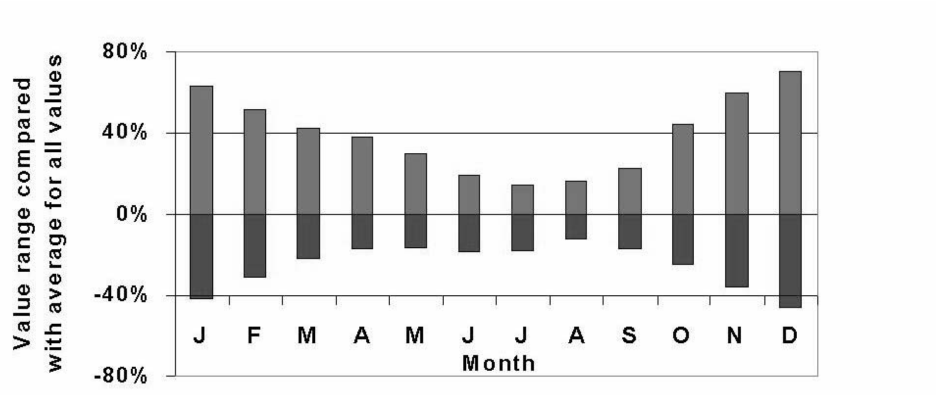


Figure 7.12: Range of average global outdoor insolation between 1981-2000 for 59 locations in Switzerland [Met03]

Alternatively, the designer may need to tolerate a certain degradation of service.

7.3.4 Charge storage components

Three basic concepts are important with regard to effective charge storage in ambient energy systems. The first is the designer should be aware of the limitations of certain technologies. For example, Nickel Cadmium batteries suffer relatively high self-discharge as well as being ill adapted to trickle charge due to the "memory effect" (see sub-section 6.3.2). Other technologies, such as Rechargeable Alkali Manganese (RAM), suffer less from these drawbacks, see the self-discharge comparison in Figure 7.13. Further charge storage technological comparisons can be found in section 6.6.

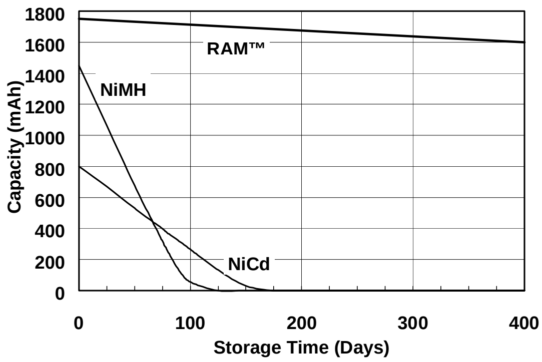


Figure 7.13: Secondary cell self-discharge technology comparison, courtesy Battery Technologies Inc., CAN

Secondly, for batteries in general, the total energy delivered by a battery is related to the current discharge profile. If a current greater than the rated current of the battery is discharged, then the ratio of the delivered energy to the energy stored in the battery may be reduced. The usable battery life may thus also be diminished. This effect is called the *rate capacity effect*. On the other hand, for a battery that is infrequently discharged for brief intervals, it may be possible to improve the ratio of the energy delivered to energy stored in the battery [Pan01]. This may be of service to IPV designers, especially for products which are relatively rarely in function as described in category b) of sub-section 7.2.1.

The third useful concept which may also pertain to extending battery life is the use of hybrid storage, especially for wireless communication applications. An example is the use of a super capacitor and a battery in parallel; the former can deliver brief peaks of power whilst the latter can deliver the majority of the charge storage capacity (see section 6.5).

7.3.5 Functionality

For the case where interaction with the product is required, one or more buttons may be used. It is technologically feasible that one or more “smart” solar cells could fulfil the button function, as well as the radiant energy collection. This hybrid idea has not attracted intellectual property right protection, unlike the use of photovoltaic switches [Der03]. The cost effectiveness of the hybrid approach may be evaluated using a cost-function analysis [Rys01].

7.4 Embodiment

In the embodiment phase, the third phase of Table 7.1, a single product design will be selected from one or more prototypes. As the product takes form, it may be easier to recognise whether its appearance is acceptable, with respect to both the solar module (sub-section 7.4.1) and the product casing (sub-section 7.4.2). The economic and production feasibility may also be confirmed (see sub-section 7.4.3 and sub-section 7.4.4 respectively).

7.4.1 PV module appearance

Product purchase decision are based on both rational and irrational reasons with a general propensity for the latter [Rys01]. It is therefore to be expected that the designer will meet concerns with regard to non-technical issues, as these may strongly affect purchase decisions. Such concerns apply whether converting an existing product to IPV or developing a new one.

One such issue is the visual impact of the product, in abstracto or relative to the area in which it will be used. In IPV, there is a potential technical conflict of interest between the PV modules which are ideally in black colours (for radiant energy absorption) and the pastel or white colours often selected for the inside surfaces of buildings for example (with the aim of reflecting incoming light).

Globally, two solution areas may be considered to alleviate issues related to the PV module. Firstly, the designer may choose a module whose intrinsic properties are appropriate. Secondly, the module can be in some way be dissimulated. The consequence of both of these approaches, as can be expected, is that the effective electrical efficiency of the PV surface may be reduced.

Select PV module intrinsic properties

The majority of solar cells and modules have a monoplanar form, appear relatively reflective (gloss rather than matt) and have a grey or dark blue colour. The advent of thin film PV technologies provides designers with a greater range, especially in terms of shape and colour. The shape of thin film solar modules may take any three-dimensional shape that has a relatively constant cross-section along one axis, as illustrated in Figure 7.14. Figure 7.15 indicates the range of colour that may be achieved, depending on PV technology and the production processing chosen.

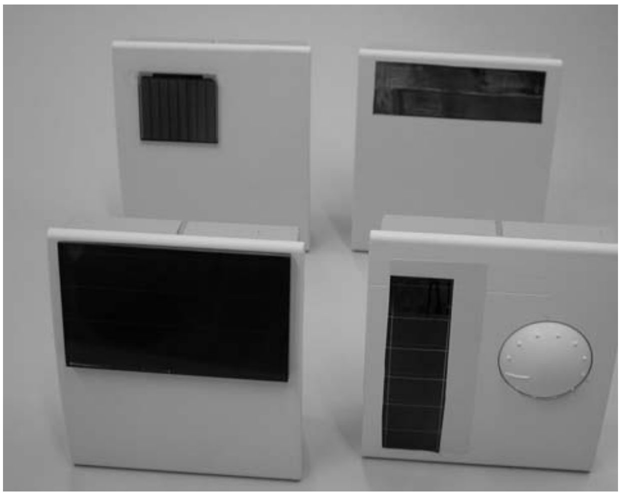


Figure 7.14: (left) Proposed solar clothing [VHF03]

Figure 7.15: (right) Comparison of three thin film PV technologies: the top left sample is cadmium telluride (light grey); the three others are amorphous silicon in red and green (top right), black (bottom left), and purple (bottom right).

Dissimulating PV module

A more common approach in IPV product design is to reduce the visual impact of the PV module by distracting attention from the PV or concealing it from view. An example of the latter is the use of a translucent cache on top of the solar module, as applied to solar watches for example. While this is a visually effective approach, it suffers the disadvantage of reduced incident radiation on the PV module. A rule of thumb is a 50% loss of available energy due to such a cache [Pri02].

Another form of cache is the use of a transparent "lens" cover as shown in Figure 7.16.

Figure 7.16: A solar powered thermometer with a rectangular transparent window (within grey oval cache) covering a 5 cell PV module. The square window below the oval is an LCD display.

The designer may choose to reduce the visual impact of the PV module by the use of colour. This may be achieved by adapting the product housing to the solar module colour, or by including some form of "dégradé" colour, such as a collar around the PV module edge of a colour(s) between that of the PV and the casing.

A final form of integration of which is the integration of the solar module as a feature, such as the company or product logo. Whilst to the authors knowledge, no examples are available on the market, the idea is patented [Gra94]. This may be achieved by the selective deposition of thin film PV modules in a shape other than the usual stripes, or by over-printing any PV module. The risk of this solution is that cells of the module may not receive balanced amounts of radiant energy, which would reduce the effective efficiency of the module.

7.4.2 Product housing

A second appearance issue is that the product housing may need to be adjusted to accommodate the solar module. This need can be minimised if sufficient product outer surface is available and a flexible thin film PV module may be adhered to it. If this is not possible, it implies that a window in the casing will be required and that the casing can need to be enlarged in at least one dimension. Both of these changes can reduce the resistance of the casing to temperature, shock and bending. It is therefore recommended that a mechanical resistance analysis of proposed modifications be made. With a change of scale, the plastic injection material properties should also be taken into account, for example to ensure that the molten plastic viscosity is still compatible with the desired moulding. Product housing solutions that the designer may consider include altering existing parts (e.g. ribs) or adding further parts (e.g. glazing):

Ribs Based on a mesh structural analysis, this involves adding extra material to ensure that the casing is not undermined with respect to shock or bending, especially in the "delicate" areas such as the corners of the window.

Glazing The IPV solar module may be deposited on glass and therefore require little protection. However, for issues related to the application such as appearance and structural integrity, it may be appropriate to use a window of transparent plastic for example. The "glazing" may also protect against dust and dirt, especially for solar modules that are not vertically oriented.

Figure 7.17: Example of window in housing protecting an LCD and a solar module

7.4.3 Cost

While cost is important at all stages of design, during the embodiment phase, the exact costs of the IPV energy system can be confirmed, such as the example in Figure 7.18. In this case the most expensive function is the charge storage. This is to be expected when a battery is necessary.

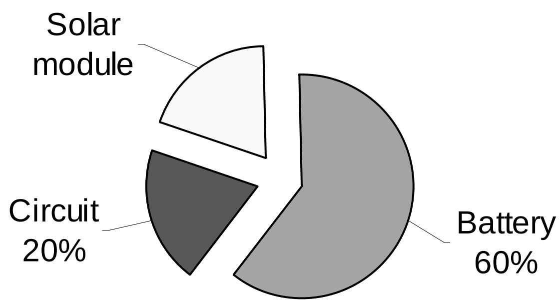


Figure 7.18: Example of cost breakdown of IPV energy system based on a total of 5US$

At this phase the designer may also be able to confirm that the ideal price of the more expensive components has been found. An indication of this may be gained by using a cost function analysis. An example is the relationship between cost and charge storage device capacity, A_h [J]. The latter can be summarised either graphically (see Figure 7.19) or mathematically (see equation 7.23) as the example of charge storage shows.

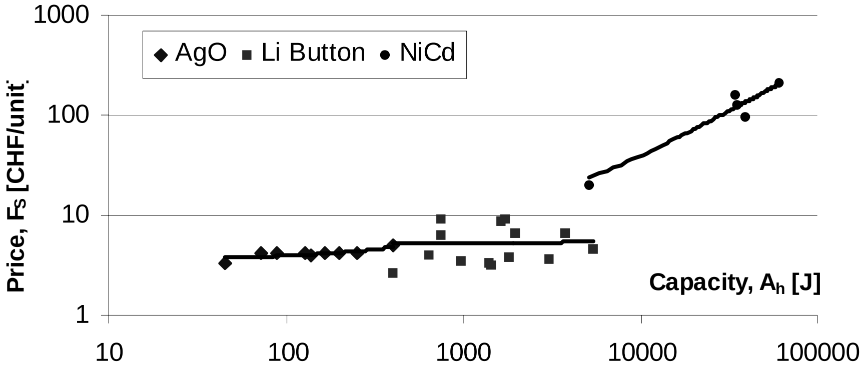


Figure 7.19: Battery cost function spanning for selected examples of three technologies (AgO=Silver Oxide, NiCd=Nickel Cadmium); data from [Far02]

$$F_S = f(A_h) \qquad \text{Equation (7.22)}$$

$$F_S = \begin{cases} 0.03A_h + 3.6 & \text{if } 13 \le A_h \le 111 \\ 10^{-5}A_h + 5.3 & \text{if } 112 \le A_h \le 1499 \\ 0.003A_h + 7 & \text{if } 1500 \le A_h \le 17000 \end{cases} \qquad \text{Equation (7.23)}$$

where:

F_S = Price of a single unit [CHF]
A_h = Capacity of the charge storage device [J]

Cost functions are useful to the designer as they summarise the effect of moving from one technology or threshold to another. This can be seen in the example shown in Figure 7.19. Assuming that no devices other than those shown on the graph are feasible, it is advisable to avoid exceeding a capacity of 1500J as this would require switching to a Nickel Cadmium device that would cost at least an order of magnitude more than the Lithium devices shown in Figure 7.19. In practice it is unlikely that single use batteries (AgO and Lithium) would be compared with rechargeables (NiCd).
Given the importance of correctly specifying the battery, the designer may use models to determine the optimum device. One such model that indicates technical feasibility of a product with respect to charge storage capacity is described in sub-section 6.5.2.

7.4.4 Production Quality

An area much influenced by design decisions is manufacturing. One way to integrate this into the design process is to predict quality levels before production. Toyota achieve this by considering three levels of product quality: that of the components (e.g. components with compatible tolerances), the assembly process (e.g. statistical process capability), and the operators (e.g suitably skilled).

In order to support the operator, the designer may also consider assembly error-proofing. The typical top three assembly quality issues can be categorised as: “use of incorrect parts”, “omission of parts” and “incorrect assembly” [Che02]. The designer should therefore minimise the risk of these problems occurring.

In general, the designer should ensure that all necessary tolerances can be respected. This can be represented diagramatically as in Figure 7.20.

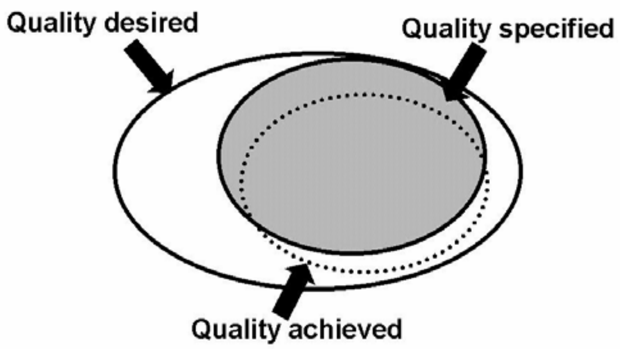


Figure 7.20: Three quality circles [Jac00] - simplified constraint based methodology

Here, the outer circle represents the customer requirements (quality desired). The two other circles are the product specification (quality specified) and the acceptability of the manufacturing output (quality achieved). Ideal quality may be represented by the coincidence of all three circles. Reality may look more like the diagram (Figure 7.20). For example, quality specified or achieved may lie outside the quality desired. This represents activity which does not satisfy customer requirements and may support the designer in the communication of the improvements that should be made.

7.5 Detailed Design

The last phase of the design flowchart in Table 7.1 is the detailed design. As the designer finalises the product, issues that may have previously appeared minor may gain importance. Examples of such issues which have been successfully resolved for IPV are described in sub-section 7.5.1. The designer may also choose to communicate to the consumer how best to use the product, especially with regard to maximising radiant energy (seen in sub-section 7.3.2). Suggestions on how this may be achieved are covered in sub-section 7.5.2.

7.5.1 Alternative energy source

A number of noticeably good design solutions have been mentioned already (see Figure 7.9 and Figure 7.16). Two others that relate to providing flexibility of energy source to the user are presented here. This may be necessary as the product user may wish to extend product life, either into environments of insufficient radiant energy (e.g. cellar) or if the ambient energy system malfunctions.

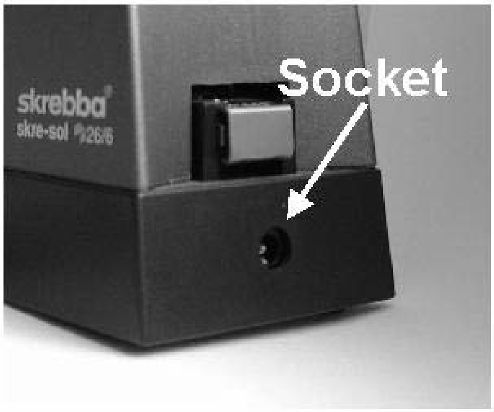


Figure 7.21: (left) The back of a solar powered thermometer with the bay for an optional battery

Figure 7.22: (right) External transformer socket on rear of solar powered stapler

Two solutions inspired by existing IPV products may be considered. Firstly, an optional battery bay may be added, as in Figure 7.21. Alternatively, a socket for an external power supply may be provided, as shown in the example from the solar stapler in Figure 7.22.

It can be seen that the three equivalent circuits shown in Figure 7.6 to Figure 7.8 use at least one diode. A simple LED may be used, as in the solar alarm clock shown in Figure 7.23.

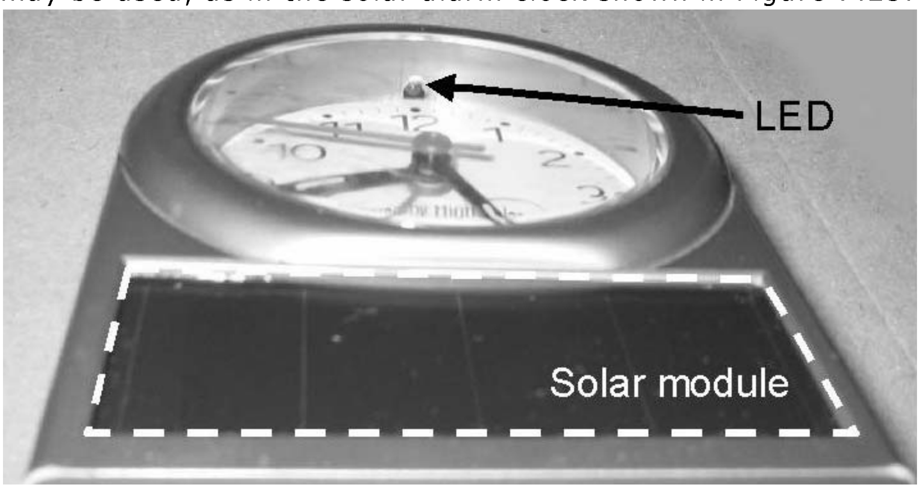


Figure 7.23: Modified Solar alarm clock to show LED used

7.5.2 Information on ideal use

Since it is unlikely that most users will appreciate where concentrations of ambient energy can be found, the designer may choose to inform them via instructions for instance. An example of this for the installation of IPV wall-mounted devices under electrical light sources has been mentioned in sub-section 3.4.3. For this same example, Figure 7.24 shows the kind of instructions that may support the user. As can be seen from this diagram, this advice may be quite intuitive provided a suitable diagram is available. Attempting to explain this in words may make for a voluminous (and therefore uninviting) user manual.

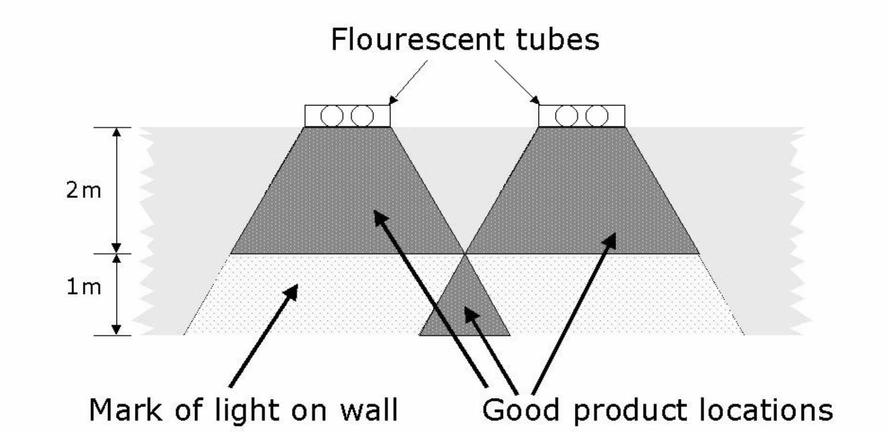


Figure 7.24: Suggestion for installation instructions or manual

7.6 Case studies

In order to further illustrate how the above design phases and chapters may be applied in practice, two case studies are presented here. The cases are representative of the two categories defined in sub-section 7.2.1, namely low storage (solar calculator, see Figure 7.17) and high storage capacity (solar wireless sensor, see Figure 7.15).

7.6.1 Clarification

The first step in clarification is to determine the ball park technical feasibility of the proposed product as shown in section 7.2. This feasibility depends on the amount of charge storage that the product will require. For very low charge storage capacity requirement products such as solar calculators (e.g. less than 10µWh/day or 40mJ/day) and functioning only in situations with sufficient radiant energy, then inequality equation 7.4 applies. If this inequality is satisfied, then the storage capacity can be estimated, see section 6.5; if equation 7.4 is not satisfied, the designer will continue as for a wireless sensor.

For greater charge storage capacity such as for wireless sensors, or use with insufficient instantaneous radiant energy, then the inequalities in equation 7.5 and equation 7.3 must be satisfied. Assuming they are, then the charge storage capacity may be specified as described in section 6.5. The above is summarised in a flowchart, see Figure 7.25.

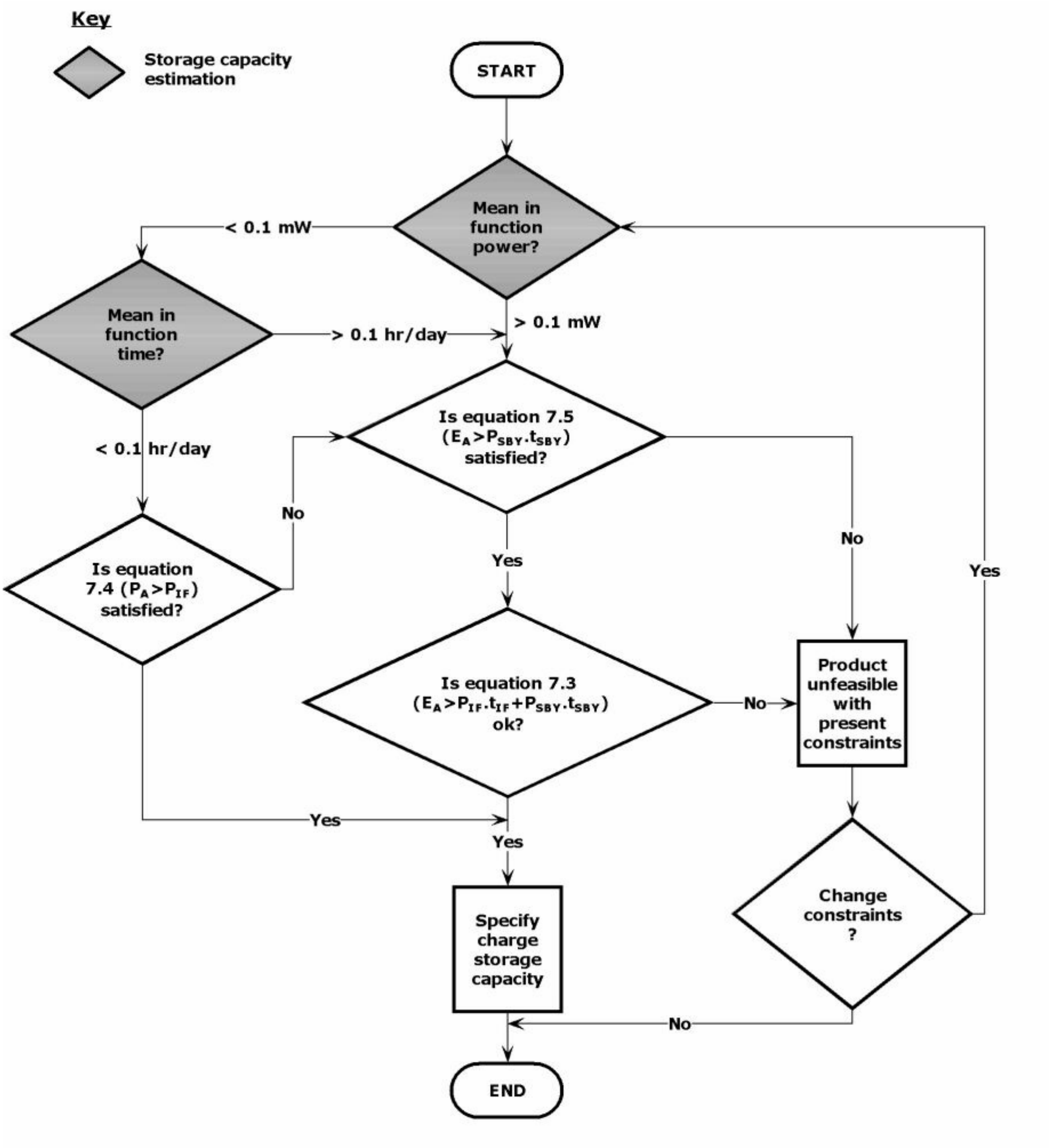


Figure 7.25: IPV product feasibility flowchart

As can be seen, if equation 7.3 or equation 7.5 is not satisfied, then the proposed product is unfeasible with the present constraints unless the latter can be relaxed, for example with the methods described in sub-section 7.6.2.

7.6.2 Conceptual Design

The probability of product technical feasibility can be increased in a number of ways, which may be necessary either to relax initial constraints, see above, or to extend the envelope of feasible situations. The ways of increasing technical feasibility investigated in this work include optimising radiant energy collection and correctly selecting photovoltaic modules and charge storage.

Radiant energy

For the case of the solar calculator, the product must function with the radiant energy available at a desk. The solar sensor has more scope for influencing available energy: firstly the position of the solar module in the built space, such as close to a window, as can be concluded from sub-section 3.3.2 and sub-section 3.4.3. Also, the importance of orientation with respect the radiant energy source as has been shown in sub-section 3.4.4 and sub-section 3.6.2. Another way to improve technical feasibility for the solar sensor is to consider the obstacles to the radiant energy associated with the windows, see sub-section 3.4.2. If the solar module collects mainly day-light, the environment in which the building is found will exert an influence. Geographical location (sub-section 7.3.3), or nearby buildings for instance, see sub-section 3.4.1 should be taken into account.

PV technology

The radiant energy available is a determinant of the appropriate photovoltaic technology, as concluded in section 5.6 and described in sub-section 7.3.2 (PV technology section). The electrical efficiency can also be improved in a number of ways; the principles are outlined in section 4.7 whilst practical solutions are described in section 5.5. Such improvements can serve for both the above mentioned product cases.

Storage selection

Lastly in this conceptual phase is the selection of charge storage. For the case of the solar calculator, the storage required is low (see sub-section 7.6.1) and self discharge should not be a limiting factor. For the solar sensor, the requirements are the opposite. Significant storage capacity is required (e.g. a month without radiant energy) and therefore minimal storage device self discharge is paramount. Techniques for the solar sensor case can be found in sub-section 7.3.4 and section 6.6.

7.6.3 Embodiment

Conclusions can be drawn for the two case studies from all four of the subsections in section 7.4.

From sub-section 7.4.1 it can be seen that *PV module appearance* will be more easily resolved for the solar calculator than the solar sensor. This is because the solar calculator colour is likely to be closer to that of the PV module than for the solar sensor. The dissimulation techniques described can be of use for the latter, such as the cache in Figure 7.16.

With regard the housing, the solar calculator is likely to be “glazed” as shown in Figure 7.17. For the solar sensor, structural issues are likely to be more important.

As the solar sensor requires relatively high storage capacity, it can be expected to have a cost breakdown similar to that in

Figure 7.18. The solar calculator is likely to have roughly equal costs for the solar module, capacitor, casing and circuit.

7.6.4 Detailed Design

From the detailed design, section 7.5, it can be seen that the alternative energy source for both cases taken here could include a battery, such as Figure 7.21. The solar sensor might also be used with an external transformer as in Figure 7.22. User information for the solar calculator is relatively intuitive as the user gets immediate feedback of lack of radiant energy i.e. the display fades. The solar sensor will not benefit from such close attention and should therefore be installed with care following guidelines such as shown in Figure 7.24.

7.7 Conclusion

A number of guidelines specific to ambient energy and IPV have been presented. They are categorised according to the design process phases [Pah01], although the exact phase in which they are found is not a prescription to the designer. Whilst it is not possible to provide an exhaustive methodology for all ambient energy products, many of the parameter relationships for IPV have been explained. Whenever appropriate, values for the expected IPV coefficients are mentioned. Links to other chapters are regularly provided, and it is hoped that this will encourage the reader to explore the rest of the thesis.

Of all the guidelines, there are three that are especially important:

a) for wireless sensors, the designer should at first be less concerned with absolute application power than the average energy consumed (see equation 7.3). Given the importance of standby current, recently released nW standby processors [Chi03] indicate new potential for IPV and AES (ambient energy sources)

b) a route to wider ambient energy source application is the use of low energy design techniques such as those covered in sub-section 7.3.1

c) independent of how well the technical design is executed, product success relies heavily on non-technical issues such as product appearance (see sub-section 7.4.1)

7.8 Further reading

Two useful general texts on low power design methods include [Rab96] and [Hav00]. More specific subject areas include [Ben98] which considers the system power and [MBP02] which focuses on memory optimisation.

Conclusion

The more you know, the harder it is to take decisive action.

Once you become informed, you start seeing complexities and shades of gray.

You realize that nothing is as clear and simple as it first appears.

Ultimately, knowledge is paralyzing.

There's treasure everywhere, Watterson B., Andrews and McMeel ISBN 0-8362-1313-0

Ambient Energy Systems (AES) are expected to be the basis for making a noticeable improvement in the quality of life experienced indoors. The key barriers to the greater use of AES by designers fall under three headings: lack of experience, lack of information and cost pressures. Taking each of these in turn, the chief contributions of this report are as follows:

1. The designer lacks experience:

A good example of this in the appreciation of what ambient energy capital is available. Given that humans are relatively insensitive to the energy flows around them, detailed characterisation advantageously counters the flawed intuitive judgements that might be made.

For the example of photovoltaic solar cells, the radiant energy in the indoor space is measured and modelled in chapter 3. The results summary in Table 3.4 indicates that a typical well oriented and located IPV product may receive of the order of a $kWh/m^2/month$ ($100mWh/cm^2/month$) of radiant energy. At least ten times this value may also be achieved, on the window ledge for example. The most significant parameters that are found along the "photon chain" between the light source and the PV device are identified. Recommendations are provided to enable the designer to achieve the best performance from a proposed IPV application.

Product design advice is another area where lack of experience may affect the designer. Such guidelines are often proprietary, and therefore confidential, or consider only a single product, so may not be applicable. In the final chapter (chapter 7) therefore, IPV guidelines and heuristics are provided. These are built on exisiting product design theories, the results of the report and further findings. It is concluded that three top design priorities are:

a) for higher power products, such as wireless, the designer should at first be less concerned with absolute application power than the average energy consumed

b) a route to wider ambient energy source application is the use of low energy design techniques

c) independent of how well the technical design is executed, product success relies heavily on non-technical issues such as product appearance.

2. There is a lack of information available to the designer, or sufficient time to collect it:

Furthermore this lack of information is likely to be most apparent at the beginning of the project, the very time when it can have the most impact on design success, see chapter 2.

One of the main areas of lack of IPV information is with regard to photovoltaic collectors under indoor conditions. The history of PV technology is briefly presented in chapter 4 which shows how PV was developed and what products have been realised. From this history, the potential for improvement can be infered, such as for wireless (communicating) PV powered indoor products. Then the technolgical basis of photovoltaics is explained including how solar cells work, the advantages and limitations of PV. A section of improvements that can be achieved is also provided. Thus forearmed, the designer is therefore better positioned in the selection of appropriate photovoltaic components, as well as the management of suppliers.

In the second chapter on PV characterisation (chapter 5) the lack of comparable low radiant energy intensity solar cell is addressed. Results for 21 samples representing 8 material technologies tested by the author under two spectra types and radiant energy in the range 1-1000W/m^2 have been presented. Thereby, it has been demonstrated that a 1 sun efficiency reference cannot be projected reliably down to indoor radiant energy intensities for all solar cells. Equally it is shown which samples performed best under indoor radiant energy intensity and spectra. Also, the reasons why such solar cell comparisons are not applicable for indoor PV (IPV) design have been explained. For example, efficiency may vary markedly with intensity in the decades 1-100W/m^2, the limiting factor being the parallel current, I_P.

The lack of appropriate models has also been described and addressed; two models are shown to correlate well to experimental results in the intensity range of interest for IPV design. These may be of service to IPV researchers and designers alike.

3. The designer is under cost pressure

In order to be able to benefit from the diffuse nature of ambient energy for higher power products (e.g. that communicate wirelessly), the energy collection time must greatly exceed the energy use time (e.g. a ratio of 300:1 for IPV). Therefore, energy collection must be complemented with energy storage. Given that many AES require charge storage and that this component often represents the majority of the cost of the system, determining the correct capacity is essential. It is shown in chapter 6 that the storage capacity (directly relatated to cost) is related to the probabilty of the storage satisfying a desired specification (a factor of the price that the product can be sold for). This is achieved by the development of a model presented in section 6.5.

All of the above elements individually contribute to improving the chances for success of future ambient energy systems. Together, and combined with the further information provided, they form a compelling argument that ambient energy technology deserves greater attention and will be developed.

Further work

A complement to the results and conclusions for the main research areas mentioned above include:

1. Characterisation of the indoor environment

Ambient energy in the built environment is available at, but not limited to, other frequencies than the radiant energy chiefly considered here. These include ("mechanical") vibrations in the 50-200Hz range [Rou01] with a magnitude of vibration from "about 0.1 to about 10 m/s^2" [Rou03]. A complement to this work would by a study of the built space for such frequencies. By combining the results of chapter 3 and this future study, a more general mapping of the ideal locations for indoor ambient energy products could be developed.

With regard to the simulation of radiant energy indoors, a well known mathematical non-diffusive billiard ball model could be applied to IPV photon modelling if the energy diffusion created by the imperfect reflectivity of the walls were taken into account. At present, whilst the billiard ball model has attracted hundreds of journals contributions, none deal with diffusion.

2. Technological selection (photovoltaic and storage)

An ideal outcome from the IPV practitioner perspective would be a model based on easily accessible data (such as 1 sun efficiency) which would provide a prediction of cell performance over the full range of intensities tested here. The phenomenological model (equation 5.8) is valid for only some of the samples across the full range tested, 0.8-1000W/m^2, namely Solems, BP Millenium and Tessag. In order to extend the validity, more terms are required to model that part of the efficiency-intensity curve where the gradient becomes negative. It is also necessary to investigate the physical meaning of the control parameters a (equation 5.10) and b (equation 5.11).

Another area requiring further understanding is the physical mechanism which induces R_P. It is thought to be related to intrinsic leakage (junction resistance) and extrinsic leakage (perimeter).

The storage capacity model presented in section 6.5 could be improved in a number of ways, some of which have already been mentioned. One approach, by which the model would be brought closer to the designer selection, would be to combine it with cost functions for the various IPV system components in order to optimise the surface of PV material and storage capacity with respect to cost and, by corollary, quality of service.

3. Power management

Ideally one would avoid batteries altogether, and some believe this may be possible in the future, especially for the low power range electronic applications such as IPV systems [Peg02].

Abbreviations and symbols

a	A constant of phenomenological model (subsection 5.3.1)
$a_{AM\ or\ F}$	Value taken by a under AM1.5 or fluorescent source respectively
a_s	A constant of heuristic model (subsection 5.3.2)
α	Ratio of machine 1 in-function duration to machine 2 in-function duration
α_c	Absorption coefficient
α_f	A constant of phenomenological model (subsection 5.3.1)
α_s	A constant of heuristic model (subsection 5.3.2)
a-Si	Amorphous silicon (photovoltaic technology)
A	Surface area of an object [m^2]
A_{CS}	Cross-sectional area
A_{ds}	Area receiving radiant flux from all directions
A_h	Charge storage capacity [mAh]
A_O	Capacitor plate overlap area [m^2]
AES	Ambient energy system[s]
AM	A variable representing the air mass spectrum
AM_0	An air mass spectrum of 1.5

AM0	Air Mass zero; the characteristics representing the radiant energy found just outside the earths atmosphere; ASTM standard E490-00a.
AM1.5	Air Mass 1.5; the characteristics representing the radiant energy typical found at the earths crust; The basis for STC; ASTM standard G159-98
A_r	Aspect ratio
b	A constant of phenomenological model (subsection 5.3.1)
b_s	A constant of heuristic model (subsection 5.3.2)
$b_{AM\ or\ F}$	Value of b under AM1.5 or fluorescent source respectively
B	Distance from building to an obstacle
B_{12}	Buffer between machine 1 and 2
β	Ratio of machine 2 non-function duration to machine 1 non-function durationt
β_f	A constant of phenomenological model (subsection 5.3.1)
β_s	A constant of heuristic model (subsection 5.3.2)
c	Speed of a photon in a vacuum = 2.99×10^8 [ms^{-1}]
χ	Distance from the semiconductor surface [m]
χ_s	A constant of heuristic model (subsection 5.3.2)
C	Current of charging and discharging [A]
C_F	Capacitance [F]
C_L	CMOS Output load capacitance
$C_{2\ or\ 4}$	Capacitance in an equivalent circuit

CdTe	Cadmium Telluride
CB	Conduction Band [eV]
CC	Correlation coefficient
CFL	Compact Fluorescent Lamp
CIS	Copper indium diselenide (photovoltaic technology)
CIGS	Copper indium gallium diselenide (photovoltaic technology)
CMOS	Complementary metal oxide semiconductor
CVD	Chemical Vapour Deposition
d	Distance between capacitor plates [m]
χ_s	A constant of heuristic model (subsection 5.3.2)
$D_{n \text{ and } p}$	Diffusion coefficients
DF	Daylight Factor
DLC	Double Layer Capacitor
e	Emissivity constant of a surface
eM_1	Effective Machine 1
E_A	Electrical energy available
E_g	Band gap energy [eV]
E_Q	Quantum energy [J]
E_{SW}	CMOS Switching activity factor
f	Frequency [Hz]

f_{CK}	CMOS clock frequency [Hz]
FF	Fill Factor
F_S	Cost of batteries [CHF]
G_n	Radiant energy intensity [W/m^2]
G_{no}	Radiant energy intensity of 1000 W/m^2
Γ	Constant defined in equation 6.6
GaAs	Gallium Arsenide
GaInP	Gallium Indium Phosphide
h	Battery capacity
h_c	Planck's constant (6.625×10^{-34}Js)
h_{MAV}	Extra storage due to the minimum application voltage
h_{IF}	In-function storage capacity
h_{SBY}	Standby consumption storage capacity
h_{SD}	Storage self-discharge capacity required
h_{TTC}	Total theoretical storage capacity
η	Electrical efficiency
H	Height of a building
$i_{1,2,3 \text{ or } 4}$	current at a point in an equivalent circuit
$i_{B3 \text{ or } B4}$	current passing through a battery in an equivalent circuit
$i_{C2 \text{ or } C4}$	current passing through a capacitance in an equivalent circuit

$i_{R1,R2,R3\ or\ R4}$	current passing through a resistance in an equivalent circuit
$i_{Z3\ or\ Z4}$	current passing through a zener diode in an equivalent circuit
I	Current [A]
I_A	Average current available [A]
I_{ds}	Irradiance from all directions [W/m^2]
I_D	Deterministic current consumption [A]
I_{Diode}	Semiconductor junction diode current [A]
I_e	Radiant energy emitted
I_{IF}	In-function current
I_L	Radiant energy induced / Light generated photocurrent [A]
I_{ls}	Intensity of radiant energy emitted from a line source
InP	Indium phosphide
I_M	Current [A] at the maximum power point
I_{PR}	Parasitic current due to parallel resistance
I_{pa}	Intensity of radiant energy from a source of parallel radiation
I_{ps}	Intensity of radiant energy from a point source
IPV	Abbreviation of the adjective indoor photovoltaic and the nou indoor photovoltaics
I_{rls}	Irradiance (received) from a line source
I_{rpa}	Irradiance (received) from a source of parallel radiation

I_{rps}	Irradiance (received) from a point source
IRE	Incident radiant energy
I_S	Saturation current, also called I_0 [A]
I_{SC}	Short circuit current [A]
I_{SR}	Parasitic current due to series resistance
I-V curve	Current against voltage graph
k	Boltzmann's constant
k	Parameter of probability density function
K	Permittivity of capacitor seperation material (at a fixed temperature)
κ	Extinction coefficient (complex number)
l	Wavelength [m]
$L_{n\ and\ p}$	Diffusion lengths
L_{int}	Light incident inside a building
L_{ext}	Light incident outside a building
$\lambda_{1\ or\ 2}$	In-function duration of machine 1 and 2 respectively
LASER	Light amplifier by stimulated emission of radiation
LED	Light emitting diode
LCD	Liquid crystal display
$\mu_{1\ or\ 2}$	Non-functioning time of machine 1 and 2 respectively

$M_{1\ or\ 2}$	Machine 1 and 2 respectively
MB	Megabyte or a million bytes (technically 1,048,576 bytes). Not to be confused with megabits (Mb - not small case b)
Mono-Si	Mono-crystalline Silicon (photovoltaic technology)
MPP	Maximum power point
Mtoe	Million tonnes of oil equivalent (12,700 GWh)
Multi-Si	Multi-crystalline Silicon (photovoltaic technology)
n_c	Index of refraction (complex number)
N	Machine non-availability. The ratio of "mean time between two consecutive in-function phases" and "mean time in function"
N_{dip}	Dipole non-availability
$N_{A\ orD}$	Densities of acceptors and donors
$N_{C\ or\ V}$	Effective densities of states in conduction and valence bands
$N_{1\ or\ 2}$	Non-availability of machine one and two respectively
NiCd	Nickel Cadmium
OLED	Organic light emitting diode
P_A	Power converted from the radiant flux and available to the ambient energy application [W]
P_{DS}	Probability that application demand will be satisfied
P_{dip}	Proportion of time that a dipole runs
P_2	Proportion of time that the application is in-function
P_I	Incident power [W]

P_{IF}	In-function power [W]
P_r	Radiated power [W]
P_{SBY}	Standby power [W]
P_{SC}	Short circuit power [W]
P_{SW}	Switching power [W]
P_T	Total power [W]
PDA	Personal Digital Assistant
PV	Abbreviation of the adjective photovoltaic and the noun photovoltaics
$PV_{1,2,3 \text{ or } 4}$	Specific photovoltaic modules in equivalent circuits
q	Electronic charge (1.602×10^{-19} coulomb)
θ	Temperature [°C]
θ_0	Temperature of 25°C
r	Distance between radiant energy emitting surface and receiving surface
R	Portion of incident radiation reflected
R_{ds}	Radiant flux from all directions
R_A	Application resistance
$R_{A1,2,3,4 \text{ or } B4}$	Specific application resistances in an equivalent circuit
R_{es}	Effective series resistance
R_S	Series resistance

R_P	Parallel resistance (also called shunt resistance, R_{SH})
s	Stefan-Boltzmann constant (equal to $5.67x10^{-8}Wm^{-2}K^4$)
$S(\upsilon)$	The number of incident photons (per unit time, area and energy)
σ	Standard deviation
SD	Spectral distribution
SMA	Shape memory alloys
SR	Spectral response
STC	Standard test conditions
$S(\upsilon)$	Number of incident photons per unit time, area and energy
t	Time [s]
t_{IF}	Time in-function [s]
t_{SBY}	Time on standby [s]
TCO	Transparent conductive oxide
T	Temperature [K]
υ	Frequency of incoming radiant energy [Hz]
$u_{B3\ or\ B4}$	voltage across a battery in an equivalent circuit
$u_{C2\ or\ C4}$	voltage across a capacitance in an equivalent circuit
$u_{R1,R2,R3\ or\ R4}$	voltage across a resistance in an equivalent circuit
u_{Z3}	voltage across a zener diode in an equivalent circuit
$U_{1\ and\ 2}$	Rate of production of machines 1 and 2 respectively (parts/s)

UPS	Uninterruptible power supply
V	Voltage [V]
VB	Valence Band [eV]
V_M	Voltage [V] at the maximum power point
V_{max}	Maximum voltage that can be delivered by a capacitor [V]
V_{OC}	Open circuit voltage [V]
V_S	CMOS Supply voltage [V]
w	Wavelength [m]
ZnO	Zinc Oxide

Glossary

Azimuth	The horizontal angle measured in a clockwise direction in degrees (0-360) from either a North or South reference line. Navigators and surveyors use North. Astronomers and Meterologists use South. Azimuth is synonymous with (compass) bearing.
Charge controller	A device that protects the storage device (battery) by managing it's charging and discharging
Collector	A photovoltaic cell or module
Compound semiconductor	A semiconductor composed of two or more elements, such as the binary semiconductor Cadmium Telluride (CdTe)
Conventional cell	A crystalline silicon cell, having a typical thickness of 350 (+/-50)µm or 3-4 times the diameter of a human hair
Daylight Factor	The ratio of the light intensity at a point indoors with the light intensity vertically upwards outdoors
Diffuse radiation	Incident radiant energy received that has been scattered (e.g. by the atmosphere) or reflected (e.g. by an object) one or more times before reaching the photovoltaic collector
Direct radiation	Incident radiant energy which apart from refraction has travelled in a straight line from source to collector. An example of such radiation is that light which creates a shadow
Doping	The addition of trace amount (e.g. ratio of dopant:semiconductor for crystalline Silicon of $<10^{-6}$) to a semiconductor material. In the case of Silicon, Group III elements for example create (electron acceptor) holes and are called p-dopants e.g. B; Group V elements such as P are electron donors and are called n-dopants
Efficiency	The ratio of electrical output of a photovoltaic cell, or module to the radiant energy incident on it

Elemental semiconductor A semiconductor in which all atoms, apart from dopants, are the same e.g. Silicon, Germanium

Emissivity, e A measure of material propensity to radiate energy. A surface with e = 1 is an ideal radiator (black body). All practical surfaces have an e less than 1. In theory, e can be zero.

Energy payback time The time necessary for an energy producing system or device to produce as much energy as was required for its manufacture and assembly. Typically 2 to 4 years for PV modules outdoors

Extrinsic semiconductor Doped (impurity added) semiconductor material usually prepared from an intrinsic semiconductor where the dopant induced conductivity dominates

Fill Factor The ratio of maximum power point power to the product of open circuit voltage and short circuit current. Ideally it has a value as close to 1 as possible, achieved by having as orthogonal an I-V curve as possible

Fresnel Lens A flat plate of glass or plastic with prismatic structuring that products a similar effect to a conventional lens. May be used to direct incident radiation more effectively onto the collector

Hybrid system An energy system combining two or more sources of energy such as photovoltaic with piezo (mechanical to electrical energy) or Peltier (heat to electrical energy) system

In-function mode The active state of an electronic device, when it is providing a desired service

Insolation The cumulative sunlight reaching a point ($Wm^{-2}day^{-1}$) measured vertically upwards

Intrinsic semiconductor Undoped (no impurity) semiconductor material where the semiconductivity dominates

IPV Abbreviation of the adjective indoor photovoltaic and the noun indoor photovoltaics

I-V curve Current against voltage graph for a photovoltaic cell or module under a range of loads from short circuit to open circuit. The resulting shape indicates the cell or module performance, in particular via the intercept of the voltage axis (open-circuit

	voltage), intercept of the current axis (short-circuit current), and the maximum power point
Load	Electrical energy consumed by the application or the photovoltaic system
LASER	Abbreviation of Light Amplification by Stimulated Emission of Radiation
Maximum Power Point	The position on a particular I-V curve at which the product of I and V (i.e. the power) is maximum
Monolithic series (inter)connection	A means of electrically connecting in a single structure the top electrode of a (typically thin film technology cell) to the bottom electrode of the neighbouring cell without short circuiting either cell. May be referred to as "structured" in PV jargon
Open-circuit voltage (Voc)	The voltage across the electrodes of a photovoltaic cell or module when illuminated but no external current is flowing
Parallel connection	A means of increasing the current of a photovoltaic module. This is achieved by electrically connecting the positive electrodes of more than one cell together and the negative electrodes of these cells together. Rarely applied in indoor PV applications
Peak power	The output of a PV module under Standard test conditions (STC). Also referred to as Watts peak (W_p)
Phonon	A quantised lattice vibration e.g. sound in a solid medium. necessary for the indirect band-gap material absorption process.
Photon	A basic unit of light energy
Photopic	Daylight seen by a human
Photovoltaic	A system which converts light to electricity. The derivation is from phos, the Greek word for light and Volt after Alessandro Volta (1745-1827), the renowned inventor of the battery at the turn of the 19th century
Photovoltaic cell	A basic photovoltaic diode device made of semiconductor materials. Like a battery, it has two electrodes. If a resistance

is placed across these electrodes it produces voltage and direct current on exposure to light

Photovoltaic module A number of photovoltaic cells electrically connected and in a form which can be used in practice. This usually implies the cells being assembled on at least 1 glass sheet and encapsulated thus protecting them from the environment

Photovoltaic System A combination of photovoltaic modules with all other necessary photovoltaic system components to form an autonomous source of power

Photovoltaic System components Typical components for indoor applications include storage (secondary batteries), storage discharge protection to prevent the cells acting as a current drain in darkness (diode). Less common components are maximum power point tracker (MPPT) and DC-DC charge converter. The cost of these components as part of a photovoltaic system can be referred to as the balance of system (BOS) costs

PV Abbreviation of the adjective photovoltaic and the noun photovoltaics

Quaternary material A compound containing four elements e.g. Copper Indium Gallium Diselenide (CIGS)

Series connected A means of increasing the voltage of a photovoltaic module achieved in the most simple form by connecting the positive electrode of one cell to the negative electrode of another cell. The voltage across the remaining unconnected electrodes will be increased in this tandem arrangement whilst the current will be constant throughout

Short circuit current (I_{SC}) The current (A) flowing when the electrodes of a photovoltaic cell or module under illumination are electrically connected via an external circuit of zero resistance

Solar constant The directly incident radiant power from the sun on the Earth's mean orbit. Outside the atmosphere, approximately equal to 1367 (+/-5) Wm^{-2}

Spectral response The relative current output of a solar cell under monochromatic light as a function of wavelength

Standard test conditions (STC) The most common testing conditions for measuring photovoltaic cell or module performance. Based on IEC-904-3, IEC

Standard (1989) i.e. $1000Wm^{-2}$, 25°C, AM1.5 (air mass), solar spectrum perpendicular to the cell surface

Standby mode The state of an electronic device that is powered on but is otherwise inactive (not in-function). Synonym of "quiescent mode"

Ternary semiconductor A semiconductor based on three elements. An example is a binary semiconductor with the addition of relatively small amount of a third element e.g. Copper Indium Diselenide (CIS)

Thin-film cells Photovoltaic cells manufactured by the super position of photo-sensitive material layers. Typical total thickness of a few µm, much less than the diameter of a human hair

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The quickest way of ending a war is to lose it

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Curriculum Vitae and Publications

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	Nationality	British and Swiss
	Marital Status	Single

Qualifications	2003	**Doctorate** (expected) Swiss Federal Institute of Technology (EPFL), Lausanne, CH
	1996	**Chartered Engineer** Engineering Council, London, GB
	1992	**BEng Degree in Manufacturing Engineering (2:1 Honours)** University of Wales College Cardiff, GB

Professional Experience

1999-2003

Doctoral Research Assistant: EPFL, CH

Thesis area: Engineering design of power sources

- Selection of materials
- Selection of applications
- Design of storage systems
- User-oriented design

Related student projects supervised:

- Antenna with integrated solar cells (2002-3)
- Photovoltaic application selection (2001-2002)
- Design of charge management circuit (2001)
- Design of solar cell sealing (2000)

Professional Experience (continued)	1998-1999	Consultant**:** University of Neuchâtel, CH Designed and costed innovative Photovoltaic Solar Cell manufacturing processes. Analysed the markets for such products
	1994-1997	Supplier Quality Engineer: Silicon Graphics Manufacturing, CH Provided the technical reference for 1000 parts worth an estimated £2,300,000 per annum
	1993-1994	ISO 9000 Quality Engineer: Silicon Graphics Manufacturing, CH Developed, implemented and managed the internal auditor program of 12 auditors. Drove the ESD (Electro Static Discharge) protection system for a site of 200 people
	1992-1993	Graduate Engineer: British Steel, GB Logistics projects. Authored five ISO 9002 procedures. Production Supervision Trainee
Recent Training	2002	Advanced digital system design
	2002	Design of Experiments
	2002	MSc in Energy (2 modules)
	2001	Photovoltaic materials
Academic Awards	1999-2000	NEFF Postgraduate Scholarship, Zürich, CH
	1991	Philip Warren Memorial Prize, Cardiff, GB
	1990	Comett Support Scheme grant via Gateway, B
	1990	Department of Production Engineering Prize, Cardiff, GB
	1988	UWIST Undergraduate Scholarship, Cardiff, GB
Languages	Fluent	English and French (Bilingual)
	Intermediate	German

Publications

Feasibility study for the realisation of large-area modules for the Micromorph solar cell with industrialisation-relevant processes, J.F. Randall, H.E. Schade, J. Gresset, R.P. Maisch, Confidential report for University of Neuchâtel, CH, 1999

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