SYN-energy in solar cell use for consumer products and indoor applications

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Final Report of Explorative Research Project (014-28-213) within the

NWO/NOVEM

Energy Research Stimulation Program

Delft University of Technology
Faculty of Industrial Design Engineering
Design for Sustainability program

Contents

Preface

This explorative project was one of the short term projects executed in the framework of the 'Energy Research Stimulation Program' of the Netherlands Organisation for Scientific Research (N.W.O.). In general this Stimulation Program is aimed at innovative energy research to solve future national and international problems in the field of sustainability. In particular this program is aimed at the development of knowledge to smoothen the transition towards sustainable energy facilities. More specific this project was focused on the feasibility of the transition towards the use of solar cell in consumer and professional products.

Looking at energy supplies in consumer and professional products it is found that solar cells play only a minor role. Therefore in this project called 'SYN-energy in solar cell use for consumer products and indoor applications', a desk research endeavor has been executed to chart the feasibility of available solar cells technologies and related application opportunities. The emphasis of this endeavor was to obtain an integral understanding of energy conversion and use of solar powered products. In addition some options were mapped in which the added value or synergy could be demonstrated by using solar cells in combination with several kinds of energy storage media. Also factors hampering diffusion of solar cell use in products were identified and analyzed.

Special features of this explorative project where:

- This research was conducted in a multidisciplinary approach since not only technological aspects but also the user context was analyzed.
- The research was conducted in close corporation between the Delft University of Technology, Utrecht University and the Netherlands Energy Research Foundation (ECN).
- The research was aimed at integration of knowledge of real product applications
- The goal was to find options for energy efficient autonomic PV powered products

This explorative research project has paved the way for a successful application of a long term projects which is also executed in the framework of the Energy Research Stimulation Program of the Netherlands Organization for Scientific Research (N.W.O.).

Executive summary for the Referees and the Program Committee

Explorative research project (014-28-213) within the NWO/NOVEM energy research stimulation program**:**

SYN-energy in solar cell use for consumer products and indoor applications

Worldwide there is a growing need for 'Electrical Energy' to be used in domestic and Consumer Electronic (CE) product applications in a combined indoor and outdoor user-context. Solar or PhotoVoltaic (PV) cells could play an important role in fulfilling this need sustainably. This explorative research is aimed at providing the background for assessing the options of such PV applications both indoors and outdoors.
The central question in this research is:

What synergy can be gained by an integral approach of PV –incl. energy storage - systems for combined indoor/outdoor application in consumer and professional products?

Note:

- 'Integral' particular in connection with efficiency optimization of photo energy-conversion, -storage and –usage.
- It is obvious that the use of PV-powered consumer products in indoor applications may be very critical due to the available levels of light. Therefore, as a first step in this explorative research project it has been necessary to assess the feasibility of this source of renewable energy for indoor applications.

This summary contains the results of a comprehensive literature study, interviews with PV experts and consumer product developers in industry, analysis and calculations of the explorative research project:

- Lighting conditions have been investigated for different circumstances.
- An overview of available PV technologies to date shows that, of all known PV technology, the high grade Si PV cells, Dye sensitized PV cells and some special a-Si PV cells are best-suited for use at low light levels indoors since their efficiency drops less dramatically than other PV cells at low illumination levels
- An overview of available electrical energy storage media to date shows that in conjunction with recharging by PV cells, the use of batteries with the so-called 'memory effect' should be avoided because of diminishing power content upon recharging. At the moment, several alternatives are already available to circumvent this drawback.
- The research project shows that synergy could be obtained in combined conversion – storage systems by using the storage media as 'integrator' and 'time delayer'. For example in a 'worst-case' user context, namely mid winter and a north facing window, calculations show that by redesigning the present generation of cellular phones, provided the best low light level performing PV cell known to date is used, a 100% mains independent and indoors functioning concept is feasible.
  The advantages of this kind of PV-powered products are: they work mainly on renewable energy, and still work in case of a blackout of the electricity grid, creating an unique added value and safety feature.
  The worst-case example demonstrates the synergy to be gained through an integral approach to the energy consumption chain. It also shows the validity of the indoor PV application concept and the possibility of innovative user-friendly designs.
- The use of indoor PV is at this moment limited to low power applications of up to about 5 Watts. However, with the introduction of energy storage media into the energy consumption chain, this limit can be boosted to a few hundred Watts, provided the frequency of use is low enough to allow for recharging of the storage media.
- There is a growing number of professional appliances, which can in principle function well with PV –Battery – combinations, in particular those appliances that are now powered by (primary) batteries.

- At a first glance, the hidden power waste introduced during stand-by and no-load modes at individual consumer and professional products appears to be insignificant. The number however of appliances per household times the number of households over one year will yield a real amount of energy. Significant global energy savings could be achieved through a small amount of photo energy available indoors, by using this energy to relieve the burden of hidden energy waste. Reductions of more than 50 % compared to the existing products are feasible.
- The case studies involved show also that a positive ecological payback time for SYN-Energy products is possible, particularly taking into account the characteristics of the future type of PV-cells.
- In an overall system design it will be a 'design challenge' to find the optimal location of the photo energy converter which, at the same time does not restrict the user too much when carrying the product around, nor causes too large a burden on the interior aesthetics. In this area more research is needed.
- More research is also needed to find a practical solution for the end-of-life discrepancies between PV and battery components. In addition, more research to establish the boundary conditions and design rules for an overall system design of consumer and professional products should be conducted in the near future. Besides, discrepancies exist between PV Battery lifetime and the 'economical' lifetime of appliances.

The results of this explorative research study have shown that there is a potential environmental gain in using grid-less consumer and professional products. In a transition towards real sustainable systems, this could be a fundamental leap.

As a result of this explorative research project, recommendations for further research have been formulated. More insight should be obtained by testing a number of research-hypothesizes in indoor/outdoor experiments in a pilot project. These experiments will involve PV-designed electronic products simulating a real user context. The research should particularly focus on:

- The interaction between the human user and the application of products. In particular with a view to improve user friendliness and acceptance of innovative design.
- The power consumption savings by synergy gained with the use of specific combined PV-storage systems,
- Special design methodology aimed at improved understanding of indoor/outdoor performance characteristics of PV cells to be used in consumer and professional products.
- The life-cycle assessment of environmental impact and user costs of the most promising options.

This research program should follow a multidisciplinary approach in which designers and experts in the fields of consumer-behavior, PV, energy storage and LCA work together.

1. Introduction

Worldwide there is a growing need for 'electrical energy' to be used in domestic, Consumer Electronic (CE) and Professional Electronic (PE) product applications in combined indoor and outdoor user-context. This electrical energy is always a 'conversion' result of energy around us, which as such cannot directly be used to power our products. Solar or PhotoVoltaic (PV) cells could play an important role in fulfilling this need in a sustainable way. Since this electrical energy generally can not be utilized at the moment of conversion, a convenient solution is to store this energy and therefore to delay the energy usage point in time, to a more convenient moment. So in view of earths limited natural energy resources and consequently the drive towards sustainable product design, one could say:

One of the challenges of this century is to make (electrical) energy-conversion with PV, energy storage and -usage in consumer and professional products more efficient and sustainable.

Given this observation as a point of departure, a research project was started funded by the Netherlands Organization for Scientific Research (N.W.O.). This explorative research project (no 014-28-213), was a joint project of Technical University Delft, faculty Industrial Design section Design for Sustainability program together with the PV section of ECN and the University of Utrecht, Faculty of Chemistry section Science and Society The aim of this research project was to provide the background for assessing the potential options of PV applications in both indoor and outdoor usage.

Therefore the main task during this research project was to gather data on PV and Electrical Storage Technologies and to compile an overview of design options in which synergy could be gained in an integral photo energy conversion, storage and usage approach in both indoor and outdoor user's context.

These data will be used in this project, to find answers to the following questions:

1. **What Synergy is to be gained from an integral approach of the PV-energy – storage – usage chain for both indoor and outdoor application in consumer and professional products? Integral means in connection with efficiency optimisation of photo energy-conversion, -storage and –usage, simultaneously and not just on an ad hoc base or as separate sub-systems.**
2. **What innovative solutions and user-friendly products can be developed as a result of meeting the challenge of efficiency improvement by synergy?**

To keep the search for answers to these two questions manageable, they are broken down in the following sub questions:

1.1 What kind and amount of photo power and photo energy is available both outdoors as indoors?
1.2 What types of PV converters are available and what are their performances to date?
1.3 How much electrical power and energy can be harvested with PV converters both outdoors and indoors?
1.4 What types of electrical energy storage systems are available and what are their performances to date?
1.5 What categories of appliances are in use to date and what is their power and energy need?
1.6 How well will the power and energy need of appliances match with the power and energy that can be harvested with PV converters both outdoors and indoors?
1.7 Which kinds of appliances are already PV powered to date?

2.1 What are the trends in PV powered products and what will be the advantage of an integral approach of the whole energy chain?
2.2 What will be the consequences of the trends?
2.3 What are the options to anticipate on the trends and to generate innovative solutions and design user-friendly SYN-Energy products?

In this project a photo energy converter that could convert sunlight directly into electricity, the Solar or Photo Voltaic (PV) cell, was chosen. The reason for this choice is that worldwide sunlight is abundant available. At this moment even, the total amount of sunlight power surpasses the average world power demand by a factor 2.
Additional reasons for this choice are:

- Photo Voltaic cells are mechanically simple systems. For example, they are rigid and there are no moving mechanical parts, which therefore need no maintenance. Such a system is quite advantageous from a reliability point of view.
- PV cells, depending on type, could have an active life expectance of 10 up to 30 years.
- Photo Voltaic power has proven to be useful for applications in remote locations, as they start to be used in outer space and in locations inaccessible or too costly for connections to the electrical grid or mains. Therefore, PV applications are not only limited to so-called newly industrialising countries (with much sunlight) such as Indonesia or India.

This report is about the applications and storage of photo energy in products. The whole approach must be seen in the light of overall optimal system design and appliance utilization by exploiting the synergy obtained by an integral design. Efficiency improvement, user-friendly product design and aesthetics are the key issues.

In the following chapters of this report the above mentioned sub research questions will be dealt with consecutively. It starts in chapter 2 with a survey on the nature of photo power and energy, and the various sources of photo energy and power both outdoors and indoors (sub question 1.1). This is followed by an overview of photovoltaic converters in chapter 3 (sub question 1.2). In chapter 4, the performance of some photo voltaic converters under indoors and outdoors illuminance are discussed (sub question 1.3). In chapter 5, electrical energy storage systems are highlighted (sub question 1.4). The appliances are categorized (sub question 1.5) and the real energy need and matching of those are analyzed (sub question 1.6) in chapter 6, followed in chapter 7 by the use of photo energy in appliances (sub question 1.7). Chapter 8 deals with the options in novel application of photo energy in appliances (sub question 2). Finally, in chapter 9, the conclusions and recommendations are presented.

2. Photo Power and Energy

In this chapter, the following question will be answered: What kind and amount of photo power and photo energy is available both outdoors and indoors?

2.1 Fundamentals

Before comparing conversion methods of photo energy into electricity, one has to return to the basic definitions to be used.
The watt [W] is quoted in specifications of PV cells as the (SI) fundamental unit of power.
One watt is defined as the rate of energy of one joule [J] per second. However, since light is actually a diversity of colors with energy depending on their wavelength, the total photo energy will be a function of both light intensity or the number of light quanta (photon) and the wavelength.

The energy of a photon Q with a wavelength λ is give by Planck's equation as:

$Q = hc/\lambda$

Where '*h*' is Planck's constant (6.623×10^{-34} Js) and '*c*' is the speed of light (2.998×10^{8} m/s).

Dealing with illumination sources such as the sun and several types of lamps one has to distinguish between Radiometric and Photometric or visible light units. Photometric units are for example: candela [cd] for luminous intensity, lumens [lm] for the luminous flux and lux [lx] for illuminance.

The candela [cd] is the base unit in light measurement and is defined as:
One candela light source emits in all directions (isotropically) one lumen per steradian.
A steradian is a unit of solid angle. There are 4 Π steradians to a sphere.
A lumen has the dimension of power and therefore the visible light flux that can emanate from a light source to illuminate a surface of for example a Photo Voltaic cell. The lumen is the photometric equivalence of the radiometric watt. As a photometric unit, the unit lumen is related to the eye response of the standard human, which is color sensitive. So to determine the light intensities of (artificial) light sources, the eye spectral sensitivity plays an important role**.** The peak of human eye sensitivity is at a wavelength of 555 nm (green). Therefore:

1 watt at 555 nm = 683 lumens

Note that the color of an incandescent bulb may vary with input voltage. The reason for this is the direct link between the voltage and the temperature of the filament and therefore with the 'black-body' radiation.
Irradiance is a measure for the radiometric flux incident per unit area; expressed in W/m2
For the PV cell, both irradiance and its photometric equivalent namely illuminance will be an important measure. Illuminance is expressed in lm/m^2 or more common lux [lx].

An example:
A (incandescent) light bulb, at 220V, which consumes 60 W of electrical power, produces only 710 lm light. A crude calculation reveals that at a wavelength of 555 nm, only about 1 W (710/683 W) of the original 60 W is converted in useful visible green light. Integrating over the eye response curve, the total yield will be about 5 W. Therefore most of the electrical power put into the lamp (55 W of the 60 W), is wasted as heat. This information is unfortunately not always indicated.
If the same light bulb is used to illuminate a Photo Voltaic cell at a distance of 1 m, the illuminance will be 710 lx or about $1W/m^2$ at green. Or integrated over the whole lamp spectrum this illumination power will be 2-7 W/m^2, depending on the type of lamp and the medium in between.

2.2 Converting radiometric and photometric units

For future reference, the relation between radiometric and photometric units is tabulated.

Table 1 Relation between radiometric and photometric units

Definition	**Radiometric**		**Photometric**	
	Name	***Unit (SI)***	***Name***	***Unit (SI)***
Energy	Radiant Energy	joule = W.s	Luminous Energy	lumen.sec
Energy per unit time = Power -> flux	Radiant flux	watt	Luminous flux	lumen
Power incident per unit area	Irradiance	W/m^2	Illuminance	lm/m^2 = lux
Power per unit solid angle	Radiant Intensity	W/steradian	Luminous Intensity	candela
Power per unit solid angle per unit projected	Radiance	W/m^2 steradian	Luminance	$candela/m^2$

2.3 The nature of Photo Energy Sources

2.3.1 General remarks

Photo energy could range from high energetic photons in the ultra-violet domain, up to low energetic photons in the infrared domain.

2.3.2 Sunlight outdoors

A. General characteristics of sunlight

Of the total amount of solar power available from outside the earth's atmosphere, about 10 up to 45 % will be lost due to reflection and absorption in the atmosphere. So, in net at sea level down to earth only about 1000 W/m2 solar power can readily be converted into electricity by a solar cell [Hazen, 1996]. In literature, this global irradiance of $1000W/m^2$ is quite often quoted for as the Irradiance of 'one sun'.

The spectrum of this solar irradiance, as received by a photovoltaic converter at sea level, is inside a fixed 'wavelength-window'. This window starts at a wavelength of about 300 nm en ends at a wavelength of about 4 um or effective at about 1.5 um. It encloses the visible range from 380 nm up to 750 nm as presented in figure 2.1.

The attenuation of the sunlight by the atmosphere depends on the optical path length to observation point. This path length is shortest at the moment that the sun is directly overhead.

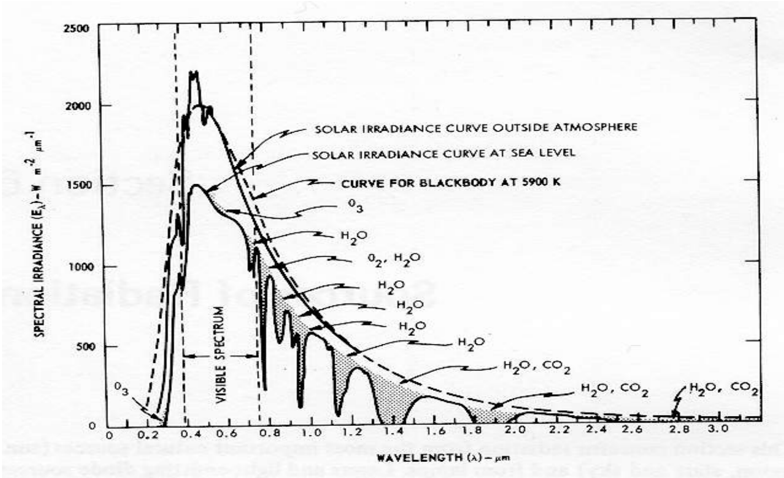


Figure 2 .1:
Spectral Solar Irradiance [Engstrom, 1974]

The ratio between 'any path lengths through the air on earth' and 'this minimum above' is called the *optical air mass* or for short *air mass*. In case the sun is directly overhead, the air mass is unity. The sun light flux in this case is called: air mass one (AM1) irradiance.
In any other case, the sun will make an angle θ to this exact overhead position and therefore the air mass is given by:

$$\text{Air Mass}(\theta) = 1 / \cos\theta$$

To allow consequential comparison between performance measurements of different PV cells throughout the world, a global standard named 'Air Mass 1.5' or *AM 1.5* is often quoted in literature. The solar spectrum of AM 1.5 is defined from a wavelength of 295 nm up to a wavelength of 2537 nm as presented in figure 2.2.

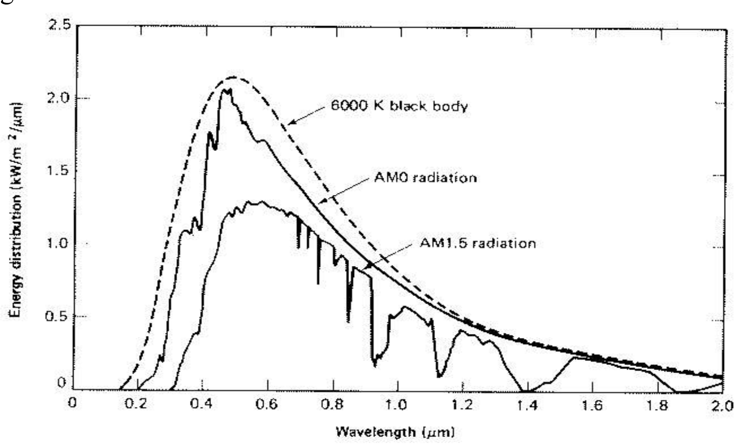


Figure 2 .2:
Spectral distribution of sunlight [Green, 1986]

Due to the reflections on the surroundings and the state of overcast, the nature of solar irradiance will always be a mixture of direct radiation and diffuse radiation. Even on a clear day, there will be still a diffuse radiation part of about 10-20 % at horizontal surfaces. The heavier the overcast, the larger the diffuse part. If the irradiance has dropped below 1/3 of the maximum value on a clear day, generally the main part will be diffuse [Li et. al., 2000]. Note that diffuse light is isotropic (uniform in all directions) therefore the contribution on vertical surfaces will relatively increase, and in addition, the difference between north-oriented and south-oriented surfaces will diminish.

There are some spectral differences between direct and diffuse sunlight. The latter will have a tendency to enhance the shorter (blue) wavelengths. So diffuse sunlight will not completely comply with the solar spectrum of AM1.5. In addition, the spectrum of the sunlight early in the morning and near sunset will be richer in the red region and therefore not comply with the solar spectrum of AM1.5.
The total amount of sun hours depends on the location on the globe and the time of the year as can be seen in figure 2.3. In summer, the amount of potential sun hours will be evidently larger than in winter.

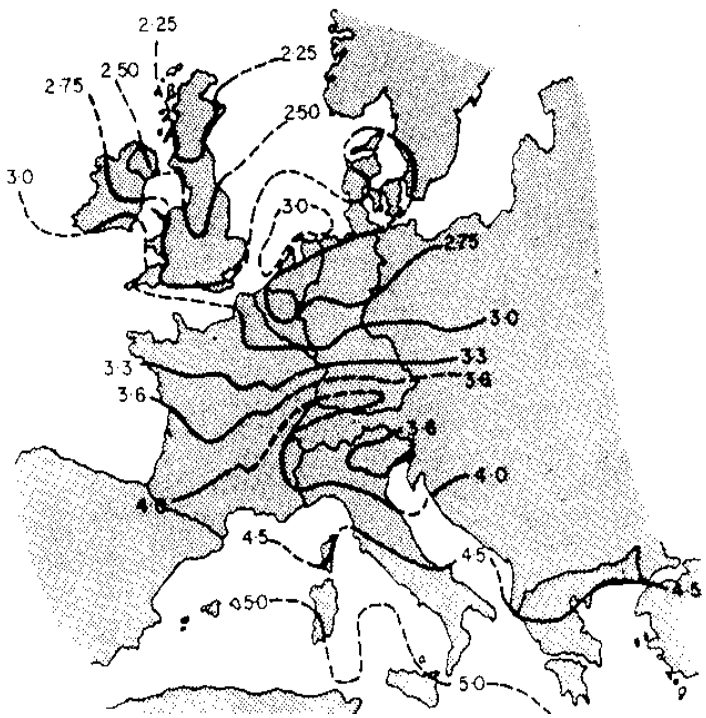


Figure 2 .3a:
Average year radiant energy harvest of sun light in Europe in kWh/m^2 [Alsema, 1986].

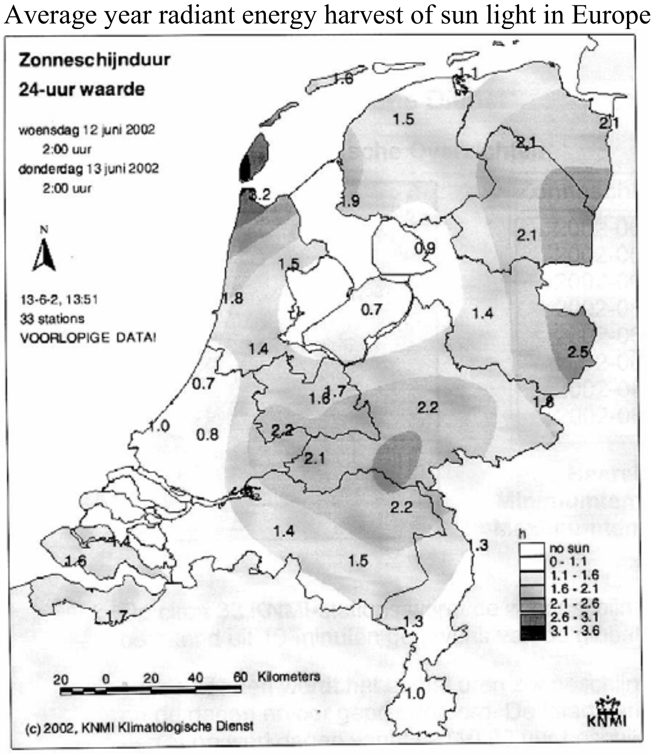


Figure 2 . 3b:
Sun hours distribution over the Netherlands during one day [KNMI, 2002]

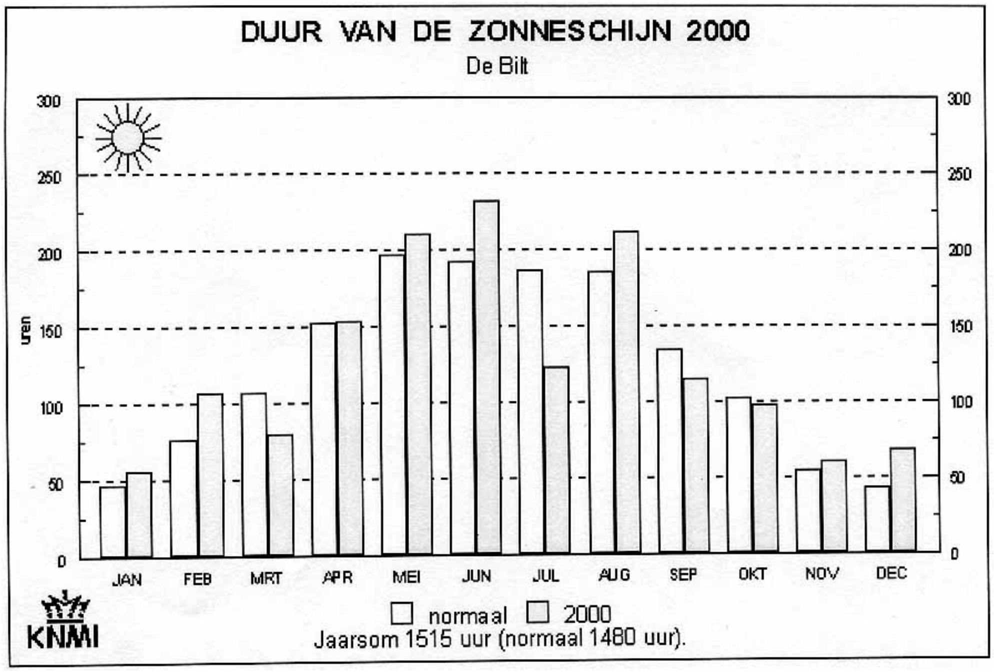


Figure 2 . 3c:
Sun hours distribution average in one month over the year 2000 [KNMI, 2002]

For direct sunlight, the total irradiance received by a surface depends on the orientation of that receiving surface. For the Netherlands, the optimum of 100 % will be achieved for a surface facing south with a tilt angle with the horizontal of about 36^0. A vertical surface (90^0) facing south would only achieve 74% of this optimum, whereas a horizontal surface (0^0) only 87 %. For surfaces facing east and west, the yield would be 85% For surfaces facing north, the direct sunlight contribution would be nearly zero and will be mainly from the sky and the light reflected elsewhere.

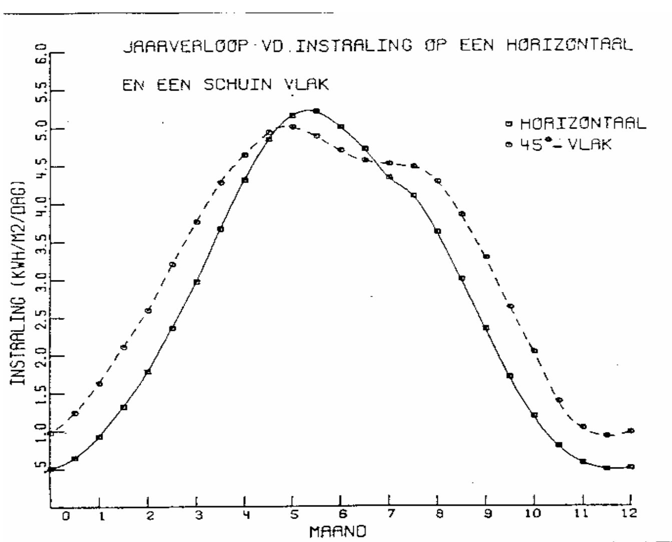


Figure 2 . 4:
Amount of radiant energy of sunlight harvested in one day averaged over one year expressed in kWh/m^2/day. In figure 3d two receiving areas are presented; one horizontal, and one vertical orientated south under an inclination of 45^0 [Alsema, 1986].

Depending on the angle of irradiation incidence towards the receiving surface, figure 2.4 shows that the difference between sunlight harvested at mid winter and mid summer might vary between 5 for the 45^0

oriented areas and 10 times for the horizontal areas. For diffuse illumination as frequently occurs in these cloudy Netherlands however, the angle did not matter so much since the irradiance will be isotropic, therefore the difference will be a factor 5.

One can also approach the magnitude of solar irradiance on the earth's surface as depending on both the distance of the earth from the sun and altitude angle for the sun above the observer horizon.

Since the sun – earth distance is quite large; the fluctuations on this distance in earth's orbit contribute only in a irradiance fluctuation of less than 3 %.

A more significant contribution is introduced by the imaginary variable altitude angle of the sun above the observer horizon due to the seasons as presented in figure 2.5.

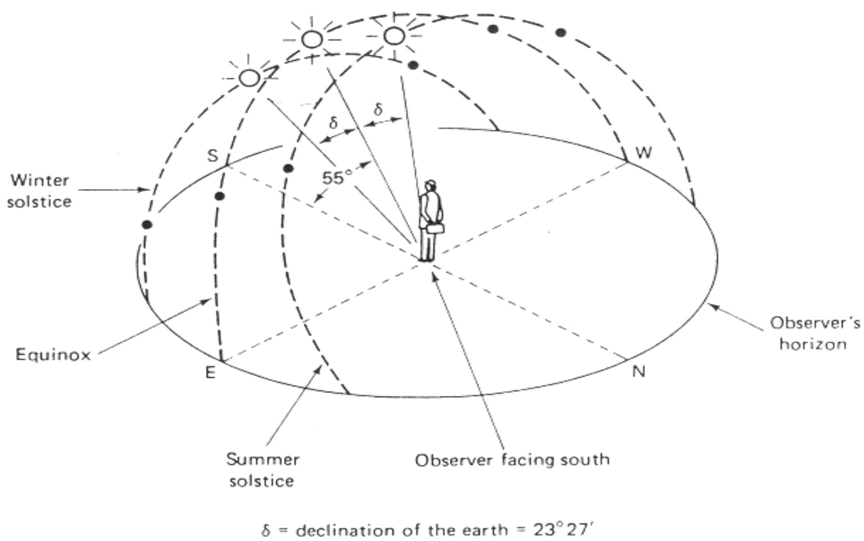


Figure 2 . 5:
Apparent motion of the sun relative to a fixed observer [Green, 1982]

This altitude angle will determine the optical path length through the atmosphere and the irradiance attenuation depends on the amount of dust, haze, smog and clouds in the sky [Engstrom, 1974].
An overview of the irradiance attenuation can be seen in figure 2.6.

An estimate of the contribution of altitude angle can be calculated using the data in figure 2.6. For the Netherlands, this latitude is at about a 52^0 north (e.g. location de Bilt: 52^0 06' 00"). In mid winter (December 22) the maximum angle above the observer horizon is 15^0 (90^0 minus 52^0 minus inclination angle of 23^0). In mid summer (June 21) this angle is 61^0.

The larger this angle the smaller the optical path length through the atmosphere, the less the attenuation. The direct sunlight illumination:

- At mid summer, horizon altitude angle of 61^0: Illumination 1,0 x 10^5 lux.
- At mid winter, horizon altitude angle of 15^0: Illumination 2,0 x 10^4 lux.
- At sunrise or sunset altitude angle 0^0 down to -0,8: Illumination 732 – 453 lux.

Therefore, the sunlight irradiance at mid summer is five times that of mid winter. This result is in agreement with the values found above.

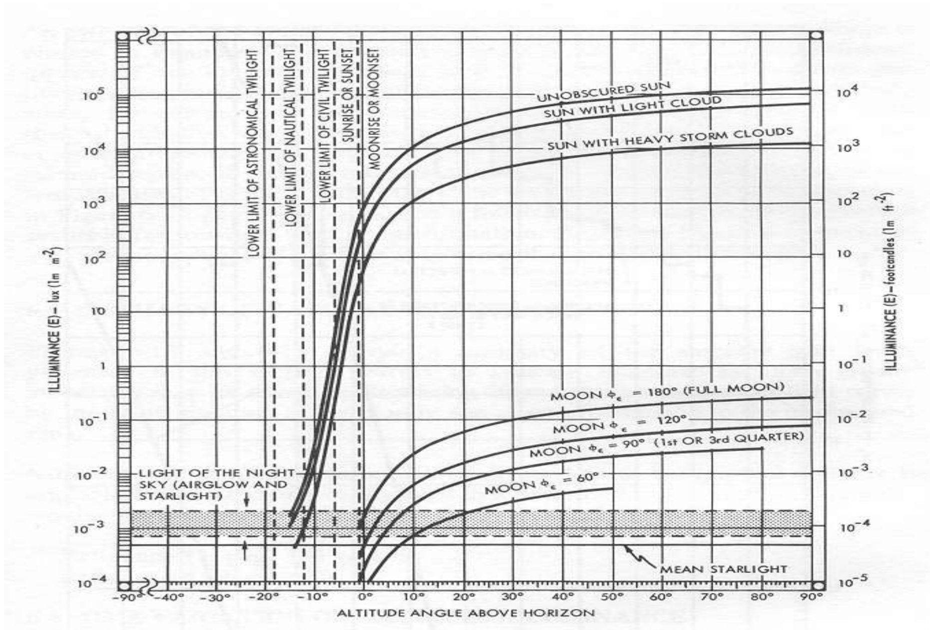


Figure 2 . 6:
Illuminance E as function of altitude angle above the observer horizon [Engstrom, 1974].

By taking as potential the whole daytime between sunrise and sunset, one can deduce the average number of sun hours in a year. For example in the Netherlands on average, there could be a maximum of about 12 sun hours per day throughout the year [KNMI, 2002]. The actual sun hours are determined by the degree of overcast. At weather stations, a threshold is introduced to count for the genuine sun hours. Therefore, the amount of actual sun hours will be less. For instance last year, 2001, the total sun hours were only 1525 in comparison to 12 x 365 = 4380. Alternatively, in percentage only 35 % of the maximum amount of sun hours in a year. Looking at the amount of sun hours in the last five years however, there seems to be a slight tendency towards more actual sun hours. A positive side of the global increase in average temperature possibly?

Note however that on a clear day about one-fifth of the total illuminance at the earth's surface is from the bright sky, i.e. from sunlight scattered by the earth's atmosphere.
As a result, the received illuminance at the earth's surface is:

	At mid summer	At mid winter
• Direct sunlight (including atmospheric scattering)	10 x 10^4 lux	20 x 10^3 lux
• Full daylight (no direct sunlight)	1,2 x 10^4 lux	4,2 x 10^3 lux
• Sun with light overcast day	6,5 x 10^4 lux	18 x 10^3 lux
• Sun with very dark overcast day	10^4 lux	3,5 x 10^3 lux

For a comparison, full moon yields just an illuminance of 10^{-1} lux.

An over view of illuminance levels is presented in figure 2.7.

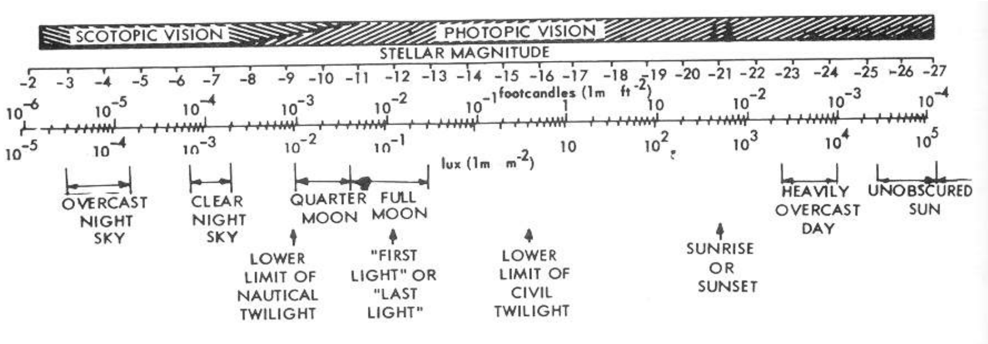


Figure 2 . 7:
Range of natural Illumination levels [Engstrom, 1974]

The translation from illuminance to irradiance is called 'Spectral Luminous Efficacy'. Originally, this concept of spectral luminous Efficacy has been introduced to measure lamp efficiency. Nowadays this translation method is also in use for sunlight.
The Luminous Efficacy of some light sources is presented in figure 2.8.

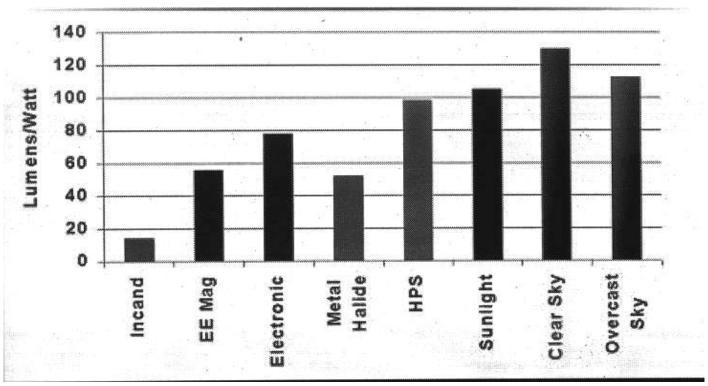


Figure 2 . 8:
Luminous Efficacy of several light sources [Alpha, 2002]

Note that the abbreviations meant:

- Sunlight----------Direct sunlight
- Incand ---- -----incandescent lamplight
- EE Mag --------discharge lamplight
- Electronic- -----LED light
- Metal halide----Halogen lamplight
- Clear sky: Just the light coming from the sky
- Overcast sky----light coming from the clouds

Using efficacy values of figure 8 the irradiance can be calculated as:

	At mid summer	At mid winter
• Direct sunlight (including atmospheric scattering)	1,0 x 10^3 W/m^2	2,0 x 10^2 W/m^2
• Full daylight (no direct sunlight)	9,2 x 10 W/m^2	3,2 x 10 W/m^2
• Sun with light overcast day	5,9 x 10^2 W/m^2	1,6 x 10^2 W/m^2
• Sun with very dark overcast day	9,1 x10 W/m^2	3,2 x 10 W/m^2

B. The Extreme low level sunlight irradiance values
To test the limit of PV applications it will be necessary to know more about the most unfavourable conditions or the extreme low level sunlight light irradiance values.
The amount of available sunlight is minim in mid winter. Therefore the distribution and total amount of sun hours during the months November, December and January of the last five years were analyzed

- The average of the total sun hours in November are 68 hours about 25% of the maximum possible 9 hours per day.
- The average of the total sun hours in December are 60 hours about 25% of the maximum possible 7,7 hours per day.
- The average of the total sun hours in January are 68 hours about 25% of the maximum possible 9 hours per day.
- The average winter sun hours are about 65 per month or about 25% of the maximum possible 8,6 hours per day.

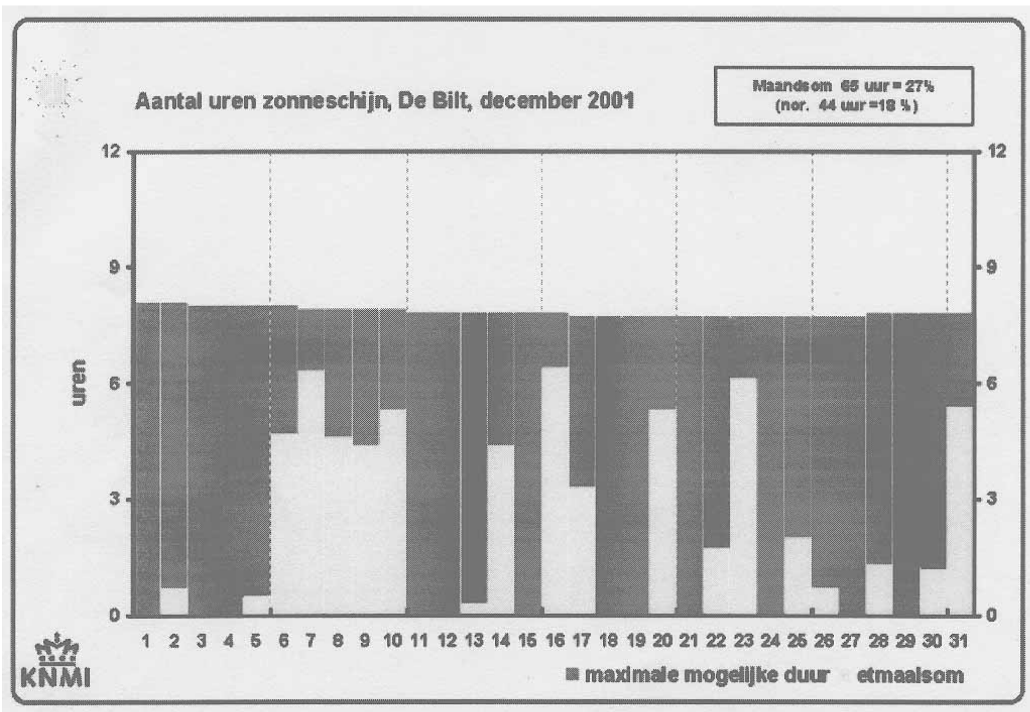


Figure 2 . 9:
Amount of potential and actual sun hours in December 2001 [KNMI, 2002]

Another parameter in conjunction with PV cell is the availability of sunlight over a short period, for instance in one week how many days are without any sun hours in that particular week (figure 2.9). How is the distribution of days without any sun hours over the whole month, season, and year or even over some consecutive years? Preliminary statistical analysis of the months November, December an January over the last five years reveal that two consecutive days without sun hours have a probability to occur of less than 15 % while three consecutive days have a probability of less than 10% but they occur and has to be taken into account in reliability calculations.
In the past measurements have been done for PV applications on roofs to obtain some insight how often over a period of 10 years (1971-1980) the nominal PV power might drop below the nominal threshold. The results are presented in figure 2.10. confirming the above trend.

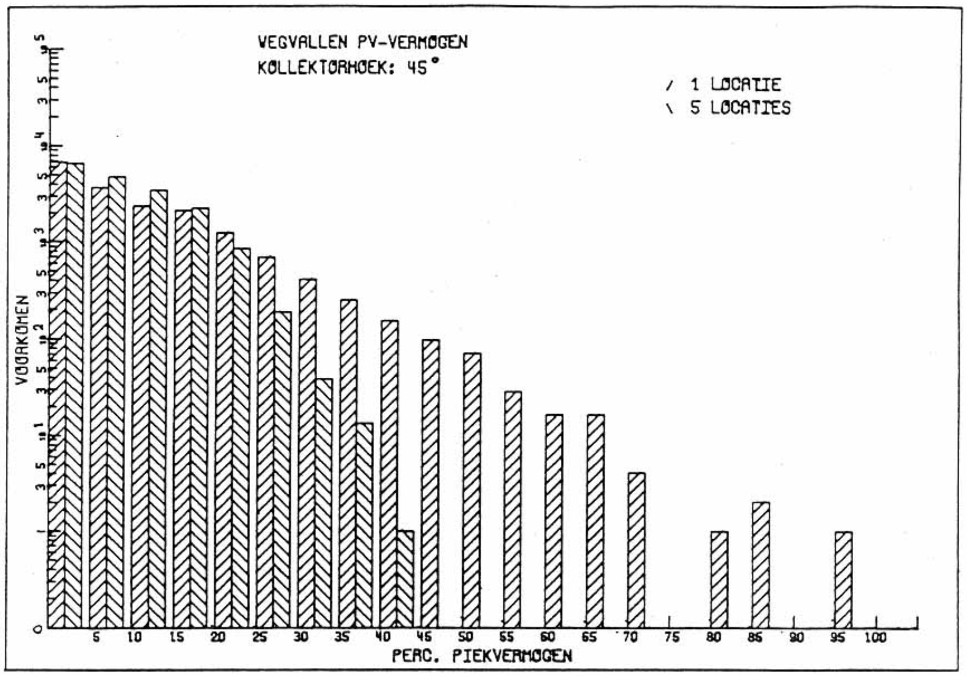


Figure 2 . 10:
Amount of occurrences in the period 1971-1980 that the in a one-hour slot the PV power will drop below its nominal threshold. The PV panels are placed at a 45^0 inclination.

2.3.3 Artificial light

A. General considerations
Artificial light (lamplight) can be divided into three general classes namely:
- Incandescent lamplights: e.g. from lamp bulbs
- Discharge lamplight: e.g. from arc and fluorescent lamps
- Solid state lamplight: e.g. from LEDs

B. Incandescent lamplight
Incandescence lamps produce light by heating a filament until it glows. Electric current is used to heat a coiled tungsten filament to incandescence. To prevent evaporation of the filament, the glass envelope (the bulb) is filled with a mixture of nitrogen and a small amount of other inert gas such as Argon or Xenon. Special cases are Halogen lamps. Unlike normal incandescent lamps, Halogen lamps use Halogen gas fill such as Iodine or Bromine. Due to this special gas fill, a process called ‘Halogen Cycle’ will occur inside the lamp. Halogen gas combines with the tungsten that evaporates from the lamp filament, causing it eventually to re-deposit on the filament instead on the bulb wall as it does in standard incandescent lamps. Incandescent lamps are strongly affected by input voltage as can be seen in figure 2.11 and 2.12 with respect to:
- Life time
- Lumens per watt (light output)
- Emission spectrum

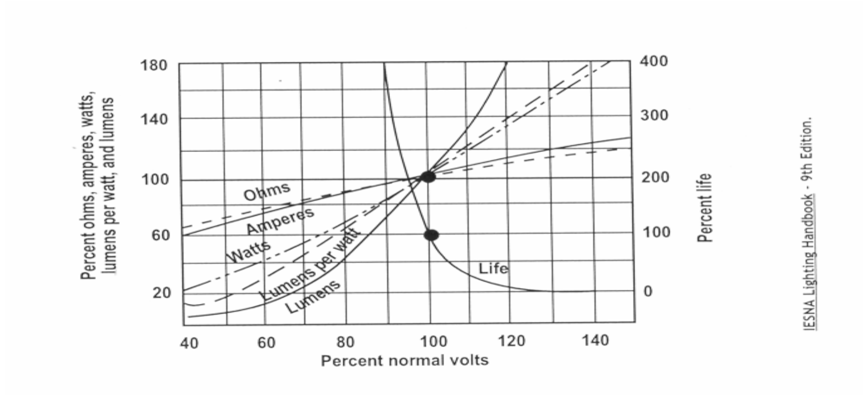


Figure 2 . 11:
Effect of voltage and light output on lamp life and light output [Taylor, 2000]

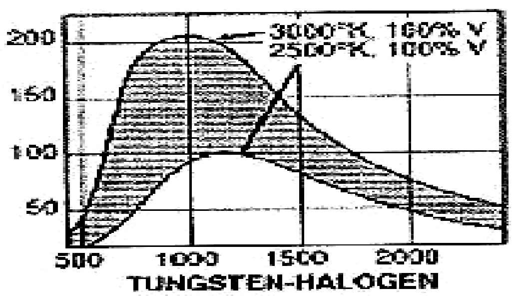


Figure 2 . 12:
Spectral output versus input voltage [PTI, 2002].

C. Discharge lamplight
Discharge lamplight is quite common in offices. With the introduction of ECO lamps, discharge lamplight nowadays is also used at home.

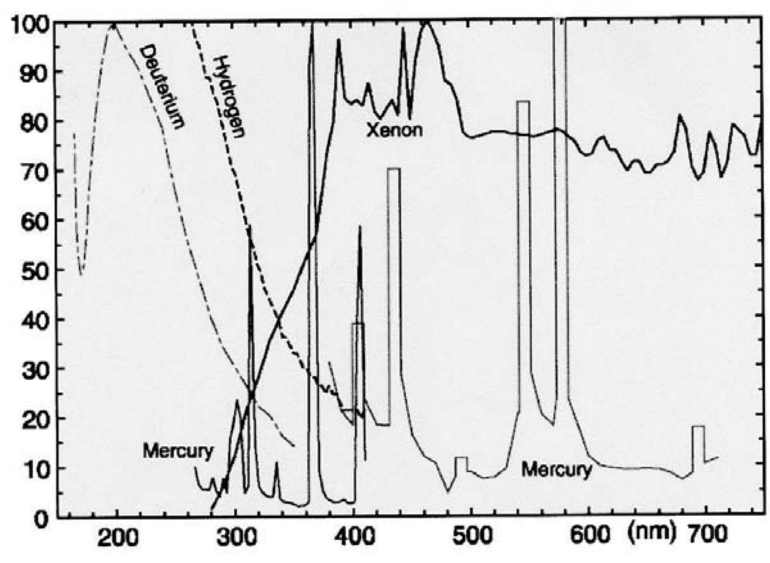


Figure 2. . 13:
Arc lamps spectrum [Ryer, 1997].

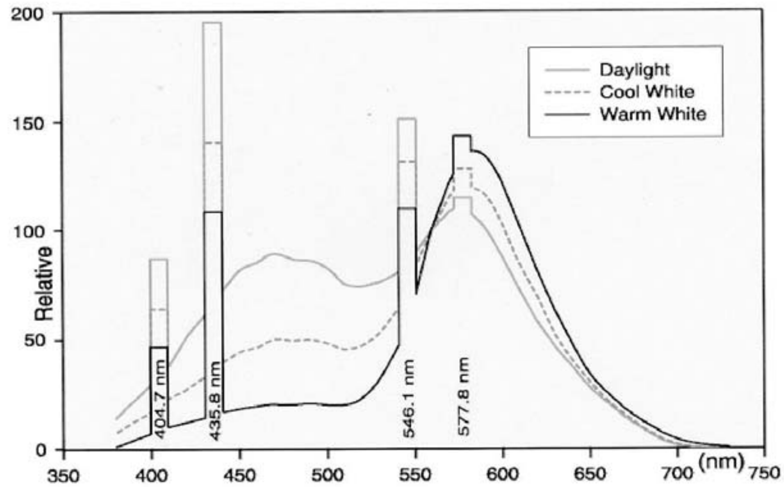


Figure 2 . 14:
Typical fluorescent light sources spectrum [Rye, 1997].

There seems to be a discrepancy between the spectrum of daylight and fluorescent light which might have some impacts on the PV cell to be used in indoor applications.

D. Solid State lamplight
A growing application of Leeds as artificial light source opens the opportunity for low power light. In particular, the White LED (WLED) as used in the 'Light the World project' is a potential sustainable light source [Holiday, 2002].

2.3.4 Indoor-light

During daytime, the light indoors will be mixture of sunlight and artificial lamplight depending on the time of the day, at night lamplight only (p.m. full moon).
The percentage of sunlight depends also on the orientation of the window and the degree of overcast. For a clear day, measurements have shown [Li et. al. 2000] that north- facing windows receive an illuminance of about 35 k lux; while in the other directions (i.e. E, S, W) there were values of 90 k lux. During overcast days, the measured illuminance was about 30 k lux for all four directions, indicating the large diffuse component of the sunlight radiation.
The contribution of sunlight inside a room depends on the distance between an open aperture and the point of observation and of course the obscuration by the open aperture. In cases of large windows for instance over the whole width of the room, the attenuation is mainly caused by the reflectance of the windowpane.

For example: direct sunlight with a south-facing window. With a glass reflectance of 4 %, it means that 96 % of the illuminance received at the window is transmitted and could penetrate deeply into the room. The other limiting factor will be the angle between the apparent sun orbit and the observer horizon, casting a shadow of the window upper rim. This angle will depend on the time of the year and the latitude. For the Netherlands, the latitude is about 52^0 north. In mid winter (December 22) this angle is 15^0. In mid summer (June 21) this angle is 61^0. Therefore, in winter the direct sunlight will penetrate deeper into the room than in summer but the intensity will be lower. This lower intensity is a result of attenuation due to a longer path length through the atmosphere. The difference between mid summer and mid winter is a factor 5 (see previous section). The overall light level will obviously also depend on the surface reflectance of the walls, ceiling and floor for this direct sunlight.

For diffuse sunlight, the decrease in radiant power is quite rapid. The attenuation at the glass window is about 10 % per windowpane. Just one meter from a window with a single windowpane, the radiant power has decreased down to less than 40 % of the value outdoors. At a distance of five meter, this decrease in radiation power is already 93 % [Wen, 2002]. With an insulation double-glass window, this decrease at one and five meters could be even respectively 70 % and 97 %. All these values were measured on a surface parallel to the window, disregarding shadows etc.

The illuminances at vertical and horizontal surfaces perpendicular to the window surface are plotted as function of distance from the window in figure 2.15.

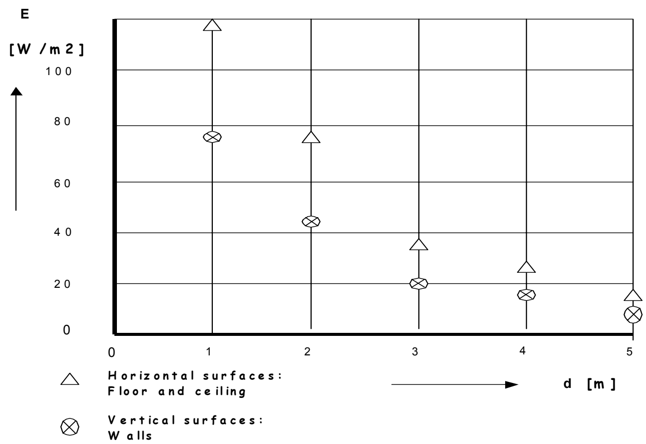


Figure 2 . 15:
Diffuse sunlight Irradiance E as function of the distance d from the window. (Window over the whole width of the building, 5m)
[Adapted in accordance with Wen et. al., 2002]

In offices, a standard minimum value of radiant power has to be available by law (ARBO) based on the minimum for reading. If the radiant power of the sunlight is insufficient, artificial lamplight must be added. For example, the absolute minimum illuminance recommended for reading is about 500 lux, which is equivalent to about 3 - 5 Watts/m^2 radiant power. In comparison the maximum sunlight outdoors yields an illuminance of about 100 000 lux at mid summer. At home, this standard minimum will be not applicable. For instance in corridors, the illuminance could drop below the one Watt/m^2. Obviously at such a location, it will not be the main task to use PV cells.

2.4 Sumary and Conclusions on Photo Power and Energy

The question in this chapter was:

What kind and amount of photo power and photo energy is available both outdoors as indoors?

The following answers have been formulated

Outdoors:

- At a clear day:
  - Spectrum: standard Air Mass (AM) 1.5
  - Optimum illuminance: 100.000 lux, about 1000 W/m^2 irradiance at mid summer.
- Overcast/ Diffuse day:
  - Spectrum: blue enhanced
  - Illuminance: less than 35.000 lux or about 325 W/m^2 at mid summer
  - The difference between mid summer (diffuse) and mid winter (diffuse) illuminance is a factor 5.

Indoors:

- For a south-facing double glass window depending on the percentage direct and diffuse sunlight the irradiance will be:
  At the windowsill 240 – 920 W/m^2 during summer.
  At a distance of about one meter from the window 160 – 900 W/ m^2 during summer.

At distances, more than one meter from the window, the size of the window will determine the contribution of diffuse sunlight. The illuminance level will drop rapidly and artificial lamplight is needed occasionally.

- For a north-facing room mainly diffuse sunlight exist
- For an east- and west-facing window about a half-day, there will be also direct sunlight in addition to the diffuse light.

- Absolute minimum illumination level for reading is 500 lux equivalent to an irradiance of about 5 W/m^2. This illumination level as minimum indoor office illumination level is in accordance to Arbo legislation and could therefore be expected for offices. At home of course lower levels are possible.

3. Photo Voltaic Energy Converters

In this chapter, answers are sought for the question: What types of PV converters are available and what is their performance to date?

3.1 General remarks

Depending on their energy conversion method, the Photo Voltaic (PV) cells can be divided into the following families:

1. The p-n or diode family.
2. Molecular Photo Voltaic (PV) family also known under the name of 'Dye Sensitized PV'

The most well known as 'solar cell' is the diode family.

3.2 The (P-N) diode family

Although the photo voltaic effect was already known since its discovery by Becquerel in 1839, it took more than one hundred years before Chapin, Fuller and Pearson developed the first solid-state solar cell in 1954. They used a diffused silicon p-n junction. So basically, this photo voltaic cell is a p-n junction or diode with a large surface area.
Taking the used materials in open literature as point of departure, one can divide the diode family into five groups namely:

- The single material semiconductor: e.g. Silicon devices.
- The IV-IV material devices based on Silicon Carbide
- The III-V material devices: e.g. Gallium Arsenide
- The II-VI material devices: e.g. Cadmium Sulphide
- The IV-VI material devices: e.g. Lead Telluride
- The polymer devices

3.2.1 The single material semiconductor devices

Today silicon devices dominate the single material semiconductors. These silicon devices can be categorised according to the used technology and the crystallographic texture:

1. Mono-crystalline silicon (mono-c-Si)
2. Poly-crystalline silicon (poly-c-Si) also called Multi-crystalline silicon
3. Micro-crystalline silicon (mc-Si)
4. High-temperature thin-film crystalline silicon (Ht-f-Si)
5. Low-temperature thin-film crystalline silicon (Lt-f-Si)
6. Amorphous silicon (a-Si)

<u>Note 1. : Monocrystalline vs. multicrystaline Silicon PV Cells</u>

Despite the new thin film technologies, monocrystalline silicon is still the main source for photo voltaic cells with a market share of about 85.5 % [Novem, 2000, Goetzberger et. al., 2000]. There is however a trend, that multicrystalline silicon usage is growing more rapidly than that of monocrystalline [Bruton, 2002].

<u>Note 2.: Thin Film Silicon PV Cells</u>

The Poly and Micro-crystalline (No 2 and 3) of the diode family are in literature sometimes put apart as different types but also sometimes treated as one type. Quite often, Micro-crystalline and low temperature thin film (no 3 and 5) are treated as similar [Novem, 2000], also technological Micro-crystalline (no 3) and resembles that of Amorphous Si (no 6).

3.2.2 IV-IV material

Usually this is used in combination with other elements.

3.2.3 III-V material

This has been the most promising material for decades. The main advantage in comparison to silicon is its larger band-gap. The larger band-gap has a positive influence on the spectral absorption characteristics and conversion efficiency. The disadvantage of this material in comparison to silicon is its very nature of being a composite, hence more expensive in fabrication. In addition, Silicon has in comparison to Gallium Arsenide one big advantage: namely 'insulation by oxidation', since SiO_2 = glass therefore an insulator.

The dilemma of these III-V PV materials is that due to their expensive fabrication process, they are not used. On the other hand, the prices did not get down because they are not widely used. A good application example of this material was demonstrated in the recent Solar World Challenge race across Australia from Darwin to Adelaide, a distance of 4000 km [World Solar Challenge, 2001]. This race was won by the NUNA, the PV powered car of the Delft University of Technology and the University of Amsterdam.

3.2.4 II-VI Material and IV-VI Material

These materials are mainly used to make thin-film PV cells. Among these, CdTe is a promising technology and is widely used in gadgets.

3.2.5 Polymer PV

Although inorganic PV cells do not yet accomplish the highest efficiencies and stabilities, there are a growing number of examples using polymer or organic PV cells [Yu et. al., 2000; Schmidt-Mende et. al. 2001] and hybrid GaAs/polymer solar cells [Mao et. al. 1998]. These polymer PV cells are due to their mechanical properties in particular interesting with respect to new consumer products like e-papers and e-books.

3.3 Dye Sensitized PV

Brian O'Regan and Michael Grätzel first developed dye Sensitized PV cells in 1991.

In this type PV cell, the light absorption and charge separation steps are differentiated. The light absorption is performed by a monolayer of dye (i.e. a Ruthenium complex) or transition metal complexes that are absorbed chemically at the surface of an oxide semiconductor such as TiO_2, ZnO, SnO2, and Nb_2O_5. Mesoporous films of these materials are contacted with redox electrolytes. When an incident photon is absorbed by the dye, its electron is raised to an excited state. The dye has the ability to transfer this excited electron to the conduction band of the oxide semiconductor. The conduction band electrons than cross the mesoporous film readily collected by a terminal to the external current circuit, and could perform some electric work. The terminal electrodes could be made of the same oxide semiconductor material [Barbe, 1997a, Kambe et. al. 2000; Chappel et. al. 2002]. The transparency of the TiO_2 electrodes makes it possible to use these cells as active solar windows [Barbe, 1997b].

The first reported efficiency was 7.1% [O'Regan et. al., 1991]. In the more recent publications, efficiencies about 10.4% are reported [Hagfeldt et. al. 2000].

One of the main concerns in using these PV cells is stability [Hinsch et. al., 2000; Hinsch et. al. 2001; Petterson et. al. 2001; Macht et. al. 2002].

Practical advantage could be gained by the replacement of the liquid electrolyte with a solid charge transport material as for example an organic p-type semiconductor [Gebeyehu et. al. 2001; Meyer et. al. 2001].

Apart from single layer systems also coupled systems are reported [Tai et. al. 2002]

The main advantage of these Dye Sensitized PV cells in view of indoor application is, their spectral sensitivity matching with lamplight. In addition, although the photocurrent diminishes proportional to the reduction in illuminance level, the output voltage remains nearly constant even at low light levels of smaller than 300 lux [Burnside, 2000]. In addition, the performance improves with increasing temperature [Phani, 2001].

The disadvantage of these PV cells is the not yet commercial availability and their long-term stability.

3.4 Efficiency of Photo Voltaic Transducers

The efficiency of a Photo Transducer is defined as the ratio between the electric power generated by the transducer as conversion product and the total photo power incident on the sensitive surface of the transducer.

The electrical power output depends on:

1. Irradiance and Illumination level
2. Spectral response or sensitivity of the transducer.

3. Surface characteristics of the transducer; for example reflectivity and transmission properties.
4. Temperature
5. Stability

The efficiency is lower than could be expected from theoretical calculations due to the light reflection losses, the leakage conductance loss and the effect of series resistance.
PV cells can be interconnected to form modules. One special way of interconnecting PV cells is monolithically [Dinetta et. al. 1995, Pena et. al. 2001]
Due to energy losses in the interconnection and other components, the efficiency of PV cells as stand alone devices will be larger than that of a module build from several cells. This loss can be from 4% up to 15 % relatively.

In 'Progress in Photovoltaics', an overview of the Solar Cell Efficiencies is presented [Green et. al., 2002]. In this report, In table 2, only the most recent updated values supplemented with other values found in other literature will be presented. In the following sections, some relevant data of this table will be quoted.

3.4.1 Efficiency as function of illumination level

The efficiency diminishes with decreasing illumination. In open literature not much data can be found. Therefore in Appendix A some calculation are presented for two high-efficient Si PV cells. In this calculation just the first diode term and the series resistance was taken into account.

	PV cell 1) efficiency: [Green et. al., 2002]	PV cell 2) efficiency: [Glunz et. al. 2002]
At 1000 W/m^2	24,7 %	21,3 %
At 100 W/m^2	22,3 %	19,1 %
At 10 W/m^2	19,9 %	17,1 %
At 1 W/m^2	17,4 %	15,0%

The decrease was found to be about 30% in case the illumination is decreased down to the 1/1000 sun.
As can be seen in figure 3.1 [Glunz et. al. 2002], the measured degradation depends on the type of PV cell. At high efficiency Si PV cells, the degradation is less than at moderate performing commercial ones. At the high efficiency PV cell a good matching between the calculation given in appendix A and measurements presented in figure 3.1 was found.

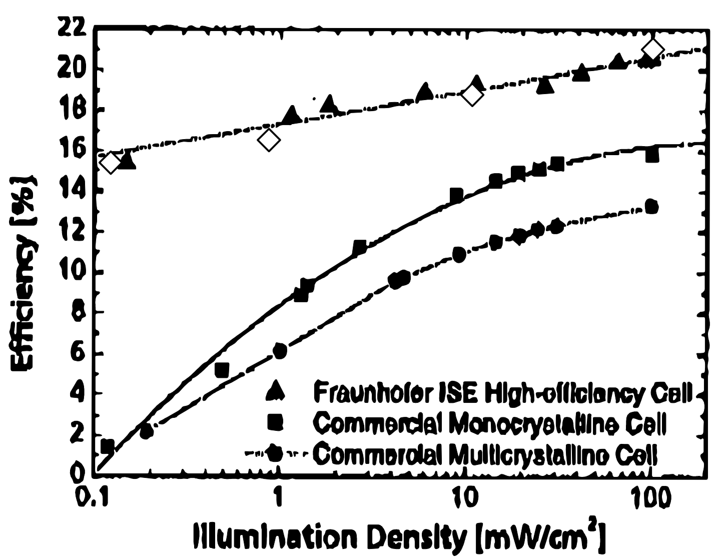


Figure 3.1:
Efficiency as a function of illumination level density:
a) For a high-efficient PV cell (η=21.3 % at 1000 W/m^2)
as calculated in appendix A and measured [Glunz et. al. 2002].
b) Measured comparison between a high-efficient Si PV cell commercial silicon PV cells

3.4.2 Efficiency as function of spectrum

Matching the band gap of the PV material to the available radiation will improve the efficiency.

Spectral response of silicon transducers is usually due to theirs band-gap in the region of near Infra Red. For instance for thin film amorphous silicon solar cells the peak is approximately at a wavelength of 600 nm [Prentice 2001].

Note that the IR part of sunlight is mostly used in applications as Solar Cookers [World Solar Economy, 2001; Medved et. al. 1996], Solar (thermal) Collectors.

3.4.3 Efficiency as function of temperature

Depending on the type of PV cell, the temperature could have a positive or negative influence. For example at mono crystalline Si PV cell, the open circuit voltage decreases 2,3 mV for a temperature increase of 1^0 C. At amorphous Si and Dye Sensitized PV cell, the performance improves with increasing temperature.

This decrease of efficiency with temperature could become a factor to be taken into account in cases in which PV cells are illuminated at a non-ventilated windowsill.

Table 2.: Efficiencies of PV cells

Classification of PV material	**Cell efficiency in laboratory [%]**
Silicon	
Mono-Crystalline Silicon	24,7*)-35
Poly- or Multy-Crystalline Silicon	16-19,8*)
Micro-Crystalline Silicon supported film	13.7-16.6*)
High-temperature thin-film crystalline Silicon	14
Low-temperature thin-film crystalline Silicon	11
Amorphous Silicon	8.6-12.7
III-V	
GaAs Crystalline	24.4
GaAs Thin-film	23,3*)
GaAs Multi-Crystalline	18.2*)-18.6
InP Crystalline	17,6-21.9*)
II-VI and IV-VI	
CdTe	16.5
Polymer	
Uniax	4.1
Dye Sensitized	
Black dye sensitizer	6,5*)-10.4

Note:

- *) Measured under the global AM 1.5 spectrum ($1000W/m^2$) at $25\ ^0$ C.
- Empty spaces in table means no data yet available.
- The references are mainly taken from the table of PV efficiencies [Green, 2002]

3.5 Means to improve efficiency of PV transducers

In literature, several ways to improve the efficiency of PV transducers have been reported. All these improvements can be categorised according to what extent the original devices have to be modified or what additional technological steps have to be taken.
Categorized according to complexity on could summarize:

1. Improvements on existing devices
2. Multi-junction devices
3. Light trapping
4. Light concentrators
5. Wavelength transformation

3.5.1 Improvements on existing devices

One way to improve the overall PV efficiency and lifespan is by surface passivation. This passivation could be done for instance by plasma enhanced chemical deposition of SiO_2 [Knobloch et. al. 1994, Leguijt et. al., 1996]. This passivation could also be done with a SiC layer [Solangi, 1994] This process improves interface and removes traps. These traps could cause interface recombination of electron-hole pairs and as a result would reduce the photo current. Another step is the so-called annealing of solar cells [Verhoef et. al., 1990]. Due to this additional thermal treatment, it was reported that the bulk effective minority carrier diffusion length increased by 10 % and as a result the solar cell efficiency by 0.5%.

3.5.2 Multi-junction devices

The efficiency of PV cells can be improved by constructing the cells as a sandwich of semiconductor layers, in fact several PV cells on top of each other. This could be done for example by depositing an additional amorphous layer on top of a solar cell [Song et. al., 2000]. They claim an efficiency of about 10% without anti-reflex coating.

These multi junctions were proposed in the early 1990' as indoor PV applications with efficiencies of 9.6 % [Catalano et. al. 1992]

However, this trick of placing one PV cell on top of another has not only yielded benefit. To begin there will be additional absorption, forcing the second PV cell to operate in a less favourable illumination. In addition, the price is still a problem. Another problem discovered in the 1970's and still occasionally pops up in literature, is the so-called Staebler-Wronski Effect, namely the degradation of the PV efficiency upon exposure to sunlight [Naseem et. al., 1993, Lund et. al 2001].

Commercial products are put on the market such as for example the triple junction amorphous Silicon PV cells and modules [Unisolar, 2002]. Due to their multi spectral sensitivity, they are well suited for application both indoors and outdoors.

Table 3 Efficiencies of multi-junction PV Cells

Classification of PV material	Cell efficiency in laboratory [%]
a-Si: H/P type c-Si	10
a-Si:H/a-Si: H	9.2
a-Si/a-SiGe:H	9.5
a-Si/:H/poly-Si	12,8
a-Si/a-Si/a-Si	25
$CuInGaSe_2$ (CIGS)	18.9*)
GaAs-AlGaAs	22.3
GaInP/GaAs/Ge	31*)
GaInP/GaAs	30.3*)

Note:

- *) Measured under the global AM 1.5 spectrum (1000W/m^2) at 25 ^{0} C.
- The references are mainly taken from the table of PV efficiencies [Green, 2002]

3.5.3 Light trapping

The efficiency of PV cell could be improved by making sure, that the incident light substantially reaches the P-N junction for conversion. One way is known as ‘light trapping’. The caught light is trapped inside the bulk of the PV cell.

In the most common way this is done by reducing the reflection at the PV surface by an antireflective coating like double layer of SiO_2 [Zhao et. al. 1996], a SiN film [Endros, 2002], carbon and silicon carbide films [Klyui, 2002] or even with the aid of light trapping cover glass [Landis, 1990]. This could also be accomplished by placing special attention towards the dimension and texture of the transparent conductive oxide layer [Wallinga et. al., 2001].

Another method is by surface treatments like anisotropic grooves and pyramids etching of the surface [Campbell et. al., 1988; Keavney et. al. 1989; Jenkins et. al., 1992; Knobloch et. al. 1994, Hava et. al. 2000].

3.5.4 Light concentrators

A method to optimized light capture and therefore achieving improved photo energy conversion efficiency is by light concentrators. One should make a distinction between indoors and outdoors applications. For outdoor application in countries like the Netherlands, which are quite often overcast, the light will be diffuse therefore concentrators, which follows optical laws, will be less effective [Novem, 2000]. In addition, there will be some thermal aspects to be taken into account. At indoor applications however due to the low light levels, these thermal aspects will not pose a problem. In addition, the light fluxes are less diffuse. Therefore, it would be interesting to take a closer look at the possibilities of using concentrators at indoor applications for example direct beneath a lamp.

There are several conceivable types of light concentrators, since any kind of geometric optical trick can be used to concentrate light on the PV surface. Up to now however, concentrators have been associated with large systems [Swanson, 2000]. Could they also be designed for small consumer products? On the other hand, could it be that the constraint in consumer product applications, that the size and appearance of the concentrator have to be tailored to match the product, just is a bridge too far?

The simplest ones are mirrors. For example with just white painted transparent plates a concentration of a factor 2 would be possible [Smestad, 1982]. Silicon material can also be used as mirrors [Lee et. al. 1994]. Even non-imaging concentrators are reported using multiple surfaces yielding a concentration of a factor 5.5 [Benitez et. al., 1999]

Another optical trick is lenses. For instance, concentrators could be made as Fresnel lenses [Piszczor et. al., 1993], and holographic concentrators [Stojanoff et. al. 1999].

E. Wavelength transformation

A method to optimise the conversion efficiency is by enhancing the light absorption in the spectral sensitive or responsive wavelength region of a transducer. This can be done by light wavelength transformation from outside to inside the photosensitive region of the transducer.

In principle, there are two kinds of transformations:

- From the ultra-violet / blue region towards the more red region
- From the infra-red region towards the more blue region

Example of wavelength transformations from the blue region towards the more red dominant part of the spectrum are reported with the aid of a luminescent porous silicon layers [Saadom et. al. 1999] and fluorescent coatings [Maruyama et. al. 2001]. In the first example an improvement of about 50 % is claimed, partially also due to the antireflection property of the porous silicon layer. In the latter case an improvement of about 30% is claimed

An example of wavelength transformation in the opposite direction is reported with the aid of so-called anti-Stokes pigments. These pigments absorb infrared radiation and convert this into visible wavelength [Martindill M. 1996]

3.6 Conclusions

In this chapter, answers were sought for the question: What types of PV converters are available and what is their performance to date?

- At this moment as found in literature the most promising PV cell types are:
    - The high performing mono crystalline Si PVs
    - Dye Sensitized PVs.
    - Specific amorphous Si PVs
- About their performance at low light levels, not much is found in literature. Therefore, some calculations have been done. The preliminary results confirm the trends found. However, measurements and more precise calculations are needed.
- The efficiency of modules is evidently lower than that of cells. In integrating of PV cells and modules in products this needs to be considered.

4. PV Performance and Energy Conversion

In this chapter, answers are sought for the question: How much electrical power and energy can be harvested with PV converters both outdoors and indoors?

4.1 General remarks

Given the irradiances and illuminances presented in chapter 2 and the PV performance as presented in chapter 3, the power and energy that could be harvested can be calculated.

4.2 First order approximation

A. General considerations

For this calculation, one of the best performing mono-crystalline silicon PV cells is taken from table 2. The efficiency is 24.7 % at an AM1.5 spectrum and irradiance of 1000W/m^2. For the degradation in its efficiency at lower light levels the first order approximation as calculated in Appendix A is taken. The actual performance degradation will be investigated further with measurements as planned in July 2002.
PV Efficiency:

- At 1 sun, 1000 W/m^2: 24.7 %
- At 1/10 sun, 100 W/m^2: 22.3 %
- At 1/100 sun, 10 W/m^2: 19.4 %
- At 1/1000 sun 1 W/m^2: 17.4 %

The actual performance degradation could be even worse according second order and third order approximations, however for the time being the calculations will be based on above first order approximations.
Another aspect is the spectral response of PV cells:
In Outdoor applications the sun will be the sole source to deliver photo energy. Therefore the sun spectrum will be the dominant factor in the performance analysis of the photo transducer and logically also in the choice of the most appropriate one to be used.
In indoor applications, predominantly lamplight will be the source of photons. Taking windowsills and incoming sun light also into account; the spectrum will be mixture of lamp- and sunlight.
If the product has to function both indoors and outdoors, the spectrum to be taken into account will also be a mixture of sun and lamplight. In this case, technological and cost aspects will be the dominant factor in the choice of the photo transducer. As can be seen in fig. 3.1, the efficiency of less expensive PV cells at 1000W/m2, is for many applications good enough. Only at applications at low illumination levels the expensive PV cells will be a must.
For the time being, spectral factors will not be taken into account in the power and energy conversion calculations.

B Power and Energy Outdoors

Outdoors the irradiance might vary between overcast and clear sky. Therefore, the value will be between 300 up to 1000 W/m^2 (in the Netherlands). With the PV efficiency above mentioned, this would yield an electrical power of about 69 up to 247 W per m^2 PV surface. For one m^2 PV cell and the actual sun hours per year of about 35 % of the maximum sun hours possible in one year, an energy could be harvested of (0.65 x 69 + 0.35 x 247) x 12 Wh = 1584 Wh on average per day. Or for one dm^2 or 10 cm x 10 cm (the standard waver size) PV surface the harvested energy will be 15,84 Wh.

C Power and Energy Indoors

C.1 On a windowsill

On a windowsill, facing south irradiance between 240 and 920 W/m^2 could be expected. With the PV efficiency above mentioned, this would yield an electrical power of about 55 up to 227 W per m^2 PV surface. For one m^2 PV cell and the actual sun hours per year of about 35 % of the maximum sun hours possible in one year an energy could be harvested of (0.65 x 55 + 0.35 x 227) x 12 Wh = 1382 Wh on average per day.
On a windowsill facing east or west the direct sunlight contribution will be only for 6 hours on average throughout the year. Due to reflections from other buildings, some contribution of the direct sunlight

reduced however in intensity will still be possible. Taking a reflectance of 50 %, this reflected sunlight will have an irradiance of 460 W/m^2 yielding an electrical power of about 113 W per m^2 PV. Therefore the energy harvested on average per day on the windowsill facing east or west becomes:
(0.65 x 55 x 12 + 0.35 x 113 x 6 + 0.35 x 227) Wh = 1143 Wh.
For the north-facing windowsill the direct sunlight will about be zero, therefore only reflected direct sunlight might contribute to the irradiance. So an energy could be harvested of: (0.65 x 55 + 0.35 x 113) x 12 = 904 Wh on average per day.

C.2 On a certain distance from the window
The same calculations could be done for various distances from the window. There will be a difference in output for different surface orientations. However, these calculations are only valid provided the window is large enough to not cause any obscuration:

a) For a distance of one meter from the window:
South-facing window:

- Horizontal orientated PV surfaces:
  - Power: 20 up to 81 W/m^2
  - Total energy on average per day: 496 Wh/m^2
- Vertical orientated PV surfaces:
  - Power: 12 up to 52 W/m^2

Total energy on average per day: 295 Wh/m^2 East- or west-facing windows:

- Horizontal orientated PV surfaces:
  - Power: 20 up to 81 W/m^2
  - Total energy on average per day: 410 Wh/m^2
- Vertical orientated PV surfaces:
  - Power: 12 up to 52 W/m^2

Total energy on average per day: 243 Wh/m^2 North- facing window:

- Horizontal orientated PV surfaces:
  - Power: 20 up to 40 W/m^2
  - Total energy on average per day: 324 Wh/m^2
- Vertical orientated PV surfaces:
  - Power: 20 up to 40 W/m^2
  - Total energy on the average per day: 192 Wh/m^2

b) For distances more than one meter from the window obscuration cannot be prevented. So only useful calculations can be made in case detailed information on window location and size is available. Only a lower limit can be indicated based on diffuse sunlight as presented in fig. 2.15.

- 2 m Horizontal PV: Power 16.5 W/m^2, Energy per day 198 Wh/m^2.
- 2 m Vertical PV: Power 8,8 W/m^2, Energy per day 116 Wh/m^2.
- 3 m Horizontal PV: Power 8,1W/m^2, Energy per day 93 Wh/m^2.
- 3 m Vertical PV: Power 4,2W/m^2, Energy per day 50 Wh/m^2
- 4 m Horizontal PV: Power 6,6 W/m^2, Energy per day 70 Wh/m^2
- 4 m Vertical PV: Power 2,6 W/m^2, Energy per day 32 Wh/m^2
- 5 m Horizontal PV: Power 3,3 W/m^2, Energy per day 34 Wh/m^2
- 5 m Vertical PV: Power 2,2 W/m^2, Energy per day 26 Wh/m^2

4.3 Energy Harvest calculated with measured efficiencies

Point of departure is the same as in section 4.2 namely; the light is a mixture of direct and diffuse sunlight. Direct sunlight with an irradiance of 1000W/m^2 and diffuse sunlight with an irradiance of 300 W/m^2. The day average is obtained by a weight factor obtained as ratio between actual sun hours and potential maximum sun hours. Instead of the calculated efficiency, here in this section the measured efficiencies as depicted in figure 3.1 in chapter 3 are used in the calculation of the photo energy that can be harvested as electrical energy on average per day with a 1 dm^2 PV cell outdoors and indoors. The efficiency of the cell at AM1.5 is 21,3 %. As a kind of visualization, the calculated amount of equivalent AA batteries is included. AA size batteries are taken since they are the most common used batteries in mobile products. To visualize as resume the amount of electrical energy that can be harvested as PV converted photo energy, it would be convenient to compare it with something well known in daily live. Namely the capacity of a commercially available AA penlight battery. A rechargeable AA battery has a guaranteed capacity of 1.2 Ah and 1.5 V output voltages. Therefore, it has output energy of 1.8 Wh. available.

4.4 Winter scenario

Point of departure is here the winter sunlight parameters as presented in section 2.3.2B.

- Outdoors direct illuminance maximum at perpendicular incidence: 2,0 x 10^4 lux or about equivalent to an irradiance of 200 W/m^2.
- Outdoors diffuse irradiance of 160 W/m^2.
- Best indoor performing PV cell with an efficiency at AM1.5, 1000W/m^2 of 21,3 %
- Measured and calculated low light level efficiencies of this PV cell as presented in figure 13 in chapter 3.
- Amount of sun hours as average in December namely: 60 hours or 25% of the max. a potential 7,7 hours per day [KNMI, 2002].
- Weight factor between direct and diffuse sunlight is 25: 75

Outdoors:
Irradiance 200 W/m^2, efficiency PV cells 20 % resulting in 40 W/m^2 electrical power.
Irradiance 160 W/m^2, efficiency PV cells 19,5% resulting in 31 W/m^2 electrical power.
The total energy that could be harvested per m^2 in December on average per day will be:
(0,75 x 31 + 0,25 x 40) x 7,7 Wh = 256 Wh. or for one dm^2, 2,56 Wh. Equivalent to about 1,4 AA batteries.

Indoors:
Windowsill:
On the windowsill the irradiance is reduced by reflection of the window. Since the altitude angle in winter is smaller than in summer, the reflectance is less. Direct sunlight at the windowsill will be reflected 2% while diffuse sunlight will be the same as in summer 10 %.
The result is direct sunlight 198 W/m^2, while diffuse sunlight 144 W/m^2. Or in the amount of electrical energy 39,6 W and 27,4 W per m^2.
For a windowsill facing south; the total energy that can be harvested on average per day per m^2 in December on the windowsill will therefore be: (0,75 x 27,4 + 0,25 x 39,6) x 7,7 Wh =234 Wh. or for one dm^2, 2,34 Wh. Equivalent to about 1,3 AA batteries. For east and west windows this will for one dm^2 be 1,93 Wh, equivalent to about 1,1 AA batteries and for a north facing windowsill, 1,5 Wh or 0,8 AA batteries.

One meter from the window:
South facing window with horizontal PV cell yield: 0,9 Wh or 0,5 AA battery per day per dm^2.
South facing window with vertical PV cell yield: 0,7 Wh or 0,4 AA battery per day per dm^2.
Due to the large diffuse part the amount of energy at east and west facing windows will be about the same, even the deviation with the north facing window will be small.
Only diffuse sunlight means 0,5 Wh/dm^2 per day this is the worst-case value in case of a north facing window.
For distances of one meter from the window and beyond the sunlight will be aided with artificial lamplight. Therefore a energy minima of about 0,5 Wh or 0,3 AA battery per day for a surface of one dm^2 can expected.
An often quoted absolute minima is the 500 lux limit dictated by law (Arbo), but also adopted by interior architects in designing the lights in houses.
This 500 lux is depending on the type of lamp equivalent to an irradiance of about 5 W/m^2. So what can be done with this 5 W/m^2?
At this low irradiance level the efficiency of the chosen PV cell has dropped to a value of 17 %, therefore 0,85 W electrical energy can be generated per m^2. During the time at home of about 12 hours there can be 10,2 Wh of electrical energy be harvested. For one dm^2 this means 0,1 Wh per day.

4.5 Summary and Conclusions

In this chapter, answers were sought for the question: How much electrical power and energy can be harvested with PV converters both outdoors and indoors?

In mid summer, the energy that can be harvested outdoors per m^2 PV outdoors is on average 1584 Wh per day. This is equivalent to about 880 AA Batteries.

Table 4 presents the photo energy that can be harvested as electrical energy on average in summer per day with a 1 dm^2 PV cell outdoors and indoors as calculated in this chapter 4, using data as given in section 4.2. As a visualization aid, the equivalent, number of AA batteries, is compared to the amount of energy as well.

Table 4 Overview Harvested Electrical Energy from the sun

Orientation / Location	South	East/West	North
Outdoors	15,8 Wh; 8,8 AA	15,8 Wh; 8,8 AA	15,8 Wh; 8,8 AA
Windowsill	13,8 Wh; 7,7 AA	11,4 Wh; 6,4 AA	9,0 Wh; 5 AA
One meter from window, PV Horz.	9,9 Wh; 5,5 AA	9,1 Wh; 5 AA	8,2 Wh; 4,5 AA
One meter from window, PV Vert.	8,9 Wh; 5 AA	8,4 Wh; 4,6 AA	7,9 Wh; 4,3 AA
Two meter, PV Horz. Min. value	1,9 Wh; 1 AA	1,9 Wh; 1 AA	1,9 Wh; 1 AA
Two meter, PV Horz. Min. value	1,2 Wh; 0,6 AA	1,2 Wh; 0,6 AA	1,2 Wh; 0,6 AA
Three meter, PV Horz. Min. value	0,9 Wh; 05 AA	0,9 Wh; 05 AA	0,9 Wh; 0,5 AA
Three meter, PV Horz.; Min. value	0,8 Wh; 0,4 AA	0,8 Wh; 0,4 AA	0,8 Wh; 0,4 AA
Four meter, PV Horz.; Min. value	0,7 Wh; 0,3 AA	0,7 Wh; 0,3 AA	0,7 Wh; 0,3 AA
Four meter, PV Horz.; Min. value	0,4 Wh; 0,2 AA	0,4 Wh; 0,2 AA	0,4 Wh; 0,2 AA
Five meters and more, Horz./Vert.	0,25 Wh; 0,15 AA	0,25 Wh; 0,1AA	0,25 Wh; 0,1AA

Table 5 presents the photo energy that can be harvested as electrical energy on average summer per day with a 1 dm^2 PV cell outdoors and indoors as calculated using the measured efficiencies as depicted in figure 3.1 in chapter 3 and the amount of equivalent AA batteries.

Table 5: Overview Harvested Electrical Energy from the sun

Orientation / Location	South	East/West	North
Outdoors	13,8 Wh; 7,7 AA	13,8 Wh; 7,7 AA	13,8 Wh; 7,7 AA
Windowsill	11,8 Wh; 6,5 AA	9,6 Wh; 5,3 AA	7,5 Wh; 4,1 AA
1 m dist., PV Horz.	9,5 Wh; 5,2 AA	7,3 Wh; 4,0 AA	5,2 Wh; 2,8 AA
1 m dist., PV Vert.	8,8 Wh; 4,9 AA	6,6 Wh; 3,6 AA	4,4 Wh; 2,5 AA
2 m dist., PV Horz. Min. value	1,8 Wh; 1 AA	1,8 Wh; 1 AA	1,8 Wh; 1 AA
2 m dist., PV Vert. Min. value	1,0 Wh; 0,5 AA	1,0 Wh; 0,5 AA	1,0 Wh; 0,5 AA
3 m dist., PV Horz. Min. value	0,8 Wh; 0,4 AA	0,8 Wh; 04 AA	0,8 Wh; 04 AA
3 m dist,, PV Vert.; Min. value	0,6 Wh; 0,3 AA	0,6 Wh; 0,3 AA	0,6 Wh; 0,3 AA
4 m dist., PV Horz. Min. value	0,6 Wh; 0,3 AA	0,6 Wh; 0,3 AA	0,6 Wh; 0,3 AA
4 m dist, PV Horz. Min. value	0,4 Wh; 0,2 AA	0,4 Wh; 0,2 AA	0,4 Wh; 0,2 AA
5 m and more dist, Horz. /Vert. Min. value	0,2 Wh; 0,1 AA	0,2 Wh; 0,1 AA	0,2 Wh; 0,1 AA

Comparison between table 4 and 5 demonstrates that with a first order approximation, a good indication can be obtained of the net energy to be gained with the aid of high-performance PV cells.

- Outdoors about 2,79 Wh electrical energy or equivalence of 1,6, AA batteries can be harvested per dm^2 per day.
- At a windowsill facing south 2,54 Wh electrical energy or an equivalence of 1,2 AA batteries can be harvested per dm^2
- At a windowsill facing west or east this figure is 2,14 Wh and 1,2 Wh respectively.
- At a windowsill facing north this figure is 1,66 Wh and 0,9 Wh respectively.
- One meter from the window a minima of 0,7 Wh or 0,4 AA battery can be harvested per dm^2
- One meter from the window with only diffuse sunlight, 0,5 Wh per day per dm^2.
- For the absolute minima of 500 lux there is still harvest of 0,1 Wh per day.

5. Electrical Energy Storage Systems

In this chapter, answers are sought for the question: What types of electrical energy storage systems are available and what is their performance to date?

5.1 General remarks

Having the photo energy harvested and converted by the PV Cells into electrical energy, there remain three options:

- The electrical energy could be used directly to power an appliance such as for example in a pocket calculator.
- The electrical energy could first be transported towards a central collecting point from where it can either be stored or transported further.
- The electrical energy could first be stored and the use of the harvested electrical energy could be delayed in time till a convenient moment for utilization.

Pro
The advantage of the first system is simplicity

The advantage of the second option is:

- Having more than one photo energy conversion point would:
    - Make the system less dependant on local fluctuations of light levels
    - Make the system more reliable
- Larger amount of energy can be harvested.

The advantage of the third option is:

- A better matching in time in relation to the abundance of light
- An efficient energy transportation as stored energy
- Direct storage would result in less power losses
- Uncoupling of instant available light power and real power need of the appliance
- A more even supply of energy utilization (no spikes), which results in an improvement of the product reliability and therefore its sustainability.

Contra

The disadvantage of the first option is that the system will be power limited. Only the amount of total power, which can be converted at that very moment, will be available for use

The disadvantages of the second option are:

- The system will be quite complicated.
- There will be energy losses due to transport

The disadvantages of the third option are:

- The system will be storage limited. In those cases in which more electrical energy is available than can be stored, the surplus will be wasted.
- Possible mismatch in operation time. PV cells have an active duty time up to 25 years whereas for storage systems (batteries) this is limited to a few years.

5.2 Rechargeable electrical storage media now and in the future

5.2.1 General consideration

At this moment electrical energy that is harnessed by PV cells is stored in the following way:

- In the earliest applications in spacecrafts, the electrical energy was stored by using it in the dissociation of water in its components oxygen and hydrogen. Combining these two elements back to form water will provide electricity. This is the basic of the fuel cell. Due to the highly explosive character of hydrogen gas however, this method has not yet gained wide use in terrestrial applications. Various solutions of fuel cells have been proposed. To date they are starting to be used in automobile applications. Also occasionally, appliances powered by fuel cells are reported such as for example a Lap Top.
- The Lead-Acid Battery could be a good candidate for use as rechargeable battery. This type of battery has a long history, is often used in conjunction with PV cells. Disadvantage is bulky and heavy. In addition the acid fluid pose a problem. Therefore not suitable for mobile products.
- Nickel-Cadmium batteries have been used as rechargeable batteries in appliances and have become proven technology. Unfortunately due to their handicap of suffering from a so-called 'memory effect' they are not well suited to be partially recharged by a PV Cell. The nature of PV cell recharging dictates the partially recharging behaviour.
- The two new types of rechargeable batteries are NiMH and Li-ion batteries. These new types suffer less from the memory effect
- The Super Capacitors can store and yield large currents therefore, they can be useful to cope with large inrush currents. These Super Capacitors are ready commercially available. The internal resistance of these capacitors is now still too high to be used as power source for power tools.

On the environmental impact of the various types of batteries there are conflicting data reported in literature, therefore this need to be investigated further.

5.2.2. Self discharge

Self-discharge of the battery could be a bottleneck if it is larger than the power that can be harvested indoors by using PV modules. In particular, NiCd batteries are notorious for their self-discharge characteristics. Therefore, this handicap of NiCd batteries is one more reason not to use this type in combination with PV modules.

5.2.3 Capacity of the Battery

The output energy of a battery depends on the amount of Ampere-hours (Ah) it can deliver and the output voltage (V). Since most of the rechargeable batteries will be damaged if they are discharged completely the effective energy capacity will be less than that of primary non-rechargeable batteries. Therefore, in this report the capacity of an AA type penlight battery will be quoted as just 1.2 Ah. The efficiency of recharging is less than 100%. This means, that to deliver 1.2 Ah, the battery will need 1.5 Ah recharge energy.

5.3 Li-ion Batteries

For portable applications, Li-ion batteries are the most promising candidates for the future. For example to name some advantages with respect to the others are [Huang, 1999]:

A better energy density, No memory effect and Less weight

An additional advantage of these type batteries is its lower self-discharge compared to NiCd and NiMH batteries.

Disadvantage of Li-ion batteries is the higher costs yet.

Although battery storage capacity typically decreases proportionally with thickness, there is a definite trend towards thinner batteries as for example in portable phone applications [Nokia, 2002]. To calculate the limited storage capacity of a battery, the term volumetric energy density is defined. This volumetric energy density depends on the type of Li-ion battery used. In particular, it depends on the electrolyte used.

One can distinguish four types of electrolytes:

- Liquid Electrolytes
- Polymer Electrolytes
- Ceramic Electrolytes
- Ceramic Electrolytes with Polymer ion-conduction enhancement

Note:
- The first two Li-ion types show a large volumetric energy density. For example, Li-ion batteries with polymer electrolytes have a capacity of 470Wh/liter [Roos, 1999].
- The last two Li-ion battery types are not yet mature and commercially available [Yak, 2001]. Therefore, these two are not included in this analysis.

5.4 Conclusions

In this chapter, answers were sought for the question: What types of electrical energy storage systems are available and what is their performance to date?

- The most promising battery type is the Li-Ion battery.
- In case large inrush currents are to be expected, the use of Super Capacitors will be convenient.
- Polymer and Ceramic electrolytes are potential interesting and should be closely monitored during the next research phase.

6. Appliances

In this chapter, answers are sought for the questions:

- What categories of appliances are in use to date and what is their power and energy need?
- How well will the power and energy need of appliances match with the power and energy that can be harvested with PV converters both outdoors and indoors?

6.1 Electrical Appliance Categories

There are several methods to categorize electrical appliances.

- From environmental perspective
  This needs to be analysed with LCAs.

- From user perspective:

- Type:
    - Professional products
    - Consumer products
- Location of use:
  Whether the product is portable, stationary or a mix: portable but is in need of a holder or docking station for recharging its battery on a fixed stationary location.
- Application:
    - Personal care: e.g. electric toothbrush
    - Communication, e.g. Cellular Phones
    - Information Technology (IT), e.g. Laptop
    - Cooking, e.g. Mixer
    - Entertainment Games and Toys, e.g. Chess Computer
    - Video, e.g. TV set
    - Audio, e.g. Tuner
    - Hobby, e.g. Musical Keyboard
    - Hobby Tools / Do it self tools: e.g. electric drill
    - Garden: e.g. lawn mower
    - Miscellaneous in and around home, e.g. Remote Controlled Garage Door
    - Travel Aids: e.g. GPS
    - Security, e. g. Surveillance Camera
    - Home Health, e.g. Glucose monitor
    - Professional Medical Appliances, e.g. Implanted Heart Pace Makers, pain treatment with electric pulses and laser knives.
    - Wildlife: e.g. monitoring strap
    - Smart products

In looking for the application it is found that:

- The user friendliness
- The appearance
- Multifunctionallity

will become increasingly an important issue.

6.2 Location of use and Light Intensity at that location

6.2.1 The most frequent location where electrical appliances are used
A Television Set will be located near the TV Antenna or Cable outlet. As a result, the VCR, CDV, DVD, Videogame box etc., will also be found near that location. The same applies for a whole chain of Audio products such as Tuners, Hi-Fi Amplifiers, CD players, ground station for cordless headphones, etc., they all are located near the audio Antenna or Cable outlet. The PC and related appliances such as printers, scanners, originally could be located anywhere at home and in the office. With the entry of Internet, the locations become more fixed, near the telephone or cable outlet. Near this same outlet the Digital Phone Ground station and the fax machine can be found. Therefore, all these appliances can be regarded as stationary located.
In the kitchen, bathroom and bedroom the appliances have also fixed stationary locations.
Portable electronic products are designed to be carried around. Where are those appliances mostly to be located? In public transport vehicles, in schools, in the sport fields in shopping malls. No statistics exist yet on these most frequent locations, indoors or outdoors. To date however all those appliances are mostly powered by rechargeable batteries. Therefore, they have to be located for a while at some kind of holder annex battery re-charger unit which itself is located near a mains outlet. In a building the mains outlets are located at fixed stationary locations.

6.2.2 Less frequent locations
In new applications, the nowadays-stationary locations might become mobile as for instance in the office of the future.

6.3 Available Photo Energy and Power versus Energy Consumption at Consumer and Professional Products applications, a Synthesis.

The available photo energy and energy consumption of existing and future consumer and professional products will be a crucial indicator for selecting which product can be equipped with PV modules and PV battery as energy medium.
In this analysis, not only the instant power need is investigated but also the duration of use and the duty cycle of use or frequency of use.

6.3.1 Power consumption classification

- From Low Power up to High Power depending on the frequency of usage. For instance if a PV module can produce 10 W, and that power has to be used at the very moment of conversion by the appliance, then all values above 10 W will be high power. If however this harvested power can be stored and accumulated during some time, regaining or even surpassing the total energy consumed, than, values above 10 W will not a priori be high.
- Depending on the power used internally, one could discern:
    - Appliances that use internally only low voltage Direct Current (DC) to power the (micro)-electronic components. Examples are MPEQ players, Tuners, Personal Digital Assistants (PDAs), etc.
    - Appliances which need high voltage and Alternating Current (AC) to function well. Examples are products with a strong electromotor such as (Clothes) Washers and Microwave Oven, etc.
    - Appliances that can function well both with DC and AC power. Examples are Kitchen Ovens, Electrical blankets etc. Since these appliances are usually connected to the mains and the power needed is rather high (more than 500 W), a preference would be to use AC power of the mains. Unfortunately these appliances are also equipped with auxiliary micro-electronic parts to control the temperature and status displays which all need DC power which are continuously active and need a power conversion system.

6.3.2 Power and Energy need classification
The nature of the power really needed by an electrical appliance is dictated by the amount of (micro)-electronical components used inside this particular product. The more electronic components the more DC power is needed.

In reviewing photo energy need and applications, it is convenient to ask the following questions:

- How likely is it that the product will have a large exposure to light?
- How much power does the product need in active operation?
- Does the product need some kind of 'standby' mode, and how much electrical power is therefore required at that very moment?
- Are there electrical voltage step-down transformers or AC adapters involved?
- Available PV area versus needed active operation power and needed standby power.
- Type of light available, sun- or lamp- or mixed-light (outdoor or indoor or windowsill)
- How frequent is the appliance used
- Type of possible electrical energy storage media
- Available space for storage media

A crude classification can be made by looking at the actual power and energy need of appliances. So, a division as follows can be made based on:

- Peak power consumption
- Power consumption in stand-by mode
- Power consumption in shut-off mode
- Frequency of use
- Duration of use

A summary of used examples is given in Table 6. In this Table 6 one can distinguish four categories concerning power consumption and energy need namely:

- Large power consumption and large energy need
- Large power consumption and small energy need
- Small power consumption and large energy need
- Small power consumption and small energy need

Since energy need is the amount of power needed over an period of time (e.g. one day) therefore:

- Large power consumption and a large energy need would mean that the power is consumed by the appliance during most of the observation time.
- A large power consumption and small energy need would mean that most of the time the appliance is not in active use.
- A small power consumption and a large energy need would mean that the power although small is consumed continuously.
- A small power consumption and small energy need would mean that most of the time the appliance is not in active use.

Opportunities for proper matching of the actually needed energy will lie mostly in the second and fourth categories. Therefore, these two categories will define a ***search field for efficiency optimisation.***

Table 6

Appliances	Peak Power [W]	Energy Need [Wh/day]	Standby Cons. [W]	Stanby En. Wh/day	No-laod En. Wh/day
Electrical Toothbrush	1	2,8		20,7	12
Shaver	7	15		47,9	0-12
Digital Telephone (DECT)					
ISDN Connection Box		50		50	0-12
Babyphone and Babymonitor		10,9		16,7	0-12
PC Central Unit	60		0,5 up to 2,3 *)		
PC Monitor	60		1 up to 10		
Ink Jet Printer		0,4	1 up to 8	13,9	
Scanner		0,5		123	
Microwave Oven + Timer	1450	520	1 up to 4	54,5	0-24
Food Mixer	127	2			
Game computer		1,9		17,9	
Battery Recharger		2	1 up to 2		
Video Tape Recorder (VCR)	175	14,7	1 up to 11,3	187	
DVD Player		2,2	15	167	
Hi-Fi Amplifier		43,8	1 up to 9	114	
CD Player		3,2	1 up to 7	23,4	
Electrical Drill	150	0,8	1up to 2	24	
Glucose meter	0,1	0,12	1 up to 2	24	

*) Note that there are new developments in the field of computers namely the Simputer.
In an effort to minimize energy consumption and price a new type computer is developed: the Simputer [Encore, 2002]. This computer is based on free software from open source such as GNU/Linux. The energy need of this computer is 2 AA sized batteries or solar powered. Due to its low-cost and low energy need, this computer can be used in developing countries.

6.3.3 Primary task, auxiliary tasks and hidden power consumption

In data sheets or operation manuals of electrical appliances, usually only the power consumption needed to perform its main task is indicated. By way of exception, 'standby' power consumption can sometimes be deduced since standby time is indicated.

Looking at the whole range of power consumption in electrical appliances one can distinguish the following power consumption elements:

- The main power consumption for performing its prime tasks.

  Note: For saving power, in some products there is an option to switch to 'sleep' or 'standby' mode in case the product is not used for a certain time.

- The power consumption of auxiliary parts that requires the appliance to be continuously plugged into the mains outlet.
  For example the LED display at a refrigerator indicating operation and temperature. At the very moment nobody is looking at this display, the power consumption to maintain it operational could be regarded as wasted.
  Note: The hidden power consumption waste occurs in both the entire power supply and the display including circuitry for measure and control.
  The same kind of waste applies for heaters in blankets and waterbeds, memories for keeping presetting etc.
- *No load power consumption*; power consumption by an electrical appliance that is still plugged into the mains outlet but is as such not performing any useful function. For example, a cellular phone charger that is plugged in the mains outlet, wastes electricity when it is not re-charging the phone battery.
  Note: The main cause of this power consumption is explained by the users 'love of ease'. Therefore a matter of human behaviour. Technically speaking the hidden power consumption waste occurs in this case at the voltage step-down transformer of a battery re-charger. Its primary coil will remain connected to the mains, even in case no battery is re-charged with the secondary coil. So there will be a continuous electrical current in the primary coil, dissipating and wasting

power as heat. The same kind of waste applies for electrical doorbells, inactive cable TV set-top boxes and digital decoders, transformers in low voltage halogen lamps, digital phones holders, electrical toothbrush holders, cordless vacuum cleaner holder, etc.

- *Standby mode power consumption;* power consumption by a consumer product that is still plugged into the mains outlet but switched off or not performing its primary function, standing by or in sleep mode, ready to attain full power when needed to perform its main task. For example, a computer printer while waiting in sleep mode is wasting electricity until activated for printing again.
  Note: Standby mode was introduced to serve two goals. At first, to save power consumption since in this mode the appliance is functioning at 'reduced' rate. The other goal is user convenience in conjunction with the remote control capability. The hidden power consumption waste in this case occurs in both the entire low power low voltage power supply of the standby unit and the complete standby circuitry. The same kind of waste applies for the stand-by modes of audio and video products, the clock and display of the magnetron and the central heating thermostat, fax machine, answer machines, remote controlled garage doors etc.

6.4 Voltage and current Matching

In an integral approach of energy-conversion, -storage and –usage it will be obligate that a proper interface matching is guaranteed. The most obvious energy interfaces are of course of electrical nature namely voltage and current.

For example the voltage of a silicon PV cell is 0,7 V while a rechargeable Li-Ion battery operates at a voltage of 3 V.

To accommodate all kinds of appliance circuitry, power supplies and batteries, the output voltage and current of the PV cell have to be matched. Therefore, some PV cells are connected in series and parallel to constitute a PV 'Module'.

By connecting for example **n** PV cells in series:

The total output voltage of the module becomes about **n** times the output voltage of one PV cell. By parallel connection, the current can be adjusted.
The constitution of a module results however in some overall performance degradation:

- The total current of a series string in the module will be less than that of one PV cell. This is due to resistance and recombination of the photoelectrons.
- The total efficiency of a module will be some percentage lower than that of one PV cell.

6.5 Power matching and Energy matching

6.5.1 General remarks

In literature, power matching is usually associated with factors such as how much power can be converted at a location by the available PV area and available irradiance or illuminance. Starting point is here the direct use in an appliance without storage.

Another approach would be to include storage media and intelligence into the energy consumption chain. The result is an integral approach towards optimizing efficiency of the energy conversion, -storage and –usage.

Consequently there is a distinction between Power matching and Energy matching. By using the storage capability, the usage can be delayed in time. Therefore, an energy matching could exist in cases where no power match would be possible. For instance, the total power burst of one-minute duration can be collected during a whole hour.

6.6 Matching Photo Energy and Energy need of appliances

Most of the circuitry inside appliances has to be powered by DC power. In case the appliance is connected to the mains, the available AC power has to be converted to DC Power.
In this context, PV recharged Batteries could deliver DC power and therefore replace the low voltage power supply unit in electrical appliances, making the transformers and rectifiers altogether obsolete.
Due to the actual low power low voltage demand for standby and no-load modes and auxiliary units in most of the appliances, good matching exists between the needed power of the appliances and the power that can be gained by PV outdoors and even indoors. A possible practical implementation could be to bypass the low power and low voltage power supply by a battery as intermediate solution in existing appliances. For example, a Smart PV Battery could be connected directly to the low voltage DC part of the product. At several appliances with external AC adapter or power supply, there exist already an input socket for this purpose.

6.7 Conclusions

- In matching for energy need, with available photo energy, one has to search on individual appliance level! No specific category was found in which all appliances would match with the light level at a certain location.
- For existing products, in searching for possible matches, the fact that a particular appliance is powered by batteries would indicate a low energy need. Therefore, these products are potential candidates for PV application.
- For future products a more general model relating pv-potentialities and products' functionalities should be generated.

7. Photo energy applications in Appliances

In this chapter, answers are sought for the question:

- What appliances are PV powered to date?
- What are the trends in PV-powered products and what will be the advantage of an integral approach of the whole energy chain?

7.1 PV applications now

Since the first photo energy powered consumer products as the pocket calculator in the early 1980's [Wakisaka et. al., 1998], the search for cheap photo energy converters results in a preference for amorphous silicon (a-Si) PV converters. The efficiency of a-Si under low illuminance levels, but also the low power need of those consumer products makes a-Si PV converters suitable to be used indoors [Green 2000]. Due to its success, the use of photo energy gets stuck at a- Si PV applications, like calculators, wristwatches, radios, flashlights, trickle charge battery chargers and garden lamps. These products provide a first and minor contribution towards global energy saving though. An overview of these products can be seen in the master thesis of Sjoerd van Beers (see appendix B)

In a systematic search for novel, innovative and improved PV applications in appliances, the advantage of energy storage and the progress in ICT will be taken into account. A possible goal could be to achieve constant readiness of the PV powered appliances, since its battery could be PV recharged during idle moments.

7.2 Trends

In searching for innovations in the appliance market, it would be useful to take the following trends into account:

- 'Booming demands of **'**portable' Consumer Electronic products'**,** for example an exploding market of portable phones and computers. This shows the consumer trend towards 'more mobility' and 'independence of the mains'**.** In other words, there is a growing need for practical mains independent energy systems especially for portable consumer products. In addition, there is also a growing market for portable professional products.
- There is a growing awareness in the society towards the use of more sustainable or 'renewable' electrical energy, which should emit less CO_2 and rely less on depletable resources. In other words, the new solutions proposed have to be designed with sustainability and renewable electrical energy in mind.
- The 'ergonomic and aesthetical aspects' of energy systems as such and in combination with the product to be powered are, up to now, often neglected. Therefore, a new overall approach in designing these energy systems is needed, taking also these ergonomic and aesthetical aspects into account. Less energy is wasted in this new design approach due to a better-adapted energy usage. This is an indirect way of improving the energy efficiency.
- In Consumer Electronics (CE) and Professional Electronics (PE), the general trend to move from analogue to digital starts to benefit from progress in the Semiconductor Technology (ST) and the Information Technology (IT) sectors. As a direct consequence:
    - Digitalisation of audio and video including still picture cameras is matured. This progress is stimulated by the introduction of new digital data storage such as MPEG players, R/W-DVDs, Internet, etc. As a result new solutions in both the consumer and the professional world became possible
    - Integration of functions.
    - Miniaturisation even on nano- and pico-meter level.
    - The other side of the digital medal is however that those digitalisations do not mean less consumption of energy. With growing speed and complexity as more functions are combined, more energy is needed. For example, a portable MPEG player consumes more energy than an analogue cassette player.

- With the current availability of powerful and fast electronic controller chips, integration of intelligence into the energy consumption chain becomes obvious. As a consequence:
  - The lifetime of rechargeable batteries can be extended significantly by proper power management, or the control of the recharge and discharge currents. In particular, the amount of overcharge and depth of discharge could affect the lifetime. This intelligence would enhance directly the sustainability of the product.
  - The built-in intelligence could also be used to serve an early warning system for empty batteries; short circuits and a health check system. This will make the product more reliable and therefore improve its sustainability but also its ergonomics or improve its user-friendliness.
  - Another application of the built-in intelligence would be proper 'Power matching'. A general sales argument is 'the more power the better'. In view of energy efficiency improvement, the user should no longer accept this argument. With an electronic controller for example, this power matching can be optimized, resulting in energy consumption 'just to do the job'.

In anticipation of these trends, please note that:

- In portable Consumer Electronic and Professional Electronic products, the main sources of electrical energy are at this moment and in the future: batteries.
- In view of sustainability, rechargeable batteries will replace disposable primary ones.
- Recharging of the batteries is in general done at the mains. This is in contrast with the growing trend towards more mobility or independency of the fixed mains power supply socket. But also inconvenient in rural areas and developing countries.
- A logical step to improve mobility would be to integrate with the battery some mobile means for (re)-charging it. This mobile battery recharge facility would incorporate some kind of energy converter. A possible solution would be batteries recharged by PV Cells. These batteries become independent of the mains since they can be recharged anywhere and at any time, provided some illuminating light is available.
- The possibility to use the PV recharged Battery as a stand-alone unit, would allow also the possibility of incorporating it as click-on unit into the structure or housing or as ornamentation of the energy-consuming product or even as part of the clothing or jewellery. Therefore, this solution allows also design and esthetical features to be taken into account. For example, the common blue colour of the Solar Cell will enhance the 'High Tech' look of the product

7.3 Points of attention

Availability
As point of departure in this explorative project, the technology to be used has to be readily available. Therefore analysis are based on PV types and Batteries now already in use. For the next study phase future developments need to be closely monitored.

Energy Need of the Appliances
In optimising the energy-conversion, -storage and –utilization chain, it would be sensible to take the real energy need of the appliance, both in nature and quantity, as point of depart.

User Convenience and Environment
The interests of these two items are not obviously alike, even sometimes opposed.

For example:

- The 'Prolongation of useful time' such as doubling the 'speak time' of a cellular phone. A solution with renewable energy e.g. PV, would demonstrate the same interest of user and environment. In solutions that result in environmental burdens, the interests are opposed.
- Recharging the battery of an electronic implant such as a pace maker and a heart stimulator requires normally some electrodes to protrude through the skin. Other solutions would make use of radio frequency (RF) power transmission and light. It turns out that the light solution is the most convenient but also the safest way. In making special PV cells and special light sources, some burdens are imposed on the environment. However, the advantages and the user conveniences are in this case decisive.

Discrepancy between technical lifetime and economical lifetime

Technical life time is dictated by material properties and use of the product. On the other side the economical life time of a product is dictated by fashion which is unpredictable. But in general the economical lifetime wil be shorter than the technical one.

From these two examples on can conclude that the choice of technology and engineering innovations have to serve both the user convenience and the saving of the environment.

7.4 Recommendations and Conclusions

7.4.1 Recommendations

In gathering data in framework of this project, some cross-links and more questions with respect to power and energy matching were found. These questions could specific define search fields for further investigation.

To illustrate this one can use the examples in Table 6 (page 41)

a) Electrical drills have a peak power of 150 W, used each month for 10 min would yield on one year base an energy need of 0,3 kWh. Averaging over one year the energy need per day would be 0,8 Wh. This energy need would be according to Table 5 compatible with the indoor PV energy up to a distance of 3 m from the window. If the drill is used 30 minute each time, the distance for recharging reduces to less than 1 m from the window. The question would be to find an algorithm to forecast the suitability of appliances for this trick. To return on the search field defined in section 7.2, could a low energy need be the decisive factor? Just taking appliances that are at this moment 'Portable" because they can be powered by rechargeable batteries will at the end not yield new innovative possibilities.

b) Some appliances have a larger standby energy need than its actual energy need for performing its primary tasks. An example would be appliances like VCR, Scanner, Modem and DVD. To take the last example the DVD; for its primary task, the energy need is just 2 Wh/day, while standby requires over 10Wh/day?!! If an algorithm or design methodology could be found to minimize this kind of standby, this appliance will be compatible with the PV energy indoors. Therefore a **search field** would be to find 'new *design algorithm'* to minimize this avoidable energy consumption. This is finding is even more surprising if one thinks back to the original purpose of standby namely: to save energy while the appliance is functioning in 'reduced activity' mode.

c) Another ***search field*** would be to consider how user friendliness can be improved by introducing energy storage and intelligence into the energy consumption chain. This is not only a technical matter but also a matter of human behaviour.
For example: It turns out that improving the active operation time of an appliance is not just enough. Some enquiries should be set up into the way a product with PV batteries is appreciated. For example: At this moment there are already some cellular phones equipped with rechargeable batteries directly coupled to a PV module. Given the advantage of doubling the speak time and the low price, the question could be asked: why not everybody purchase and use this phone-type?

7.4.2 Conclusions

- Application of PV cells in appliances becomes more likely with a direct coupled means of storage
- There is a discrepancy between the economic lifetime and the technical lifetime

8. Options for innovations and user friendly product design

In this chapter, answers are sought for the question: What are the options to anticipate on the trends and to generate innovative solutions and design user-friendly products?

8.1 Introduction

In the chapters above, it was shown that the combination PV – Battery is essential for proper Energy matching. What trends could trigger innovation and what could be improved to make appliances user-friendlier?

Investigation into the use of batteries in appliances yielded the following observations:

- A general disadvantage of batteries is their unpredictable active life cycle. At the most critical moment, without a warning, they will just not deliver enough power. It is therefore recommendable to have some kind of intelligence inside the battery not only for monitoring the recharging process, but also to activate an early warning system. Therefore, a possible combination of battery and PV cell in one functional unit becomes a 'Smart' PV battery [Kan, 2002].
- Replacing batteries often requires some cumbersome steps with additional risk of damaging the product or battery or both. The reason for this is simply the ambiguity in shape and polarity of a cylinder. By shaping the Smart PV Battery above in such a way that insertion on top of the product will always be unambiguous, this problem is solved. At the same time, the product becomes more ergonomically sound or in other words more users friendly.
- Another disadvantage of changing the battery is that you always have to start-up completely new at for instance the phone or lap-top after changing the battery.

Having established the possible option of a Smart PV Battery what would be the other options to improve user-friendliness?

Investigation into power supplies and battery powered products yields the following observations:

- Appliances with large inrush currents are vulnerable to malfunctions in case they are powered by batteries. Usually those appliances are bound to be connected to the mains instead.
- The use of Super Caps or booster caps could be a possible solution for this problem.

8.2 Innovative System Options

8.2.1The Smart PV Battery

What innovations would the Smart PV Battery yield?

A. Smart PV Battery embodiments

At this moment, at least four embodiments of this concept are conceivable:

1. The Building Integrated Smart PV Battery
2. The wearable Smart PV Battery
3. The Standardized Smart Click-on PV module – Battery sandwich.
4. Special Dedicated Smart PV Battery

A.1 The Building Integrated Smart PV Battery

To power non-portable or stationary electrical appliances, the PV modules could be attached to the exterior surfaces of the building. To minimize serial resistance and related power loss, these PV modules are connected by the shortest way at each floor/room to separate battery units. Such battery unit serves for that particular part of the building as a 'DC Power Distribution Centrum' (DCPDC). The DCPDC is therefore located for convenience and safety at the inside of the building for instance under the windowsill. One DC Power Distribution Centrum can deliver a range of DC voltages depending on the series and parallel interconnections between the battery cells inside this DCPDC. Therefore, it can facilitate, even simultaneously, several non-portable appliances and holders or battery chargers of portable products, which are located at more or less fixed points in the room.

A.2 The wearable Smart PV Battery

The Smart PV Battery concept could be incorporated into clothes, bags and jewellery. Nevertheless, obviously this concept could also be extended to a new class of 'Wearable Electrical Appliances'. For example to recharge cellular phones inside the pockets of a Smart PV Battery waistcoat, which in addition could emit light at night?

A.3 The standardized Smart Click-on PV module – Battery sandwich

To power small portable electrical appliances, a standardized Smart Click-on PV module – Battery unit is proposed, in which the PV module is attached directly to the battery in a kind of sandwich construction. Due to the proposed standardisation, an ease of interchange ability and recharging will be feasible. For instance the recharging can be accomplished while remaining clicked-on the products, but can also be as an unattached PV battery on the windowsill. In addition, naturally, the Smart PV battery can also be carried around as spare battery.

A.4 The special Dedicated Smart PV Battery

The Smart PV Battery can be made to be especially dedicated to one specific appliance. For instance, it can completely be integrated within the surface of the product.

In this dedicated embodiment, both the shape and the size can be tailored for an optimal integration. This optimal integration implies an optimum performance, an optimum appearance and of course an optimal ease of use.

Two types of embodiments can be distinguished:

- For professional appliances
- For the less expensive consumer products

Examples of the first type are medical electronic implants [Goto et. al., 2001]. Due to their special dedicated nature, both the PV module and the Battery can be optimized on the application. Expensive high efficient PV modules are by definition not excluded. Also to boost reliability, the battery can be in a redundant implementation. Other examples are security and emergency appliances such as GPS aided personal beacons.

Examples of the second type are consumer products with large light exposed PV coated surfaces. The battery could have another shape inside the product and could in addition even serve as a constructive component.

8.2.2 PV –Battery – Super or Booster Cap and Intelligence

What options would be possible in the combination Smart PV Battery extended with a Super or Booster Cap?

A Super or Booster Cap is capacitor that can store and discharge large amounts of charges. At least the following remarks could be placed:

- The problems with large current at switch on the so-called in-rush currents can now be coped with.
- For click-on embodiment, the additional volume of the Super Cap could pose a problem.

8.2.3 PV-Fuel Cell

What option would be possible in the combination PV as energy conversion and Fuel Cell as storage medium? Can the Fuel Cell be used for bridging the gaps between battery low power or are the also other applications possible?

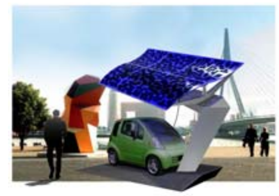
At least the following items need further investigation:

- Maturity matching of the components
- Performance parameters such as energy density, stability, peak power etc.
- Volume, Shape requirements
- Efficient Hydrogen compression

8.3 Novel Products

8.3.1 Novel products developed within the framework of master thesis's at DfS/IO

During this explorative project several novel PV products were designed, developed and analyzed by Industrial Design Engineering students within the framework of preparing their master thesis (See appendix B). These students and their master thesis's were:



1. Martijn Verkuijl: Verlichting op zonne-energie
2. Sjoerd van Beers: Zonnemobiliteit Milieudienst Rijnmond
3. Bernadette Weitjens: PV applicaties voor consumenten producten
4. Lonneke van der Kamp: Een educatief speelobject met zonne-energie

All these master theses projects have been co-supervised by S.Y. Kan and used by him as case studies to analyze the specific product design applications, in particular with respect to the various application and implementation forms of PV and storage systems in these novel products.

Ad.1:
In this master thesis project a novel street illumination system was designed. The synergy of using the PV panels both as Solar Cell and as light reflector of the streetlight has been demonstrated. The storage was done at lamp location introducing a mobile design concept. The use of curved PV panels enhanced the aesthetics.

Ad 2:
In this master thesis project a novel recharge station for electrical vehicles was designed. The storage capacity of various storage media and PV cells have been analyzed including the environmental impact of this recharge station. The synergy of roof and Solar panel has been demonstrated. By introducing curved solar panels the aesthetics was enhanced and the movement of mobility was stressed.

Ad 3:
In this master thesis project the combination Solar recharger and mobile products was demonstrated. A existing backpack was equipped with a click-on unit comprise of a solar panel to generate electrical power and a compartment with electrical power storage and buffer unit including electronic charge-recharge control electronic. The rechargeable mobile products such as cellular phone, PDA, etc., were placed either in the special compartment or just inside the backpack. The recharge process could be done all the time the mobile products were carried around both outdoors and indoors. The environmental impact of this design was analyzed with the aid of LCAs.

Ad 4:
In this master thesis project a novel educative toy was designed that rotates with the aid of solar energy. In order to start the rotation, the electromotor has to overcome 'stiction' or need to be powered with a minimum level of current. This current could not readily be delivered by the solar panel. The solution was a starter made by a large capacitor. Therefore this master thesis demonstrates the feasibility and elegance of using booster capacitors as was indicated in section 8.2.2.

8.3.2 The Cellular Phone and Battery recharger
Point of depart is the Cellular Phone + recharger now available on the market as for example Nokia 1610.

Energy and Power need
According to test [Nokia, 2002]
335 mA at 5,95 V gives 2 W talk power consumption
7 mA at 5,95 V gives 42 - 50 mW standby power consumption

- For the five consecutive days, assuming during each day 35 min is used as talk time and the remaining 23 hours and 25 min as standby. The total energy consumption per day would be 35/60x2 + 23x0,05 + 25/60x0,05 Wh = 2,34 Wh or for five days 11,6 Wh.

Available energy
Mid-Winter time, North facing window, one meter distance from the window:

- Taking only diffuse sunlight into account as described in section 4.4: 50 Wh electrical energy could be harvested, per day per m^2, using the high-efficiency PV cell as described in figure 13.
- Three consecutive days without direct sun of 50 Wh/day, followed by two days clear winter with also bright reflected sun and sky yielding a total 70 Wh per day per m^2
- At this moment there exist already rechargeable batteries which provide normal talk time for a fully charged battery, not solar recharged, as follows:
    - 600 mAh / 5,95 V gives 3,57 Wh yield 3,57/2 = 1,78 hours talk time
    - 900 mAh / 5,95 V gives 5,36 Wh yield 5,36/2 = 2,68 hours talk time
- With the existing rechargeable batteries, the normal standby time for a fully charged battery not solar recharged:
    - 600 mAh / 5,95 V gives 3,57 Wh yield 3,57/0,05 = 71 hours standby
    - 900 mAh / 5,95 V gives 5,36 Wh yield 5,36/0,05 = 107 hours standby

Design

- In the new design, the mains battery recharger is replaced by a PV recharger, which consists of a PV module and an intermediate storage battery. The PV module has a surface area comparable with the common DECT base stations, of 200 cm^2 and a mechanism to place the module in the most favourable angle toward the sunlight.
    - After one days recharging the recharger has accumulated: 50x200x0,0001 Wh energy= 1Wh energy which would be equivalent to and compensating half an hour talk time that day.
    - After tree days recharging the recharger has accumulated: 3 Wh
    - After five days recharging including the two sunny days the recharger has accumulated: 3x50x200x0,0001 + 2x70x200x0,0001Wh = 5,8 Wh. The 5,8 Wh would be equivalent to or compensate 2,9 hours talking time. Equally distributed over five days would yield 35 min.
- Full normal battery + PV gained energy in PV recharger together would yield:
    - 600 mAh / 5,95 V: 3,57 Wh + 5,8 Wh = 9,37 Wh therefore this option will be falling 11.6 Wh –9,37 Wh = 2,23 Wh short. Not a good option for 100% autonomy.
    - 900 mAh / 5,95 V: 5,36 Wh + 5,8 Wh = 11,16 Wh therefore this option will be falling 11,6 Wh – 11,16 Wh = 0,44 Wh short. Nearly good.
- By enlarging slightly the area of the PV module in the recharger. For instance the area become 300 cm^2 instead of the 200 cm^2 proposed above, the accumulated and harvested energy in five days will be: 3x50x300x0,0001 + 2x70x300x0,0001 Wh = 8,7 Wh. instead the 5,8 Wh calculated above. Therefore:
    - 600 mAh / 5,95 V, normal battery: 3,57 Wh + 8,7 Wh = 12,27 Wh surpassing the needed energy by 12,27 Wh – 11,6 Wh = 0,67 Wh
    - 900 mAh / 5,95 V, normal battery 5,36 Wh + 8,7 Wh = 14,06 Wh surpassing the needed

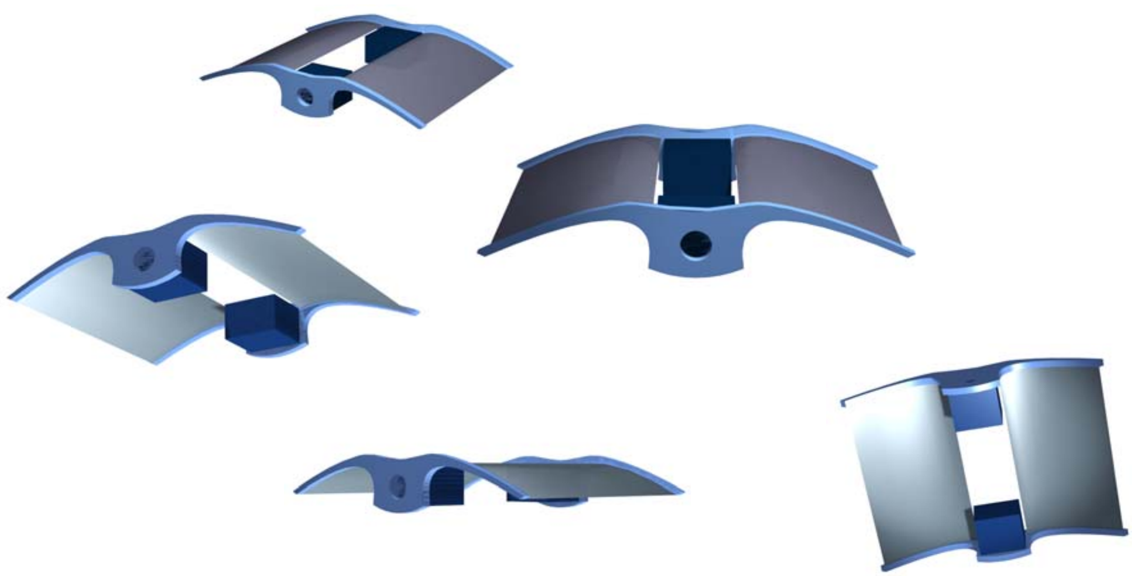
energy by 14,06 Wh – 11,6 Wh = 2,46 Wh

- By another increase of the PV module to an area of 400 cm^2 would yield: 3x50x400x0,0001 + 2x70x400x0,0001 Wh = 11,6 Wh instead of the 5,8 Wh above. The additional energy could be used to cope with more dark days or to facilitate more functions
- The realization of the recharger unit could be a folded PV module. This folded option has an area of 100, therefore practical and portable. As base the battery and 100 cm^2 PV and socket for recharging. On the base, there are three foldable PV wings each having an area of 100 cm^2.

Conclusions:

- A 100 % autonomous Cellular Phone + Battery Recharger is feasible.

Autonomy is even possible at mid winter, one meter from a north-facing window if the PV recharger surface has an area of minimum 300 cm^2.



9. Overall Conclusions and Recommendations

In this explorative project the emphasis was on the technical performance of PV cells and storage media. The environmental aspects and the user contexts were analyzed within the framework of several master thesis projects.

For the envisaged follow-up doctoral thesis research program the following items that need further investigation have been identified:

- The interaction between the human user and the application of products. In particular in view of improving user friendliness and acceptance of innovative design.
- The power consumption savings by synergy gained with the use of specific combined PV-storage systems.
- Special design methodology, aiming at improved understanding of indoor/outdoor performance characteristics of PV cells to be used in consumer and professional products.
- The life-cycle assessment of environmental impact and user costs of the most promising options.

As a result of this explorative project, the following items have been identified:

- According to the literature, the most promising PV converters for indoor applications are high efficient mono crystalline Si PVs, Dye-Sensitized PVs and special a-Si PVs. More measurements are needed.
- Indoor PV use at this moment is limited to low power applications of up to about a few Watts. However with the introduction of energy storage media into the energy consumption chain, this limit can be boosted to few hundred Watts provided the frequency of use is low enough to allow a recharging of the storage media.
- There is a growing amount of professional appliances, which can be functioning well with PV –Battery combinations.
- The ‘ergonomic and aesthetical aspects’ of energy systems as such and in combination with the product to be powered are, up to now, often neglected. Therefore, a new overall approach in designing these energy systems is needed, taking also these ergonomic and aesthetical aspects into account. Less energy is wasted in this new design approach due to a better-adapted energy usage. This is an indirect way of improving the energy efficiency.
- Large global energy saving could be achieved with the small amount of available photo energy indoors, by using this energy to relieve the burden of hidden energy waste introduced during stand-by and no-load modes in consumer products.
- In an overall system design it will be a ‘design challenge’ to find the optimal location of the photo transducer, which at the same time does not restrict too much the user in carrying the product around, nor cause a too large burden on the interior aesthetics.
- More research is needed to find a practical solution for the end of life discrepancies between PV (ca. 30 years) and battery (ca. 2 years) components. In addition, more research, to establish the boundary conditions and design rules for an overall system design of consumer products, should be done in the near future. In addition, discrepancies between PV Battery lifetime and the ‘economical’ lifetime of appliances require further study.
- In an overall system design of appliances, a good balance should be reached between all its *functions* including *ergonomics,* its *sustainability,* and its *overall design* including *aesthetics.* Therefore, these items should be taken into account in new appliances incorporating PV cells.
- Search fields have been defined in looking for appliances with low energy need, in which the peak power consumption plays only a minor role.

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APPENDIX A: PV cells performance at low light levels

1. Introduction

1. Performance Parameters of PV cells

1.1 General

The performance of a PV cell, in particular its energy conversion efficiency η depends on a number of parameter. In an ideal case it is characterized by the following parameters [Green, 1986]:

- The open- circuit voltage (V_{oc})
- The short-circuit current (I_{sc})
- The fill factor (FF)

The energy conversion efficiency η is given by:

$$\eta = (V_{oc} \text{ x } I_{sc} \text{ x } FF) / P_{in} \qquad (1\text{-}1)$$

1.2 The short-circuit current (I_{sc})

$I(V) = I_1 + I_2 + I_3$

With I_1 the ideal diode current and I_2 and $I_{3,}$ the non-ideal contributions taking into account the series and shunt resistance of the diode model.

1.3 The open- circuit voltage (V_{oc})

In ideal cases, ignoring both (1-2)

1.4 The fill factor (FF)

$$FF_0 = \{v_{oc} – \ln (v_{oc} + 0.72)\} / v_{oc} + 1 \qquad (1\text{-}4)$$

With v_{oc} the normalized voltage:

$$v_{oc} = V_{oc} / (kT/q \qquad (1\text{-}5)$$

The measured fill factor FF is given by:

$$FF = FF_0 (1-r_s) \qquad (1\text{-}6)$$

with r_s being a normalized resistance:

$$r_s = R_S / R_{CH} \qquad (1\text{-}7)$$

R_S being the series resistance and R_{CH} the characteristic resistance defined by:

$$R_{CH} = V_{oc} / I_{sc} \qquad (1\text{-}8)$$

2. A near ideal PV cell Example: The high performance mono-crystalline Si PV

2.1 Parameters of the best known mono-crystalline Si PV cell at AM 1.5 and 25^0 C

The parameters of this PV cell at AM 1.5,and 25^0 C are taken from the Solar Cell Efficiency Tables [Green, et. al. 2002]. As first example the best of these PV cells as presented in this table was taken. This Silicon PV cell has the following parameters:

- Efficiency: 24,7 +/- 0.5 %
- Designated illuminated area: 4,00 cm^2
- The open- circuit voltage (V_{oc}): 0,706 V
- The short-circuit current (I_{sc}): 42,2 mA/cm^2
- The fill factor (FF): 82,8 %

By using these parameters in the open-circuit voltage V_{oc} as defined in equation (1-2), the ratio between the light generated current I_L and the saturation current density I_0 at one sun (1000 W/m^2) can be calculated.

$V_{oc} = kT/q. \ln (I_L/I_0 +1)$

$k T/q = 0,026$ at 25^0 C (298 K)

$0,706 = 0,026 \ln (I_L/I_0 +1)$ ----- $\ln (I_L/I_0 +1) = 27,154$ ----- $I_L/I_0 = 6,205 \times 10^{11}$

To check in how far the equations of section 1 correspond with the measured values of the Solar Cell efficiency tables, the incident light power found in equation 1-1 can be compared with the stated experimental value of 1000 W/m^2.

$P_{in} = (V_{oc} \times I_{sc} \times FF) / \eta = (0,706 \times 42,2 \times 82,8) / 24,7 \text{ mW/cm}^2 = 998 \text{ W/m}^2$, therefore about a match.

The ideal fill factor is given by the expression:

$$FF_0 = \{v_{oc} – \ln (v_{oc} + 0.72)\} / v_{oc} + 1$$

with v_{oc} the normalized voltage:

$$v_{oc} = V_{oc} / (kT/q) = 0.706 / 0,026 = 27,15 > 10$$

$$FF_0 = \{27,15 – \ln (27,15 + 0,72) \} / 27,15 + 1$$
$$= \{27,15 – 3,328\} / 28,15 = 23,822 / 28,15$$

$FF_0 = 84,62$ %

The measured FF is related to the ideal fill factor by equation (1-6):

$$FF = FF_0 (1-r_s) = 84,62 (1-r_s) = 82,8 \text{ ---- } r_s = 0,02$$

2.2 Performance at 1/10 sun

At 1/10 sun the incident light power will be 1/10 x 1000 W/m^2 or

$$P_{in} = 100 \text{ W/m}^2.$$

For this calculation, it is assumed that in an ideal case there is a linear dependency between the incident light flux and the ratio between the light generated current I_L and the saturation current density I_0.

At one sun it was calculated: $I_L/I_0 = 6,205 \times 10^{11}$.
Therefore at 1/10 sun this ratio will be: $I_L/I_0 = 6,205 \times 10^{10}$.

The open-circuit voltage V_{oc} will be:

$V_{oc} = 0,026 \ln 6,205 \times 10^{10} \text{ V} = 0,646 \text{ V}$

The short-circuit current I_{sc} is also assumed to decrease linearly with the reduced light flux.

At one sun in the table the short circuit current was given as 42,2 mA/cm^2, therefore at 1/10 sun it will be 4,22 mA/cm^2.

$I_{sc} = 4,22 \text{ mA/cm}^2 = 42,2 \text{ A/m}^2$

The fill factor FF will 1/10 sun be according equation (1-3):

$FF_0 = \{v_{oc} – \ln (v_{oc} + 0.72)\} / v_{oc} + 1$

with v_{oc} the normalized voltage:

$$v_{oc} = V_{oc} / (kT/q) = 0.646 / 0,026 = 24,846 > 10$$
$$FF_0 = \{24,846 – \ln (24,846 + 0,72)\} / 24,846 + 1$$
$$= \{24,846 – 3,241\} / 25,846 = 21.605 / 25,846$$

$FF_0 =$ 83.59 %

$FF = FF_0 (1-r_s) = 83,59 (1-r_s)$ with $r_s =$ 0,02

$FF = 81,91$

The energy conversion efficiency η at 1/10 sun is:

$$\eta = (V_{oc} \times I_{sc} \times FF) / P_{in}$$

Substitution of the parameter values at 1/10 sun yield:

$$\eta = (0,646 \times 42,2 \times 81.91) / 100 \% = 22.3 \%$$

This means a reduction of:

$$\Delta\eta = (24,7- 22,3) \% = 2,4 \%$$

Or a relative reduction of :

$$\Delta\eta_{rel.} = 2,4 / 24,7 \times 100 \% = 9,7 \%$$

2.3 Performance at 1/100 sun

The same assumptions as per 1/100 sun.

The parameters:

- $P_{in} = 10\ W/m^2$.
- $V_{oc} = 0,026 \ln 6,205 \times 10^9\ V = 0,586\ V$
- $I_{sc} = 0,422\ mA/cm^2 = 4,22\ A/m^2$
- $v_{oc} = Voc / (kT/q) = 0.586 / 0,026 = 22,538 > 10$
- $FF_0 = \{22,538 – \ln (22.538 + 0,72)\}/ 22,538 + 1 = 82,38 \%$
- $FF = 82,38 (1-0,02) \% = 80,73 \%$

Substitution of the parameter values at 1/10 sun yield:

$$\eta = (0,586 \times 4,22 \times 80.73) / 10 \% = 19,9 \%$$

This means a reduction of:

$$\Delta\eta = (24,7 –19.9) \% = 4,8 \%$$

Or a relative reduction of :

$$\Delta\eta_{rel.} = 4,8 / 24,7 \times 100 \% = 19,4 \%$$

2.4 Performance at 1/1000 sun

The same assumptions as per 1/100 sun.

The parameters:

- $P_{in} = 1\ W/m^2$.
- $V_{oc} = 0,026 \ln 6,205 \times 10^8\ V = 0,526\ V$
- $I_{sc} = 0,0422\ mA/cm^2 = 0,422\ A/m^2$
- $v_{oc} = Voc / (kT/q) = 0.526 / 0,026 = 20,246 > 10$
- $FF_0 = \{20,246– \ln (20,246+ 0,72)\}/ 20,246+ 1 = 80,09 \%$
- $FF = 80.09 (1 – 0,02) \% = 78,48 \%$

Substitution of the parameter values at 1/10 sun yield:

$$\eta = (0,526 \times 0,422 \times 78,48) / 1 \% = 17.4 \%$$

This means a reduction of:

$$\Delta\eta = (24,7 –17.4) \% = 7,3 \%$$

Or a relative reduction of :

$$\Delta\eta_{rel.} = 7,3 / 24,7 \times 100 \% = 29,5 \%$$

3. The Fraunhofer ISE High-efficiency PV Cell

3.1 The parameters of Fraunhofer ISE PV Cell

To see to what extend the first approximation calculation as given above, could give an indication of the expected degradation in efficiency at low light levels, the measured values of an existing high-efficiency PV cell [Glunz et. al., 2002] were compared with the calculated values.

The parameters of the ISE PV Cell:

- Efficiency: 21,3 +/- 0.5 %
- The open- circuit voltage (V_{oc}): 0,674 V
- The short-circuit current (I_{sc}): 39,5 mA/cm^2
- The fill factor (FF): 80,0 %

2.2 Performance at 1/10 sun

In accordance to calculations above the efficiency at 1/10 sun become

η = 19,1 %

This means a reduction of:

$\Delta\eta$ = (21,3- 19,1) % = 2,2 %

Or a relative reduction of :

$\Delta\eta_{rel.}$ =2,2 / 21,3 x 100 % = 10,3 %

2.3 Performance at 1/100 sun

In accordance to calculations above the efficiency at 1/10 sun become

η = 17,1 %

This means a reduction of:

$\Delta\eta$ = (21,3- 17,1) % = 4,2 %

Or a relative reduction of :

$\Delta\eta_{rel.}$ = 4,2 / 21,3 x 100 % = 19,7 %

2.4 Performance at 1/1000 sun

In accordance to calculations above the efficiency at 1/10 sun become

η = 15,0 %

This means a reduction of:

$\Delta\eta$ = (21,3- 15,0) % = 6,3 %

Or a relative reduction of:

$\Delta\eta_{rel.}$ =6,3 / 21,3 x 100 % = 29,5 %

Appendix B: Supervised Master Thesis projects

Appendix C: Paper Eurosun 2002

Appendix D: financial overview