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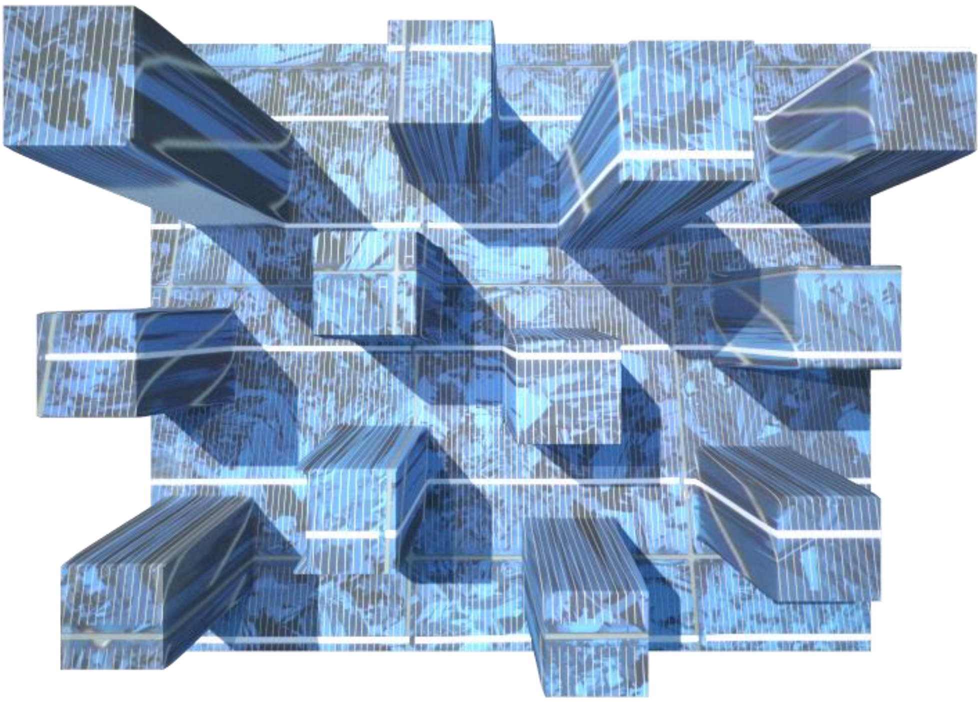
TOWARDS A CO2 NEUTRAL URBAN ENVIRONMENT

Cutting the Wire

ForskEL project 2008-1-0113



1. Resumé

The outcome of the project "TOWARDS A CO2 NEUTRAL URBAN ENVIRONMENT" - cutting the wire has been:

- Development of an advanced and flexible LED based artificial light source for testing solar cells and small panels under low light conditions (0-200 W/m^2) and spectral variations in 400 nm – 1100 nm.
- Development of hardware and software/user interface for electrical characterization of solar cells and panels by obtaining IV-curves and spectral response curves for solar cells and panels irradiated by the LED light source.
- Develop and production of 10 advanced 100 nm spectrally resolved light logger units for stand-alone battery powered action for at least half a year in the addressed interval from 400 nm – 1100 nm.
- Development of a stand-alone software tool and user interface for setup and data output of the data logger units.
- Measuring the light condition at various spots for one whole year in two streets in Copenhagen.
- Datahandling and comparison irradiation measurements with calculated and normalized data from solar simulation software and data from rooftop measurements at Danish Technological Institute and Danish Meteorological Institute.
- Organization of a workshop for architects and city planners for who the results from this project should catalyze and lower the barriers for creating new or installing more solar powered applications in the urban environment.
- Branding of the potential for saving energy and CO2, cost of wirering and a lot of other secondary costs by using solar power as a source of energy directly where the need is in the urban environment.

The ultimate outcome of the project should have been creation of a simple software tool for selection and dimensioning of solar panels for applications by entering some parameters about the spot of placement. Due to the very ambitious project group more time was invested in hardware development for raising the quality of the LED Sun and the data logger unit. This gives the possibility of the software tool for selection and dimensioning of solar panels to meet the demands of the future with a marked going towards new technologies. It will help people choose the right size, technology and calculate the return on investment through spectrally resolved light energy data measurements merging with mathematical modeling and statistical calculations for giving the best estimate possible.

The extended time for hardware development was sadly taken from the lengthy light measurements which had to be downsized. Therefore the software tool was not possible to finish.

If the global energy consumption shall shift towards green technologies at meet the climate demands the barriers should be lowered for innovation and new use of solar cell technologies. Highly advanced scientific data material needs to be evaluated and put to use by the more creative part of workforce and last not least the costumers. This project has created the advanced hardware tools necessary and hopefully the group can reach the ultimate goal in a project in extension of the present reported here.

Report by:

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2. Introduction

The present report is the final report in the PSO funded project *Towards a CO_2 neutral urban environment –Cutting the wire*, no. 2008-1-0113 and reports on the work and results achieved in the project. The project was funded under the ForskEL program.

The project was started up, as a clear need to map solar energy potential in the urban environment was seen. When asked to dimension solar cells, a clear answer could never be given, because the surrounding conditions in especially urban scapes, are of great influence for the light actually striking the PV installation. If realistic dimensioning of PVs could be performed, the potential for stand-alone products powered by the sun (light, security, cleanliness etc.) could decrease the installation - and energy costs and provide a cleaner and safer urban environment.
The light from the sun during season and the day changes and possible shading objects influences the light striking the solar cell. In order to dimension solar cells correctly based on the enhanced amount of information of the light a test facility to characterize the different types of solar cells would be of need.

The project group was formed to address the need to develop and design a light measurement program in the city and a new solar cell test characterization facility as well as branding and market study.

The project has been a 2-year long collaboration between:

faktor 3 | TEKNOLOGISK INSTITUT | DTU Fotonik Institut for Fotonik

Faktor 3 **Danish Technological Institute** **DTU Fotonik**

, with Faktor 3 as project manager who would like to thank the project partners for the collaboration.

Further, thank you to ENERGINET/DK and Jesper Bergholdt Sørensen for supervision and guidance.

3. Background for the project

Introduction

Edmond Becquerel demonstrated the first solar cell device in 1839 but it was not until the very end of the 20th century PV began to gain ground. It is more often seen as grid-connected systems installed on rooftops but also PV farms are starting to contribute to the huge electrical energy consumption of human beings.

These grid-connected devices are placed in optimal positions for the solar irradiation with no shadows, facing south and with the right angle to vertical. Though not placed under optimal conditions are smaller stand-alone applications powered solely by solar energy shooting up especially in the urban environments. Trash cans compressing trash by energy supplied by integrated solar cells minimizes manpower for emptying and the solar cells gives the flexibility of positioning without cables being drawn. The energy and money saved by avoiding digging up the asphalt, repaving and loss in long cables is quite large and more and more of these small flexible applications powered by solar cells are gaining a foothold. In the centre of Copenhagen the PV driven parking meters are starting to be a part of everyday life.

Between the low energy consumption applications as the parking meters and BIPV lies a broad spectrum of possible applications with a large potential for CO_2 savings. This project aims to address this subject.

Off-grid Photovoltaics once represented more than 90% of global installed PV capacity, but due to governmental support and feed-in tariffs, the market for off-grid PVs didn't see the same boom as for grid-connected Photovoltaic systems, see Figure 1.

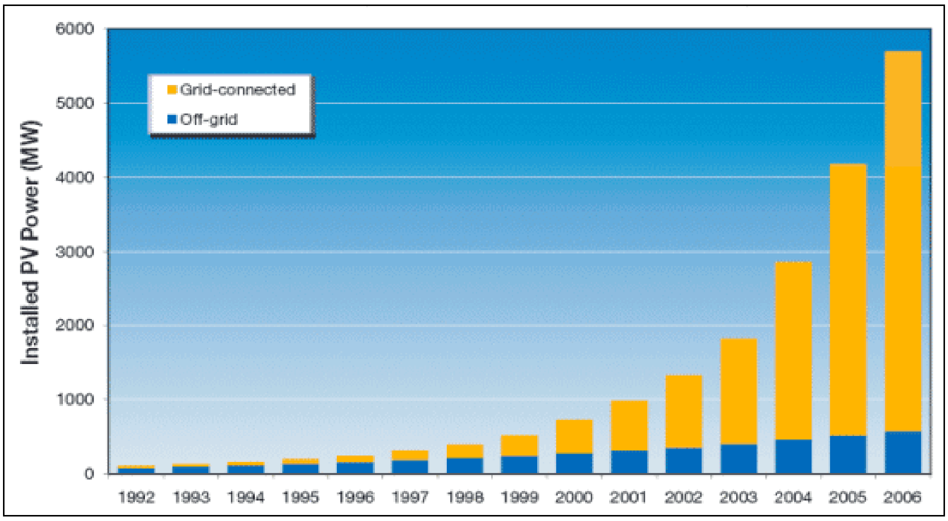


Figure 1 Installed PV power, globally[i]

There is still a huge potential for PVs used in off-grid applications. Not only PVs in small scale applications as the described trash can and the parking meters but to secure electric power supply to the developing countries in areas which will never be covered by power grid.

"according to the World Bank 1.6 billion people worldwide live without access to reliable electricity".

Greenpeace estimate that in a moderate scenario, 2,023 million people will receive electricity from off-grid PV systems by 2030.

PV Technology

PVs are formed by semi conducting material, which is characterized by being an insulating material at low temperatures, but conducting when energy or heat is available The material absorbs energy and separation of charges as well as charge transport takes place in the material [B 4].
The use of silicon for solar cells is most widespread as this is the most mature technology within the world of solar cells. Currently more than 90% of installed PVs are made from silicon. The working principle as well as the behaviour of the silicon solar cell under various conditions are known and well documented.

The development of the photovoltaic cell has been strongly increased since the 1960's. Production requirements, energy consumption, efficiency, stability and price have led to so far 3 generations of solar cells.

1st generation PVs are:
Monocrystalline Silicon and Polycrystalline Silicon Solar cells, Figure 2.

Characteristics:
- Relative high conversion efficiency:
  15-18 % mono-c
  10-15 % poly-c
- Well established and documented technology
- Long life time > 25 years
- High material consumption (Silicon)
- High cost
  2,7 USD/Wp[ii] for mono-C module
  2 USD/Wp[ii] for poly-C,

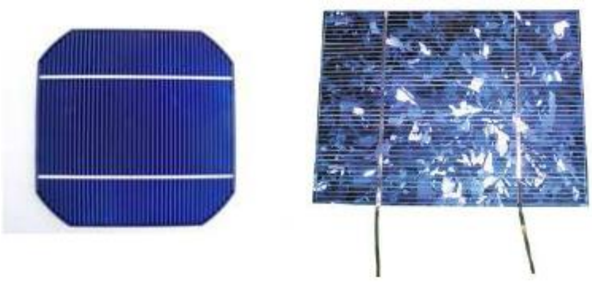


Figure 2 Mono- and Poly crystalline silicon solar cell

2nd generation:
Various thin film technologies, like:
Amorphous Silicon, CdTe, CIS, CIGS, GaAs, Figure 3.

Characteristics:
- Conversion efficiency (4-10 %)
- 1/100 usage of Silicon for amorphous cells, in comparison to mono/poly crystalline cells
- Relatively long life time > 10 years
- Flexible
- Better price per installed Wp than 1st generation solar cells cost
1,75 USD/Wp[ii] for thin film module
- possibility for semitransparent modules

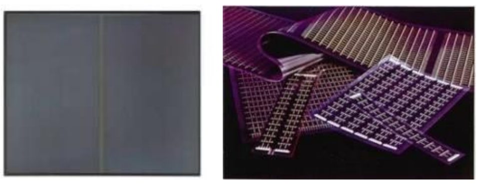


Figure 3 Amorphous silicon

3rd generation:
Technologies still in the research/laboratory stage, like:
Organic PVs (Polymer and dye solar cells), nano cells, Figure 4.

Characteristics:
- Conversion efficiency (1-7 %)
- No usage of silicon
- Forecasted to be very low cost due to low technology requirements < 1USD/Wp
- Still in the lab, not long term tested
- Stability and reproducibility is still a problem
- possibility for semitransparent, flexible modules
- high degree of design freedom

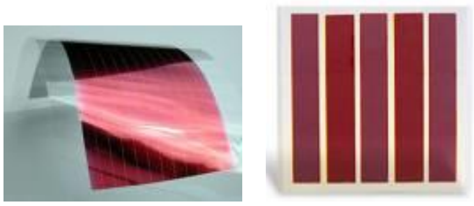


Figure 4 Polymer and dye solar cell

Standard Test Conditions

The performance of solar cells is evaluated under Standard Test Conditions (STC), referring to:
- Cell temperature of 25°C
- Irradiance in the plane of 1000 W/m^2
- Spectral energy distribution according to the standard spectrum of Air Mass (AM) 1.5.

These conditions are also termed 1 Sun.

The result of this test gives the electrical output and performance of the solar cell under these specific conditions and is generally used to compare different solar cell types and technologies.
As the performance of solar cells are dependent on parameters such as cell temperature, irradiance intensity, spectral distribution and incidence angle of the light source it is possible that the solar cell works better under other conditions.
The STC conditions correspond to an irradiation level of a clear sunny day, the module temperature of a clear winter day and the spectrum of a clear spring day.

Electrical response of solar cells

As described in the latter, solar cells are characterized by different technologies, and therefore they have specific electrical characteristics under specific conditions.
The technologies are dependent on irradiation intensity, cell temperature, spectral distribution of light and incident angle of incoming light. It is therefore crucial to know which climatic conditions, the solar cell will be installed under in order to predict the performance of the PV.
The spectral response of solar cell technologies is displayed in Figure 5, where the green graph (luminous level of human beings), refers to the visible area for human eyes.

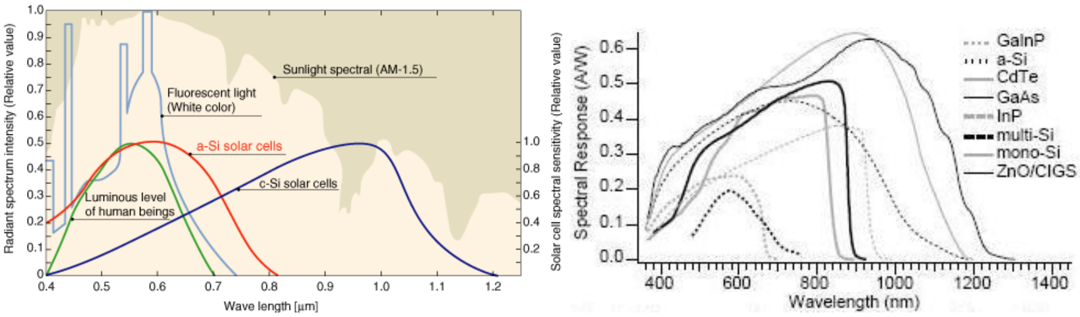


Figure 5 Spectral response of various PV technologies [iii]

Furthermore the dependency of PV efficiency to light intensity is important, as this has great impact on performance under different than the Standard Test Conditions, under which solar cells are rated.

In Figure 6, the efficiency under varying light intensity is related to STC efficiency and it is clear, that crystalline silicon (mono- and poly) have a markedly reduction in efficiency under low light conditions. The thin film technologies (amorphous silicon and GaAs) show almost independent conversion efficiency to varying light conditions. Therefore it might be more meaningful to use thin film cells in applications subjected to low light intensities.

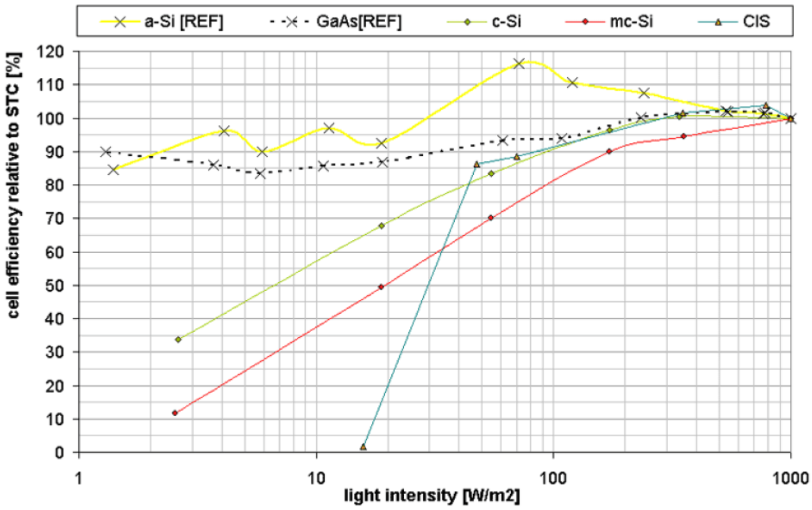


Figure 6 Relative PV conversion efficiency as function to light intensity[iv]

Estimation of annual yield

The annual yield of a PV installation can be estimated by various simulation tools available on the market. These simulation programs have built-in climate reference data and an algorithm to take the location of the PV installation into account. It is possible to simulate the surroundings in a simplified degree with horizon shielding and shadowing objects.

The simulation programs don't take the changing spectral distribution of light into account, which in this project will be addressed.

4. Objective of the project

The aim of the project is to investigate the potential of exploiting the advantages of solar cells in non-optimal light conditions in the urban environment from <1000 W/m^2 in best cases of light.

It addresses the gray scale from BIPV to minor applications driven by solar cells and thereby cutting the grid-connection saving CO_2, energy and manpower in the mounting phase. Cable-laying inevitably involves digging up and repaving public roads, and thus also underground work which in average cost 400 DKK pr. meter and up to 10 times more in the city center and the energy used goes to waste CO_2.

If this potential for savings should be exploited the following task needs to be addressed:

- Measuring and deriving irradiance data in not-optimal conditions in the urban environment.
- Measuring a variety of solar cells (different manufacturers and technologies) to have data material for matching suited solar cells to given conditions.
- Examine potential PV CO2-neutral substitutes for existing applications in the city and a look into the market potential, drivers and obstacles.
- A firm documentation presenting the data and experiences in a user-friendly way giving Danish companies a guide to investigate the potential of integrating solar cells in their products and for Denmark to take a lead in this growing market.

The project "Towards a CO_2 neutral urban environment – Cutting the wire" is portioned into 3 phases having 4 activities, as described in the latter.

1. Phase – A. & B. Measurements

A. Light conditions in the urban environments

If solar cells shall be used to supply the energy for any applications the amount of solar energy present shall be known. Irradiation data for not optimal solar cell positioning are scarcely available and therefore needs to be produced. In the project >40 representative sites for light measurements will be selected and logging equipment placed to measure how much light actually meets the solar cell. The sites should be chosen so that a relation can be derived and prediction of light conditions on street level in any Danish town be done reasonable for solar cell dimensioning and angling to meet the energy requirements for a given application by a set of a criteria characterizing the spot. By comparing these data with weather data, which the group has access to, important information can be gathered and it is the ambition, that by this methodology the light conditions in urban environments on other degrees of latitude can be extrapolated from knowledge of the spot and generic weather conditions from degree of latitude.

Light sensors with data logging for the measuring purpose will be developed in the project and data processing software developed to handle the large amount of data in an efficient way. By the end of the project an efficient data material will be produced being a powerful tool for the Danish industry wanting to integrate solar cells into their products for use in light conditions not optimal.

B. Measuring solar cells

When ordering solar cells only electrical data for standard conditions (1000 W/m^2 – 25°C) are supplied. Solar cells behave very different especially <200W/m^2 and care should therefore be taken in the selection process for solar cell applications for medium light conditions. Solar simulators made of high pressure Xe arc lamps used for testing solar cells can work in the area of 200-1200 W/m^2, but below this intensity they are not stable and all sorts of filters need to be introduced between the solar cell and the light source.

An artificial lamp made of LED components will be developed resembling sunlight with at maximum mismatch of ±20% to AM1.5. A large amount of solar cells will be characterized electrically at 25, 50, 75, 100, 125, 150, 175, 200, 250, 300, 400, 500, 600, 700, 800, 900 and 1000 W/m^2. A database will be created with cell data and manufacturer, technology etc. Especially newer cell technologies based for example on heterojunction mc/amorphous Si will be analyzed as well as a representative extract of the present technologies on the marked (Si, a-Si, CdTe, CIGS, CIS etc. – flexible/not flexible). The test facility will be built in a scalable way of 10 cm x 10 cm LED modules, so a larger test area easily can be created when one module is behaving perfectly. The test facility will have a measuring area of 30 cm x 30 cm by the end of the project. The test facility itself has a marked potential as it has a possible lifetime of 100.000 h where a Xe arc lamp only lives for 1000 h and have a huge energy waste both in the lamp and in the cooling tower it is supplied with.

To get the right light distribution and homogeneity lenses will be developed for the specific application. The LED light should be quite perfectly mixed and distributed, which also is taken care of by the lenses. Software both controlling the individual colors of the LED's separately and the data acquisition will be built. As the data for irradiance the solar cell data for the individual types will be of importance for choice of solar cell type for a given application.

2. Phase – C. Potential

After a given measuring phase a market study phase will address the application side of solar cells. An energy consumptions overview of about 30-40 existing applications used in the urban environment will be made and the potential of using solar cell systems will be evaluated by the group on basis of the measurements in phase 1. This includes an evaluation of the potential CO-2 savings and the marked potential of an optimized PV solution and estimated prices of the applications. This study is matched up by a study of the marked trends in the existing PV-application marked for the urban environments. The applications in this field are booming right now and a thorough study of the marked trends and the hurdles to overcome is important to bring the data assembled in this project in use in products of Danish companies.

3. Phase – D. Documentation

Throughout the project a huge amount of data and experience will be collected for exploiting the opportunities of solar cells in the urban environment. These experiences and the projects partners preceding thorough knowledge of solar cells will be used to make documentation for using solar cells in products in the urban environment. The measured data for light conditions and the measured output of the different solar cells will be assembled and presented on a CD-rom (or DVD depending on the size) with a user-friendly setup giving the interested user (usually a company interested in what solar cells can do for their products) an idea of size, price at positioning potential of a given energy consuming application. The guide will be published as a documentation including CD-rom giving Danish companies an easy short cut to foresee the potentials of integrating solar cells into outdoor applications towards a CO_2 neutral urban environment.

5. Process

The project group was formed with intercultural partners with great experience in research & development projects, strong scientific background as well experience with end-use design, products and user behavior.

The role of the project partners are:

Faktor 3:	Project leader and coordinator Knowledge about PVs and characterization (**B. Measurements**) Survey of PV potential (**C. Potential**) Branding and marketing (**C. Potential**)
DTU Fotonik:	Developer of light loggers (**A. Measurements**) Developer of LED simulator (**B. Measurements**) Branding and marketing of LED Sun and light loggers (**C. Potential**)
Technological Institute:	Responsible for irradiance measurements (**A. Measurements**) Data Evaluation (**A. Measurements**) Knowledge about PVs and characterization Responsible for documentation (**D. Documentation**)
dnp:	Developer of lenses for optical system in LED Simulator

Quite early in the project, it was discovered that the role of dnp was undertaken by DTU Fotonik. It was agreed that the competences of dnp to build up an optical system with lenses wasn't the optimal solution for the LED Sun simulator, where the best diffuse scattering would be achieved by a reflecting sphere. All parties agreed that dnp would be on the sideline of the project. Therefore the finances were allocated to DTU Fotonik.

The work in the project has consisted of individual work tasks which has been determined at group meetings. The group meetings has been held with the partners involved at the most relevant site (eg. At DTU Fotonik when discussion about LED Sun and loggers were on the agenda). Resumés of the meetings have been written with the tasks agreed and revised deadlines.

Background for developing LED Sun and light loggers

A need for developing and manufacturing a larger amount of loggers is necessary in order to characterize and map the available light in a city environment.
The project had access to 6 identical TinyTag loggers at a price of approx. 2500 Dkr/piece, but this limited amount of loggers cannot provide a representative data set of available light in general. Further it was concluded that the bit resolution of the TinyTag logger at 8 bit was not sufficient for the logger interval that is to be investigated. 16 bit input resolution would be preferred in order to cover the entire irradiance range with a sufficient accuracy.
The market has been investigated for other types of commercial data loggers with a higher resolution and one technically suitable product has been found. It is a TruTrack Model mV-HR mark 4 from the company Intech Instruments. It is a small two channel high resolution (16 bit)

milli-voltage data logger housed in a rugged stainless steel case. However, in the light of the considerable number of sites intended to perform light measurements, the price of approx. 3500 Dkr/piece, is prohibitive. Furthermore, practical experience has shown that it is very difficult to program and mount this logger.

Therefore a clear need for creating a light logger that can be mass produced at a low price is seen. Hereby it is possible to tailor the logger to the specific needs of the project.A logger is therefore being developed in corporation with DTU Fotonik and Faktor 3 which has a higher resolution that the existing TinyTag. Further it contains the added feature that it can measure the spectral distribution which is important information when dimensioning the solar cell. This logger will be easy to mass produce as it consists of Printed Circuit Board (PCB) with sensors for measuring spectral distribution and light intensity, a battery and a water proof casing. The production price is estimated to approx. 1000 Dkr.

Artificial solar simulators used to characterize the solar cell electrically are common on the market. These lamps usually consist of a Xenon bulb where different filters can be applied, in order to change spectral distribution. The light intensity is high, as solar cells are characterized under 1000 W/m^2.
In the project, an artificial lamp made of LED components will be developed resembling sunlight with at maximum mismatch of ±20% to AM1.5. It has been determined that the focus and strong turning point for the LED Sun to outstand from other solar simulators lies in the ability to test solar cells under low light conditions that resembles solar irradiation well. The ability to change spectral distribution (color temperature) is essential as different solar cell technologies have different response to the spectral light distribution. Therefore it has been accepted that the LED Sun can be used to test in irradiation range of 0-200 W/m^2 in at homogenous area of 30 cm x 30 cm. The LED Sun provides diffuse illumination to the test surface, and will due to the LED lamps, not generate heating of the test surface in same extend as commercial solar simulators.

6. Results

Measurements of irradiance in urban environment

Method for data collection

A phase of parameter definition concerning the outdoor measurements was carried out. In this phase it was decided to focus on real light measurements in the city, and therefore not work further on the model city. The model city was seen as a supplement to light measurements carried out in the city, and with the loggers being developed (see section ***Loggers***) it is believed that the mapping of light in the city will be adequate. Therefore it was decided to pass the build-up of a model city, since measurement in 1:1 scale will be most realistic.

For characterizing and mapping the solar distribution the following parameters must be considered:

- Surroundings, buildings, elements for shadowing as trees etc., reflecting elements as building material, shape and size of building.
- Orientation
- Season (radiation intensity, spectral distribution, solar height)
- Position of logger (solar cell or sensor).

From this parameter definition 2 sites in Copenhagen was selected which had the desired orientation, building form and surroundings. Approval from the building administrators to hang up loggers were sought and approved.
As 6 identical loggers were available for the project an initial series of measurement was been started up in November 2008 at the 2 test sites. The loggers were rebuilt to fit the desired data range area. The series of measurement was started up with the main purpose of gaining practical experience on how to attach the loggers and gain knowledge of data range area.

Logger Specifications

The logger system is composed of a Tinytag 0-200 mV voltage logger from Gemini, see Figure 7, which is measuring the short circuit current of a small solar panel through a resistor. The resistor value determines the range of irradiance input to the logger. This system is relying on the fact, that the irradiance is linearly related to the short circuit current of a solar panel. The size of the resistor is determined so, that the full input voltage range of the logger is utilized while at the same time securing that the solar cell is operating in the current generator range, see fig. ?? with the characteristic curves.

Figure 7 TinyTag logger

6 TinyTag Gemini dataloggers were configured similarily:

Measurement range:	0-320 W/m^2	
Resistor:	3.9 Ohm	
Calibration factor:	200 mV -> 320 W/m^2	=> 1.6 W/m^2/mV
Resolution:	320 W/m2 -> 256 bit	=> 1.25 W/m^2/bit

The loggers were programmed to measure every 3rd minute, starting at November 19th 2008, 00:00.
The solar cell is a polycrystalline, commercially available silicon solar cell, see Figure 8, with the following specifications:

Parameter type	Parameter value:
U_{max}	3.3V
I_{max}	150mA
P_{max}	0,446 W
U_{OC}	4.6V
Temperature coefficient	-16mV/°C
Dimensions	148x80x10mm
I_{SC}	160mA

Figure 8 Solar cell used as light logger

Synthetic characteristic IV-curves in dependence of irradiance-level have been calculated from the parameter values of the solar cell, see **Figure 9**.

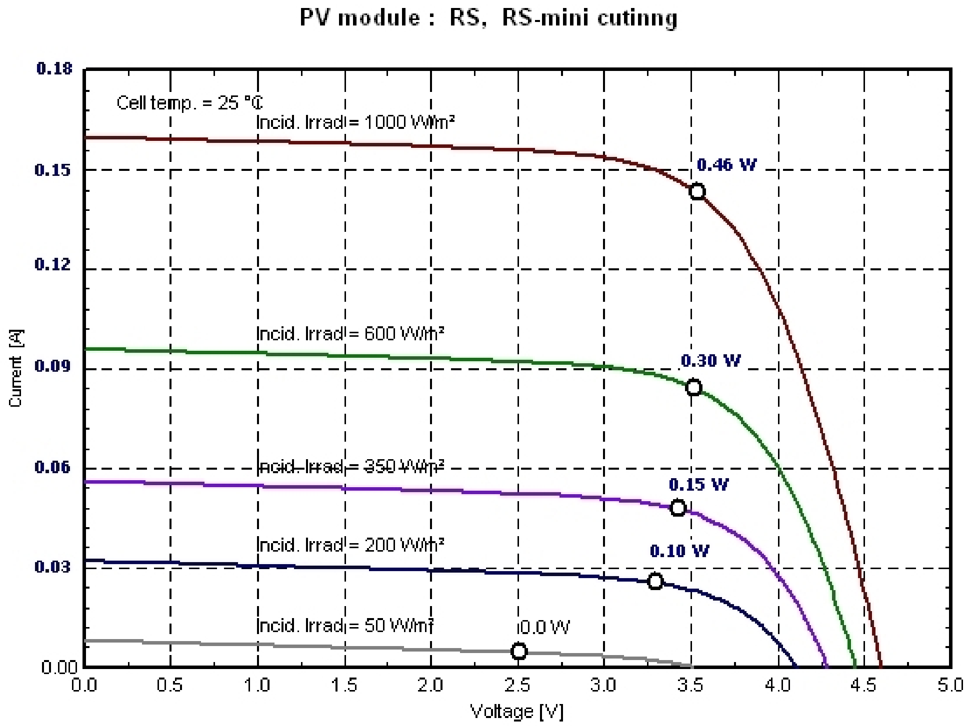


Figure 9 Characteristic curves of solar cell used as light logger

Site description

The 6 loggers were placed at 2 sites, respectively a north/south-oriented and an east/west-oriented street. When selecting the sites it has been desired that the site was located in a city-environment and that the buildings on each side of the street were of equal height.
Contact have been taken to the administrators of the relevant buildings in order to obtain the needed permission to attach the loggers to the building, and information about the project and light measurements were provided to the implied people living in the building.

See Figure 10 & Figure 11 for the position of the selected sites, shown by the red mark. It should be noted that both locations are affected by cross roads, so direct sunlight might occur depending on the position of the sun.
Distance has been measured by a digital laser meter.

Figure 10 Århusgade 39 (East/west-oriented street)

Figure 11 Oehlenschlægersgade 49 (North/south-oriented street)

Århusgade 39

The building is in 5 stores. See Table 1 for placement of the loggers:

Table 1 Placement of loggers in Århusgade

	Placement	Vertical distance to street level
Logger 1	4th floor	14.4 m
Logger 2	3rd floor	11.5 m
Logger 3	2nd floor	8.6 m

The width of the street has been measured to 18.9 m.

The solar cells are attached on the outside wall with Gaffa tape. The wire has been led through the window, so the loggers can be placed inside in the floor separation. See Figure 12-Figure 14.

Figure 12 Solar Cell on outside wall

Figure 13 Logger placed at floor separation

Figure 14 View after attachment of logger

Figure 15-Figure 20 documents the building where the loggers have been attached as well as the surroundings.

Figure 15 The three solar cells, Århusgade 39

Figure 16 House on opposite site of the street

Figure 17 Left side view

Figure 18 Right side view

Figure 19 View of street to the left (East)

Figure 20 View of street to the right (West)

Oehlenschlægersgade 49

The building is in 5 stores. See Table 2 for placement of the loggers:

Table 2 Placement of loggers in Oehlenschlægersgade

	Placement	Vertical distance to street level
Logger 4	3rd floor	11.1 m
Logger 5	2rd floor	8.1 m
Logger 6	1st floor	5.1 m

The width of the street has been measured to 12.7 m.
The solar cells are attached on the window frame with Gaffa tape. This creates the possibility that the loggers can fall of if the window is opened, but it is our belief that the staircase windows are not opened as we have spoken to some of the inhabitants. The wire has been led through the window, so the loggers can be placed inside in the floor separation. See Figure 21-Figure 23.

Figure 21 Solar Cell on window frame

Figure 22 Logger placed at floor separation

Figure 23 View after attachment of logger

Figure 24-Figure 29 documents the building where the loggers have been attached as well as the surroundings.

Figure 24 Solar Cells on the facade, Oehlenschlægersgade 49

Figure 25 House on opposite site of the street

Figure 26 Left side view

Figure 27 Right side view

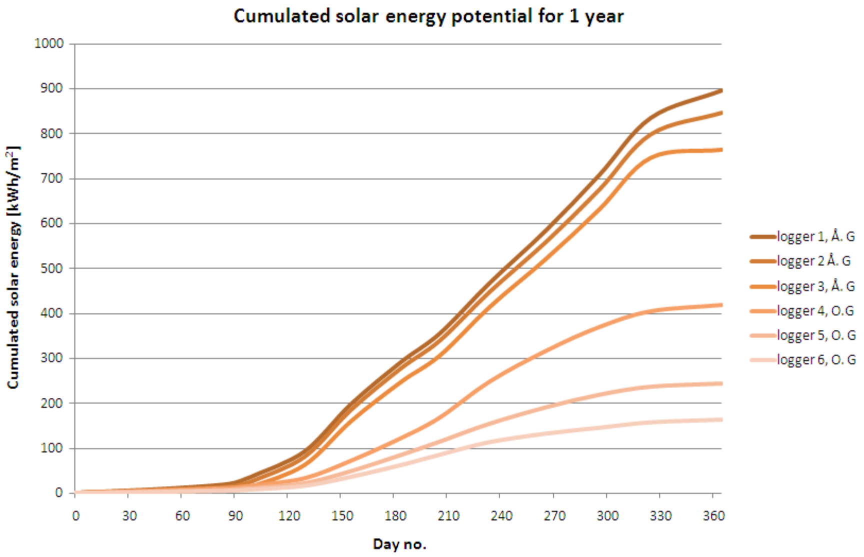
Figure 28 View of street to the left (South)

Figure 29 View of street to the right (North)

Light logger results for 1 year

The loggers have been inspected continuously, since it is necessary to offload data monthly. The placement of the loggers has been without inconvenience for the users of the building and the loggers are mounted securely on the facades.
The loggers were configured to match the light level of the season in order to utilize the full measurement range, and since they were placed in winter time, the measurement range was set to an irradiation intensity interval 0-320 W/m^2. In order to achieve the best match to season, the resistance in the loggers have been changed twice – in spring corresponding to a data range from 0-830 W/m^2, to summer with a range from 0-1042 W/m^2. This has been performed in order to prevent the data loggers going into saturation.

In the following, the logged data over 1 year is cumulated, Table 3, and graphically displayed, Figure 30.



Day no.	Date
0	19-11-2008
90	17-02-2009
120	19-03-2009
150	18-04-2009
180	18-05-2009
210	17-06-2009
240	17-07-2009
270	16-08-2009
360	14-11-2009

Figure 30 Cumulated light measurements for 1 year

Table 3 Cumulated solar energy measured by light loggers

	logger 1, Å. G	logger 2 Å. G	logger 3, Å. G	logger 4, O.G	logger 5, O. G	logger 6, O. G
	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]	[kWh/m^2]
Cumulated solar energy	896	846	765	419	245	163

The placement of the loggers is specified in Table 1, Århusgade and Table 2, Oehlenschlægersgade. As it would be expected the higher light sensor is placed on the building, the more solar energy is measured. The time with no obstacles between the sunbeam and the light sensor is lowered with the vertical distance from the street level.

It is logical that the sensors facing south (logger 1-3 in Århusgade) receives much more sunlight than the sensors facing west (logger 4-6 in Oehlenschlægersgade). In the winter period the sun is setting before the sunbeams can hit the west-facing sensors at an incidence angle small enough to bring energy.

Day 0 refers to the starting day of the logging period (Nov. 19th 2008).
Until the end of February (day 100) not much solar energy is measured. The elevation of the sun is even at noon very low. So low that the sunlight has little energy and that the sensors are heavily exposed to shadows from the buildings on the opposite side of the street. From the beginning of March 2009 the curves for the data loggers in Århusgade (Å-gade) takes off, while the curves for Oehlenschlægersgade (O-gade) remains flat for another month, before they start to increase.

If there were no shadows at all, the curves in each of the streets would be identical, only with minor differences due to the different influence of the ground reflectance. The curves in Å-gade differ relatively little, while the curves in O-gade differ relatively much. This can be explained with two facts. The narrower the street, the more pronounced it will be that the lower sensor receives much less energy than the upper one. O-gade is much narrower than Å-gade.

And the second fact: the more west-facing position of the sensor, the lower the sun height will be when it reaches that compass-direction, and this effect amplifies the relative difference in the amount of sunlight energy hitting the different sensors on the building wall.

If there were no shadows at all another effect would be seen on the curves. Then the growth rate of the cumulated energy would increase until about spring equinox (21-03-2009) and then slowly start decreasing again, assuming that the ratio of diffuse light energy and direct light energy would stay constant during this period of time. But the growth rate is actually increasing until about middle of April in Å-gade and beginning of May in O-gade, the reason being that the reduction in the influence of the shadows is more than offsetting the effect of the decreasing growth of the length of the day.

Finally it can be concluded from the graph, that in case a designer wants his product to be powered by PV even in the darkest months, he really has to focus on energy distribution and a possible energy storage to cover the power consumption, because the sunlight brings very little energy at that time of the year.

PVSYST simulation of sites

The measured data have been compared with simulations carried out with the advanced software-tool, PVSYST ver. 4.37. PVSYST is an internationally recognized simulation tool for PV-systems producing reliable results when estimating the electrical yield from PV-systems placed in the open field and on buildings. However, estimating the yield from PV-systems placed in the urban environment is much more challenging due to the more complex models for description of shadows, reflectance, albedo etc. The comparison has been made with the objective to verify the simulation tool and to get an idea to which extent the tool can give reliable input to the elaboration of a more simple-to-use design guide for architects and designers of PV-products for the urban environment in a later phase of the project.
In order to build the shadow scene in PVSYST, at first some photos are taken and processed with another tool, HORIcatcher. HORIcatcher allows a quick and precise survey of the horizon and obstacles on site in order to determine exact sunshine durations for solar energy and other applications. The analysis can be performed on site. Figure 31 shows a picture of the hardware part of HORIcatcher.

Figure 31 HORIcatcher, hardware-part

Figure 32 to Figure 34 show three steps in preparation of a description of the horizon for Århusgade logger 3 to be put into PVSYST. At first a 360° photo is taken. Next the horizon is outlined with software. And finally the horizon is drawn and converted to a text-file and put into PVSYST. Because of the placement of the loggers on the façade outside the building, it was necessary to lean out of the windows in a rather inconvenient position, and for Århusgade logger 1 it was not managed to get a photo of a quality to allow for an acceptable description of the horizon.

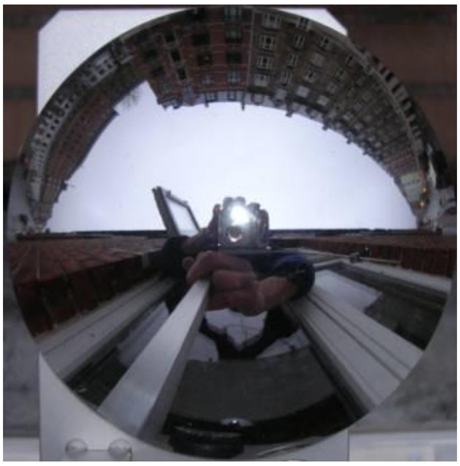


Figure 32 HORIcatcher, 'raw' photo, 360°

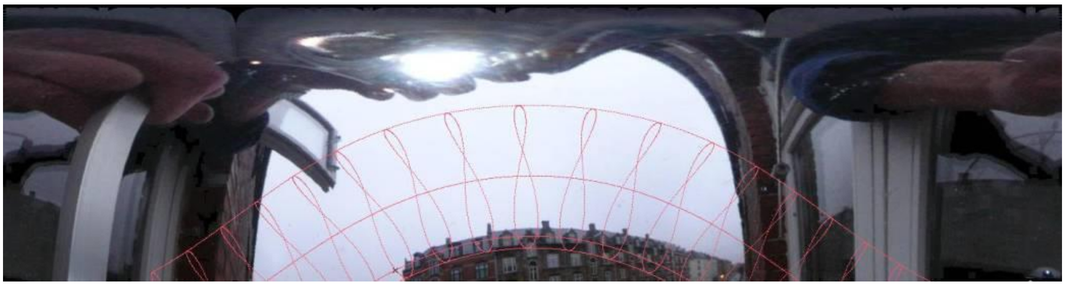


Figure 33 HORIcatcher, the 'raw' photo stretched out, azimuth -180° to +180°. The sun path during one year is sketched.

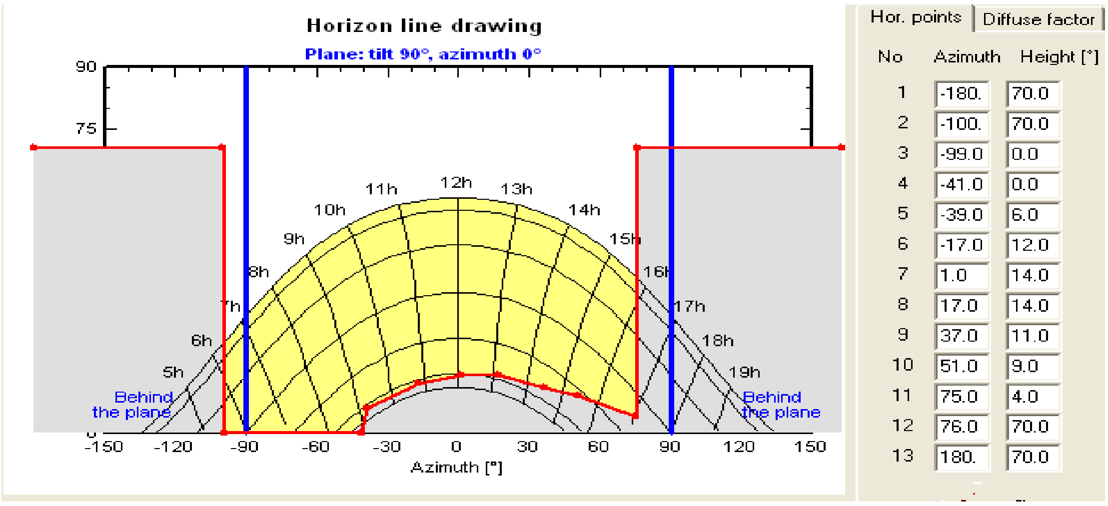


Figure 34 HORIcatcher, horizon outlined in PVSYST, ready for simulation.

Comparison of measurements with simulations

Before heading for the comparison of measurement results with simulation results it is investigated, whether the irradiated solar energy on the horizontal plane has deviated from a reference year over the period of measurement. For that purpose measurement data from a station (Holbæk Flyveplads) belonging to the Danish Metorological Institute (DMI) and data from a weather station installed at Danish Technological Institute (DTI) as part of a national measurement program for solar energy managed by the utility, EnergiMidt, are compared to data from PVSYST . PVSYST holds a major database with long-term average climate data for a number of stations in Europe. The data for Copenhagen comes close to the Danish "Design reference Year". The data measured by DMI are assumed to be more accurate than the ones from DTI due to the use of a professional pyranometer (thermopile) in comparison to a simpler solarimeter (mono-Si) at DTI and due to factors explained below.

The results for annual global irradiation (in a horizontal plane) are: PVSYST (988 kWh/m^2), DMI (1143 kWh/m^2) and DTI (950 kWh/m^2). The monthly distributions for the three data sets are shown in Figure 35. It is noted that the DMI-measurement results are significantly higher than DTI and PVSYST in the summer months. PVSYST and DTI are in the same level, but the confidence in the DTI-set is not so high, because the solarimeter has a small pool preventing rain water from running effectively off, and because it has not been cleaned systematically. This means that rain water and deposited dirt periodically has reduced the light energy reaching the sensor, and this leads to the conclusion, that the total measured solar energy is a little too low. The indication from the DMI data set is that it has been a significantly more sunny year than reference climate years. This conclusion is confirmed by measurements from other DMI-stations. The final conclusion is that when looking over the year it might be expected that the measurements of irradiation in Aarhusgade and Oehlenschlægersgade will be a little bit higher than the simulation results from PVSYST.

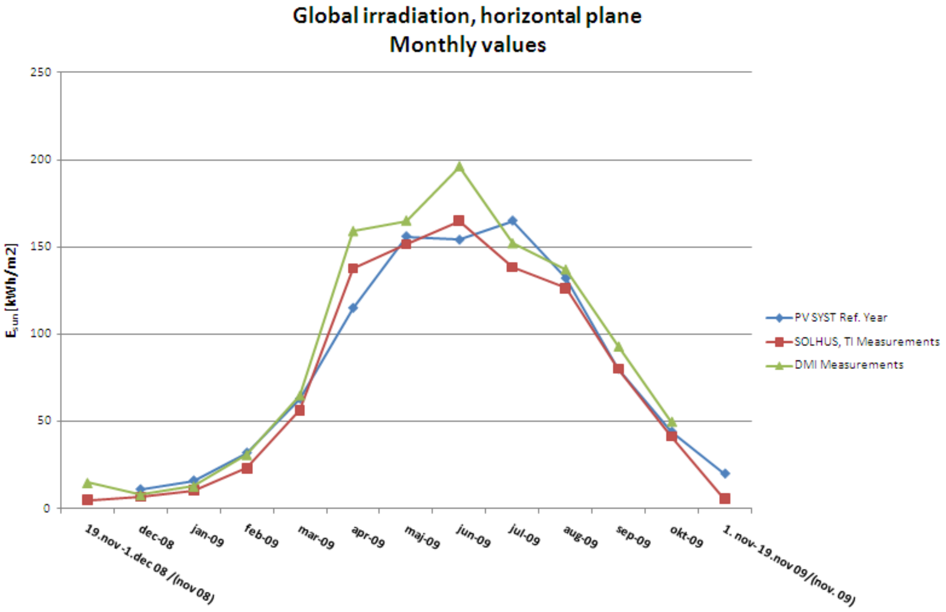


Figure 35 Global irradiation horizontal plane

Figure 36 and Figure 37 show the measurement results compared with the simulation results for Århusgade. In the reference simulation it is assumed that there are no obstacles for the sunlight in the horizon at all. For logger 1 simulation results are missing because of the failure of the horizon photography. It is seen that the loggers 2 and 3 in Århusgade over the year have produced about 20 % *more* than estimated by PVSYST. This was expected from the conclusion that it has been a very sunny year. When looking at the monthly deviation between measurements and simulations it is noted that the measurements are relatively higher in summer and lower in winter compared to PVSYST (see Table 4). Again the summer months can be explained with a higher irradiation than normal (i.e. than reflected in the PVSYST data set). An explanation for the winter months might be the inaccuracy of the rather simple measurement system, when used at very low irradiance levels. For instance at very low irradiance like in winter there is a shift of dominating wavelengths in the sunlight towards the infrared spectrum where the thermopile based instruments keep the full sensitivity while x-Si based solarimeters have reduced sensitivity. The loggers on site were of the solarimeter-type.

Table 4 Århusgade. Solar energy potential, measurements and simulations

	ÅRHUSGADE									
	PVSYST	Logger 1			Logger 2			Logger 3		
	Reference	Simulation	Measur.	Deviat.	Simulation	Measur.	Deviat.	Simulation	Measur.	Deviat.
	[kWh/m2]	[kWh/m2]	[kWh/m2]	%	[kWh/m2]	[kWh/m2]	%	[kWh/m2]	[kWh/m2]	%
jan	29,11		4	-	26,8	3	-89%	18,3	2	-89%
feb	46,96		27	-	45,01	16	-64%	41,57	11	-74%
mar	58,7		64	-	55,84	63	13%	51,14	55	8%
apr	88,96		128	-	84,64	127	50%	77,67	120	54%
maj	91,11		91	-	85,55	90	5%	76,64	84	10%
jun	82,07		107	-	76,69	104	36%	68,06	102,3	50%
jul	93,32		108	-	87,43	103	18%	78	101	29%
aug	90,29		136	-	85,54	130	52%	77,91	124	59%
sep	73,76		126	-	70,49	121	72%	65,03	115	77%
okt	54,15		90	-	51,88	78	50%	48,16	45	-7%
nov	37,01		8	-	34,9	5	-86%	28,78	4	-86%
dec	25,12		5	-	22,83	4	-82%	7,53	3	-60%
YEAR	**771**	-	**894**		**728**	**844**	**16%**	**639**	**766**	**20%**

Measurements: Jan-Oct 2009. Nov sum of time intervals 19-30 Nov 2008 and 1-18 Nov 2009. Dec 2008.

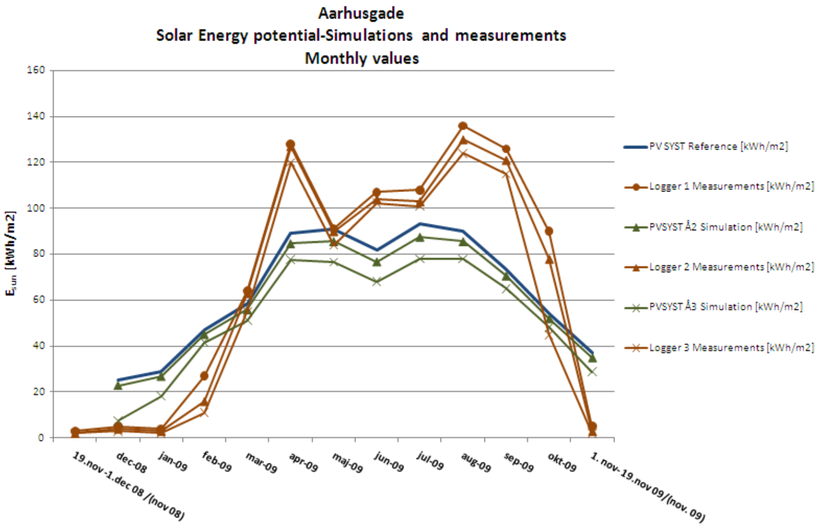


Figure 36 Århusgade. Solar energy potential, measurements and simulations

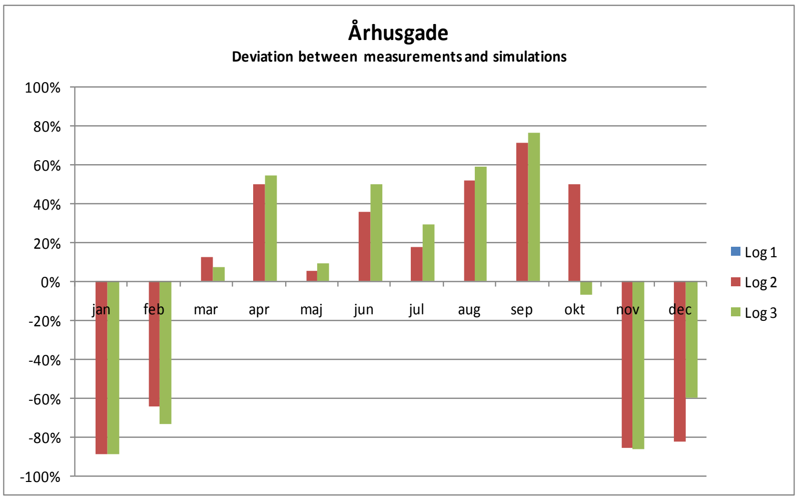


Figure 37 Århusgade. Solar energy potential. Relative monthly deviation between measurements and simulations

Figure 38, Figure 39 and Table 5 show the measurement results compared with the simulation results for Oehlenschlægersgade. It is seen that the loggers over the year have produced *less* than estimated by PVSYST. This is not in line with the conclusion that it has been a very sunny year. And again it is noted that the measurements are relatively lower in winter compared to PVSYST. One probable explanation for the generally much lower measurement results compared to simulation results in Oehlenschlægersgade might be that the angle of incidence of the light on the solar cell at nearly all times of the year is very high, because the façade is facing west. At high incidence angles reflections of the sunlight from the surface of the solar cell can be significant causing a reduced irradiance input to the sensor (the mono-Si cell). Another explanation might be that the air in Oehlenschlægersgade is rather dirty due to particles from cars and busses, and the dirt settled at a high rate on windows – and the solar cells.
The solar irradiation in Oehlenschlægersgade is mainly diffuse irradiation, and it is known, that x-Si solar cells doesn't have high electrical response to this type of irradiation. This might also cause the generally lower solar potential that has been measured on site.

Table 5 Oehlenschlægersgade. Solar energy potential, measurements and simulations

	OEHLENSCHLÆGERSGADE									
	PVSYST	Logger 4			Logger 5			Logger 6		
	Reference	Simulation	Measur.	Deviat.	Simulation	Measur.	Deviat.	Simulation	Measur.	Deviat.
	[kWh/m2]	[kWh/m2]	[kWh/m2]	%	[kWh/m2]	[kWh/m2]	%	[kWh/m2]	[kWh/m2]	%
jan	11,02	8,85	2	-77%	7,43	2	-73%	6,3	1	-84%
feb	22,07	17,46	9	-48%	15,02	6	-60%	12,72	5	-61%
mar	40,18	29,72	18	-39%	25,02	13	-48%	21,18	10	-53%
apr	73,6	54,32	53	-2%	46,3	37	-20%	39,04	27	-31%
maj	89,94	68,51	60	-12%	59,21	41	-31%	50,18	31	-38%
jun	87,46	66,88	77	15%	57,86	33	-43%	48,98	31	-37%
jul	94,91	73,13	71	-3%	63,21	36	-43%	53,43	21	-61%
aug	82,22	60,98	61	0%	51,12	33	-35%	42,77	15	-65%
sep	55,54	39,89	40	0%	32,76	21	-36%	27,53	12	-56%
okt	26,88	20,67	20	-3%	17,74	14	-21%	15,45	8	-48%
nov	14,24	11,64	4	-66%	9,71	2	-79%	8,22	2	-76%
dec	7,88	6,41	3	-53%	5,82	2	-66%	5,23	1	-81%
YEAR	**606**	**458**	**418**	**-9%**	**391**	**240**	**-39%**	**331**	**164**	**-50%**

Measurements: Jan-Oct 2009. Nov sum of time intervals 19-30 Nov 2008 and 1-18 Nov 2009. Dec 2008.

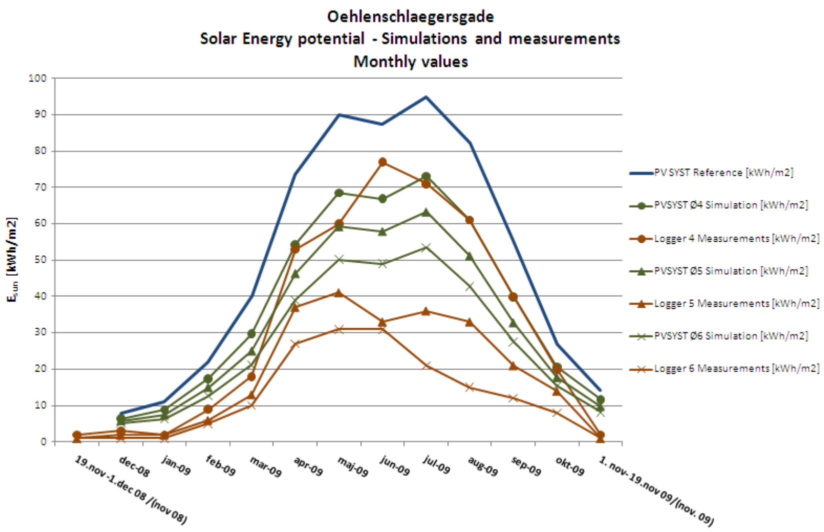


Figure 38 Oehlenschlægersgade. Depiction of solar energy potential, measurements and simulations

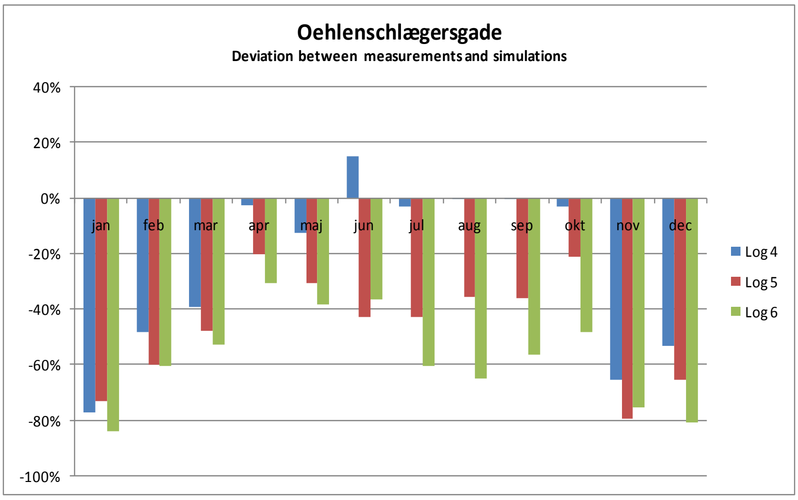


Figure 39 Oehlenschlægersgade. Solar energy potential, depiction of monthly relative deviation between measurements and simulations

Sub-conclusion

Much valuable experience has been gained from the measurement program of solar energy potential incident on two facades in the city-environment of Copenhagen. A few challenges, not to be underestimated, concerning the more non-technical part of the program can be mentioned:

find two suitable building facades, one facing due south and one facing due west (or east), with buildings of similar height on the opposite side of the street

- identify a contact person at each location and get permission to setup the data loggers
- develop a method to fix the sensors on the façade in a non-destructive way
- fix the sensors on the façade when leaning out of a window
- get regular access to off-load the loggers

Though the quality of the measurements is questionable for more reasons, there seems to be no doubt that even a very professional simulation tool like PVSYST falls short, when it comes to estimating solar energy potential in a 'tough' city-environment with a high accuracy. In fairness it must be added, that PVSYST cannot produce better results than the quality of the input data like for instance the description of the horizon. For the logger 1 in Aarhusgade it was found that the horizon photo did not have a quality well enough for making usable simulations. So an important learning has been that the description of the location, where measurements are made, needs to be very precise in order to provide usable input to form the basis of a simple-to-use design guide for architects and designers of urban PV-powered products.

It had been desirable with measurement equipment with a higher quality. The used data loggers have an input resolution of only 8 bit, which is rather low. However, suitable data loggers with higher resolution appeared to be quite expensive. Furthermore the equipment only provides information about total solar energy potential and not the potential distributed on the different wavelengths of the sunlight, which is important to know, if the best match between a PV-powered urban product and a solar cell should be made. Therefore it was decided in the project to develop a high-quality data logger especially suitable for mapping the sun light potential in urban areas, see description in the next section.

Light loggers

Specification of light logger functionality

Originally it was the intention to map the irradiation on selected surfaces in the urban environment as an accumulated irradiation measurement. This could be done quite simple with a photodiode or solar cell connected to a data logger. Since a lot of effort was put into this work package and it is extremely important for the selection of the right solar cell for the given application it was selected to extend the sensitivity of the measurement of the radiation by use of a color sensor instead of a photodiode. The chosen color sensor was a TAOS TCS230 giving the following spectral responses, Figure 40:

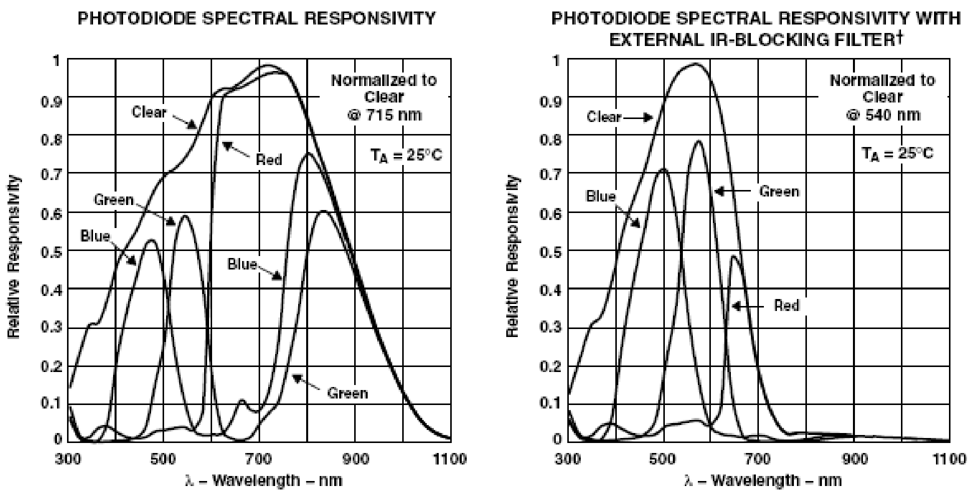


Figure 40 Spectral response of the TAOS TCS230 sensor

The sensor is composed of an 8x8 array of photodiodes – 16 with a blue filter, 16 with green filters, 16 with red filters and 16 photodiodes with no filters. The four types (colors) of photodiodes are interdigitated to minimize the effect of non-uniformity of incident irradiance. The TAOS TCS230 sensor unit is shown below, Figure 41:

Figure 41 TAOS TCS230 color sensor

Datasheet: **http://www.taosinc.com/getfile.aspx?type=press&file=tcs230-e33.pdf**

The importance of having the spectral distribution of the measured light for choosing the correct solar cell technology is shown on the curves below, Figure 42 which was also displayed in Figure 5, showing the very different spectral responses of different solar cell technologies.

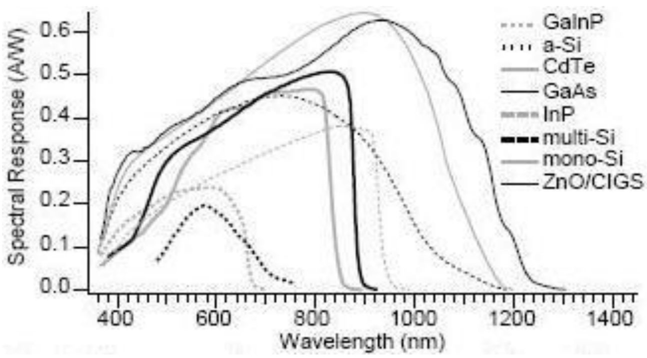


Figure 42 Spectral response of different solar cell technologies

The optimal measurement source would be a spectroradiometer but this kind of measuring unit costs >50.000 DKK. The color sensor works as a cheap solution in between spectroradiometer having a resolution of about 100 nm. A stand alone logger unit attached to a color sensor is not available on the market.

In order to make the sensors work and store data an electronic circuit is developed and software created for it to be able to be programmed. A flow diagram of the system is shown (see Figure 43).

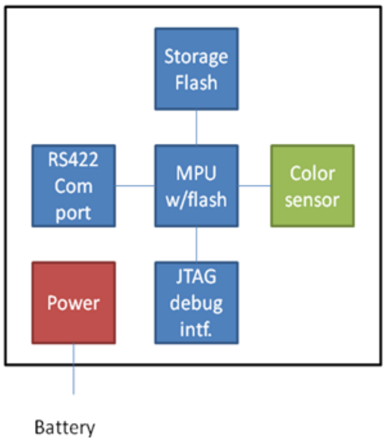


Figure 43 Flow diagram for the light logger

The units target production price is <1000 DKK when ordering >50 pcs. The refinement of the projects target from making a model of solar light energy distribution in the urban environment without the spectral distribution to a target where this is also measured and calculated into the model is a major improvement when a model should be derived of light energy receivement for potential solar cells installed at surfaces in the urban environment. But the development of the relatively complex light logger system from scratch was a challenging and time consuming task but worth the effort.

For developing the water proof casing following requirements have been set up:

- An IP67 box with lens for the light sensor and PC socket (Cable exit to withdraw data)
- Containing 3 AA batteries, circuit board, sensor etc.
- Mounting both vertical and horizontal
- Easy to mount: gaffertape or cable ties
- Safety line when mounting (wrist strap)
- Sensor lens must be free and as far from the wall as possible

The light logger has a Flash memory with the capacity of 4MB, corresponding to 200.000 measurements. The output of one measurement will be the distribution of Red, Green and Blue and total light at a given time.

Mechanical system

The mechanical system of the sensors was constructed as shown below seen from the three possible mounting angles, Figure 44.

Pink:	Battery box for 3 AAA (ELFA 6952113: 68X47X17 mm)
Green + white + black:	3 filters (lens)
Black:	Plug for data unloading and programming (ERA.2E.308.CLL)
Red:	Printed circuit board with components (20x65x18 mm with components)

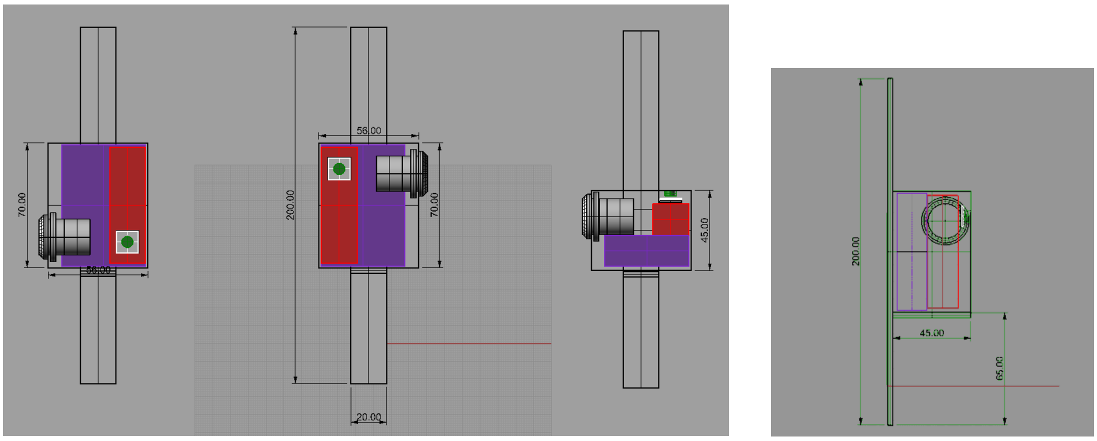


Figure 44 Mechanical system of loggers

Optics

The total optical setup is shown below in Figure 45.

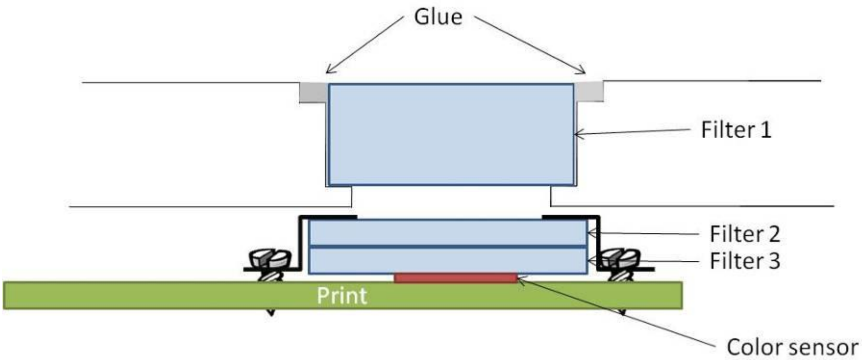


Figure 45 Optical setup with filters

To guide the light down to the sensor in a foreseeable manner a Gaussian diffuser filter (Filter 1) is chosen and mounted in the top of the box. Below filters can be mounted optionally but as standard an IR cut off filter (Filter 2) is mounted on top of one sensor to get a measurement of 400-700 nm in a resolution off, as a minimum of 100 nm. A small PCB with just a sensor mounted (not shown on the image above) is placed with an identical optical setup just with a visual light cut off filter. The measurements by this sensor therefore give information on the IR part of the spectrum in 700-1100 nm in 100 nm intervals. By adding up all the datas for the two sensors the total irradiance can be calculated. The filters are shown below.

Figure 46 Filter 1: Diffuser Opal 12.5 mm in diameter – thickness 2.7 – 3.3 mm.

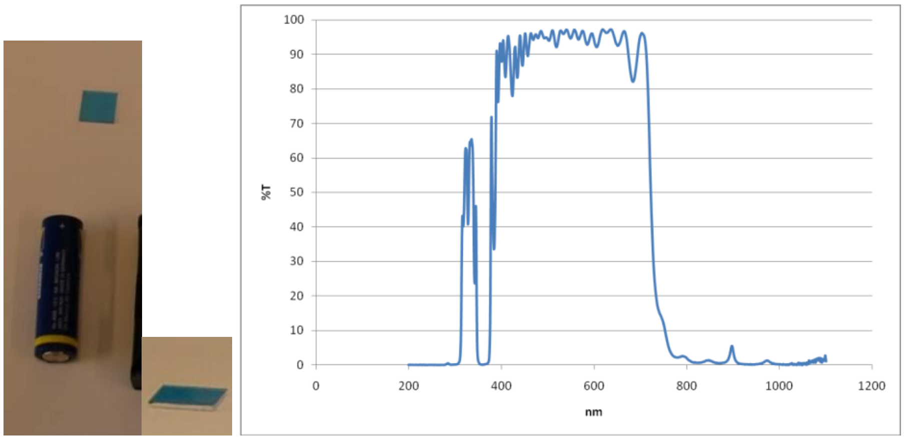


Figure 47 Filter 2: Filter IR or vis cut off. 12x12 mm – thickness 1.1 mm

The IR filter is the blue filter in Figure 47 (the blue color comes from a protective foil protecting the coating on the glass filter). On the right is shown a transmittance curve for an IR cut off filter.

Filter 3 is an optional ND-filter.

Since the sensor is very sensitive if measurements should be made in direct sunlight it is necessary to reduce the light X% (X depending on the expected maximum irradiation value) identical throughout the whole measurement area from 400-1100 nm. This can be done by a Neutral density (ND) filter which is made in several percentages of light reduction. By filter 3 the resolution of the sensor can varied dependent on the measurement spot. Different transmittance curves to reduce the sensitivity are shown in Figure 48.

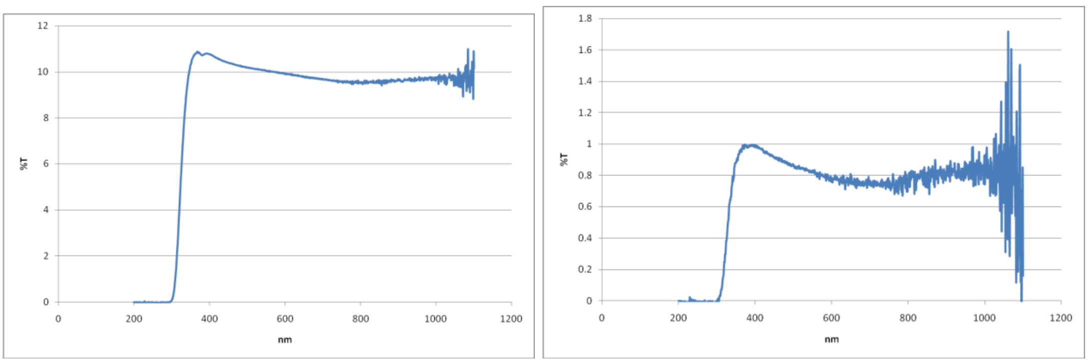


Figure 48 Transmittance curves of ND1.0 og ND 2.0 filters

An image of the 1 filter glued into the lid of the sensor box is shown below, Figure 49:

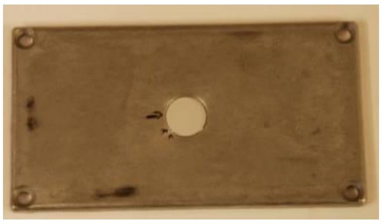


Figure 49 Filter 1 in sensor box

In order to only receive light through the filter surface, the edges needs to be blocked from light to enter. This is done by coating the glued area with a black paint.

Results of 1st prototype

Several measurements were made to test the software in the microprocessor and the electronics circuit of the first prototype of the logger. The first logger was made for testing the internal principles and making a simple user interface for setup of the logger and unloading data from the logger unit, see Figure 50. Figure 51 displays the first measurements made with the prototype without calibrations.

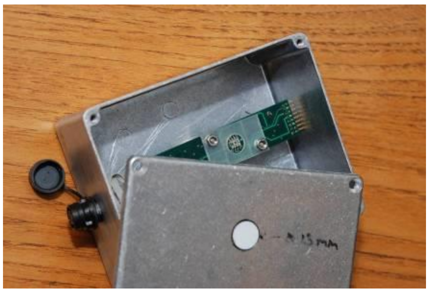


Figure 50 1st prototype of logger

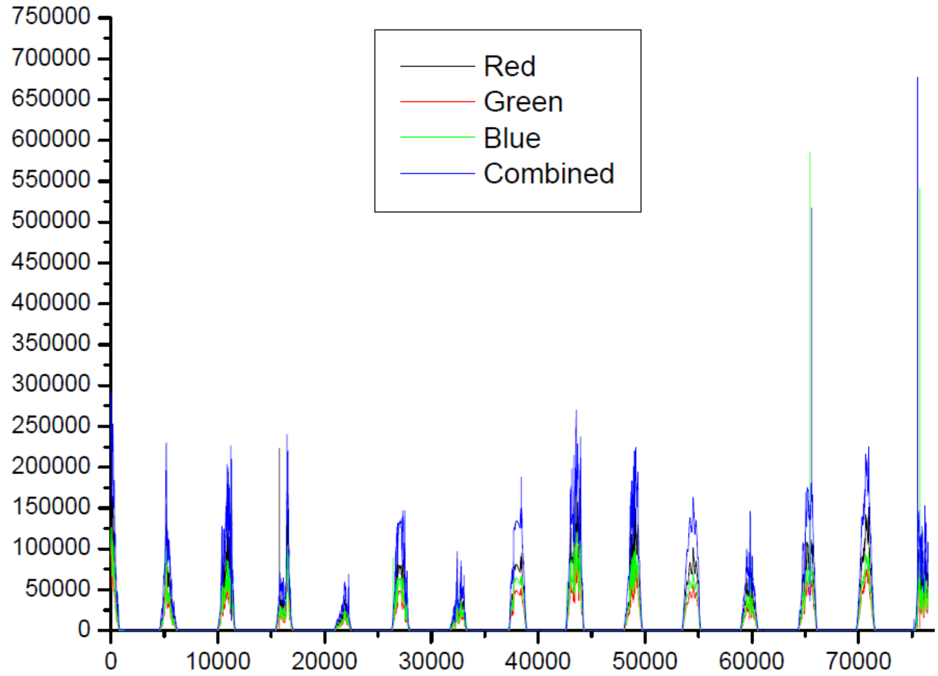


Figure 51 Logger measurements from 1st prototype

Below is shown a zoom in on the days from the 1st of January to the 4th of January

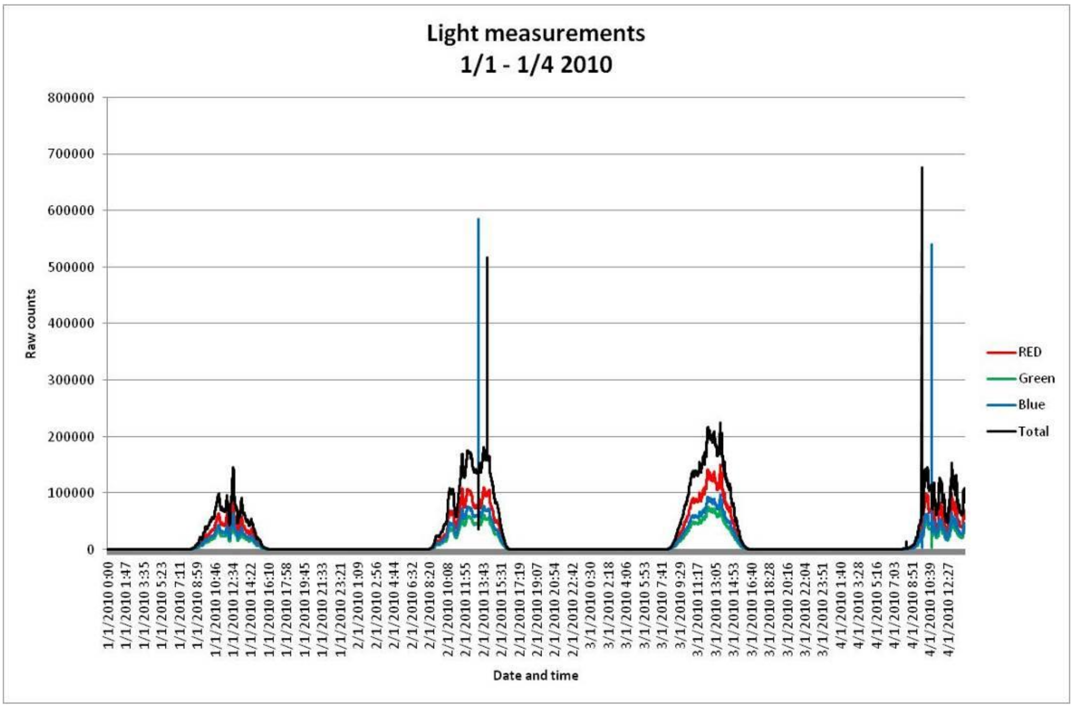


Figure 52 logger measurements from 1st prototype

User interface

There are two ways of programming and emptying the logger. Below is shown a terminal window with several macro calls for the sensor.

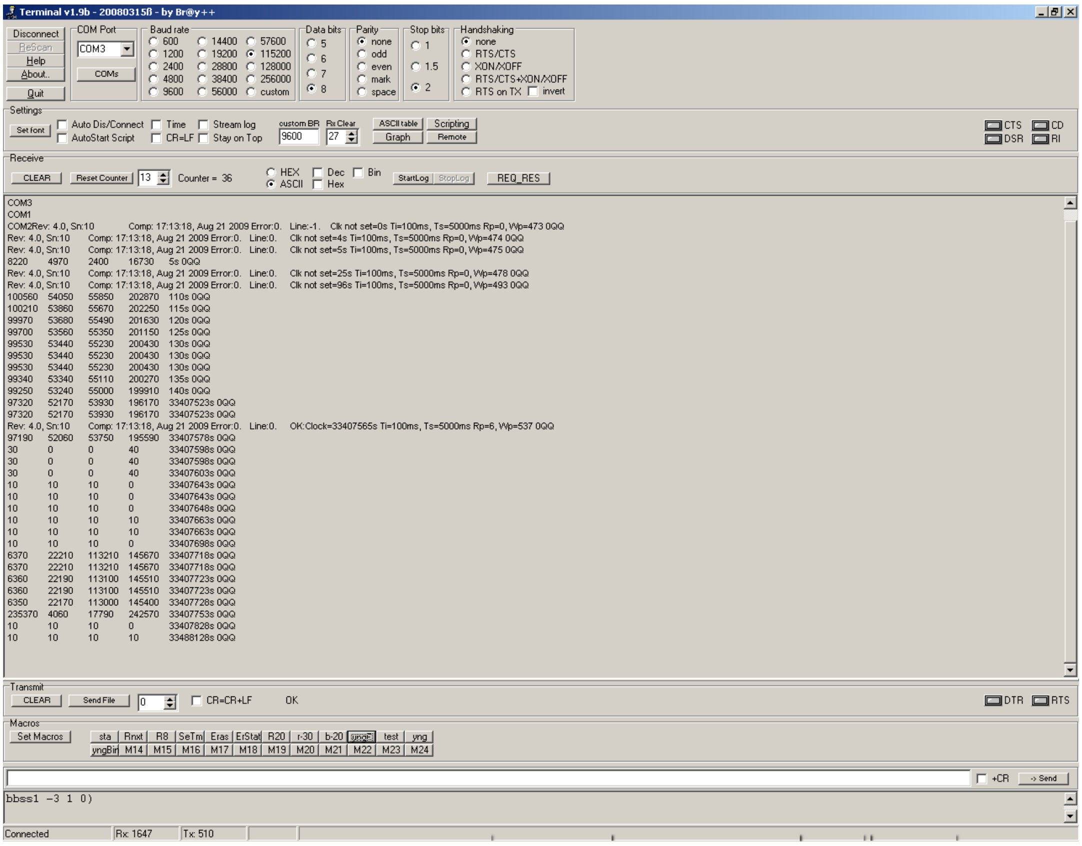


Figure 53 logger communication by terminal and macroview

This communication method is not very user friendly but good for debugging and also reading out simple calls from any computer having an USB port without needing to install the Labview user interface stand-alone platform. The latter is shown below.

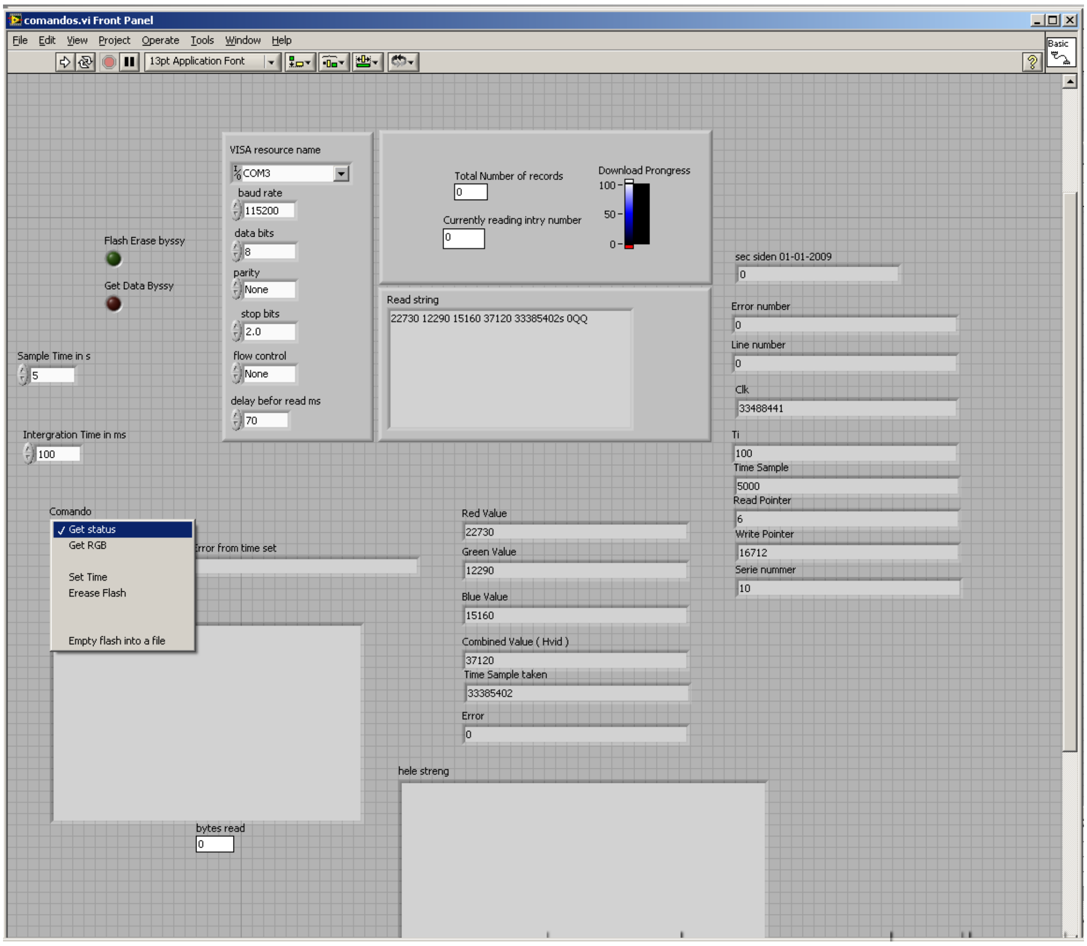


Figure 54 Labview stand-alone interface

Through this interface, which can be installed on all computers without needing to have Labview installed the logger can be programmed. Data can be read out and stored in a file. Key values that can be set in the interface are:

- Setup for COM port communication via USB to Serial
- Time between measurements
- Integration time in ms
- Stored RGBT values can be read out if needed.
- Time can be set (default is PC time)
- The Flash can be erased
- Flash can be read out into a CSV file
- Several error codes can be read out

A guide of the hardware calls and error codes can be found in appendix A.

Calibration of logger

The sensitivity curves of the TAOS TCS230 color sensor chip is supplied by TAOS to be as shown below:

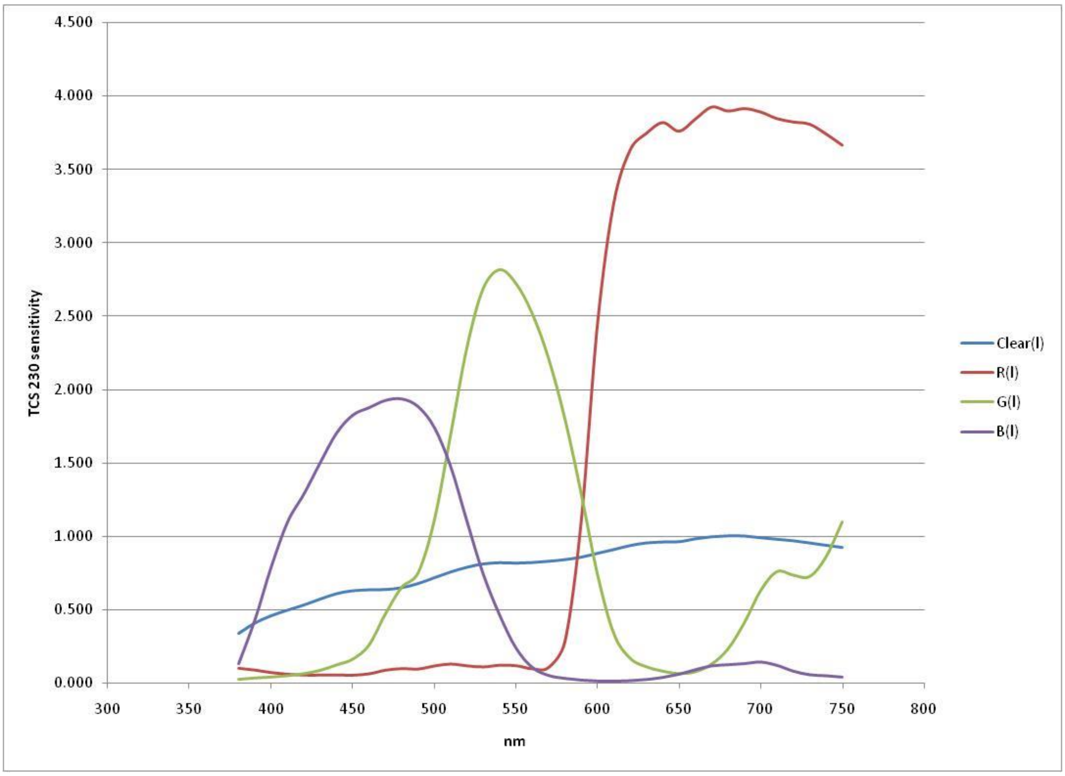


Figure 55 Sensitivity curves of the TAOS TCS230 chip

It is clear, that the individual color responses changes with wavelength so a good way to calibrate the optical system first is to use non full spectrum light.

The sensor is divided into two systems as shown below

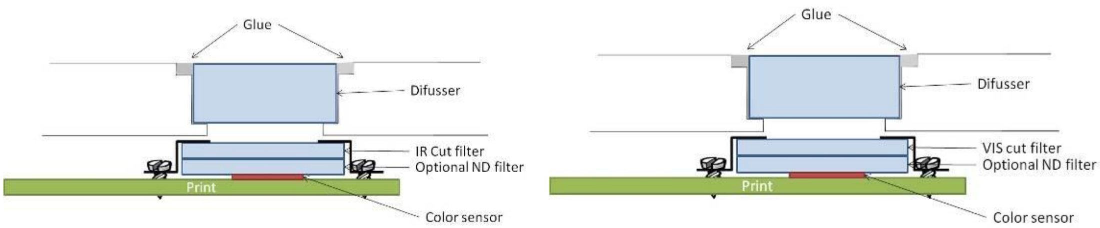


Figure 56 The left is a UV-VIS sensor and the right an IR-sensor setup

First the UV-VIS setup of the system is calibrated. The 4 coordinates of sensor response under the 33 individual LED light source conditions shown below is obtained.

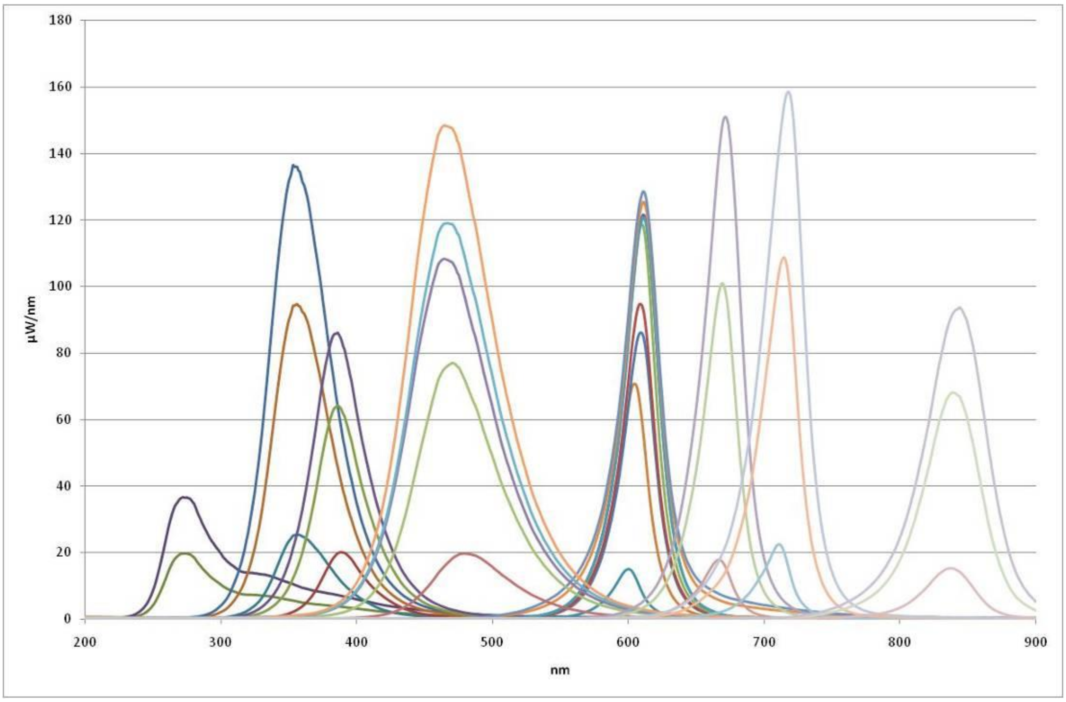


Figure 57 LED light

By correction for the sensitivity curves in figure 55 and the filtering effect in figure 47 the optical system has been calibrated. When an unknown spectral distribution needs to be measured the 4 sensor coordinates even when calibrated for the optical system cannot give the spectrum. But since we are measuring on sunlight direct or in reflected forms the sensor output is supposed to be like Planckian curves. Therefore the f(R,G,B,Total) should be fitted to a planckian curve at a color temperature given by the first 3 factors in the sensor output. The last response determines the intensity and it can be divided into smaller intervals such as 100 nm by the curve fit. A very simple curve fit is shown below (the red curve).

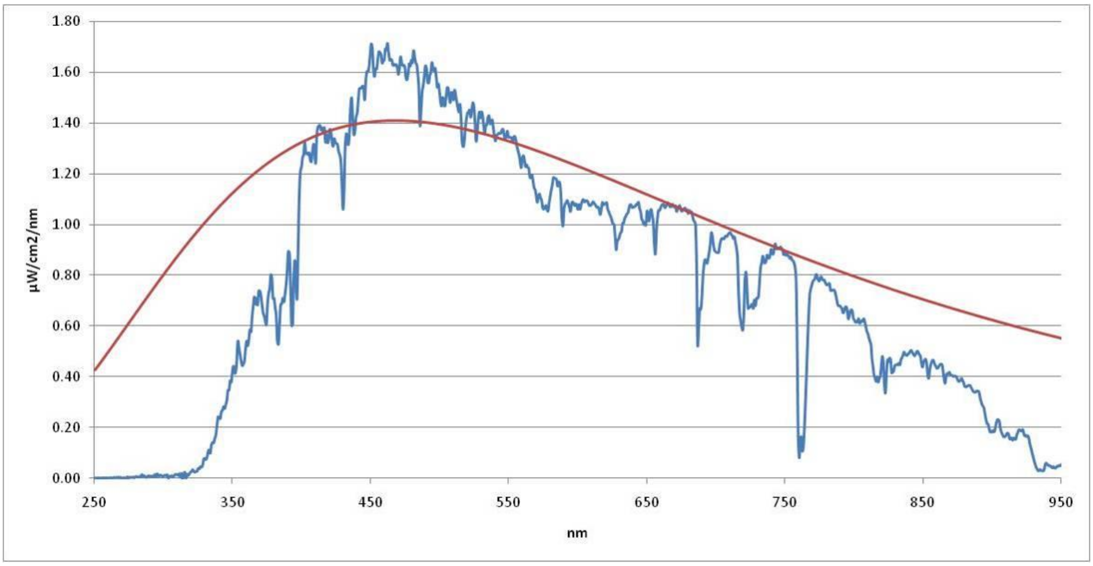


Figure 58 planckian fit to measured sun spectrum

The fitting was done in Matlab to different daylight specters by finding the correlated color temperature (CCT) from the RGB values and fitting it to planckian curves or daylight curves respectively for CCT values below or beyond 5000K. By 4 sample measurements of quite different spectral distribution it was found that the energy distribution was within ±10% of what the spectrometer measurements when parted in 100 nm intervals from 400 nm – 700 nm. The radiation intensity was 20-60 W/m^2 for these calibration measurements. The predictions in the IR was quite far when only using the R,G,B,Total values for the visual area but when incorporating the sensor measuring the IR light the IR measurement was in the same error region as the visual. There were produced 10 loggers as the one shown below.

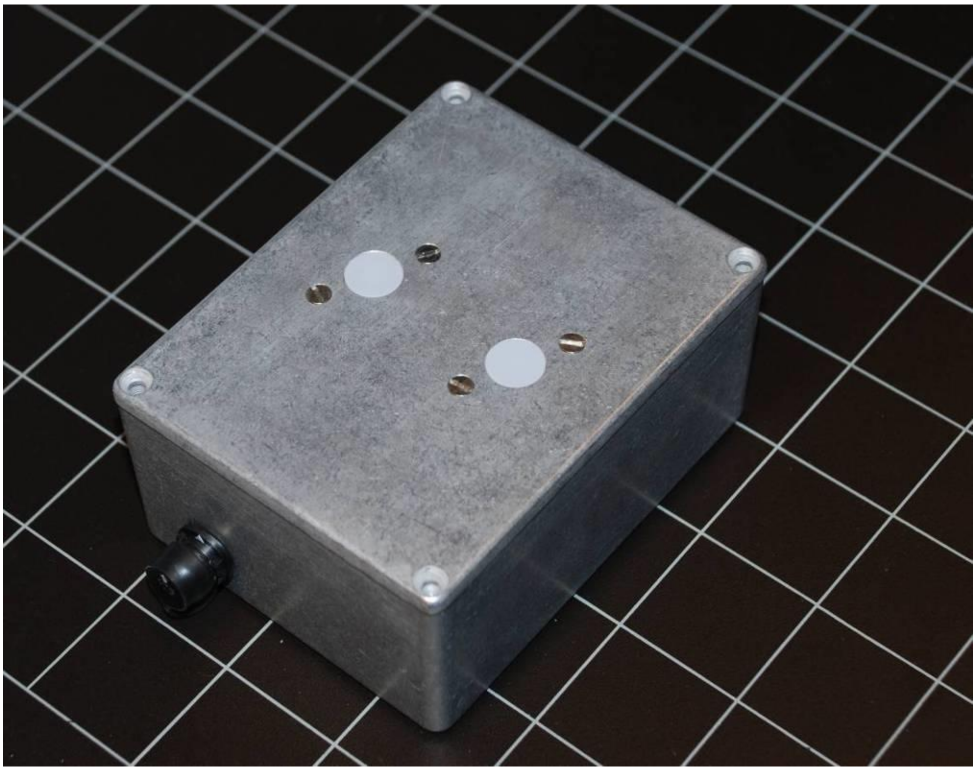


Figure 59 one of the 10 light logger units

Applicability and production

During this project several presentations was made at conferences, seminars etc. about the project and its contents and the development of the color sensor unit. There is a huge interest from a lot of players for such a logger unit. There seems to be a market potential in the two major market areas

- Indoor light measuring
- Outdoor light measuring

Indoor light measuring:

Scientist and companies working with light distribution indoor is usually working with a luxmeter. This gives the light intensity in lux which is a value correlated to the eye response curve for the human eye. Totally different spectral light distributions can give the same lux value. Since new studies have shown that humans behave very differently when exposed to different light distributions and intensities the lux value is actually a far from perfect way to measure light. The spectral response is simply lost in the measurement and the developed sensor in this project is therefore very interesting for people working with data collection and handling in this area. The sensor developed in this project can also give the lux value which is just a matter of calculation.

Furthermore a new market for IPV (Indoor Photo Voltaic) is rapidly building up. As in the paragraph: Light loggers, Figure 42, sharing the spectral responses of the different solar cells it is very important to know the light distribution to choose the right solar cell technology and the size of the panel to run the given application correctly. The electronics market is very focused on making more and more energy efficient microprocessors and chips which opens a market for solar cells driving a lot of applications instead of having to replace batteries. Just to mention a few applications: Wireless mouses, wireless keyboards, fire alarms, gas alarms, remote controls etc. The ELFORSK Project "The CO2 neutral work space – a platform for reducing the standby consumption with solar cells"[v] has shown that it is possible to reduce the stand-by consumption of an electrical table to 0 by implementing a simple solar cell setup and an electronic switch. The microprocessor waiting for the user to press the button for elevating the table uses about 2W when the energy comes through the AC/DC converter. But by bypassing the AC/DC converter and giving the power to the MPU by a little PV panel only 350 µW has to be supplied saving about 17.5 KWh pr. year for an electrical table. 10% of the energy consumption in the household is wasted in standby consumption – and the PV bypass of the AC/DC converter giving 0 standby and still being running and listening for the user to press the remote control opens a new market for IPV.

The rules for standby consumption is rapidly made harder to meet in EU (in 2013 they will be even more strict). The PV solution might be the solution for a lot of product manufacturers since it is relatively cheap compared to a high efficient AC/DC system just for the standby/wake functions and saves development time since it usually is a simple add-on to the electrical system. The system though needs to receive some light from artificial lighting and/or daylight through e.g. a window and therefore some dimensioning tools for PV needs to be made to be able to meet the requirement. The sensors developed in this project are an important data assembly tool for making such measurement and creating the very important data for such a dimensioning tool where the traditional lux measurements are of no use at all.

Outdoor light measuring

A market for creating measurements on light distribution of the incoming light at different surfaces outdoor is also seen. Usually measurements of the energy on a surface are measured in W/m2 but this value says nothing about the light spectrum. Since most solar cells for outdoor use earlier has been of silicon the spectral response is mostly the same from solar cell to solar cell. And if the cells are not of very high quality their response to light $<100\ W/m^2$ is nothing at all compared to the performance under direct sunlight in the middle of the day, which makes the system very unpredictable and can easily be wrong-dimensioned. Since the production in these years are going towards more and more thin film (Figure 60) which has a totally different response to solar light than silicon both on the spectrum and on intensity variations it important to know the spectral distribution on the energy to choose the best solar cells for the given point of use being a BIPV installation or other field of use.

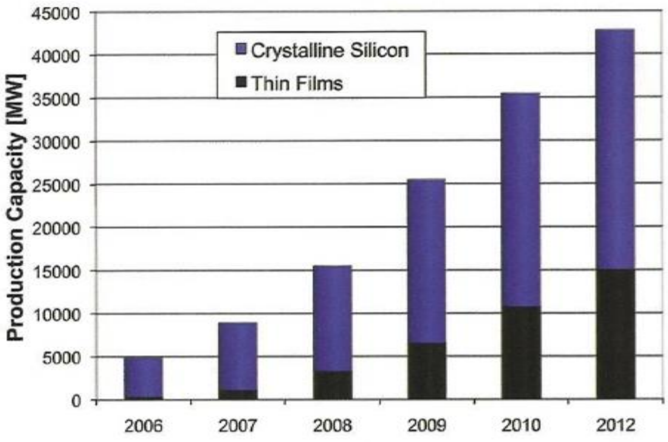


Figure 60 Actual and planned future production of thin film and crystallins Si solar cell modules

Since the thin film technologies have the potential of becoming cheaper pr. Wp installed than silicon will ever be (Figure 61), a tool to forecast what a given solar cell type placed in a given spot will create in energy pr. year is important to create. This is a topic of this project but many groups all around the world is working with similar studies in this field and the sensor from this project seems to fullfill their need quite nice as well as ours.

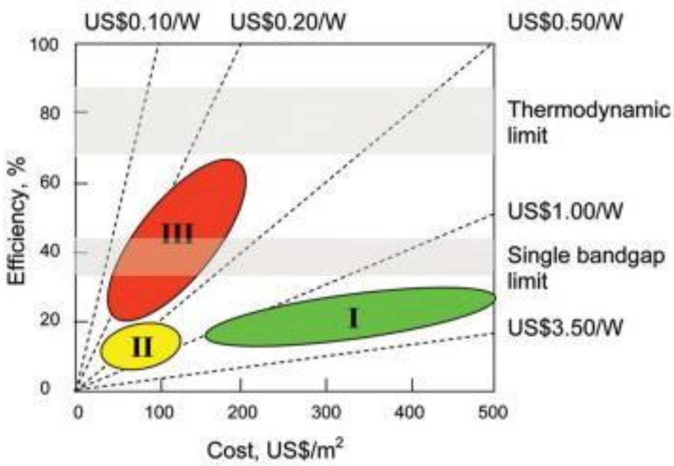


Figure 61 Price-performance ratio for the three generations of solar cell technologies

The sensor has two weaknesses.

- Stand-by consumption of about 1 mA
- It is not a wireless module

The market analysis shows a good market possibility for the sensor. The prototype uses a little too much energy – and should be around 10 μA in stand-by mode. It would be a strong improvement, if the system could be programmed and unloaded by a wireless interface. This would increase the stand-by consumption though.

Sub-conclusion

A sensor platform has been build in the project and calibrated. The system works very nicely, but it has been a challenge to build it up from scratch. Hardware has been made successfully and a user interface likewise. Ten logger units have been produced in the end of the project measuring the energy distribution within an error margin of about ±10% compared to at AvaSpec-2048 Standard Fiber Optic Spectrometer. The radiation intensity was 20-60 W/m^2 for these measurements.

LED Sun

To characterize solar cells for use in lowlight conditions a special and flexible measurement facility not available on the market today is required. Solar cells are classified today by producers at standard conditions, which is not consistent if the use is moved away from use in direct sunlight. The spectral distribution along with the intensity of light becomes increasingly important the further down the solar cell is placed in the urban environment since the sunlight is reflected instead of direct light from the sun. Therefore the working conditions becomes very different from the standard conditions (1000W/m2, AM1.5) and a characterization facility that can characterize solar cells under conditions similar to those in the urban environment will be relevant for selecting the right solar cells for applications in these environments.

Originally it was intended that the LED sun setting should be "flash" type, which is characterized by emitting light in very short intervals by which solar cells are not heated by the very high light intensity and the characterization can occur at room temperature, as prescribed in the standard. This is especially suited for inorganic solar cells such as the silicon type where charge separation occurs momentarily. This is not ideal for all solar cell types (especially the new organic), where some of the chemical system time constants are in the seconds region - so the facility must at least be able to maintain uniform illumination during this interval. Since the facility in practice should characterize solar cells for use in mostly reflected light the maximum intensity of the system was set to around 200W/m^2 when following the standard IEC904, standard for measuring solar cells.

Specification of LED Sun functionality

The IEC904 standard for measuring solar cells have the following requirements for the distribution of the light, as given in Figure 62.

Wavelength (λ) interval, μm	Percentage of total irradiance between 0,4 and 1,1 μm
0,4 to 0,5	18,5
0,5 to 0,6	20,1
0,6 to 0,7	18,3
0,7 to 0,8	14,8
0,8 to 0,9	12,2
0,9 to 1,1	16,1

Figure 62 IEC904 standard requirements

The light source in this project should be based on LEDs which is a much more robust light source than e.g. a xenon lamp which is usually used for characterization of solar cells and panels. The AM 1.5 condition and distribution is shown Figure 63.

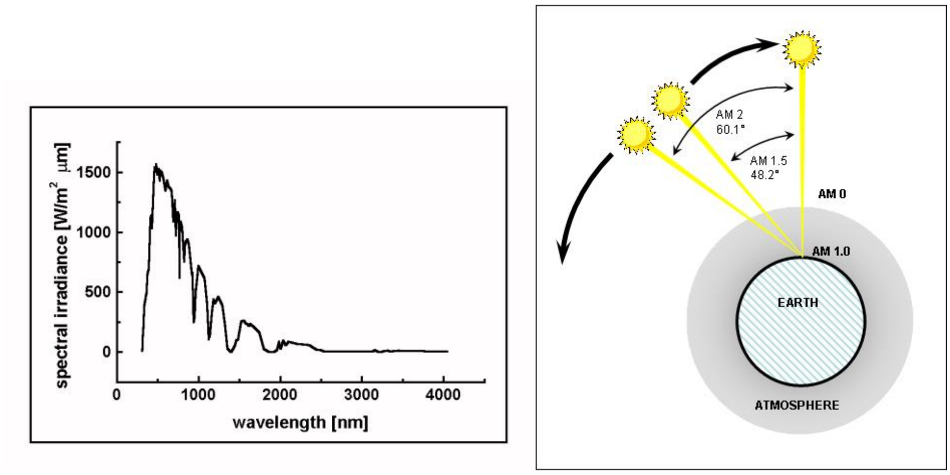


Figure 63 AM 1.5 spectral distribution of light

The Air Mass (AM) value describes the spectrum of sunlight at a particular latitude. It is defined as the distance through the atmosphere that the light from the sun travels in order to reach the solar cell. This is expressed relative to conditions at the equator, where the sun is almost directly overhead, and where the light is as described in AM1. Thus in space, with no atmosphere, the spectrum is referred to as AM0.

Several LED setups and lamp designs was considered and some were actually build in different aspects. The system principle was finally chosen to be as shown in Figure 64.

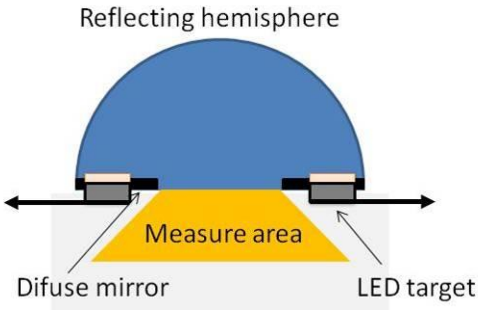


Figure 64 LED Setup

To ensure that the measured solar cell receives perfectly mixed and homogenous light, only reflected light from the LED targets is irradiated onto the measuring area. The light from the LED target is shined into a large spherical geometry painted with a >98% (400nm-1000nm) reflecting material on the inside.

To electrically characterize solar cells and panels a setup with a sourcemeter is developed. The whole system should be controlled by a PC via Labview. The parameters that the system should be able to measure are:

- Energy conversion efficiency
- Maximum power point
- Fill Factor

- Serial resistance
- Shunt resistance
- Quantum efficiency

Energy conversion efficiency

The energy conversion efficiency (η) of a solar cell is the percentage of power converted from absorbed light to electrical energy and collected, when a solar cell is connected to an electrical circuit. The term is calculated using the ratio of the maximum power point, P_{out} or P_m, and the irradiated light energy on the solar cell surface, P_{in}.

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}}$$

The maximum power point can be found by a voltage sweep from 0V to V_{oc} (open circuit voltage) where the largest multiplication of voltage and current is V_{mp} (Voltage at maximum power point) and I_{mp} (maximum power point current). The multiplication of these parameters represents P_{out}. See Figure 65.

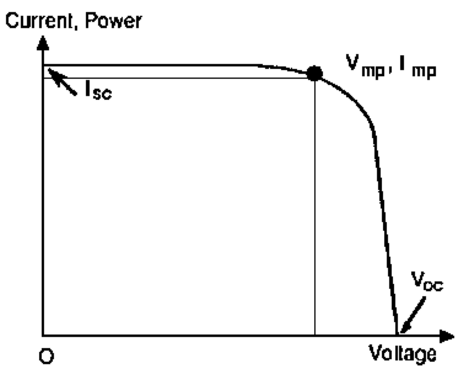


Figure 65 IV-curve of solar cells

This term is calculated using the ratio of the maximum power point, P_m, divided by the input light irradiance (E, in W/m^2) under standard test conditions (STC) and the surface area of the solar cell (A_{sc} in m^2).

The short circuit current (I_{sc}) and the open circuit voltage (V_{oc}) are the maximum current and voltage respectively from a solar cell. However, at both of these operating points, the power from the solar cell is zero. The fill factor (FF) is a parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc}. Graphically, the FF is a measure of the squareness of the solar cell and is also the area of the largest rectangle which will fit in the IV curve. The FF is illustrated in Figure 66.

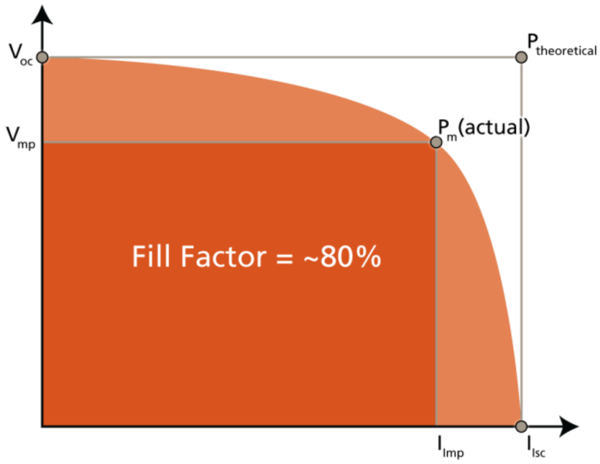


Figure 66 Fill Factor definition

A very simple solar cell model is the one diode model where a diode and current source is connected in parallel, see Figure 67.

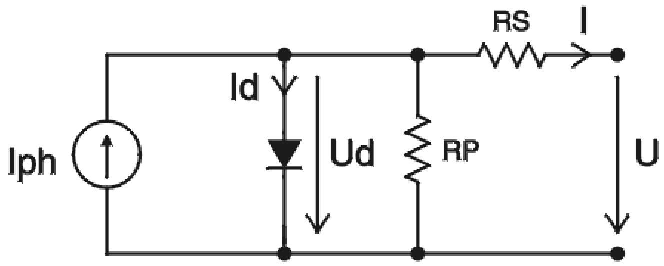


Figure 67 One diode model

By fitting the measured I and V data to the equation system of the model the serial resistance and shunt resistance of the system can be obtained. The influence of serial resistance on the performance of the solar cell can be seen below:

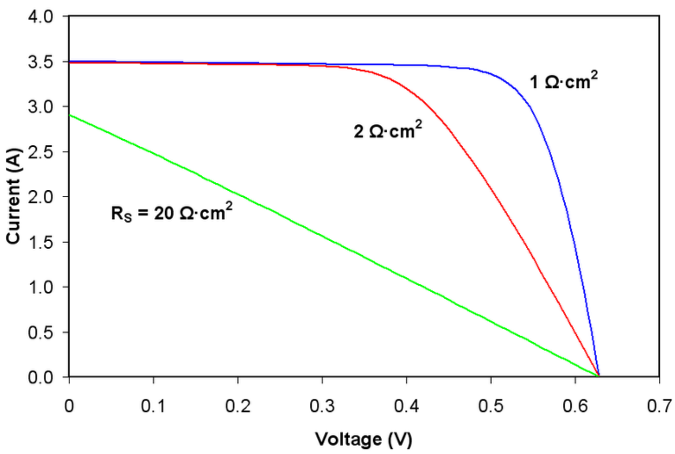


Figure 68 Serial resistance influence on solar cell performance

The influence of the shunt resistance is shown in Figure 69:

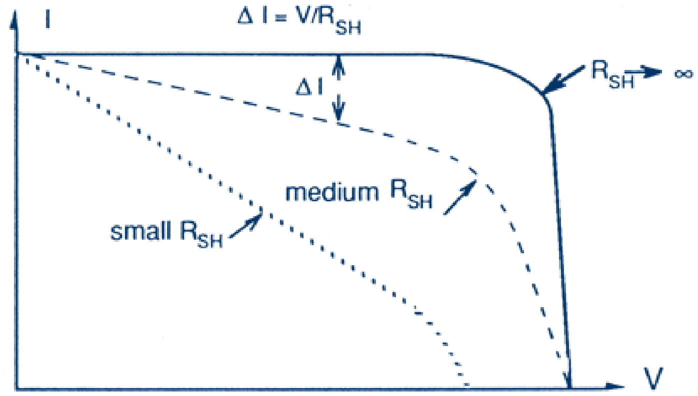


Figure 69 Shunt resistance influence on solar cell performance

The Quantum efficiency

Quantum efficiency (QE) is the ratio of the number of charge carriers collected by the solar cell to the number of photons of a given energy shining on the solar cell. QE therefore relates to the response of a solar cell to the various wavelengths in the spectrum of light shining on the cell. The QE is given as a function of either wavelength or energy. If all the photons of a certain wavelength are absorbed the QE at that particular wavelength has a value of one. The QE for photons with energy below the bandgap is zero. The QE is reduced because of the effects of recombination, where charge carriers are not able to move into an external circuit. The QE for some different solar cells can be seen in Figure 70.

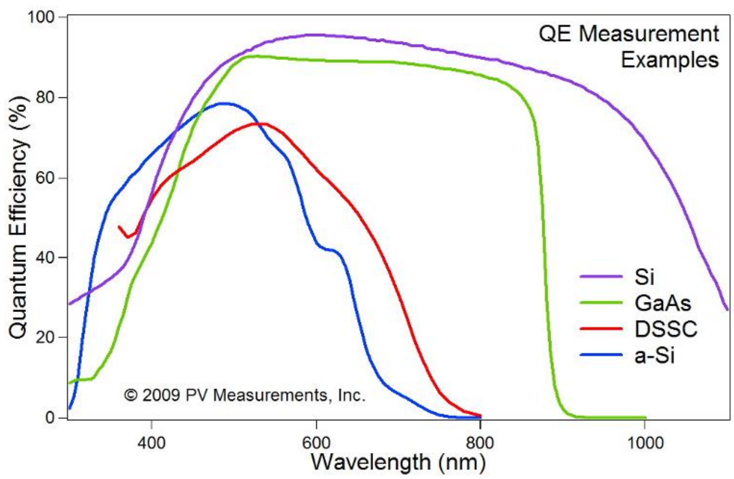


Figure 70 Quantum Efficiency for various solar cells

By using LED's as the light source the solar cell electrical response can be measured by only turning on the LEDs one at a time. The QE at different intensities can the by measured by measuring full IV curves for each point in Table 6.

Table 6 Electrical response measurement table

Measurements	400-500 nm	500-600 nm	…	800-900 nm	900-100 nm
x W/m^2					
2 x W/m^2					
… x W/m^2					

The total electrical response of a solar cell or panel can then be calculated.

The QE is a refinement of the equipment compared to the original project description and is seen as a strong addition to the possibilities to test a solar cell. Since the spectral distribution as well as the total irradiation in the urban environment will now be measured in relation to wavelength by the developed light loggers it is essential to know the solar cell responses to different wavelengths in order to choose the best cell for a given application.

LED module

The chosen LEDs for the setup are defined in Table 7:

Table 7 LED modules

No	**Color**	**Peak Wave length**	**Width**		**Poptical [mW]**	**Wish [mW]**		**No of LEDs**	**Realized [mW]**	**[mW/nm]**
1	UV 1	395	10	LEDengin	550	1000	1,8	2	1100	110,0
2	UV2	405	10	LEDengin	550	1900	3,5	2	1100	110,0
3	Blue	455	20	LEDengin	591,5	2300	3,9	3	1774,5	88,7
4	Dental blue	480	20	LEDengin	800	2300	2,9	2	1600	80,0
5	Green	520	40	LEDengin	200	2000	10,0	14	2800	70,0
6	Amber	590	20	LEDengin	210		5,0	10	2100	105,0
	PC amber	590	80	Rebel	312		5,0	5	1560	19,5
9	red	630	20	LEDengin	405	1700	4,2	5	2025	101,3
10	Deep red	660	20	LEDengin	450	1400	3,1	4	1800	90,0

11	Far red	735	30	LEDengin	280	1200	4,3	5	1400	46,7
12	IR 780	780	40	Roithner	1000	1000	1,0	1	1000	25,0
13	IR 810	810	30	Roithner	1000	1000	1,0	1	1000	33,3
14	IR 870	870	40	Roithner	1600	1000	1,0	1	1600	40,0
15	IR 940	940	40	Roithner	1200	1000	1,0	1	1200	30,0
16	IR 970	970	55	Roithner	480	500	1,0	1	480	8,7

The LEDs was divided onto two PCBs being - one containing the IR LEDs and the other containing UV and VIS diodes. The LED targets can be seen below installed in the system.

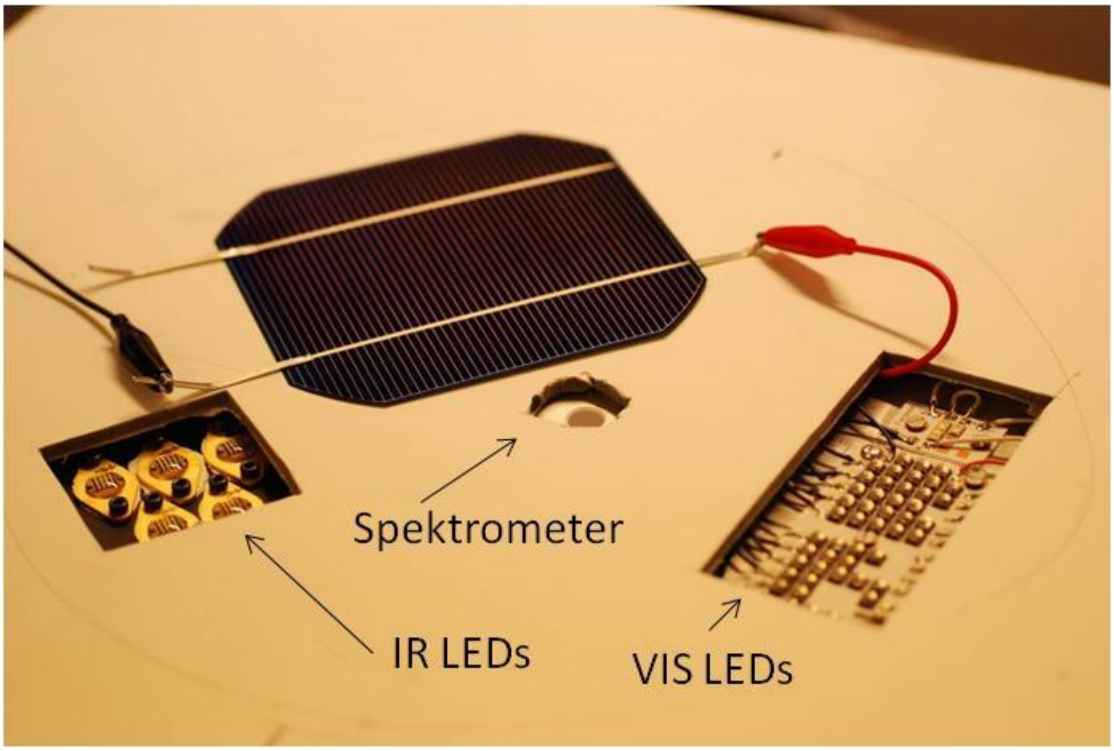


Figure 71 LED targets in LED Sun

Below are close-ups of the LED target.

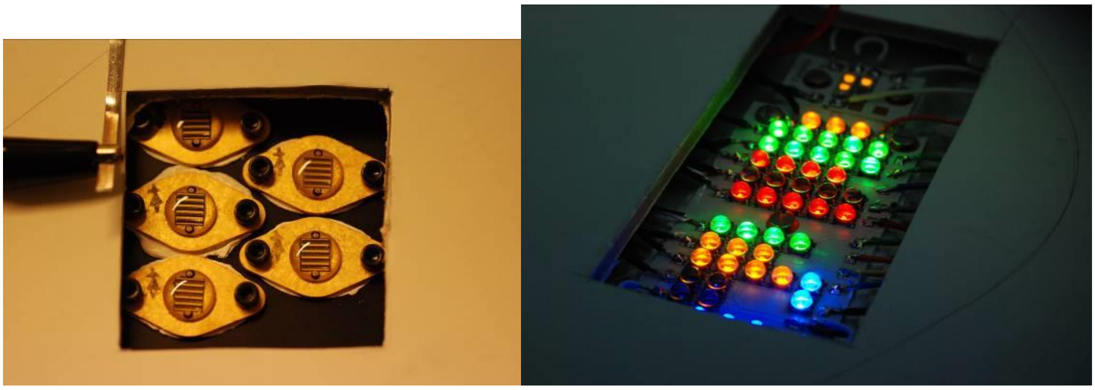


Figure 72 close up of LED targets

The LED targets are made modular and as compact as possible so the system is scalable if a larger measurement area should be needed.

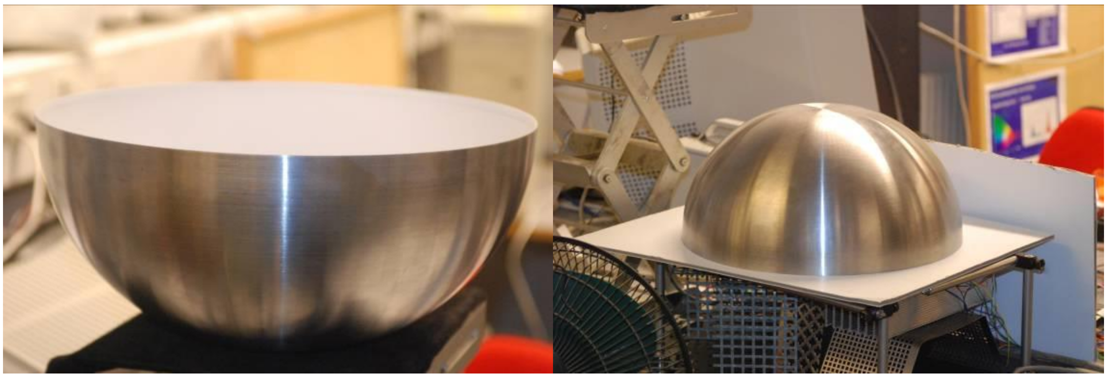
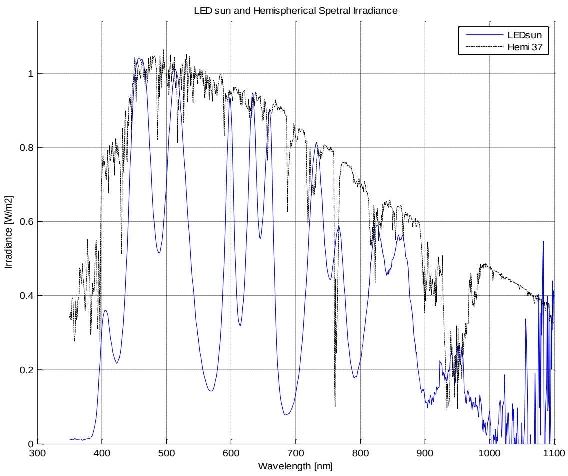


Figure 73 reflective semisphere

For distributing the light homogeneously all over the measurement area a semisphere was coated inside by a diffuse reflecting material having an overall lambertian scattering of >98% from 400 nm – 1100 nm. More about the coating in the next section. For at setup of 270 W/m2 when looking only at the requirements in the IEC904-9 standard these cannot be met in the IR region (see below).

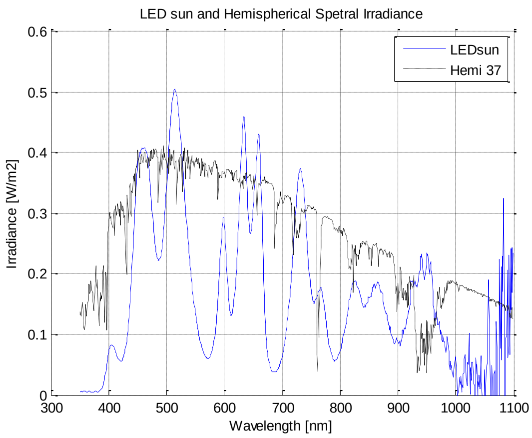


Wavelength (λ) interval, μm	Percentage of total irradiance between 0,4 and 1,1 μm
0,4 to 0,5	18,5
0,5 to 0,6	20,1
0,6 to 0,7	18,3
0,7 to 0,8	14,8
0,8 to 0,9	12,2
0,9 to 1,1	16,1

Wavelength Interval and Total Percentage
400 - 500 nm : 59.5045 [W/m2] 21.9879 %
500 - 600 nm : 52.6016 [W/m2] 19.4372 %
600 - 700 nm : 48.0721 [W/m2] 17.7635 %
700 - 800 nm : 44.8523 [W/m2] 16.5737 %
800 - 900 nm : 42.5262 [W/m2] 15.7142 %
900 - 1100 nm: 20.9089 [W/m2] 7.7262 %

Figure 74 Irradiance level 270 W/m2 fit to IEC904-9.

For an irradiance level of 120 W/m2 the requirements can nicely be met for the LED setup.



Irradiance: 120.44 [W/m2]

Wavelength Interval and Total Percentage
400 - 500 nm : 22.322 [W/m2] 18.5337 %
500 - 600 nm : 23.9654 [W/m2] 19.8982 %
600 - 700 nm : 21.9482 [W/m2] 18.2234 %
700 - 800 nm : 17.7066 [W/m2] 14.7016 %
800 - 900 nm : 14.4862 [W/m2] 12.0277 %
900 - 1100 nm: 19.424 [W/m2] 16.1275 %

Figure 75 Irradiance level 120 W/m2 fit to IEC904-9.

In the standard the irradiance level is 1000 W/m2, but since the system is scalable it was early in the project stated as a state of reference that the systems should be able to fulfill the AM1.5 requirements for an class A solar simulator just with lower light intensity which can be scaled up to fully comply with the IEC904-9.

Reflecting sphere

One of the major obstacles has been creating the mechanical system where >98% lambertian scattering is required over the adressed spectrum from 400 nm to 1000 nm. Commercial paint from Labsphere based on Barium Sulphate can do the job but the cost is close to 30.000 DKK pr. square meter covered surface. This might not be a problem in the optical laboratory industry where a few players on the market and the laboratories can pay the high price for having the best quality equipment for their measurements. Meanwhile, in this project, where several systems needs to be built to find the best suited, this cost is killing. Therefore 3 alternative routes to success were identified:

i: Home made BaSO4 solution

The Labsphere system primarily contains $BaSO_4$ and PVA (Polyvinyl acetate) and based on these ingredients the system cost is <100 DKK pr. square meter. Several systems was made containing different parts of $BaSO_4$, PVA and water and the resulting coating was measured against a reference to be >99% reflecting in the relevant spectral area. But small cracks easily develops in the brittle coating.

ii: Alternative materials

A system based on the polymer PTFE pressed in a special way is even better than the $BaSO_4$ system. It has the tradename Spectralon® and small amounts of the material was tested to have superior optical properties. The material is also extremely expensive and even when bought from alternative suppliers the low cost model OptoPolymer cost about 2.20 DKK/cm^3. So just a tiny block of 10x10x10cm of the material costs 2200 DKK. It is very easy to machine though and work with mechanically. The problem about bying it in blocks is that huge amount of the material is wasted when machined into a coating. The PTFE material is also found in sheets and if that can be for example vacuum formed into a coating on the inside of an aluminum sphere without changing its optical properties, this could very well be the solution.

iii: Low cost BaSO4 solutions

The market has been screened and the best product regarding price/properties appears to be from an Austrian company called IPAC. Here the price of $BaSO_4$ based paint is about 1000 DKK pr. L but the amount needed to meet the requirements for 1 m^2 is not stated. It is estimated that the system is way below 1/10 in price compared to the Labsphere system. The system has been tried and meets the requirements nicely.

To conclude on the reflective coating matter, cost has been a major hurdle to overcome. The group has come up with several solutions where the low cost $BaSO_4$ solution from IPAC had the desired optical properties, robustness and an affordable price. 7 layers of the paint needed to be sprayed inside the hemisphere and each layer dried for 10 minutes before applying the next for obtaining the required optical properties.

IV-characterization facility

For measuring the electrical characteristics of the solar cells a Kiethley 2400 Sourcemeter was connected by a 4 wire setup to the solar cells exposed to the LED light. The equipment was controlled by the same Labview interface also controlling the LED setup. Several solar cells was tested and below is shown a few examples

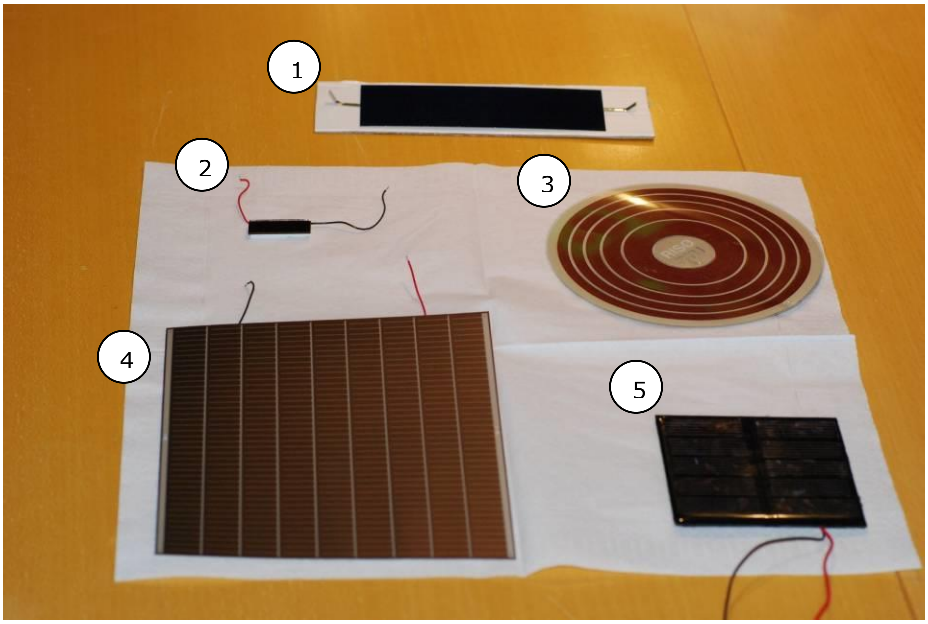
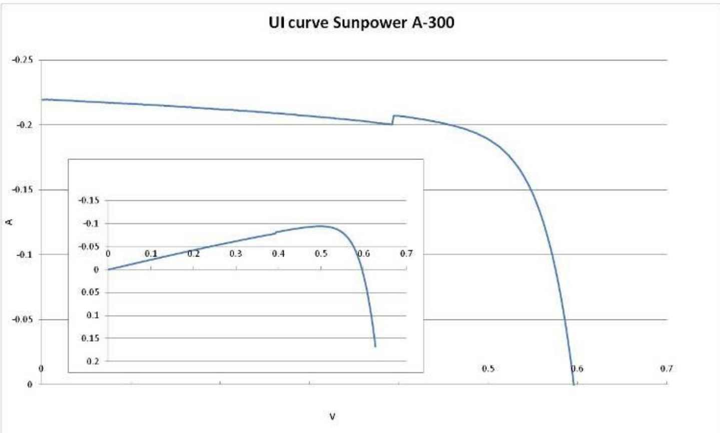


Figure 76 Different solar cells measured

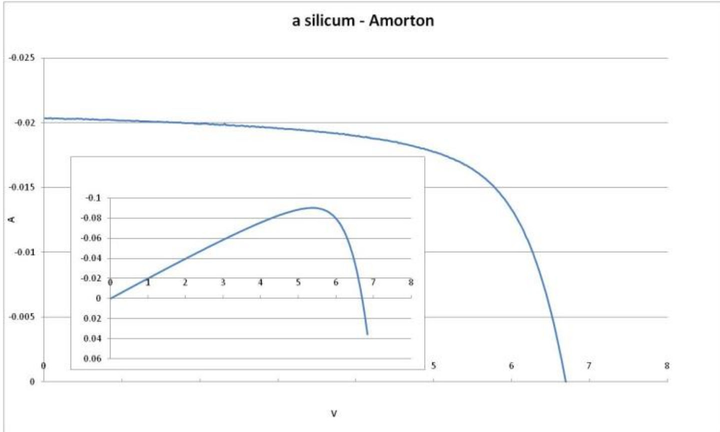
The solar cells are 1)mc-Si Sunpower A-300 thirds cut, 2)amorphous silicon from a calculator, 3) Polymer solar cell from the Danish Polymer Center at RISØ, 4) amorphous silicon solar cell, Amorton from Sanyo and 5) a polycrystaline silicon solar panel from a cheap solar cell lamp. The characteristics of 1) at AM1.5 95,4 W/m2 irradiance is shown below:



Effektivitet	20.31124	%
Indstråling	95.4	W/m2
Umppt	0.4979	V
Imppt	-0.18972	A
Pmppt	-0.09446	W
Isc	-0.2194	A
Uoc	0.59715	V
FF	0.721004	
Rshunt	31.53307	ohm
Rs	4.768152	ohm

Figure 77 electrical characteristics of Sunpower A-300 mc-Si solar cell

The cells is expected to perform at about 20.9% at 1000 W/m2 and it seems reasonable that the efficiency has dropped to 20.3% at 100 W/m2 which is very good for a silicon solar cell. Data for the Amorton solar cell is shown below



Effektivitet	4.138653	%
Indstråling	95.4	W/m2
Umppt	5.3735	V
Imppt	-0.01687	A
Pmppt	-0.09063	W
Isc	-0.02034	A
Uoc	6.6955	V
FF	0.665645	
Rshunt	6877.504	ohm
Rs	0.028865	ohm

Figure 78 electrical characteristics of amorphous silicon solar cell from Sanyo

The data are fine in line with the data from the datasheet.

Response curves

Instead of irradiating the solar cells with a mixture of colors, IV curves for the individual colors can be obtained and thereby a variant of a spectral response curve of the solar cell or panel can be obtained. The short circuit current could also be used. For an irradiation level of 10W/m2 of each LED array of colors the response curves of the image above (without the polymer cell which had a contact problem) is shown:

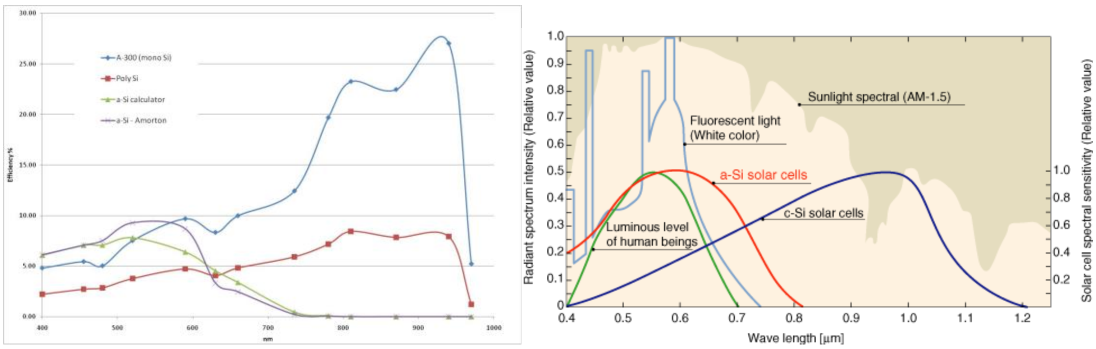


Figure 79 measured spectral response curves compared to literature

The measured characteristics fit nicely with literature from where an example is shown on the right for the two cell technologies. Even though the LED system is much rougher than a typical Incident Photon to Charge Carrier Efficiency (IPCE) measurement setup where a resolution of often below 1nm can be obtained it is a nice and easy to use and much cheaper, robust and flexible than the traditional setup. And furthermore it can take larger panels which are usually not possible by the competing setups based on Xe light sources coupled to a monochromator.

Sub-conclusion

It can be concluded that an LED based solar simulator has been build and follows the IEC904-9 requirements for a Class A solar simulator though at an irradiation level of about 100 W/m2. It is much more advanced that was first intended but since the spectral distribution of the sunlight in the urban environment became a point of interest the solar simulator needed to be able to characterize panels electrically for this parameter also by the spectral response curve for the solar cells/panels. The system works nicely for measuring IV curves for different spectral distributions and especially of intensities of 2-100 W/m2 of AM1.5 light.

Workshop with architects and city planners

Objective and description

A workshop was carried out in Febuary 2009 (in Copenhagen) with the objective to gather inputs from architects, city planners, designers and engineers with regards to integration of solar cells in the urban environment. The participants are listed in Appendix B.

The project group gave an introduction to PV technology and various possibilities for application and usage, Figure 80. The difference in visual appearance among the generations of PVs brought much attention.

Figure 80 Introduction to workshop

The involvement in the workshop was high and good discussion was achieved. The focus was laid on both on-and off grid PV installations, where the participants could think of using PVs in the urban scape.

The following was put up as hypothesis:

- Where should the future light measurements be performed?
- Which type of city environment? – Characteristics of the city: street width, building height…
- Which surrounding characterizes the urban city?
- Placement of the solar cell: horizontal, vertical?

Results

The participants were divided into two groups and should look at respectfully:
PVs for *off*-grid installations
PVs for *on*-grid installations

The group working with *off*-grid PVs focused on **Social relations, temporary, seasonally, independent systems**, Figure 81**.**
They could imagine the PVs used as autonomous systems which could be movable, unpredictable in location and installation time, as a factor to enhance outdoor life (light in the summer evenings) or as temporary commercial like big banners at platforms.

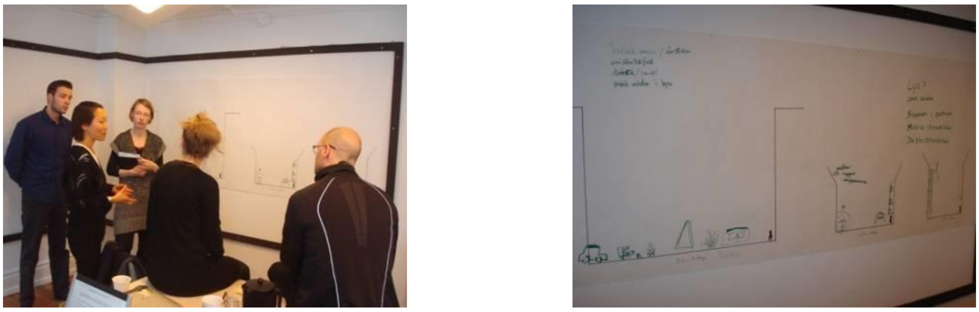


Figure 81 Off-grid group

This gave a good indication of where the focus group could use solar cells off-grid, but didn't indicate a clear need for a specific site for the future light measurements.

The group working with *on*-grid PVs focused on **max. Yield of the solar cells, optimal placement, light/noise filtering and multi functionality**, Figure 812.
The focus was on trade buildings with big facades where the solar cells could have double functions as shading and electricity generating branding.
The solar cells should be placed where best performance can be achieved (at roofs).
The group also suggested that the Danish government should give financial support to building owners if they would agree on installing solar cells on the roof.
On-grid installations could be placed at open squares, noise protection at high ways and parking places.

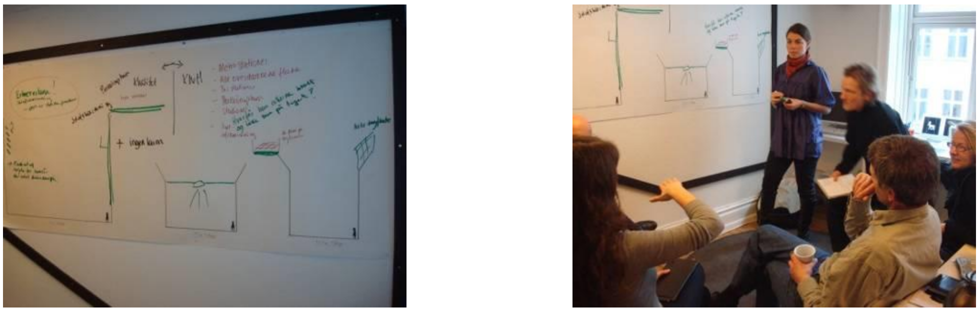


Figure 82 On-grid group

The light measurements could be performed at buildings in different heights, so the performance of the PVs could be estimated more realistically.

Sub-conclusion

The workshop was a good experience and gave insight into the questions architects and city planners have concerning implementation of solar cells. The interest in the different types of solar cells and their aesthetical appearance was huge. The outcome of the workshop was several ideas of where the participants could imagine usage of solar cells, but more generally a clear picture for a huge demand of 'common' knowledge about PV potential was seen. Today the focus regarding PVs is on payback time, because knowledge about performance dependence of exposed light and surrounding conditions is not well known.

Architectural Engineers and solar cells

An interview with two architectural Engineers was performed in the fall 2009. The Architectural Engineers has throughout their master degree studied the processes of both engineering and

architectural work, and now functions as bridge builders between the two fields. They are both working on their PhD concerning building energy consumption and daylight filtering and are associated with a well-renouned architectural studio in Denmark: Henning Larsen Architects.
A talk about which simulation tools are commonly used, what their thoughts towards solar cells are and how the barriers for usage of solar cells can be brought down gave good insight in future work possibilities.
Their knowledge about solar cells was not very high (from their own words), and that was the reason why solar cells are generally rejected early in the projecting phase. Therefore solar cells are rarely still considered when simulation tools are used to estimate the energy frame of a building and the thermal and visual comfort. One of the programs used for daylight simulation is *Ecotect*. It was discovered that this program has a plug-in where the PV potential can be estimated, see Figure 83, but the Engineers had not discovered this, as they had never worked with a building with PVs on this stage.

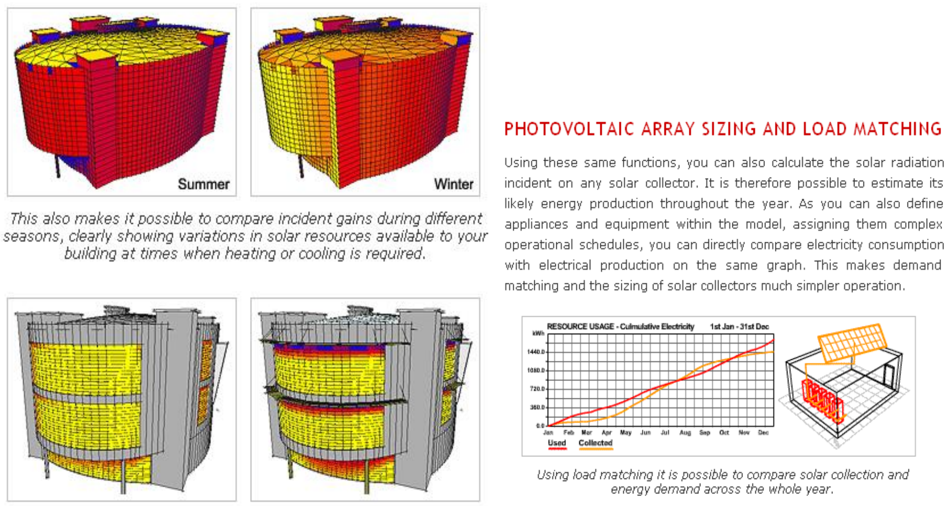


Figure 83 Ecotect simulation

The program Be06 is used to calculate the energy frame of a building and also takes solar cells into account. To include solar cells the program needs input on panel area, orientation, horizon, shading, peak power and system efficiency, Figure 84.

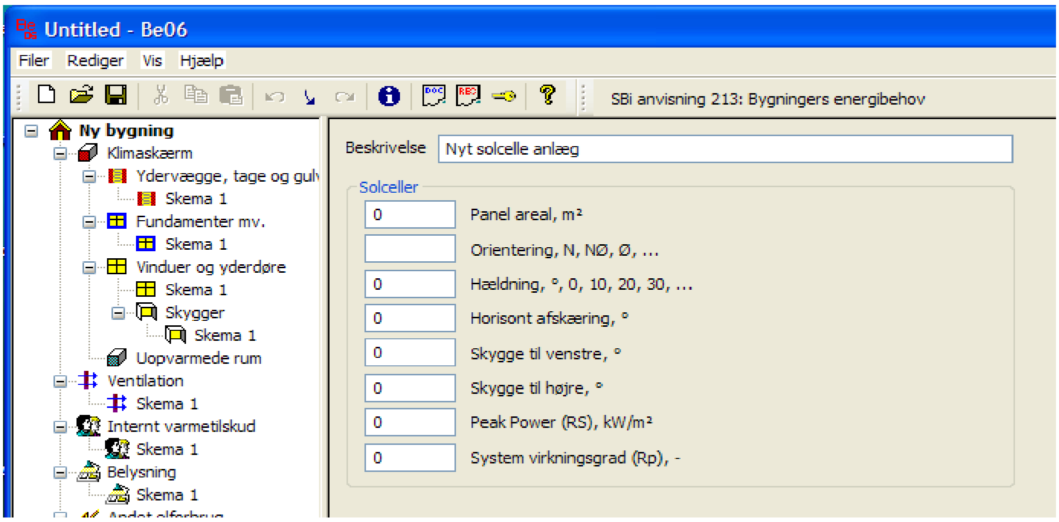


Figure 84 Be06 Screen shot

The Architectual Engineers requested for 'rules-of thumb' for different PV technologies to input in Be06.

Solar Cells at Educational Institutions

A research project 'solar cells in education'[vi] has been conducted, and recently finished in December 2009. The objective of the project has been to gather a collective view of all educational materials and the actions taken at different levels in the educational system towards spreading out knowledge about solar cells.
The conclusion of the survey at architect schools was that no collective material has been established and that the courses held at the different schools is driven by the engagement of individual professors. This has also been concluded for the Technical Universities investigated.
The architect schools had a wish for educational material consisting of:

- 'ready to download' material about solar cells
- physical material collection of different solar cell technologies
- structure of a workshop/ theme day

The result of the investigation showed that focus should be on establishing a network of professors in order to stimulate a professional environment for knowledge-sharing.

The results of the project will be published at www.soliundervisningen.dk, but it is unknown who will take the further steps to generate the educational material. Network at the Technical Universities have been established, so hopefully this will generate brighter knowledge about solar cells.

7. Branding of results

Intersolar

The project was branded at Intersolar, held in Munich from May 27th to May 29th 2009.

Intersolar introduces the fair as: *the world's largest solar technology trade fair and the number one meeting point for everyone in the solar industry. Intersolar focuses on the Photovoltaic and Solar Thermal branches.* Faktor 3 had a stand at the fair (Figure 85), and displayed a poster of the outdoor measurements and presented the project orally as well. The project was given interest by several visitors at the stand.

Figure 85 Faktor 3 stand at Intersolar 2009

PV SEC, Hamburg

The work in the project is seen to gain interest from the PV World as seen at Intersolar. Further the project was represented at the 24th European PhotoVoltaic Solar Energy Conference and Exhibition: *The most inspiring Platform for global PV Solar Sector*, held in Hamburg from September 21st to 25th 2009, by two poster presentations. The project received invitations to presents posters based on abstracts submitted in January 2009

24th European Photovoltaic Solar Energy Conference and Exhibition

*The Conference will provide an **excellent platform** for dialogue and information exchange across the World. The **'who is who'** of the **PV solar branch will meet at Hamburg** to discuss the latest developments in science and industry.*

There was a widespread interest for the project and > 50 business cards were collected and small copies of the posters was send to these stakeholders after the conference. In addition to the dialogues during the poster session this gave a nice picture of who the stakeholders were. 60% were from universities, 30% from industry and about 10% were architects. Since only very few architects attend this conference this gives a slightly distorted picture of especially this groups interest. The architects with whom the project group spoke to was very interested in having this feature of calculating solar cell performance over the year integrated into the software used for architects to draw their buildings. The aspect of comparing output of different solar cell technologies placed in different light exposed environments they found very interesting.

The conference also showed some competitors to the present project even though none of the systems takes spectral distribution into account. The LED sun was also a great point of interest. There was a lot of LED based solar simulators – but not based on diffuse light and with the present optical principle used in this project. It was commented, that our system can be used to make individual IV curves of the layers in a tandem solar cells which are usually very complex since the electrical characterization is a mix of the exposed junctions. But with our setup it might be possible to saturate one of the layer for example by shining a lot of red light on it and characterize the other junction at the same time separating the signals this way.

The roughly spectrally distributed light loggers also drew positive attention from a few of the spectators but it was the project itself and the LED Sun that gave most response.

The abstracts/ scientific papers/posters are found in appendix C.

Press release

(dec. 10th, 2008)

In order to promote the project and the possibilities it will bring, work on a press release has been carried out in this period. A learning phase with a journalist on how to write a good press release has been performed in FAKTOR 3, which has also been lead writer on the press release. The purpose of the press release is to create interest and knowledge about the project, so possible interest groups can be formed. Unfortunately not much interest was gained, which primarily was caused by the limited number of recipients.

Appendix D

8. Future outlook

The project has generated important knowledge about practical implementation regarding light measurements, but also an awareness of the need to characterize light and solar cells with varying spectral light distribution. This was identified by the project group, who has a desire to bring the project further. The following is abstracts from the new application where the end-output should be a new test platform with the light loggers and the LED Sun.

From the ForskEL application, sep. 2009: *PV Potential – Getting most out of solar cell technologies*, Project no. 10492.

In order to assess the real price/performance ratio of a solar panel, the ideal basis would be to have knowledge about the exposed light conditions and the spectral and intensity response of the solar cell. The illumination data used to evaluate electrical performance today rely on total irradiation and is thus not an expression of the spectral light distribution as function to intensity, and therefore 2 identical light intensities with varying spectral distribution can result in extremely different electrical output of the same solar cell. Even internally among producers a dramatic variation in performance as function to light intensity of the solar cells is seen. This is not considered by panel producers today, when the solar cells are stringed together in panels, as the cells are only classified by their performance under STC. As the panels has to function under different conditions than STC, the solar cells should ideally be stringed together from their spectral and light intensity response, in order to ensure the panels functioning well under all light conditions.
To estimate the true potential for a solar panel placed in a given position, it is crucial to have precise information about the light conditions which the panel is exposed to. This knowledge becomes progressively more important as more and new solar technologies enter the market, as their response to various light conditions are quite different,

In order to more accurately predict the price/performance ratio on a yearly basis of a solar panel in a given position, the panel needs to be electrically characterized by the range of wavelengths that are photoelectric active. By measuring response and electrical characteristics for intensity variations at different wavelengths, the precise electrical response of a given light distribution can be predicted.

Relevance:
The price per generated photovoltaic kWh is a key parameter in the deciding whether solar cells should be used in new buildings, retrofit or not. As the development in photovoltaic technology increases the prices are bound to go down and it will be necessary to distinguish the relevance of one technology to a particular installation from another.

In relation to *'ForskEL udbud 2010 – teknologibeskrivelser'*, where it is stressed that focus is laid on reducing the kWh-price, this project is well suited in pursuing the overall objective. The software developed in this project will assist engineers and designers in dimensioning photovoltaic systems with regards to application, local settings and energy demand. This will ease the use of PV as building components and also falls under the project of interest: Prognose tools/models for solar production. Since the yearly energy production can be estimated based on PV technology and irradiation data, the energy flow to the grid will be easier to predict and take into consideration.

At the end of this project, the 1st prototype of the light loggers was developed and a 20 cm x 20 cm LED Sun was finished. A clear goal for the future is, in DTU Fotonik reign, to upscale the LED Sun. The potential platform to characterize solar cells with the light loggers and the LED Sun is already needed.

Danish Technological Institute, who also runs the PSO-funded project "Application of thin-film technology in Denmark" (ThiFiTech), sees great potential in using the developed light loggers in their work. The project evaluates the potential of Thin Film solar cells by long term measurements on commercial panels and could use the additional information about spectral distribution of light in the analysis of panel performance.

The investigations of architects and engineers showed a clear need for 'simple' design instructions of the potential of solar cells. This could be very schematic introduction to solar cell technology, aesthetics and 'rule of thumbs' for rough dimensioning. Research about current material was performed in the project: www.soliundervisningen.dk[vi)] but it is not known how this research will be brought further. It will be of great importance to spread out knowledge about solar cells at educational institutions if the desire is to enhance usage of solar cells in industries of design and buildings.

9. Conclusion

The aim of the project was to investigate the potential of exploiting the advantages of solar cells in non-optimal light conditions in the urban environment from <1000 W/m^2 in best cases of light. The focus shifted early in the project since the group found that the project would be much more valuable if the energy input on the addressed sites was measured spectrally distributed. In the near future focus in the solar cell industry will shift heavily towards thin film technology and since they behave spectrally different than silicon the design tool this project should provide would be much stronger if it could make this choice easier and evident in terms of real spectrally distributed energy calculations and measurements.

Since such a measuring unit as a logger is not commercially available it was decided to construct it. Naturally more time was spend developing such a unit which was time taken from light measurements in the field. A light sensor platform has though been build during this project and calibrated. The logger unit measure the light roughly in 100 nm intervals from 400 nm to 1100 nm. Hardware has been made successfully and a user interface likewise. There have been produced 10 logger units in the end of the project measuring the energy distribution within an error margin of about ±10% compared to at AvaSpec-2048 Standard Fiber Optic Spectrometer. The radiation intensity was 20-60 W/m^2 for these measurements. The target price for the loggers in materials has been <1000 kr. for 40 units which has been reached even though only 10 was produced when the project ended.

While developing the advanced light loggers the valuable experience has been gained from the measurement program of solar energy potential incident on two facades in the city-environment of Copenhagen with simple logger units measuring the total irradiance on the surface. A few challenges, not to be underestimated, concerning the more non-technical part of the program can be mentioned:
find two suitable building facades, one facing due south and one facing due west (or east), with buildings of similar height on the opposite side of the street

- identify a contact person at each location and get permission to setup the data loggers
- develop a method to fix the sensors on the façade in a non-destructive way
- fix the sensors on the façade when leaning out of a window
- get regular access to off-load the loggers

Though the quality of the measurements is questionable for more reasons, there seems to be no doubt that even a very professional simulation tool like PVSYST falls short, when it comes to estimating solar energy potential in a 'tough' city-environment with a high accuracy. In fairness it must be added, that PVSYST cannot produce better results than the quality of the input data like for instance the description of the horizon. For the logger 1 in Aarhusgade it was found that the horizon photo did not have a quality well enough for making usable simulations. So an important learning has been that the description of the location, where measurements are made, needs to be very precise in order to provide usable input to form the basis of a simple-to-use design guide for architects and designers of urban PV-powered products.

It can be concluded that an LED based solar simulator has been build and follows the IEC904-9 requirements for a Class A solar simulator though at an irradiation level of about 100 W/m2. It is much more advanced that was first intended but since the spectral distribution of the sunlight in the urban environment became a point of interest the solar simulator needed to be able to characterize panels electrically for this parameter also by the spectral response curve for the solar cells/panels. The system works nicely for measuring IV curves for different spectral distributions and especially of intensities of 2-100 W/m2 of AM1.5 light.

The workshop held in the project was a good experience and gave insight in the questions architects and city planners have concerning implementation of solar cells. The interest in the different types of solar cells and their aesthetical appearance was huge. The outcome of the workshop was several ideas of where the participants could imagine usage of solar cells, but more generally a clear picture for a huge demand of 'common' knowledge about PV potential was seen. Today the focus regarding PVs is on payback time, because knowledge about performance dependence of exposed light and surrounding conditions is not well known.

At the end of the project the project team has build and effective and advanced LED based solar cells characterization unit, which is unique of its kind a can be used for research purposes as well as for matching solar cells for solar cell products. The project team has developed an quite advanced and cheap light logger that can give more information than traditional light loggers. The group still finds it extremely relevant to create a simple to use tool for designers of solar cell products to pave the way for extending this marked. Furthermore this tool should take the architecture into account so that different solar cell technologies can be compared in electrical gain taking into account their very different properties. The interfacing module to the most used drawing tools for architects should be created on the basis of the obtained data. It is the project groups hope that they can find the capital somewhere to create such tools on the basis of the results and developed hardware in this project.

10. Appendix

Appendix: A guide of the hardware calls and error codes

Appendix: B Workshop

Appendix: C PV SEC – abstracts, posters, papers

Appendix: D Pressemeddelelse

11. References

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