CHARACTRERISATION OF PHOTOVOLTAIC MODULES FOR BUILDING INTEGRATION

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1 Introduction

In the research project MULTIELEMENT, Fraunhofer IWES together with 15 partners from industry and economy, is conducting studies to develop production, testing and implementation methods of multi-functional photovoltaic (PV) building elements in building services engineering. The objective of the project is to evaluate the technical and economic potential for PV building elements and to reduce the cost by systematically including multi-functionality. For this purpose, the physical properties are described; guidelines and respectively standards have to be worked out with respect to material and quality aspects. At the same time, testing equipments and testing procedures have to be developed. A major task of this project is to cooperatively develop test requirements in order to characterize electrical, mechanical and constructional properties of PV building elements. The integration of multiple functions of a PV element in buildings is often made difficult due to a lack of specifications, component descriptions and testing certificates as well as existing information deficiencies. This is mainly due to the fact that at least three different sectors are involved in the realization of building integrated PV (BIPV) projects: construction engineering, electrical engineering and building legislation. Each sector brings along its own requirements, which are not harmonized in any case. That means, an optimized product from the electrical point of view may not match the requirements which result from the building legislation. For example, due to the maximization of the energy yield a certain glass type, thickness and construction is selected for a BIPV module, however the used components and constructions are possibly not listed in the building rules list. Thus, the application of BIPV products in the building is only possible, if a product specific certification is issued. On the other hand, the realization of constructional and legislative requirements in a PV building element may lead to curtailments in the electrical performance. To overcome this gap again three measures need to be taken: exchange of information, adaptation of constructional and legal requirements as well as further development of technical rules and regulations.

2 Multi-functional properties of PV modules

PV building elements are deemed to be electricity producers primarily. However, depending on the design and application they offer additional features like weather protection, thermal insulation, noise protection or electromagnetic shielding only to mention just a few. In the case that photovoltaic modules take one ore more of these functions of the building envelope they are referred to as “integrated PV building elements”. Generally, a building function is realized by PV modules, provided that conventional building product can be omitted. PV building elements can be used to build roofs, facades, overhead glazing, balustrades, semi-transparent windows or skylights. The role of PV modules is far beyond solely current generation, when used as integrated building elements. Building integrated PV (BIPV) elements interact with the environment, the building itself and the inhabitants. Furthermore, they are connected via an inverter to the electricity grid. Consequently, the product must comply with several requirements which arise from building codes as well as from electrical and PV installations rules and standards.

In order to exploit the various multi-functional features of PV building elements their properties must be sufficiently described. A comprehensive overview on the possible functions of BIPV is shown in Figure 1. Several products realizing some of these functions in the building are available on the market. Examples are PV-modules for facades in post and beam constructions carried out as single or double glazing in ventilated curtain walls or thermal insulating facades, PV roofing tiles, sun shields or window shutter. Furthermore complete systems for slanted and flat roofs as well as for shed roofs are available.

Depending on the installation situation the function of the PV module for the building can be quite evident. PV-modules used as roof covering represents the weather protection for the building. PV modules used as balustrade provide a fall protection. At the same time the modules generate electricity in any case. However, in order to accept PV modules for several building functions from a legal point of view in terms of building codes, various properties must be proved. Due to the building law it is in most cases not allowed to use PV modules as an integral part of a building without any permission or certification. That means that various mechanical and functional aspects like remaining bearing capacity and fire characteristic must be certified.

Besides the requirements arisen from the building legislation, further requirements result from a planning point of view. When used in a façade for example the planner need to know the thermal characteristics in order to respect the PV building element in the calculation of the total energy demand of a building. In that specific case U-value (heat transfer coefficient) and g-values (total energy transmission value) of the product must be specified.

Other additional functions of PV modules besides electricity generation are not obvious at first sight. These are for example the functions “shielding” and “antenna” or “day-night lighting”. A summary of various multi functions is shown in Figure 1.

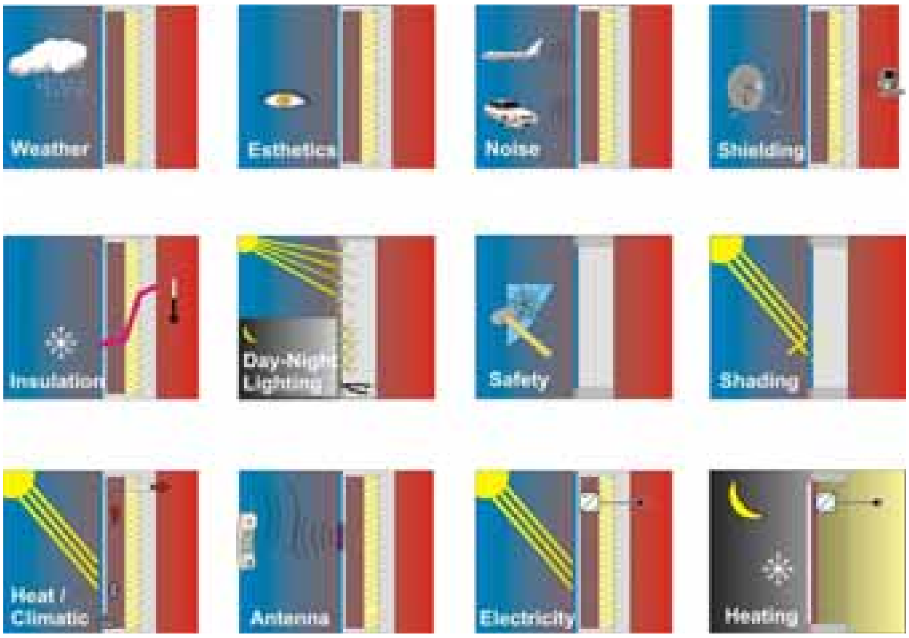


Figure 1: Multi-functions of BIPV

2.1 *Visual assessment of BIPV modules*

There is no doubt, that PV modules must meet all electrical and mechanical requirements in order to ensure safe operation and compliance with the provisions of the European Constructions Products Directive [1] in terms of

- mechanical resistance and stability,
- safety in case of fire,
- hygiene, health and the environment,
- safety in use,
- protection against noise,
- energy economy and heat retention

However, besides these important requirements on BIPV modules, two further preconditions must be fulfilled for the applications of photovoltaics in buildings. On the one hand the PV module must be of high quality in order to ensure an operation as intended. On the other hand, the PV module must be attractive and aesthetical from a visual point of view. For the application of photovoltaics in buildings the quality and visual appearance are of major significance and important decision factors of building owners. Therefore criteria are needed in order to assess the quality of PV modules. Within the project MULTIELEMENT appropriate criteria have been developed. This visual assessment concentrates on 5 different aspects: specification of inspection zones and methods, dimension of PV-module, glass assessment, PV active cell assessment, and electrical connection techniques [2].

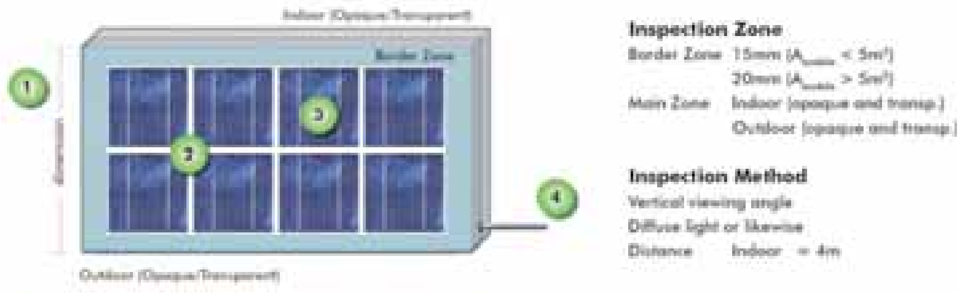


Figure 2: Visual inspection of PV-modules

The inspection specification could be evaluated in terms of inspection zones and inspection method. For the inspection zones, the module is classified into border and main zone, whereat the main zone could further be classified in Indoor/Transparent, Indoor/Opaque, Outdoor/Transparent and Outdoor/Opaque. According to the dimension of PV modules, it had to conform with relevant building codes in order to replace the conventional building products. The criteria for the visual assessment are summarized in Figure 3.

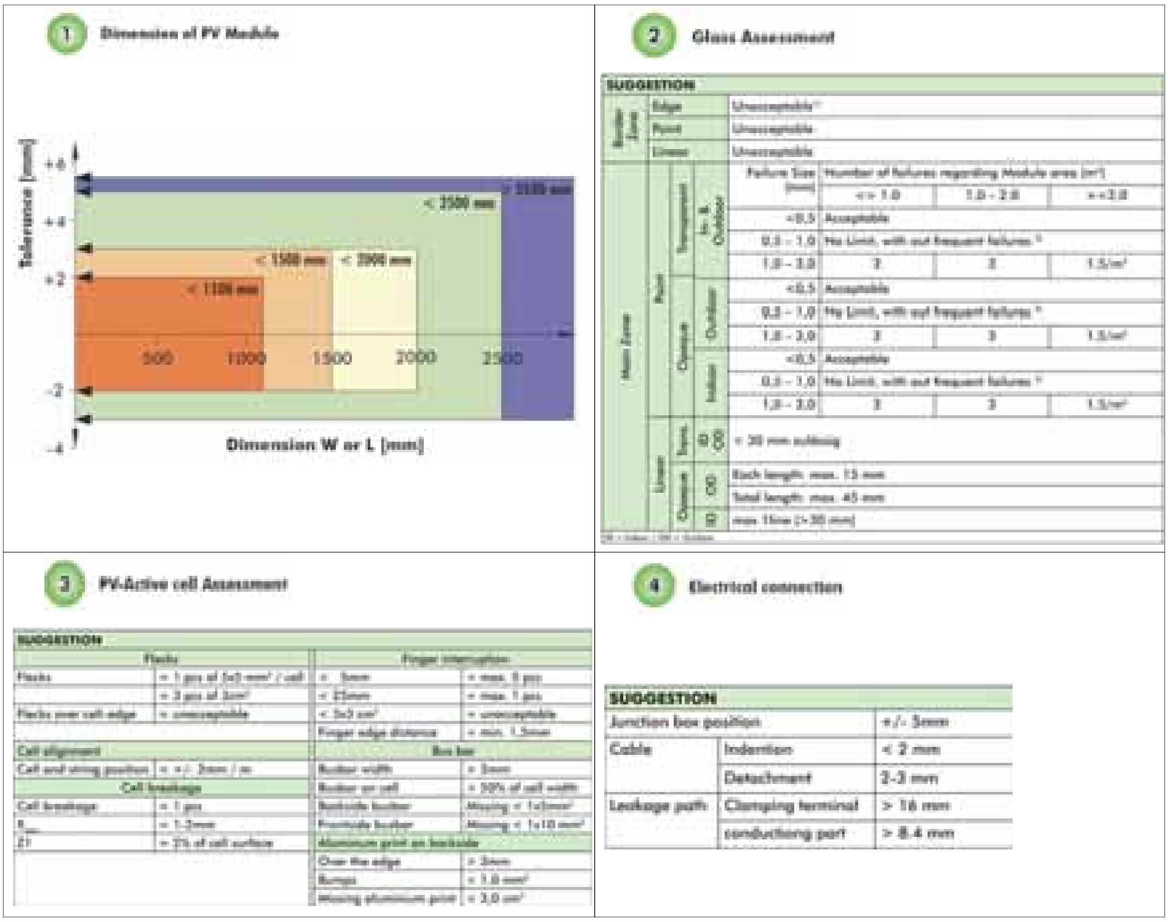


Figure 3: Visual evaluation criteria.

Dimension of PV module: The dimension of PV module has to conform to relevant building codes in order to replace the conventional building products. This can be estimated with tolerances of dimension, thickness and displacement of laminated glass.

Glass assessment: The following failures are to be assessed within the glass assessment:

- Edge failures: fractures or chipping
- Point failures: delamination, bubble and blur
- Linear failure: scratch on the module

PV active cell assessment: The PV active cell have been assessed in various terms, such as cell breakage, grid interruption, crack, fleck, cell alignment etc. However, these terms are differently evaluated by manufacturers due to no relevant standards or guidelines and individual criteria. Therefore, the PV Active cell assessment is needed.

Electrical connection: There are many parameters related to this aspect, such as junction box, electrical connector and cables, leakage current, reverse current etc. However there are some parameters with no relevant standards or guidelines.

In this assessment, we are trying to set the first guideline for the visual assessment of PV modules quality. This assessment will act as a benchmark of PV module specification. It allows the manufacturers to conform the quality of PV modules to this assessment. At the same time, it allows the planers to assess the quality of PV modules from the same assessment. Nevertheless this standard should not be an obstacle for the manufacturers, if the ranges are strength. At the same time, it should also answer the customer needs of quality.

2.2 Solar shading with BIPV modules

Shading is frequently mentioned among the possible multifunctional properties of BIPV elements. However, BIPV elements are not only capable of shielding against the direct sun light, their abilities are much more diverse. In addition, the requirements for indoor climate are complex. The term “daylight management” is much more suitable to take these circumstances into account. In general the overall tasks of daylight management are to optimise the building’s heat balance, to reach a high light quality, especially at workplaces, and to ensure an unhindered view. In detail the indoor daylight illumination can be defined by applying the following requirements:

- Under “normal” outdoor lighting conditions the room should be supplied with sufficient daylight. This should be the case at clear weather with direct sun light as well as at overcast sky with diffuse irradiation
- The illuminance must be adequate also in deeper parts of the room.
- Especially at the workplace glare of direct sunlight must be avoided
- A view to the outside should also be possible when shading is activated.
- An overheating of the room, caused by daylight, must be avoided.

Of course, these requirements vary according to the utilisation of the room. It should also be mentioned that at dawn artificial and day light should complement one another imperceptibly. For the daylight quality in a room there are several evaluation criterions, e.g. mean daylight factor, day light factor 4 m deep in the room, evenness, daylight situation at the occurrence of sun. Further criterions for the workplace are e.g. contrast reduction at the computer screen and the Unified Glare Rating. Additional systems factor are daylight autonomy, controllability and simplicity. Some of these factors are regulated by standards:, E.g. in DIN 5034-1 resp. DIN V 18599-4 the daylight factor is defined as the ratio of the illuminance in the room compared to the one outside. In DIN EN 12464-1 the standard value for the Unified Glare Rating Index is defined which can be used for the assessment of dazzling effects.

BIPV elements are generally appropriate to be applied for daylight management. Several design options such as transparency and colour allow a wide range adaption. Through sun-position tracking an optimised adjustment for energy production and shading can be realised at the same time. In order to apply BIPV elements for daylight management their lighting properties need to be characterised by suitable factors. These concern the heat transfer, transparency, light reflection, total energy transmission and colour rendering. Software-Tools for the planning of daylight management should be amended with the characteristics of BIPV elements.

In order to respect the lighting properties of PV modules within the daylight management of a building the following characteristic data of transparent BIPV modules should be provided

- Heat transfer coefficient U_g in W/(m²K)
- Translucency TL in %
- Degree of light reflection R_{La} in %
- Total energy transmittance G in %
- Colour rendering index R_a

2.3 Mechanical characterisation of BIPV modules

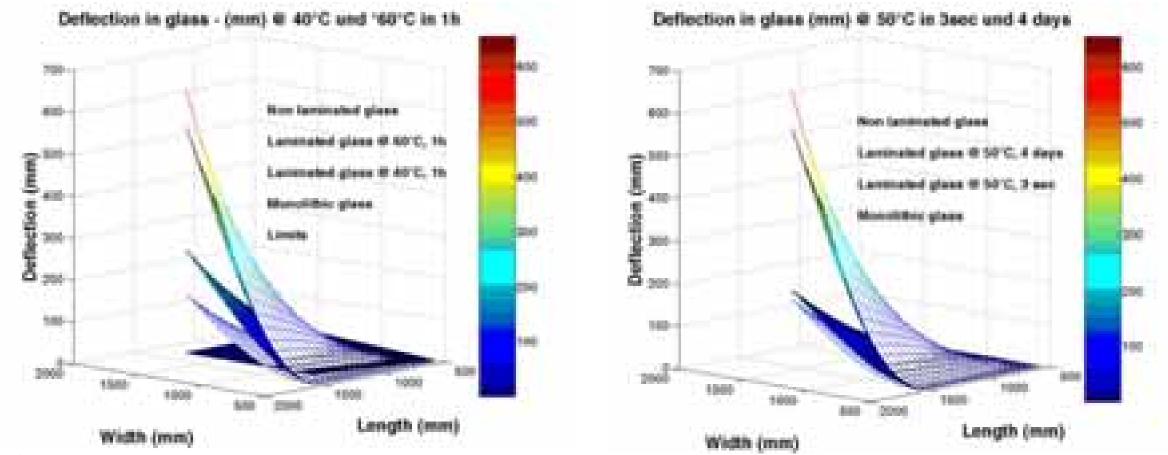
An experimental study was carried out with the goal to analyse the mechanical behaviour of the building-integrated photovoltaic modules (BIPV) and to identify failure mechanisms of the existing BIPV system [3]. The mechanical load test was performed with different load scenarios in order to simulate the combined wind and snow loads. In combination to the mechanical load test, simulations were done to compare and predict the results.

This mechanical behaviour of building products is one of the main issues under ‘‘Mechanical Resistance and Stability’’ in the Construction Products Directive (CPD) [1]. Therefore, BIPV products have to comply with both the conventional building codes and PV standards. With respect to different operating temperature and load duration, there are neither common regulations nor relevant building codes for evaluating the mechanical behaviours of BIPV Modules.

The problem that arises is basically of building regulatory nature, because alternative interlayers (e.g. EVA foil) which are used in PV-modules are not described in building codes or technical rules. The result is that PV products using these interlayers need to run through laborious certification processes. Even though the adhesion and bonding characteristic is better compared to conventional interlayer (e.g. PVB foil), it is not allowed to respect these composite for the calculation of the mechanical behaviours.

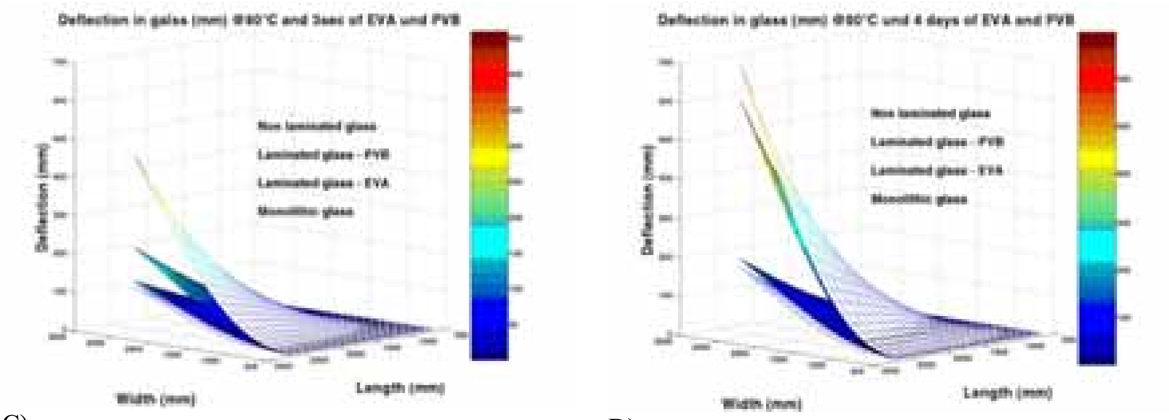
Indeed PV modules are able to take over mechanical requirements in façade or roof-integrated installation, however from a regulatory point of view it is cumbersome or even impossible to exploit this function in a building. Thus the mechanical characterisation of BIPV modules has the following objectives:

- Develop new load scenarios based on different operating temperatures and load duration.
- Develop the mechanical behaviors model for BIPV laminated glass (Bending stress and Deflection)
- Investigate the BIPV laminated glass under different boundary conditions
- Acceptability of laminated glass with EVA interlayer as a laminated safety glass.



A)

B)



C) D)

Figure 4: Deflection of PV modules; Temperature dependency (A), Load duration dependency (B), EVA & PVB interlayers at different temperatures and load durations (C, D)

The mechanical behaviours were defined by bending stress and deflection occurred in glass. It is influenced by the temperature, load and load duration. The investigation in [3] proves that at lower operating temperature, both laminated glass with EVA or PVB interlayers have better mechanical behaviours than monolithic glass. On the other hand, laminated glass with EVA-interlayer shows better mechanical behaviours than with PVB-interlayer at higher operating temperature due to lower storage module reduction. In particularly at longer load duration, laminated glass with EVA-interlayer shows much better mechanical behaviours than with PVB-interlayer due to lower creep characteristic. Therefore, EVA can be proved to be used as laminated safety glass in building applications.

2.4 Electrical characterisation of BIPV modules [9]

Photovoltaic (PV) solar cells and PV modules have certain electrical and thermal properties. These properties are primarily determined by the used PV technology. Today the materials used by common PV technology can be divided into two overarching categories: thick-layer and thin-film technologies. Thick-layer technologies are photovoltaic cells based on crystalline silicon, for example mono-crystalline or polycrystalline silicon. The layer thickness ranges from 100 microns to 300 microns. Thin film technologies are for example cadmium telluride (CdTe), copper indium diselenide (CIS) or amorphous silicon (a-Si). The layer thickness is here in the range of <10 microns.

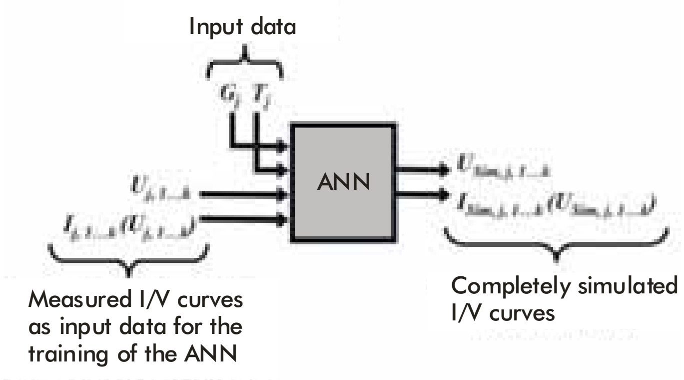
An important physical property of these PV modules is the current / voltage characteristic (I / V curve) which defines current in dependence of the voltage. The I/V characteristic can be a determined with variable load and a special measuring technique (I/V curve analyser, for example ISET-mpp meter [4]). Basically, the shape of this curve depends on the technology of the cell. Further influencing factors are the irradiance of the sun, the composition of the spectral components of sunlight and the cell temperature.

A mathematical / physical emulation of this characteristic curve can be made with different models. By suitable parameterisation of these models, the characteristic can be generated for each operating point. Examples which may be mentioned here are the one-or two-diode model shown in [5] or [6], the modified one-diode model [7] and the modified one-diode model [8]. These models work perfectly for crystalline cells and modules. The model according to [8] has been developed for CdTe technologies, which describes this type very well. CIS technology can be described with the two-diode model quite well. However, for amorphous silicon, or for tandem or triple cells, these models fail completely. In a-Si there is the problem of the annealing effect, which complicates the modelling extremely. This is an effect which influences the physical properties and the characteristic curve due to different seasonal temperatures. The annealing effect can not be explained by the existing models.

Besides these technological reasons, also the different installation methods affect the electrical behaviour of PV-modules. Depending on the installation in facades or roofs, the module is exposed to different temperature conditions. Furthermore, the orientation of the module (e.g. vertical in a facade) has an influence on the electrical performance. In order to respect the technology and installation based impacts on the electrical behaviour, new and flexible models are required.

An important tool for the determination of the energy yield of PV systems is the simulation. To get accurate results of a simulation, it is necessary to recreate the reality as accurately as possible. As mentioned above the simulation of photovoltaic cells has some deficits. Yield calculations are performed using special simulation programs. In that, several years of weather data are used, which are available for example as 15-minute or hourly averages. Through mathematical modelling of the electrical components (PV modules, inverters, cables, transformers, etc.) time series of the power are calculated. The summation (integration) over time finally gives the energy yield. In this context new and accurate models are required.

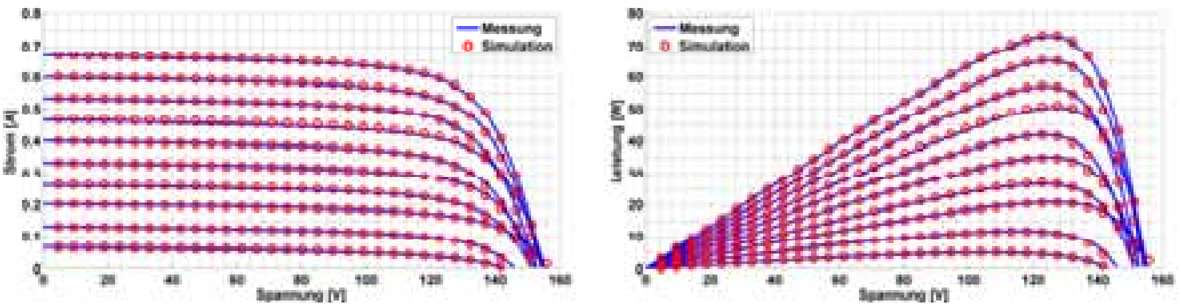
The one- or two-diode models mentioned above belong to the category of so-called physical models. Another approach is to describe the characteristics by numerical models. For this purpose an artificial neural network (ANN) is used. ANNs are able to approximate functions, including those which are highly non-linear. An ANN consists in principle of a network of weighting factors and transfer functions. The structure of the network has a decisive influence on the result. Similar to the parameters of the two-diode model the weighting factors of the ANN can be optimised. This process is called the training of the ANN. For training, there are different learning methods available. A very efficient variant is provided by the so-called back-propagation method which is used in the model described here. As optimisation algorithm, Levenberg-Marquardt method is used. With selected I/V curves, which were measured with the ISET mpp meter, the ANN was trained. The advantage of this model is that the characteristics of each cell or each module of both crystalline and thin-film technology can be described regardless of the technology. Figure 5 shows the input and output data of the new model.



G: Irradiance at the module level [W/m2]
T: Module Temperature [° C]
j: j-th measured characteristic
k: Number of points per curve

Figure 5: Input and output data of the new numerical model.

To test the new model real measurement data of a CIS module were applied. Naturally, different I/V curves were used for the training phase and verification of the ANN. Figure 6 shows a variety of characteristic curves that were obtained using the ANN model for this module. The model provides very good results. For instance ten selected characteristic curves at different times are shown in these figures. For clarity only every seventh simulated data point is shown.



a) b)

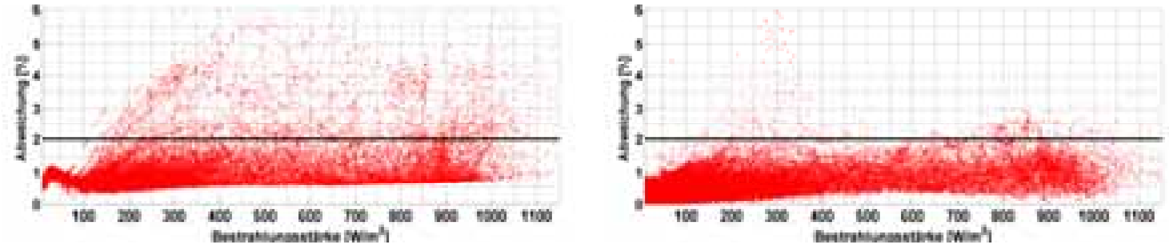
Figure 6: Measured and with ANN simulated I/V curves and P/V curves of a CIS PV-module.

To validate the new model, characteristics curves were simulated by means of the ANN and the one-diode model respectively and compared with real measurement data. Data were used from the period from July to December 2009. A total of about 68,000 characteristic curves were analysed. To determine the deviation from reality, the mean square error (RMSE) of each simulated and measured characteristics curve was calculated according to:

$$RMSE_{\%,j} = \frac{\sqrt{\frac{1}{k}\sum_{v=1}^{k}\left(I_v - \hat{I}_v\right)^2}}{I_{K,STC}} \cdot 100\%$$

I:	measured current curve [A]
$\hat{I}$:	simulated current curve [A]
$I_{K,STC}$:	Short-circuit current in the PV module under STC [A]
j:	j-th measured characteristic curve
k:	Number of points per characteristic curve

Figure 7 shows the percentage RMSE for all characteristic curves (68166). The evaluations show that with the new model a significant improvement in accuracy is possible. The line at 2% is shown in order to improve clarity and comparability. The errors in Figure 7b are located further below the line as compared to Figure 7a. In addition, the number of errors above this 2% line is significantly lower with the new model.



a) b)

Figure 7: RMSE of I/V curves simulated with a) two-diode model and b) ANN model.

Besides the described ANN a complete procedure was developed in order to determine all required parameters for the ANN based on real measurement data automatically. This procedure enables the modelling of arbitrary PV modules with different technologies and different installation methods. This is beneficial for module manufacturers in order to include high accurate models of their PV modules in simulation software.

2.5 Electromagnetic shielding capabilities of PV modules

At Fraunhofer IWES a measurement method for the electromagnetic properties of PV modules was developed. Here, the measurement object is placed in front of an opening of a metal chamber. Antennas for transmitting and receiving are placed behind and in front of the opening. Different frequency ranges (30 MHz –300 MHz, 300 MHz –1 GHz, 1GHz -5 GHz) are covered with suitable antennas. The attenuation of shielding results from the difference between the measurements with and without covered opening. Figure 8 compares the results from a monocrystalline and thin film PV module.

Up to 400 MHz the crystalline modules have almost no influence on the signal strength. Furthermore, the shielding is dependent of the polarization. For the thin film module the attenuation of shielding is much higher. This is due the homogeneous conductive surface of the thin-film modules. The interstices between the solar cells in crystalline modules cause a decrease in the attenuation of shielding. In summary it can be concluded that the attenuation of shielding is the range of 20 – 30 dB. This equals a shielding of 99 to 99.9% of the high-frequency power.

Further outdoor investigations on BIPV facades are planned. Here the attenuation is expected to be lower because of additional propagation paths.

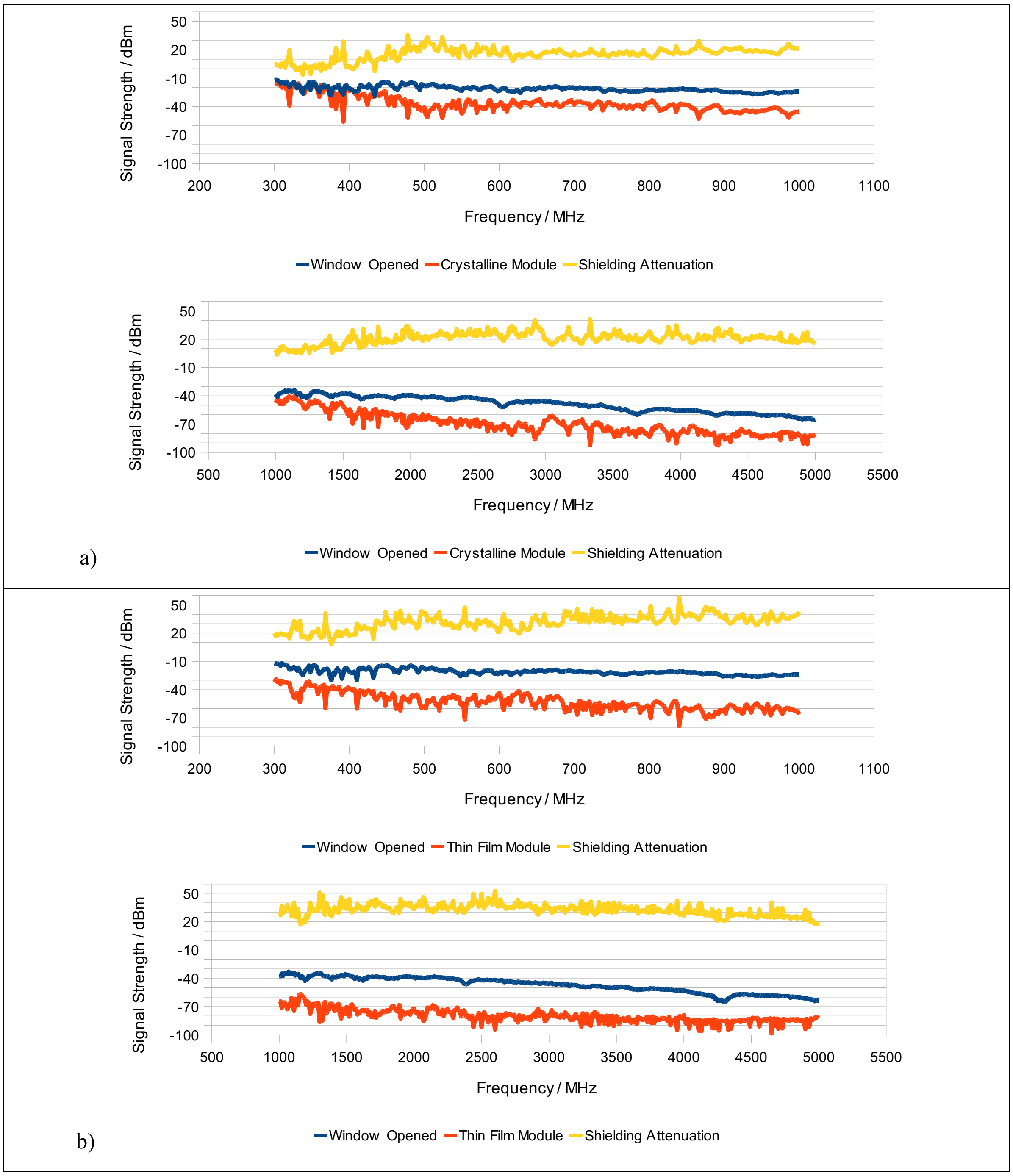


Figure 8 Shielding capability of a) crystalline and b) thin film PV modules.

3 Effect of BIPV on the primary energy demand

The most obvious function of PV modules in any application (additive on buildings, integrated in buildings, free-standing) is the production of electrical energy. The electricity generated by PV modules can be exploited in various ways. In grid connected systems the owner receives compensation according to the feed-in tariff. Furthermore, also the self-consumption of photovoltaic current is funded. In this way, photovoltaic helps to avoid overload situations in the electricity grid, due to a local consumption of the generated current. Thus the generated electric energy will directly benefit the energy demand of the building. At this point now, photovoltaic on or in buildings takes over a “function” in the calculation of the total primary energy demand of buildings. According to the European Energy Performance of Buildings (EBP) Directive [11] all new buildings by 2020 must be nearly zero energy buildings. Its implementation takes place in Germany through a combination of laws and regulations whose content is often connected with each other. One of these regulations is the Energy Conservation Regulation, EnEV 2009 [13], which defines the maximum permitted energy demand of buildings. It includes both the quality of the building envelope in terms of insulation as well as the building service. As a first priority, it limits the primary energy demand Qp of a building, as a side request it sets minimum standards for the quality of the building envelope, which is expressed in a maximum value for the transmission heat loss HT [12]. According to § 5 EnEV 2009 the electricity produced from renewable energy sources can be deducted from the final energy demand, if the system is in direct spatial relationship with the building and the electricity produced is primarily used in the building itself and only the excess amount of energy is fed into a public grid. In doing so, only building relevant electricity may be considered, e.g. auxiliary energy, current for direct heating or water heating as well as for air conditioning. In non-residential building the energy demand for lighting may be considered additionally.

For nearly zero energy houses according to the EPB Directive photovoltaic systems are of utmost importance, since they help to reduce the energy demand of the building. In order to show the effect of PV generated current on the energy demand comprehensive studies have been performed by means of simulation, where standard houses as defined in EnEV2009 were considered [10].

For the evaluation several reference buildings were considered according to the EnEV 2009, in which characteristic values of the building and building products are defined. In Figure 9 the effect of four different PV systems

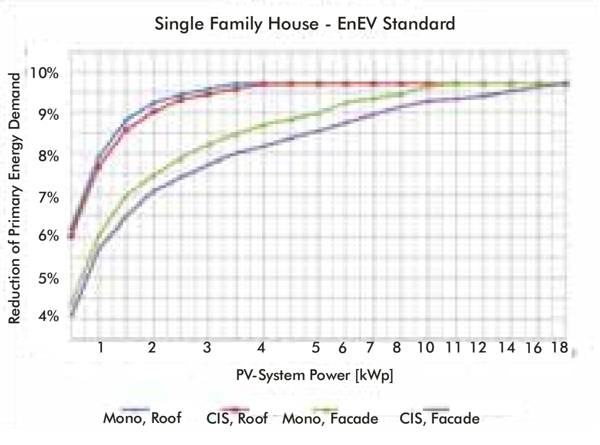
1: PV roof system, 30°-south orientation, mono-crystalline cells,
2: PV roof system, 30°-south orientation, CIS modules,
3: PV façade system, 90°-west orientation, mono-crystalline modules,
4: PV façade, 90°-west orientation, CIS modules

on the primary energy demand of three different building standards

1: single family house, EnEV Standard,
2: single family house, EnEV standard with heat pump,
3: single family house, passive house (with heat pump)

is shown.

For the interpretation of the results in Figure 9 the primary energy demand as well as the final electric energy demand needs to be considered as shown in Figure 10. In order to calculate the primary energy demand, the specifications of the building according to EnEV 2009 were used as reference (e.g. heat transfer coefficients of walls and windows, type of building services, heating, air condition etc.). It is needless to say, that the primary energy demand is reduced with a better building standard. However, the final electric energy demand has the highest value when a heat pump is used due its high power consumption. In a passive house the total useful energy is lower, and thus less electric energy is required in order to cover this demand. In order to determine the primary energy demand it must be considered, that a primary energy factor is assigned to each energy carrier depending on the energy expenditure for its production, transformation and distribution. In the case of electric energy this factor amounts to 2.6, which is relatively high.



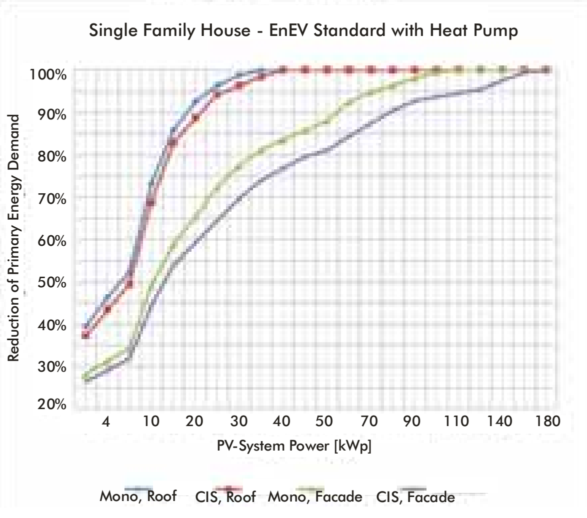


Figure 9: Reduction of the primary energy demand of one familiy houses in different standards.

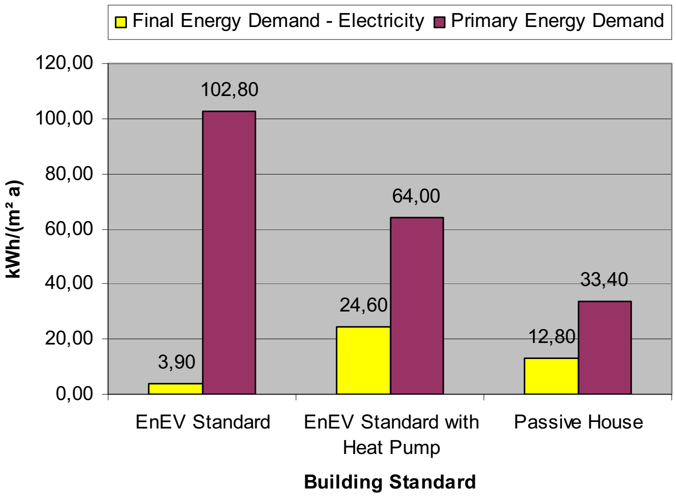


Figure 10: Primary energy demand and final energy demand (electricity) of different building standards according to EnEV 2009 [10].

If in buildings according to EnEV standard the final electric energy demand of 3.9 kWh/m²a is completely covered by photovoltaic current, the primary energy demand can reduced by $2.6 \cdot 3.9 kWh/(m^2 \cdot a) = 10.14 kWh/(m^2 \cdot a)$ at most. This corresponds to 9.8% of the primary energy demand. According to Figure 9 the primary energy demand of a EnEV standard building can be reduce by 9.8% if a PV roof system of about 4 kWp is considered. In case of a PV façade system, at least 10 kWp are required, when using mono-crystalline PV modules.

The situation changes dramatically when heat pumps or passive houses are regarded. In these cases the primary energy demand can be covered completely by PV generated current. This is possible due to the high power consumption of the heat pump in connection with the high primary energy factor of electricity. In case of passive energy houses the primary energy demand can be covered with a PV roof system of about 15 kWp and a façade system of about 50-80 kWp depending on the technology. These evaluations show that PV plays a significant role in the reduction of the primary energy demand of buildings.

4 Conclusion

In the project MULTIELEMENT the utilization potentials of the physical properties of PV building elements are investigated systematically. Besides physical properties (electrical, thermal, mechanical issues) also its place in the legal environment (building codes, energy conservation regulation) is considered. The results show that PV building product can take over several building functions besides electricity generation. However, gaps in rules and regulations as well as in technical guidelines hinder the application of PV as an integral part of buildings. The project results clarify the deficits in regulation, guidelines and standards and propose new approaches for test specification and standards.

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