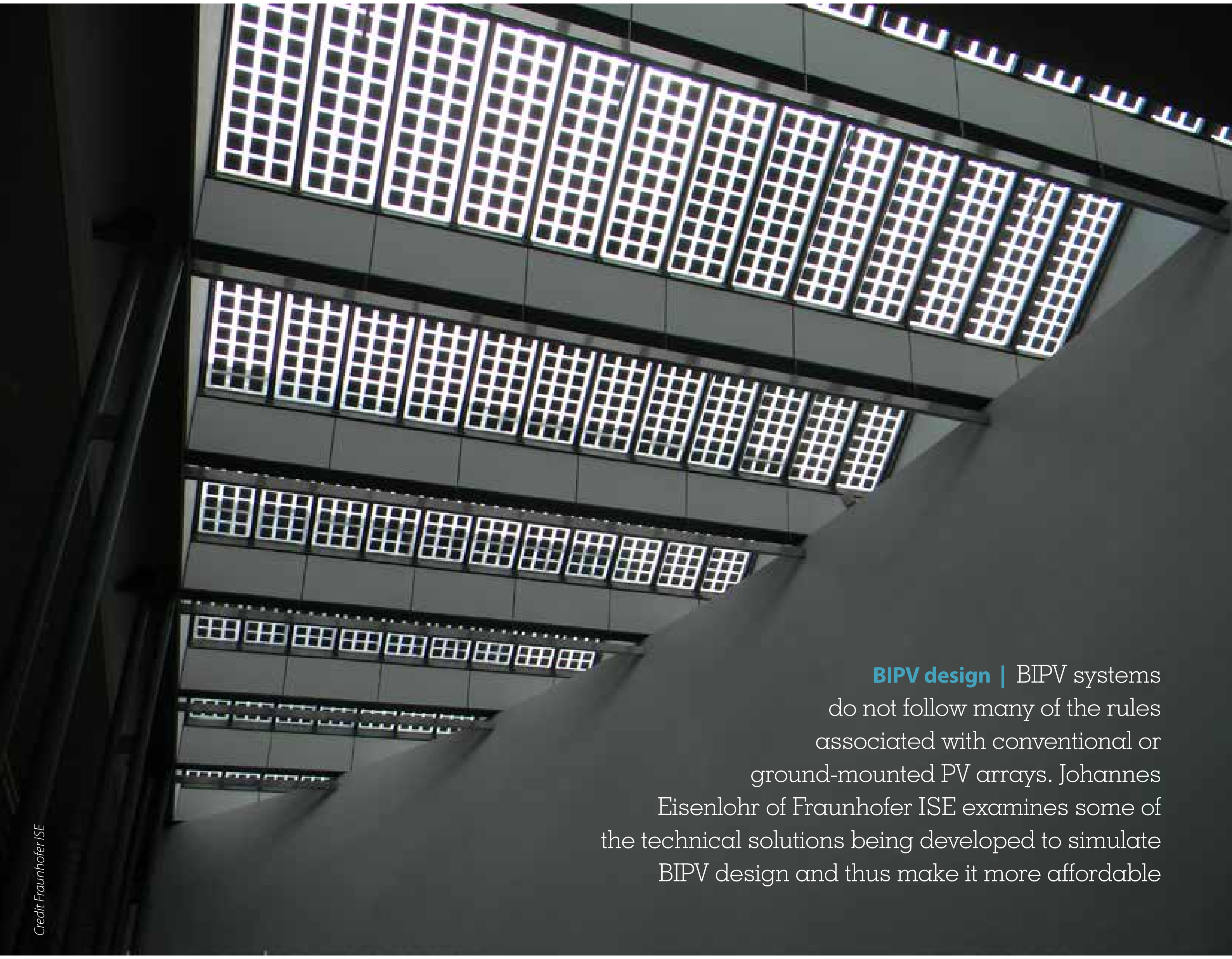
Detailed yield analysis and optimisation of BIPV systems by simulation



BIPV design | BIPV systems do not follow many of the rules associated with conventional or ground-mounted PV arrays. Johannes Eisenlohr of Fraunhofer ISE examines some of the technical solutions being developed to simulate BIPV design and thus make it more affordable

A significant amount of the global energy consumption is caused in and by buildings. In Germany, for example, the building stock is responsible for 35-40 % of the final energy consumption. Generating electric power directly on site is one promising approach to realise buildings with a low net consumption and consequently low CO2 emissions. Due to the massive price reduction over the last decade, PV became an obvious choice to generate renewable energy directly at the building level. In many cases, it is economically beneficial for building owners to harvest the energy the sun sends to their building skin.

Figure 1. BIVP system in the atrium of Fraunhofer ISE main building with semitransparent glass-glass-modules as an example of one specific form of BIPV. Other BIPV systems look completely different and have different requirements

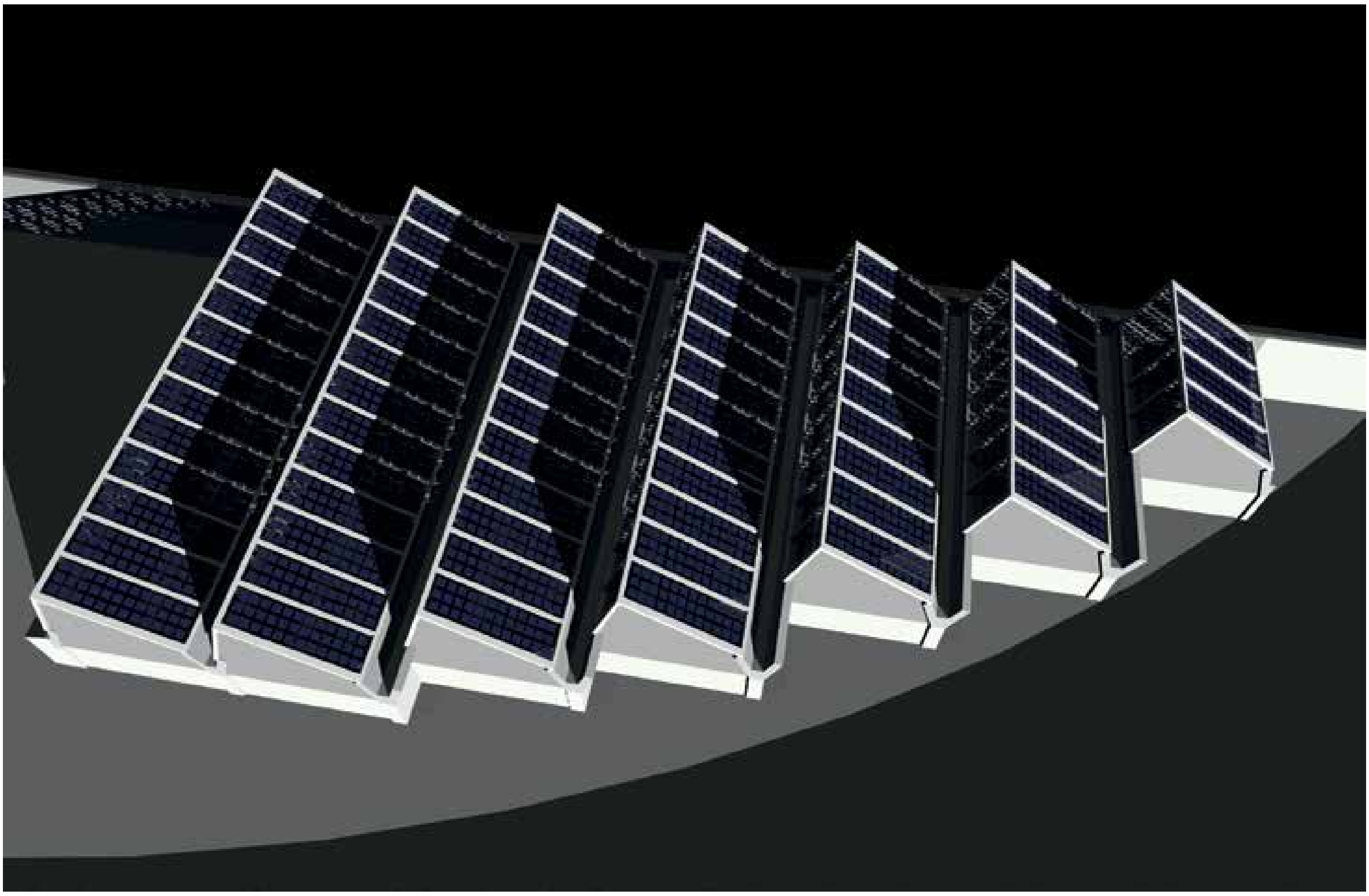


Figure 2. A rendered image of the BIPV system shown in Fig. 1 based on a RADIANCE model. Partial shading of the system at this specific time step is clearly visible [3]

While for small single-family houses, the roof area is often large enough to cover a significant share of the energy demand, for higher buildings also the façade gains in importance. Either way, on the roof or in the façade, active PV-elements can replace conventional building materials and fulfill conventional functions of the building skin, in addition to the PV functionality. So from the perspective of a single building, BIPV is a promising approach. But there is another perspective: For overall renewable energy systems, we need large areas for PV. Especially in densely populated regions, the area available on buildings can contribute a significant share to that. According to recent studies in Germany [1], the available technical and even economic potential on building skins exceeds the area required for PV in a 100% renewable energy scenario by far.

One of the challenges to overcome on the path to more BIPV in the market is to handle the complex planning process. If you look at many different BIPV projects, you will notice that each one is different and unique. Most obvious, the geometric situation of each building and its surroundings is different, which leads to different and often inhomogeneous irradiance levels. The degree of standardisation, which massively contributed to the success of conventional PV in the last decade, is significantly lower for BIPV. This makes also each planning process unique and complex. The following article will give a short overview of what has to be considered in such a planning process to result in an efficiently and safely working BIPV system, in the end focusing on a simulation-based approach.

What is important for planning and simulating BIPV systems?

Before focusing on BIPV simulations, it is essential to keep in mind that BIPV components are multifunctional building elements, where the PV functionality is only one amongst many. From mechanical resistance over safety in case of fire to aesthetic demands, there are lots of further aspects to consider and requirements to fulfill. The European standard EN50583 [2] provides the normative framework for BIPV – including the PV functionality as well as all other building-related requirements. The standard is divided into two levels: modules and systems. For both levels, different mounting categories are defined. BIPV can be roof- or façade-integrated and accessible from the inside or externally mounted. Corresponding to the category, a different set of standards applies. On the basis of EN50583, an IEC standard is currently in preparation (IEC TC 82 PT 63092). Everybody who realises a BIPV system should consider this normative framework.

Beyond the multifunctionality, the electrical system design is a challenging task for BIPV. While for the design of PV systems in typical plant or rooftop configurations a lot of simple design rules and specialised software tools exist, the electrical system design for each BIPV system is different, complex and less standardised. To design a yield-optimised BIPV system, one has to understand the behaviour of each solar cell for all the operating conditions occurring in reality in advance. To approach such a detailed understanding, several aspects have to be considered. We presented a BIPV simulation tool suite elsewhere [3–5], which covers all the following aspects, and at some points I refer to this tool suite. The five main aspects are summarised in Figure 3.

Irradiance (1)

Investigating the irradiance situation for a planned BIPV system is the first step. Analysing the partial shading due to topography, neighbouring buildings, trees, features of the building itself or the mounting system is mandatory. There are simple tables or tools to calculate the annual irradiance on an area depending on the geographical position and the orientation and slope of the area. This can give a very first basis to decide if a BIPV system comes into consideration.

To plan and optimise a system, however, a more detailed analysis is required. As shading of single cells can have a strong influence on the performance of the complete system, a high spatial resolution is required. Via ray-tracing, the irradiance on each solar cell for each time step can be calculated. RADIANCE (www.radiance-online.org/), for example, is an open-source ray-tracing tool that can be used for this task. As input for such a ray-tracing calculation, the following data is required: the 3D-geometry of the building and the relevant surroundings, including the optical properties of the materials and meteorological data containing the direct and diffuse part of solar radiation. The meteorological data is used to generate a sky model, e.g. the one by Perez et al., that is used as light source in the ray-tracing calculation.

At the position of all solar cells, the irradiance is calculated, typically with a time resolution of 1-15 minutes. The hourly data often used for standard PV installations do not reveal all partial shading effects. The shadow of a simple antenna, for example, can move over many cells during one hour, which would not be covered by hourly calculations. The time-resolved irradiance data can already be used to identify suitable strings and sub-systems or to narrow down the needs for power electronics. Already at this level, it is possible to get an impression of whether one large inverter, several small inverters or module level power electronics like DC-DC power optimisers might be suitable. Figure 2 shows an exemplary 3D-model of the BIPV system installed in the atrium of Fraunhofer ISE.

Temperature (2)

The second aspect to investigate is the temperature of all solar cells for each time step. The temperature is relevant for two reasons: First, maximum and minimum temperatures as well as quick changes are important for all materials in a BIPV module. Especially encapsulant materials might only be suitable for certain temperature ranges. As BIPV systems quite often are weakly ventilated, higher temperatures can occur. Second, the efficiency of solar cells depends on temperature. For crystalline silicon solar cells, typical relative temperature coefficients are about -0.3%/K. Depending on the ambient air temperature, the irradiance, the layer structure of the module and its mounting, the temperature can be calculated. There is a variety of methods; a good overview is given, for example, in [6]. Some models also take into account the wind speed, but the actual wind speed at building surfaces can vary strongly over short distances and, thus, is an input parameter difficult to determine precisely.

Electrical model of individual solar cells (3)

To understand a complete BIPV system, an equivalent circuit model of the individual solar cell is needed. In these models, the electric behaviour of a PV cell is represented by an equivalent circuit consisting of one or more diodes, series and shunt resistance. The simplest version would be the ideal single diode model with only three parameters: photocurrent I_{pv}, saturation current I_0 and ideality factor a. However, the practical relevance of the ideal single diode model is low, as at least an additional series resistance has to be considered to describe a real device. Therefore, the single diode R_s-model, also known as four-parameter model, has been introduced [7]. Adding also a parallel shunt resistance leads to the single diode R_p-model, also known as five-parameter model (e.g. [8]). All single diode models inherently neglect the recombination losses in the depletion region. These can be included by extending the equivalent circuit by an additional diode leading to the two-diode model with two additional parameters: saturation current I_{02} and ideality factor a_2 of the second diode. With these seven parameters, the two-diode model gets computationally demanding, but also results in a high accuracy especially at low irradiance conditions, which often occur in the case of BIPV.

For all equivalent circuit models, a precise extraction of the parameters from typically available data sheet information or IV measurements can be challenging and a lot of algorithms have been presented. A good overview about equivalent circuit models and corresponding algorithms can be found in [9]. With an equivalent circuit model, the electrical behaviour under all operating conditions (irradiance and temperature) can be predicted. Note that the diode models originate from the description of a solar cell as a plane pn-junction of differently doped semiconductor layers and their validity for different cell technologies has to be rechecked. Furthermore, the reverse bias behavior has to be modeled. Especially the breakdown voltage is important to understand the systems behavior in the next step when partial shading occurs. An equivalent circuit model can be set up for a complete

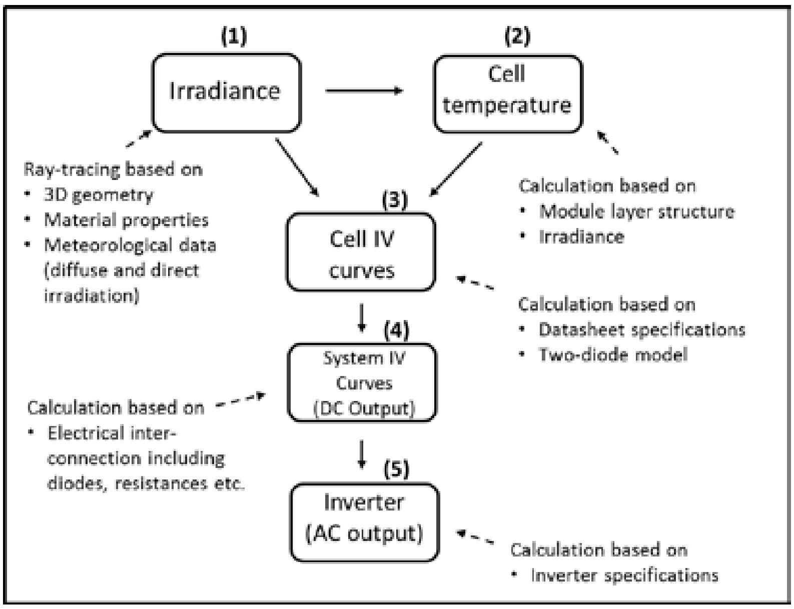


Figure 3. Summary of the five main steps of a detailed BIPV simulation with the major input required.

module, but as already mentioned in (1), it is required to understand the system not only on module level, but on cell level. Thus, the parameters should be extracted for each individual solar cell.

Electrical model of interconnected cells and modules (4)

Knowing the irradiance, temperature and the equivalent circuit model of each solar cell for each time step, everything can be combined according to the electrical interconnection of cells. Additionally, bypass diodes have to be included in this step, as they play a key role when some of the cells in the system are shaded and delivering a lower current. Series and/or parallel interconnections have to be considered and all IV curves have to be added up according to Kirchhoff's laws resulting in an IV-curve of the complete (sub-) system that will be connected to power electronics components, typically an inverter. Also DC-DC power optimisers can be applied to BIPV systems to attenuate the losses due to partial shading. We recently extended the BIPV simulation framework at Fraunhofer ISE for optimisers. There are optimisers with different typologies and control strategies. Either buck- or buck-boost-converters are typically used. Depending on the actual optimiser used, this step (4) has to be adjusted. The MPP-tracking has to be performed for each unit connected to a power optimiser (typically a single module) and the output of these units has to be connected according to the control strategy of the optimiser system. As DC-DC power optimisers also lead to some additional conversion losses, the benefits have to be quantified for each specific system and balanced with the losses. Besides the system IV curve, in this step also the operation points of all individual components of the electric circuit can be checked. Especially the question of whether are cells in the systems that are strongly reverse-biased at certain time steps should be answered due to the risk of hot spots.

Step (4) is the central step of the BIPV simulation and allows for a detailed optimisation. The use of bypass diodes, the connection to strings and the division into sub-systems can be varied here and optimised with respect to yield maximisation and a fail-safe operation. As BIPV modules and systems are customised very often, the simulation tool in this step needs to be very flexible and should not only be able to handle standard PV modules with 60 cells and three bypass diodes.

Electrical model of inverter (5)

Finally, an electric model for the inverter is needed. Depending on the DC output of the system and the inverter data sheet specifications, the AC output can be calculated. We use a parametric model for the inverter according to [10]. In the first part of this step, the MPP tracking can be performed (if not already done in step (4) in case of DC-DC-optimisers) and in the second step the inverter model applied resulting in the time-resolved AC output of the BIPV system. Step (5) allows for choosing a suitable inverter or combination of inverters for a specific system. As low irradiance conditions occur more often in BIPV applications, the inverter layout might differ from the simple rules well-known for standard PV applications.

From BIM to BIPV

The detailed simulation steps (1) to (5) require a detailed input. Results can only be reliable and precise if the input is correct. The input described above has to be collected from various sources, and for different projects, it might be available in a different structure and different formats. As Building Information Modelling (BIM) is more and more used in the construction industry, a direct and automated link from a BIM model to a BIPV simulation is a promising approach. Collecting all the input data by hand is time consuming and error-prone. It makes detailed BIPV planning processes expensive. If there is already a 3D model of the building and its surroundings, it is obvious to use this model for the irradiance calculation in step (1). Therefore, a colleague at Fraunhofer ISE developed a tool that filters and wraps IFC data to RADIANCE files. IFC (Industry Foundation Classes) is a neutral data format to describe, exchange and share information related to buildings, including the 3D geometry.

Also product-related data like the electrical cell properties for step (3) or the inverter properties for step (5) could be automatically extracted from digital product databases instead of transferring information of PDF data sheets manually. This, however, requires flexible and parametric product data modules, as BIPV modules are not only available in one specific size and layout. We are working on the holistic integration of BIPV components into construction processes in the project SolConPro [11][12]. Also other research projects like PVSites (www.pvsites.eu) aim at the connection of BIM to BIPV modelling. Including BIPV into BIM offers many further advantages for the whole lifecycle, not only for the planning stage but also for operation and maintenance until deconstruction.

Conclusion

With a detailed simulation like the one described above in the steps (1) to (5) and a flexible and versatile link from BIM to BIPV, BIPV can become cheaper, more efficient and more reliable. It can be ensured that BIPV systems work safely and contribute a significant share to energy-efficient and CO2-neutral buildings.

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