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Assembly cell for the manufacturing of flexible solar modules in building integrated photovoltaics

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Abstract

The current use of photovoltaics is often limited to the utilization of roof surfaces or ground-mounted systems. In particular, building integrated photovoltaics (BIPV) have enormous potential to make energy production more sustainable, because the energy is generated where it is used. However, most of these modules either do not meet the aesthetic requirements of the architects as well as the building owner or are uneconomical, since visually appealing building-integrated PV modules cost several times more than standard modules. In this article, an approach for a (semi) automated assembly line that allows geometry- and material-flexible manufacturing of PV modules is presented. The challenges in automating the flexible manufacturing processes include mainly the handling of limp components and the complexity of geometry variability. Appropriate gripper systems are required to ensure safe and reliable handling of the components. A gripper developed in this article offers the ability to flexibly deposit solar strings. Preliminary tests show that 66% of all conducted trials meet the accuracy requirements.

Keywords: photovoltaic; flexible production cell; gripper developement

1. Introduction

Climate change is considered one of the most important political and scientific issues of today. Germany, for example, has issued the Climate Protection Act with the goal of achieving greenhouse gas neutrality by 2045 and to have 65% less emissions by 2030 compared to 1990 [1].

The energy production takes a share of 37.6% worldwide emissions and is therefore the emission group with the highest share [2]. One way to reduce these emissions is the use of renewable energy sources such as wind, water and solar energy. For example, large wind or solar parks are being built to provide industry and private households with energy without CO2 emissions. However, this energy has to be distributed via appropriate power grids in the respective country. One approach to reduce transportation is to generate energy where it is needed. The integration of renewable energy generation in the building skins offers the advantage that generation and consumption coincide spatially. PV on buildings has so far primarily meant using suitable roof space. However, to achieve climate targets and the local energy demand of office or apartment buildings, there is an urgent need to develop additional areas on structural systems and in buildings [3]. In cities, building facades offer a large potential area that has not yet been tapped. A recent study shows that the potentially usable facade area in Germany alone, at 12,000 square kilometers, is about twice as large as that of roof areas [4]. Installing PV with different orientation also helps to match the

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energy production and consumption in time to reduce the size of the required energy storage. In addition, a study shows that cities can make a relevant contribution to the energy transition. Using the example of the Hannover region, buildings alone offer a PV potential of 2 GW [5], which is equivalent to 50% of the total PV capacity installed in Lower Saxony to date. This aspect is of special interest as highly populate countries typically have a high energy demand and limited space to satisfy all demands from agriculture, nature conservation, industry etc. and thus using urban areas for energy production helps to relax the demand for land use.

Among architects and building owners, the currently widespread approach of applying standard PV modules into the building skin creates acceptance problems for aesthetic reasons. The demand for a uniformly designed building envelope is not met, which prevents the widespread use of facades for energy generation. On the other hand, it is state of the art to produce facade elements from very different materials in countless appearances. However, combining such facade elements and PV-active elements while maintaining a uniform appearance, especially considering economic aspects, is currently an unsolved task. Custom-fit solutions therefore have the potential to make efficient use of building surface and to be aesthetically pleasing. Today, appealing building integrated PV (BIPV) modules cost 4-9 times more than standard modules [6]. The reason for the high costs is not only a lack of standardization, but especially the small batch sizes, which leads to long changeover times of previous production lines. In contrast to conventional systems that produce highly standardised PV-modules with a high level of automation, a lot of manual work makes BIPV modules too expensive for a wide application [7]. The global market for building-integrated photovoltaics is expected to grow by 15% from 2019 to 2024, to seven billion U.S. dollars by then [8], which is likely just the beginning of global development. Moreover, the developed processes are not only suitable for PV modules for facades, but can also be applied to other forms of integration in surfaces, e.g., of vehicles (e.g., passenger cars, lightweight vehicles/cargo wheels, ships...), infrastructure, and mobile devices.

In this article, an approach for automated, flexible production of building-integrated photovoltaics is presented. This requires production systems that allow both geometric and material flexibility. A major aspect is the handling between the individual production machines. Here, it is necessary to develop appropriate gripping systems for the flexible pick-up and placement of solar cell strings. The approach developed here also allows for deposition on simply curved surfaces, which should offer significant design freedom in the future, especially for the design of building or vehicle-integrated photovoltaics.

First, the state of the art of the current production of solar modules or building-integrated solar modules is explained. Then, the approach for a flexible production system is presented. In the further course, the focus is placed on a gripping system for solar cell strings for placement on straight and single-curved surfaces. Preliminary tests are used to evaluate whether the approach is applicable for use in building-integrated solar module production. Finally, the results are summarized and an outlook on further research activities is given.

2. Building-integrated solar modules and production

Building-integrated solar modules usually consist of the layers rear cover (typically glass but may also be a facade element), lamination foil (encapsulant), interconnected solar cells, lamination foil and a front cover (see Fig. 1). The front cover can be made of glass or polymer film. The assembly is usually done on the rear cover, which is placed first. Then the first lamination foil is applied and the solar cells are placed on top of it. Classically, solar cells have edge length between 156 mm and 210 mm [9]. A distinction is made between full cells, half cells or even small fractions. The half or third cells are divided beforehand.

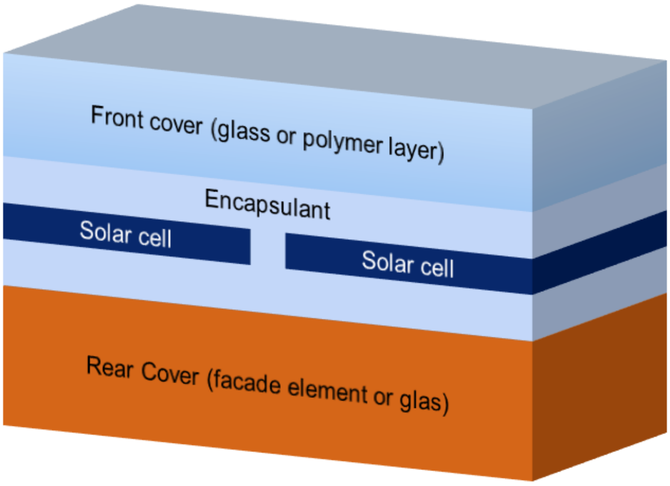

Fig. 1 Exemplary cross-section through a PV module built on a facade element to illustrate the layer sequence.

The solar cells are already prepared in a stringer that interconnects the cells in series to form solar cell strings. For this purpose, the individual cells are contacted with each other. The solar cell strings often have a size in between 800 mm and 2000 mm. These are dimensionally stable in handling, but highly brittle and sensitive and must be handled with appropriate gripping systems. However, for BIPV-application they could vary even between 400 mm and 3000 mm. Subsequently, another lamination film is applied to the solar cell strings. The entire assembly, including the final glass plate or polymer film, is joined in a laminator under vacuum and heat to form a complete package.

Research for the current state of the art in PV module production for rooftop or ground-mounted applications has focused on optimizing the throughput of identical module production to reduce costs. The level of automation is very high. In the field of handling, manufacturers are already using gripping systems specially adapted to the application. For example, there are corresponding cell and string grippers that are being developed especially for the solar industry [10]. Converting a "state-of-the-art" production line to, for example, a different module format is only possible in a time-consuming and cost-intensive manner. A large number of different PV modules cannot be produced on the same production line. Since adaptability is needed in building-integrated photovoltaics for the reasons mentioned in Section 1, the production processes in this area must be much more flexible. Therefore, the flexibilization of automated production for the manufacturing of customized PV modules of batch size 1 is a relevant research focus [7]. For this purpose, a system that enables a material- and geometry-flexible production of building-integrated PV modules is developed and implemented.

3. Automated cell for the flexible production of solar modules

Developing an automatic and flexible production line and assembly cell is in focus of present research in BIPV, as shown in Fig. 2. It depicts a flexible manufacturing line [11].

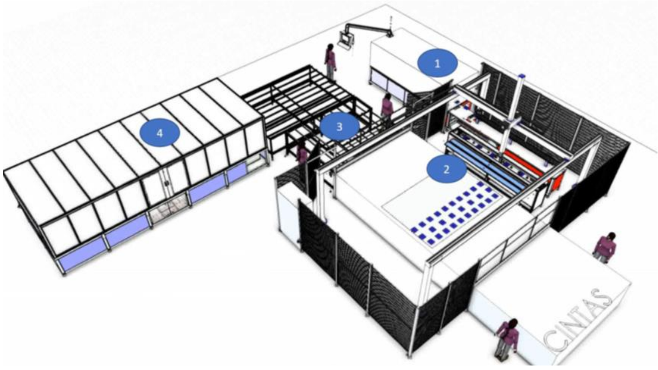

Fig. 2: An example of a flexible manufacturing line for BIPV products from [11]: (1) A automated stringer equipment for cell interconnection (2) Automated Lay-up machine with robot (3) Interconnection (bussing) station (4) High-resolution electroluminescence quality before lamination

The production process begins with the manufacture of the semi-finished products. In order to provide the materials (glasses, foils, etc.) in the necessary size, they need to be cut in size by laser cutting, milling or other processes. This allows different materials to be made available for the next process step without functional or aesthetic impairment.

For the placement of the materials, a handling unit is needed that, in addition to handling the bendable materials, can also position heavy, planar objects (such as 3.4 m² glasses weighing up to 50 kg) in different sizes and geometries with high precision. Flexibility in particular is an important factor, as today's solar module production uses highly automated lines that produce modules with a consistent structure. The required handling equipment and associated gripping technology is specifically adapted to the materials and geometries, as no variations take place. This rigid system must be made more flexible in order to be able to produce modules with a higher degree of freedom in size and material variation. For example, grippers need to be developed that can pick up and deposit limp films (lamination film) and composite materials (outer layer of the module) with high accuracy. Conventional gripping systems are not practicable for this purpose, since in the case of limp components, gripping must be flat or on the outer edges to avoid overlaps when placing. In order for this to be implemented in a geometrically flexible manner, concepts and approaches must be developed to adapt the gripper according to the different shapes of the gripped object, e.g. the lamination foil. A similar challenge also arises when handling solar cell strings, which, due to the variation, do not necessarily have to have consistent cell geometry and cell numbers. Therefore, in this paper, a gripper concept is presented and evaluated that can adapt to the respective string without compromising the handling of the sensitive components.

The cell strings are deposited on the prepared lay-up station, see Fig. 2(2). There are already the semi-finished products adapted in size, such as the transparent module front side, a layer of lamination foil and, if necessary, further layers for the aesthetic design of the PV modules. These individual layers have a size range from 0.25 m² to 6 m² or even larger.

On this deposition station the solar cell strings need to be connected at their edge in order to interconnect them in series (bussing). This requires for the flexible production of BIPV modules to solder the strings on variable positions with high accuracy. Subsequently, the strings are laminated as discussed above before adding the frame or back rails, junction box and external contacts.

In order to implement the goal of an automated process sequence for the production of customized modules, the individual processes are combined into a continuous, centrally controlled automated process flow for the production of size-variable PV modules. One obstacle lies in the design-related pronounced variability of the modules (e.g., in size, color, and material composition), since these must be adapted to the conditions accordingly. Although the general structure and manufacturing processes remain similar for these modules, the individual production processes must be adapted to the changing parameters. This often leads to difficulties in automated production because, for example, positions can no longer be approached with the required accuracy or objects can no longer be handled safely and optimally.

4. Gripper system for flexible placement of solar strings for building integrated applications

Therefore, in the following an approach for an adaptive gripper for the handling of material- and geometry-flexible handling of solar cell strings for BIPV modules is presented. Based on the requirements for the gripping system, different sub systems are developed and the impact on the cells are measured. Finally, trails are carried out to prove the functionality and accuracy of the gripping system.

According to the requirements, the strings are to be picked up on a flat surface and have the possibility to be placed on another flat surface as well as on a simple curved surface. The approach shown in this article is first considered for handling short strings of four interconnected solar cells. Transferability will also be validated for longer strings after successful testing of the concept, but is not the subject of this paper.

The stranded solar cells offer only low stiffness, so they will bend without reasonable fixation. Damage to the cells or the cell strings can occur if the bending is too large. Consequently, the gripping system must be able to grip the solar cells or string securely, but have the flexibility to adapt to the shape of the support surface.

Vacuum gripping systems are widely used in the handling of solar cells [12]. The approach chosen here is also based on the use of vacuum systems. Since the solar cells are also to be deposited on simply curved surfaces, area gripping systems are not considered. The vacuum grippers used are flat suction cups from the company Schmalz with a diameter of 15 mm [13]. According to the manufacturer, these are well suited for flexible workpieces.

The adaptability of grippers to different surfaces or objects is often investigated, for example, in the handling of carbon fiber or glass fiber fabrics or process with high adoption requirements to various parameters. Approaches investigated in this context include the FinRay effect [14, 15] and gripping using granular grippers [16]. The approach adopted here is based on a belt system that can lift and handle the string.

4.1. Design and Function of the gripping system

The developed gripping system consists of five subsystems, which are explained in more detail below (see Fig. 3).

- Carrier system
- Belt system
- Tensioning system
- Air cushion
- Suction system

The carrier system is a stable platform to which the other modules are attached. It serves as the interface between the robot flange and the gripper system. As the central carrier, it is connected to the clamping system, the cushion system and the belt system. The carrier system also includes laterally arranged rollers that guide the belt around the required angle with as little friction as possible.

The belt serves as a support system for the suction system, which serves to hold the solar cell string. To ensure that the distances between the suction cups remain constant throughout the process, the belt is made of a non-stretchable material. The belt is guided over rollers attached to the carrier system to prevent damage and ensure good functionality. Since the belt does not have to transmit torque, it is a flat belt sufficient due to its low thickness and non-elastic properties.

The tensioning system is used to tension and release the belt. This enables a stiff take-up and a form-flexible placement of the string. To pick up the string, a tensioning pulley is pushed upwards by means of a pneumatic cylinder, so that the belt is tensioned and a flat pick-up is possible. When the string is deposited again on a flat surface, the cylinder remains tensioned and the string does not change its position (see Fig. 3a). For placement on a single curved plane, the belt is released so that the belt becomes flexible and conforms to the contour of the surface as it comes into contact.

The compressed air cushion produces counterpressure for the belt, on the one hand to accommodate the string with increased stiffness and, on the other hand, to generate a contact pressure during deposition and to distribute this pressure evenly over the effective belt length (see Fig. 3b). The pressure cushion is attached to a frame that serves as a connection between the cushion and the support structure. In order for the cushion to retain its shape, it should be made of a non-stretchable and air-impermeable fabric.

The suction system is the active system of the gripper and includes the flat suction cups. The suction cups are mounted with a small distance to the outside of the belt so that the stresses in the solar cell string are minimal. Angled push-in fittings are used on the inside of the belt as a counterpart for attaching the suction cups. These push-in fittings are intended to protect the compressed air or vacuum hoses from kinking due to the compressed air cushion. The compressed air/vacuum hoses are routed to the ejector via the robot.

4.2. Detection of damages inducted to the solar cells during handling

In order to check whether the gripper damages the solar cell while handling, four half silicon solar cells are inspected for microcracks, scratches, surface defects or other marks by photoluminescence imaging [17] before and after they are handled by the gripper. Photoluminescence imaging is a common characterization technique for solar cells because material defects can be visualized in a spatially resolved manner. This technique exploits the fundamental phenomena of generation and recombination of electron-hole pairs in semiconductors. The solar cell under test is homogeneously illuminated by a widened and homogenized laser beam with a wavelength of around 800 nm so that the emitted photons have more energy than the bandgap energy of silicon of 1.12 eV. These photons generate free electron-hole pairs in the solar cell, but since the solar cell is operated in open circuit and the generated free charge carriers are not extracted, they recombine after a certain lifetime through various mechanisms. The most important recombination mechanism for photoluminescence imaging is radiative recombination. In this case the electron-hole pair recombines by emission of a photon with approximately the bandgap energy. These photons can be detected by a camera with a suitable filter combination to suppress the laser light. The detected counts per camera pixel being proportional to the spatially resolved light emission of the solar cell results in a gray scale image. At defect points of the

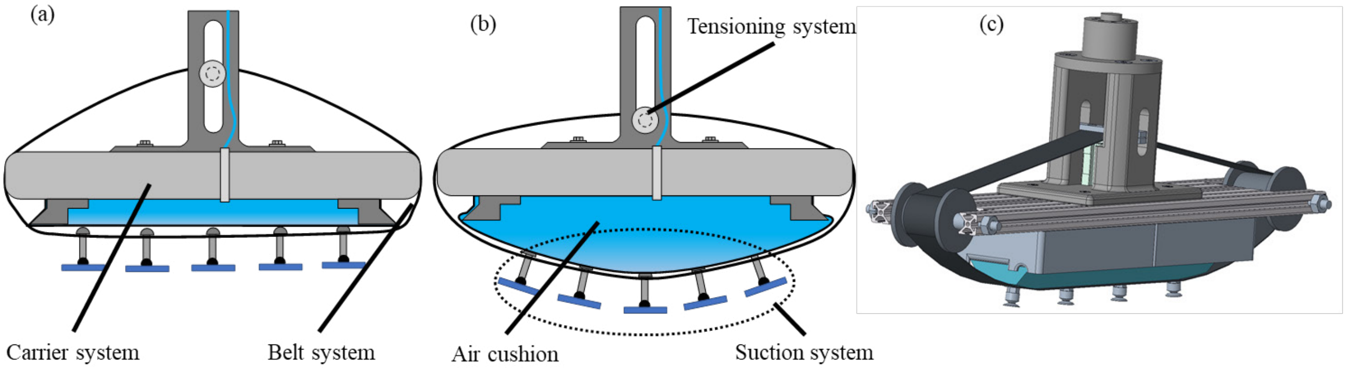

Figure 3: Schematic design of the developed gripper (a) in the tensioned state; (b) in the untensioned state; (c) model of the developed gripper

solar cell nonradiative recombination mechanisms, especially Shockley-Read-Hall recombination via impurity states within the bandgap, dominate so that these areas appear darker in the photoluminescence image than the intact areas of the solar cell, where radiative recombination dominates.

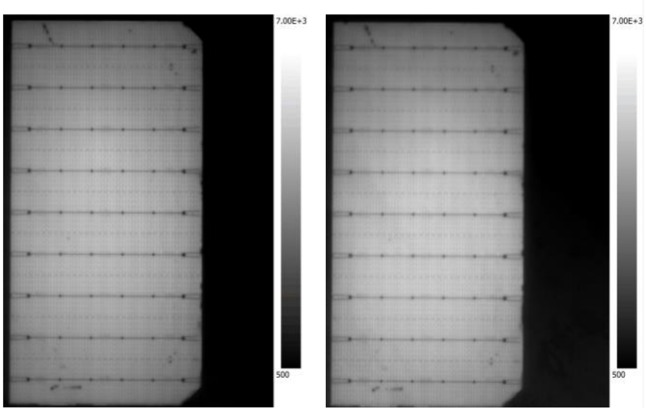

Fig. 4: Photoluminescence image of a half silicon solar cell before (left) and after (right) handling with the gripper. As there are no additional dark marks visible after the handling it can be concluded that the gripper does not damage the solar cell.

In Fig. 4 the photoluminescence images of a half monocrystalline silicon solar cell before and after being handled by the gripper are shown. For this purpose, three solar cells were picked up from a plane and moved approx. one meter at a speed of 2 m/s. The cells are then tilted by 90° so that the suction cups are vertical. Subsequently, the cells are deposited back along the same path. This process was repeated ten times with one cell, which does not occur in reality because the cell is only deposited once. This was done to make sure that the cell is loaded more than in the normal process to ensure that no damage occurred. The result is identical for all three solar cells. As the pictures before and after the handling do not show any differences, it can be concluded that the used suction cups do not damage the finished solar cells for module production.

4.3. Investigation of the placement accuracy

The strings must be laid down with an accuracy of 100 µm. The difference to the adjacent string is the relevant target size, so that they do not lie on top of each other, but at the same time to maximize the relative area coverage by the solar cells (i.e., minimize the area not covered by solar cells in order to increase the module power per area). The accuracy is of special importance for shaped surfaces with edges or curved surfaces, where the cell gaps have to be aligned to the structure in order to avoid fracturing the cells. Fig. 5a shows a string with two half cells. The y-direction describes the extent along the string. The x-direction is perpendicular to it and runs along the width of the string. Consequently, the placement in x-direction must be investigated in this experiment.

Preliminary tests have shown that half cells can still be deposited well on a bending radius of 750 mm. Therefore, the test with gripping system will be carried out on such a depositing surface. The test surface to be used and the test setup are shown in Fig. 5b.

For the experiment, a Kuka KR6 Agilius picks up a string with four half cells and positions it on the curved support surface. Then, a line laser sensor attached to a linear actuator determine the distance between the edge of the solar cell and the edge of the bended surface (Fig. 5c). Thus, the deviation of the actual position from the target position can be determined. The string is held in position by the gripper during measurement to eliminate movement due to release. According to the data sheet, the robot repeatability is given as 30 µm [18].

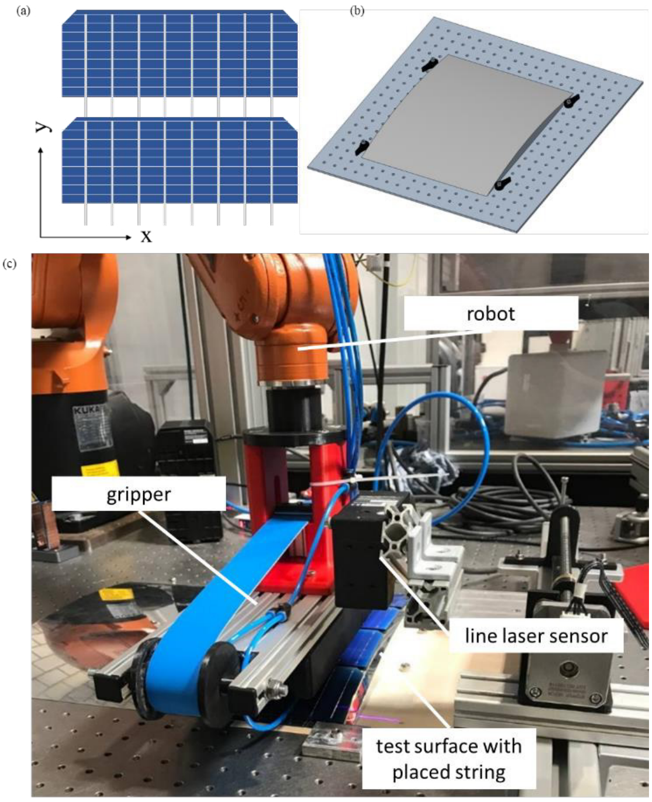

Fig. 5: (a) schematic structure of a half cell string; (b) schematic representation of the test surface with a bending radius of 750 mm; (c) Experimental setup with gripper and line laser for determining the position

For this experiment, 50 strings are picked up, placed and measured. The robot moves the solar cell at 60 percent of the nominal speed during each pass. The initial conditions are the same for each cycle, so that the pickup and placement positions are always the same and fixed. The pickup position is fixed by lateral stops to ensure an exact initial position. The line laser sensor then determines the position of the string. The most important factor is a small deviation from the nominal position.

4.4. Discussion of the placement accuracy

Fig. 6 shows the deviation of the respective deposit position from the nominal position. The average value of the deviations is 122 µm, although this is influenced by some outliers with values of up to approx. 1 mm. As can be seen in Fig. 6, 33 of the 50 measurements meet the requirements of 100 µm, which corresponds to approx. 66%. Within 200 µm 41 of the measured values lie, which corresponds to approx. 82%. A trend in the measured values is not evident, so that a dependence on the test duration is unlikely. In the case of the outliers, inaccuracies during the pickup of the solar cells cannot be ruled out.

The accuracy of the robot in combination with the gripper alone is not yet sufficient to reliably place the solar cells accurately in an automated process. However, in contrast to the grippers currently in use, the gripper offers the possibility of placing solar cells on simply curved surfaces. In further steps, design adjustments regarding the positioning of the belt can be considered or additional sensors can be integrated into the gripper to adjust the position of the cells during placing.

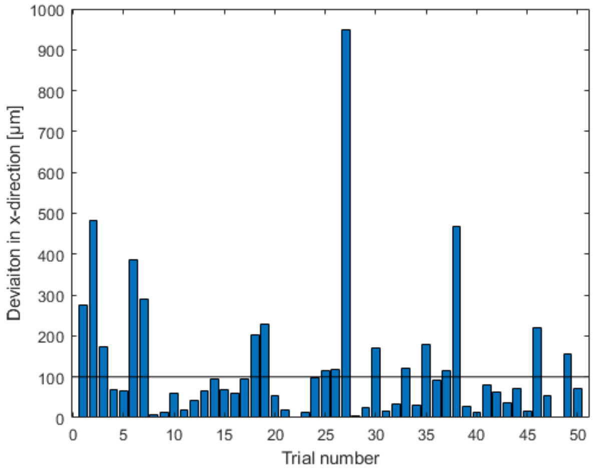

Fig. 6: representation of the deviations from each test run

5. Summary and Outlook

BIPV require a high level of acceptance among architects and building owners for widespread use. In order to achieve this, corresponding design freedoms must be available in an economical manner. In high-wage countries, this can only be achieved through appropriate automation. The approach presented here shows a basic structure of such automation. The focus is on a gripper system for handling stranded solar cells, which have different geometric properties.

The gripper shown here is capable of depositing strings on single curved surfaces. The photoluminescence measurements show that the vacuum grippers used have no negative impact on the functionality of the cells. However, the deposition results show that the required 100 µm deposition accuracy cannot be achieved with the current system. A possible improvement approach is the integration of sensors to detect deposited strings and to perform an appropriate alignment to them. In addition, further test series must determine the limits of the system in terms of the bending radius of the placement surface so that damage to the strings can be prevented.

In the future, the general production system should enable the production of geometry- and material-flexible solar modules within the scope of sensor integrations, the use of digital twins and learning processes. A data feedback system is to be established so that experience already gained in the production of solar modules can be applied to the production of future solar modules. For this purpose, appropriate sensor concepts and algorithms will be developed and implemented in the plant in future research projects.

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