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Optimization of PV-system design for household

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***Abstract*—The research deals with the design of an optimal photovoltaic system for a specific location in the Czech Republic. Commercially available different types of PV panels were installed in the selected locations for the collection of data was used Arduino platform. Optimal technical and economic recommendations were developed for the four types. The work was successful in confirming some characteristic features of these types of panels according to theoretical models. In some cases, the effect of the technical performance of the measurement and the behavior of the panel was slightly different.**

***Keywords*—photovoltaic system, photovoltaic panel, monocrystallin panel, polycrystalline silicon panel.**

I. Introduction (*Heading 1*)

Solar energy infrastructure and technologies may require additional investment for further development. Implementation of photovoltaic systems for households in the world in modern conditions is an increasingly common practice. Many countries are turning their attention to solar energy as one of the key solutions for transitioning to sustainable development and reducing carbon emissions. This development is explained by several factors. First, the prices of solar panels are coming down significantly, making them affordable for a wider range of consumers. Technological progress also contributes to the improvement of the efficiency of photovoltaic systems, which allows obtaining more energy from a smaller area and at lower costs. Secondly, the governments of many countries provide incentives and benefits for citizens who install solar panels on their homes. These can be "green" tariffs, tax benefits or financial support in the form of subsidies. Thirdly, increasing environmental awareness and ensuring sustainable development [1-4].

The situation with solar energy in Ukraine is quite promising. In recent years, the number of installed solar power plants has been growing significantly. According to the International Renewable Energy Agency, in 2020, the capacity of photovoltaic power plants in the country was about 6 GW. The Government of Ukraine actively supports the development of solar energy by introducing various benefits, incentive programs and legislative initiatives. For example, the system of "green" tariffs, which guarantees a fixed price for the sale of electricity from solar power plants for 10 years. However, there are also challenges and challenges. For example, low profitability of certain projects due to changes in the legislation on "green" tariffs [5-7].

Installing a photovoltaic system for a household involves several steps:

1. Planning: Determining the need for electricity, estimating the capacity and calculating the number of solar panels needed. It is also important to determine the location of the panels on the roof or on the ground.

2. Design: Creation of detailed design including panel diagrams, mounting structure, inverters and other equipment. Also, the design includes the calculation of the energy parameters of the system.

3. Purchase of equipment: Selection and purchase of photovoltaic panels, inverters, cables, fasteners and other necessary equipment. It is important to pay attention to the quality and certification of the equipment.

4. Installation: Placement of panels on the roof or on the ground according to the project. Connecting the panels to the inverter, as well as installing cables and switching devices.

5. Connection to the electrical network: Organization of the connection (on-grid and off-grid).

Many factors influence power generation by PV system (temperature [8], technical condition – degradation [9], type system, and installation [10, 11]). The main goal of this study is to compare four types of PV-panel for usage by householders and design systems of measurement main parameters.

II. Selected Panel Types

Small power panels were selected for measurement. Specifically, it is a polycrystalline silicon panel (top left in Fig. 1), a monocrystalline silicon panel (top right), a CIS panel (copper-indium-diselenide, bottom right) and an organic panel (bottom left). The location of the light intensity sensor is also visible on the frame of the CIS panel.

Fig. 1. View of the model installation

Fig. 2. Detail of the model installation

A. Polycrystalline silicon panel

A cell embedded in a plastic roof bag was selected as a representative of polycrystalline cells. Unfortunately, the panel is only provided with the name of the manufacturer PHOTOWATT without a type designation, and only the label parameters written in table 1 are listed on it [12].

TABLE I. LISTED LABEL PARAMETERS OF THE POLYCRYSTALLINE PANEL

P_{max}	4.5 Wp
U_{MPP}	18.2 V
I_{MPP}	0.25 A
Uoc	24.5 V

Due to the absence of voltage and current values for the point of maximum power, it is not possible to determine the nominal power of the cell from the given parameters. Even an attempt to find the parameters of the cell according to the code markings on the panel was not successful. Only when measuring the V-A characteristic was it possible to get a rough overview of the panel's performance capabilities. A polycrystalline panel is expected to have better properties in poor lighting conditions and a faster start of production in the morning, and longer production in the evening compared to a monocrystalline panel.

B. Monocrystalline silicon panel

A monocrystalline silicon panel embedded in an aluminum frame was also used in the model installation. Although silicon technology was already represented by a polycrystalline panel, my goal was to investigate the differences between silicon panels processed using other technologies. This is a panel from SOLARTEC, model STR 36-13, the parameters of which are listed below in table 3.2.

TABLE II. LISTED LABEL PARAMETERS OF THE MONOCRYSTALLINE PANEL

$U_{nom,max}$	**300 VDC**
I_{sc}	2.9 A
U_{ocv}	4.8 V

According to assumptions, monocrystalline technology should have the highest efficiency, and therefore the most delivered power per unit area.

C. CIS panel

Another panel used in my installation is a panel based on CIS technology. Compared to previous silicon panels, this panel is a representative of thin-film (amorphous) technology. The panel used is from the manufacturer Ascent SOLAR, namely model WSME-0045-024-DB-03. Its parameters are listed in table 3.

TABLE III. LISTED LABEL PARAMETERS OF THE CIS PANEL

P_{max}	13 Wp
U_{nom}	12 V
U_{MPP}	17.4 V
I_{MPP}	0.75 A
U_{oc}	21.5 V
I_{sc}	0.82 A
$U_{sys.max.}$	750 V

Based on the general properties, the panel was primarily expected to have better properties depending on the temperature of the panel, i.e. a smaller drop in performance as a result of high temperatures.ˇ

D. Organic panel

The last representative in the model installation was an organic-based panel, also falling into the category of thin-layer panels˚. It is from the manufacturer KONARKA, and it is a Power Plastic Series 20 product series. This panel is the smallest of the entire product series, model 120. Its main parameters, given by the manufacturer on its website, are listed in Table 4. The parameters given in table 4 are related by the manufacturer to a unit of 1 sun (American manufacturer). This unit represents an illumination value of 100 mW/cm^2 [13], i.e. 1000 W/m^2 in recalculation and therefore corresponds to the standard test conditions (STC).

TABLE IV. LISTED LABEL PARAMETERS OF THE ORGANIC PANEL

Pmax	1.3 W
UMPP	8.0 V
IMPP	0.159 A
Uoc	11.1 V
Isc	0.199 A

This representative of organic panels, which stand out for their extremely low price, flexibility together with low weight (thus also the possibility of use, for example, during hiking), or the possibility of translucency/transparency, was included in the installation primarily for the reason compared to other common panels. Organic panels have fundamental disadvantages, and the reason for their inclusion is therefore primarily to examine the salience of these disadvantages and to evaluate specific measured results in relation to the stated advantages.

III. CONNECTING THE SYSTEM

In normal, commercial use, the panels are connected to the load via an inverter. The load that can be created is either a network with different consumptions, or possibly a battery that is being charged. In the vast majority of cases, the inverter itself is equipped with the MPPT (Maximum Power Point Tracking) function. This means that the inverter is able to monitor the point of maximum power. The voltage and current draw change with different illumination, at which the panel reaches maximum performance (for the given illumination). The inverter, equipped with the MPPT function, is able to determine this point and operate the panels at such a point when they deliver the maximum available power.

Due to the purchase prices of such shifts, after consultation with the supervisor, a different approach was chosen for this measurement. Each of the panels was loaded with a ceramic power resistor with a value of 68 Ω and the ability to dissipate power up to 15 W. The power produced by the panels is wasted on these resistors, even if the panels are operated outside the ideal load point. was measured by sliding resistance.

Due to the possibilities of storing the measuring system, the voltage sensors were placed near the measuring resistors. For this reason (even due to the relatively small power of the panels), emphasis was also placed on ensuring that the conductors between the panel and the resistor were not too long, and thus there was no excessive distortion of the measured voltage. The location of the damping resistors was also chosen due to the fact that in practice the PV plant operator is primarily interested in the performance that the system is able to deliver to the load. The overall wiring diagram is shown in Figure 3.

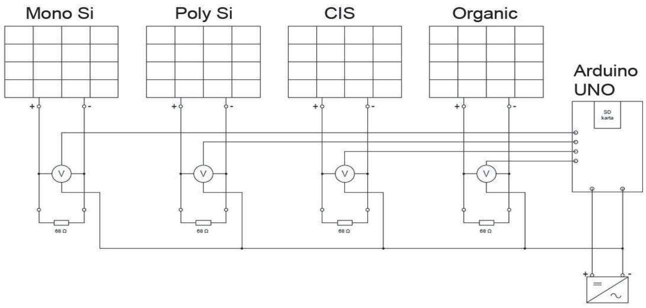

Fig. 3. Wiring diagram of a model installation

IV. MEASURING SYSTEM ON THE ARDUINO PLATFORM

Arduino was choisen as the platform for the system of measuring selected parameters. It was primarily due to the favorable price and easy availability of various necessary modules, the open-source concept of the entire platform, and also due to the universality of using Arduino development boards. The Wiring programming language used here is based on the C++ language. Also, the logic of building the entire system and connecting various peripherals has a lot in common with classic PLCs.

A. Main measuring system

In the course of preparations for the installation in the spring of 2022, several intended versions were created. The first version included wireless data transfer to Arduino servers, measurement of load voltage, load current and panel temperature using an NTC thermistor. A number of problems appeared here, primarily with the compatibility of voltage sensors (it is essentially only an analog voltage divider) and development boards with wireless transmission. The sensors worked with a voltage range of 0 to 5 V, while the intended Arduino Nano 33 IoT development board allowed a maximum voltage of 3.3 V on the analog input. When trying to solve this problem, however, the primary voltage divider was found a significant effect on the accuracy of the measured voltage (it began to differ by approximately 10% when using a divider). Another problem arose when using current sensors that worked on the basis of the Hall effect. The installed panels provided a very small current and the current sensors provided relevant data up to a current of 300 mA. For these reasons, the second version of the measurement system was created.

It was built only with an NTC thermistor for measuring the temperature of the panels and with voltage sensors (one for each panel). The load current is calculated based on the knowledge of the value of the connected resistance and the voltage across it. The Arduino Nano board was chosen as the core of the system, which does not allow (without additional peripherals) to send data wirelessly, but offers a range of up to 5 V on the analog input. Data storage was solved by adding a module for an SD card with a "Real-time clock" module. . The measured data is saved in a text file on the SD card with a time stamp. A modular AC/DC power source from the LY-ONZG company, specifically the S-50-12 model, was chosen for power supply. The one at the output provides a stabilized DC voltage of 12 V and is capable of supplying a current of a maximum of 4.1 A. This system measured data from May 2022 until the beginning of August, when during manipulation during data collection there was an unwanted contact of the board with one of the wires from the PV panel, and thus irreversible damage to the SD card module. Unfortunately, it turned out that the backup SD module did not work as it should, and it was necessary to stop the measurement for a week. During this time, due to current availability, it was decided to replace the Arduino Nano board with an Arduino Uno board with the appropriate module. During this time, the temperature sensor was also connected to the second, auxiliary system (see below). For better connection of the sensors, the development board was equipped with a terminal block. Only the voltage sensors remained connected to the Arduino Uno board, and the system worked in that form for the rest of the measurement. The specific sensors, development boards and modules of the main and auxiliary systems used are listed in Tables 5 and 6 below.

TABLE V. COMPONENTS USED IN THE ORIGINAL VERSION (05/22 - 08/22)

Device	Model	Producer
Plate	Arduino Nano R3, ATmega328P Klon	LaskaKit
Voltage sensor	Analogový senzor DC napetí, VDC 0-25Vˇ	LaskaKit
Temperature sensor	NTC termistor 10K1% 3950	LaskaKit
SD card module	DS1307 NANO V3.0 Data Logger	DIYMORE MODULE
Terminal block	Arduino Nano terminál shield	LaskaKit
Power supply	LYONZG S-50-12 12V/4,1A	LYONZG

TABLE VI. COMPONENTS USED IN THE NEW VERSION (08/22 - END OF MEASUREMENT)

Device	Model	Producer
Plate	Arduino UNO R3, ATmega328P Klon	LaskaKit
Voltage sensor	Analog senzor DC voltage, VDC 0-25V	LaskaKit
SD card module	TZT Data Logger Shield V1.0	LaskaKit
Power supply	LYONZG S-50-12 12V/4,1A	LYONZG

B. Auxiliary measuring system

As part of monitoring the parameters of the panels, it was also necessary to continuously evaluate relevant climate data with them. First of all, the temperature of the panels, which has an effect on the production, as well as the intensity of the lighting. The original measurement was to measure the incident energy with a switched-on pyranometer. However, for technical reasons, it was not possible to implement it, and that is why I decided to measure at least the intensity of illumination. Due to the missing data on the spectrum of the incident radiation, it is not possible to determine exactly the incident energy, but it is at least possible to get an overview of the course of the illumination. It is then possible to compare the measured production courses and thus obtain at least a partial overview of the behavior of the panels when the illumination changes. During the change of the main measuring system, after it was damaged, the climate data was measured using the second Arduino board, which was originally supposed to be used to measure the delivered power. This is the aforementioned Arduino Nano 33 IoT board, which enables wireless data transfer and their storage on the Arduino Server. Another and decisive reason for using the second board was the exhaustion of the necessary inputs on the Arduino UNO board. Another of the reasons was the reported problem behavior of the SD module, when some of the users described writing failures when writing a large amount of data to a file on the card more often.

This created a second, auxiliary measuring system that recorded meteorological data. Thanks to the separation of these two systems, the measurement could take place in shorter intervals and it was thus possible to obtain a better overview of the meteorological situation. For temperature measurement, the original thermistor NTC sensor was physically left and only connected. However, it was necessary to adjust the algorithm in software, because the soldering voltage changed from 5 V to 3.3 V. The GY-302 module containing the BH1750FVI sensor was chosen to measure the illumination intensity. This sensor enables digital transmission via the I2C serial bus, which simplifies installation and places less demands on the occupancy of the microcontroller's pins. After measurement, these two values are stored via WiFi on the Arduino IoT Cloud. As part of this server storage, a graphic interface for greater data transparency was created. Of course, these can also be downloaded in CSV format and could then be evaluated together with the data stored on the SD card. A common power source with the main measurement system is used to power the auxiliary measurement. The components used are listed below in Table 7.

TABLE VII. COMPONENTS USED IN FINAL VERSION

Device	Model	Producer
Plate	Arduino NANO 33 IoT	Arduino.CC
Light intensity sensor	BH1750	LaskaKit
Temperature sensor	NTC termistor 10K1% 3950	LaskaKit
Terminal block	Arduino Nano terminál shield	LaskaKit
Power supply	LYONZG S-50-12 12V/4,1A	LYONZG

Figure 4 shows the wiring diagram of the auxiliary measurement.

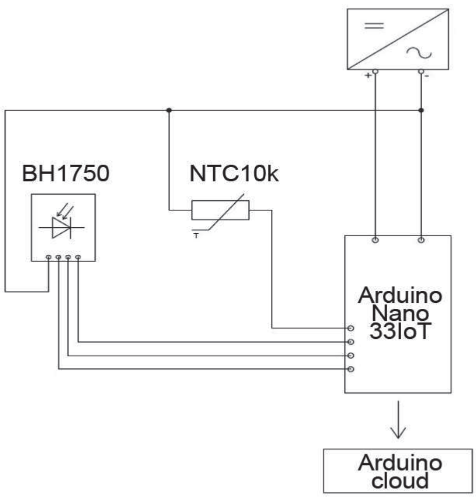

Fig. 4. Connection diagram of auxiliary measurement

Data is stored in two forms. The voltage data is stored in a text file on the SD card, and the meteorological data is stored on the Arduino IoT Cloud server, from where it is downloaded in CSV format. Figure 5 shows a preview of the web interface, which is used to preview the captured data directly on the server.

Fig. 5. Web graphic interface for displaying current data (here about the intensity of illumination).

A total of two tools were used to program the Arduino microcontroller. Both are official Arduino tools. The first of them, Arduino IDE in version 1.8.19, is recommended on the manufacturer's website as the official software for creating a program for Arduino development boards. In addition to the development environment and the program compiler, it also contains tools for uploading software to specific boards (depending on the installed processor). It also contains a database of available libraries that can be added to your project and examples of working with these libraries.ˇ

The second tool used was the development environment directly integrated in the Arduino IoT Cloud [15]. It was used this primarily due to better compatibility with the Arduino Nano 33 IoT board when uploading software and using integrated libraries (for example, transferring data via the WiFi interface). It also enables remote management and remote software uploading if this board is connected to the Internet.

When learning to work with individual libraries, sensors and modules, the open-source concept of Arduino helped a lot. The broad user base is very active, and this activity is supported by the Arduino company itself with the existence of an official forum and an official project database where users share their created projects. Therefore, when learning, it was almost always possible to study the issue both from manuals and from specific applications. It was also possible to use custom libraries for sensors and modules. In the measuring system designed by me, specific libraries are used for the SD module, time processing, wireless data transfer, I2C serial communication, reading data from the light intensity sensor and general work with Arduino.

During the creation of the system, a number of larger or smaller obstacles and problems occurred. There were malfunctions (faulty sensors and modules) and hardware deficiencies, such as an imperfect connection between the 0 V wires in the connector, which caused erroneous data to be read. Obstacles also occurred during software debugging, when, for example, a sufficient distance between reading data from individual sensors was required. Among the biggest challenges was the need to debug data storage. This turned out to be the most problematic and prone to problems (even with code changes not directly related to storage). The system also had to be sized to withstand not always favorable conditions. For example, the temperature range, when in an uninsulated building, the temperature under its roof can rise high in the summer, and on the contrary, in the winter, during frosts, it can drop well below the freezing point. It was also necessary to ensure that the entire measuring system was able to operate again without external intervention after a power failure. In the end, all these obstacles were overcome and an autonomous system was created, which only requires the transfer of data from the SD card to the computer for processing. This problem could be solved with an additional wireless module. However, this solution would be unnecessarily complex and would introduce additional possibilities for the failure of the measuring system. It was possible to create a simple, reliable and effective measuring system that enables the collection of data and their storage for further processing (Fig. 6). It also has the potential for further expansion if additional modules or sensors are needed.

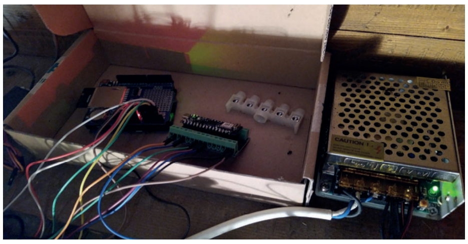

Fig. 6. A view of the microcontrollers of both measuring systems

V. System Installation

Several environmental factors had to be taken into account during the installation itself. Both natural, for example lighting (height of the sun), and technical. Among them, when placing the panels, the limiting factor was primarily the location of the measuring system, so that it was accessible for data collection and at the same time the connecting wires (sensor-microcontroller) were not too long. It was also necessary to place the power supply of the measuring system in a suitable place. From a technical point of view, it was also necessary to solve the placement of the resistive load in a place where it will cool sufficiently well. Due to the wooden structure of the garage, it was also necessary to take into account fire safety when placing the measuring system (mainly its power supply) and heating resistors. For the proof of the measurement, it was also necessary to take into account obstacles that can cast a shadow. First of all, it was the roof of the family house, the chimney, or possibly the neighboring family house on the eastern side. Finally, the optimal height was chosen, at which it is possible to conveniently place the measuring system, suppressors, and power supply on the inside of the roof, and at the same time the panels are not affected by shadows for most of the year. In the course of the measurements, it was found that the panels in the bottom row began to be covered by the shadow of the roof in the late afternoon in November, as can be seen in Fig. 7. The passing shadow of the chimney also began to appear, which can be seen in Fig. 8. Both of these pictures were taken on 11/12/2022.

Fig. 7. Shading of the front two panels by the roof of a family house

Fig. 8. Shading of the panels by the passing shadow of the chimney

The most important factors include the age of the panel, its location, and method of attachment to the roof, and the suitability of its load or slope. Abnormalities in meteorological conditions for a given month or year can also play a significant role. The technological and constructional recommendations in the evaluation of this work are therefore based not only on measured data and established facts, but also on generally valid assumptions and theoretical knowledge, the validity of which could be impaired by abnormal weather fluctuations or by the method of technical solution some aspects of measurement [14].

In the monocrystalline panel, the changes are not as pronounced as in the case of two amorphous cells. In Figure 9, where there is a detail of the progress on a monocrystalline cell, it can be seen that the biggest drop was recorded just before 12 o'clock, the other drops in illumination were not so marked.

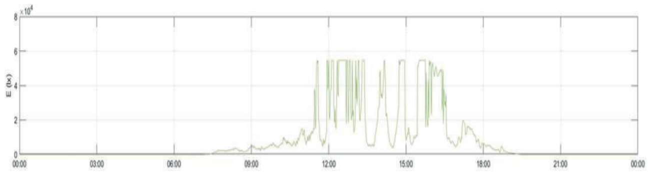

Fig. 9. Temperature of voltage and illumination intensity on a monocrystalline panel, April 6, 2023

This could be due to the character of passing cloud cover, when during the afternoon, the value of scattered radiation could be higher than before noon. Due to the relatively good sensitivity of the monocrystalline panel to diffuse radiation, this would correspond to milder decreases. Another reason could be the moment of voltage measurement, which could coincide with some fluctuation in its value. Also in Figure 10 there is a clear voltage drop in the morning hours, approximately around 8:00. When this fluctuation was initially detected, it was not entirely clear what was causing it. However, during further observation, it was found that the chimney of the house, which is adjacent to the installation site on the east side, casts a shadow on this panel when the sun is low in the morning. If shading is combined with a lower level of illumination in the morning hours, such a dip is possible.

VI. Dependence on Intensity

The curves in Figure 10 illustrate another example of how strongly production depends on the intensity of illumination. As it is clear from them, all the voltages copy the fluctuations of the lighting intensity, either upwards or downwards.

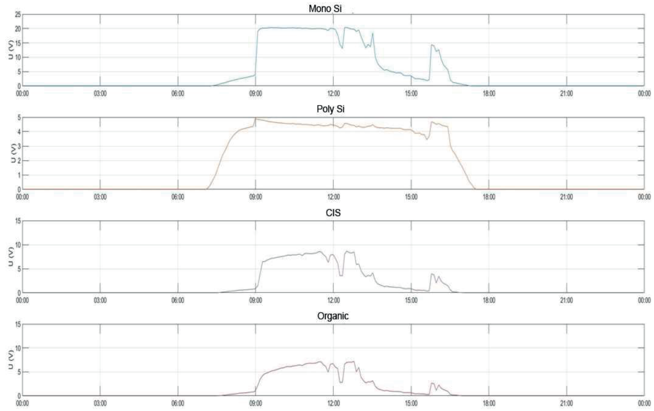

Fig. 10. : Time course of voltage and lighting intensity, 10/02/2023

It is worth noting here the morning performance of individual panels. If we look at the course of the lighting intensity, we can say that it increases linearly from approximately 7:30 to 9:00. The voltage curves on all panels, except the polycrystalline one, correspond to this. It is the only one that grows exponentially at this time, and it can be said that at 9:00 a.m., when the light begins to increase significantly, the polycrystalline panel is almost at full capacity. As part of the increase in performance, a difference can also be observed between the CIS and the organic panel, which otherwise behave very similarly throughout the measurement period. However, there is a small difference here, namely in the speed of the power ramp-up. In the case of the CIS panel, after 9 o'clock the increase is only slightly faster than in the case of the organic cell. A relatively steep increase can be observed for a monocrystalline panel with increasing irradiation.

VII. Acknowledgment

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VIII. Conclusion

The aim of the recommendations is to present solutions that can help optimize the system according to certain priorities set by the operator. Each of them, therefore, emphasizes a different requirement, and it is impossible to say in general terms which of them is the best for a given location. It will always depend on the requirements that will be placed on the PV plant and what results will be expected. It was divided the solutions based on the most common required properties, mostly yield maximization, purchase price, service life, and, possibly, greater production in certain cycle - times. Overall, the best solution from the mentioned possibilities seems to be using monocrystalline panels. This solution is also, together with the use of polycrystalline panels, the most common variant in commercial practice. Although it requires a slightly higher initial investment, it offers the best use of space, which is often considerably limited when installed on roofs. The service life of crystalline panels also exceeds the service life of amorphous panels many times. Using CIS or organic panels would represent a time- and financially demanding replacement of all installed PV panels in a short time horizon. For these reasons as well, amorphous panels are not very widespread commercially despite some of their indisputable advantages. The current development of PV cells, even amorphous ones, is still increasing their lifetime and efficiency. Therefore, in the future, it is possible that even amorphous panels will appear more often in the commercial sphere than is the case now.

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