Engineering Symposium at Bánki
(ESB 2022)
http://bgk.uni-obuda.hu/esb/

Investigating the possibility of a solar hydrogen producing energy island concept in cooperation with a small settlement

[1] Bozsik Nándor, [2]Molnár Ildikó PhD

[1]Óbuda University Doctoral School for Safety and Security Sciences, Budapest, Hungary, bozsik.nandor@bgk.uni-obuda.hu
[2]Óbuda University Bánki Donát Faculty, Budapest, Hungary, molnar.ildiko@bgk.uni-obuda.hu

Abstract

The energy demand of the world is constantly growing while fossil resources are running out, and the costs of exploiting new resources are higher and higher. This fact and the increasingly urgent climate protection aims necessitate using renewable energy sources (RES). However, most of these energies depend on the weather, which means that the period of production and consumption are only sometimes in line. [1; 2] As a result, these systems require an external network, an energy storage solution, or a combination of both. Nevertheless, from an economic perspective, the produced renewable energies are worth using on location. After being stored, they can be used later in the form of different transformed energy, especially if the location is far from the network.

Keywords: renewable energy, CO2 emission, green energy, solar energy

1. Introduction

In China, Liu and his co-workers examined in detail the production of hydrogen from surplus renewable energy sources. The results showed that combining hydrogen and solar/wind power systems could reduce CO2 emissions and increase the amount of energy produced. Hydrogen will play a significant part of industry, energetics, and transportation in the following decades.

The production and use of hydrogen with water electrolysis are among the most promising solutions to achieve carbon neutrality by 2050. The use of solar energy in electrolysis processes proved to be the most cost-efficient and environmentally friendly. [3] Such energy-producing units create „islands” in larger energy networks. In some cases, they are created independently, forming energy-producing islands.

At first, when most people think of the term „energy island”, they think of wind farms protruding from the European North Sea. Today, this name has broadened in terms of content. It is often used for physically well-defined energy generating, transforming, and storing objects. These are no longer necessarily connected to the seas and coasts. These „islands” can also be inland. What they have in common is energy production based on renewables. (This is why it is bold to call the nuclear power plant installed by the Russians on a barge an energy island.) Their common characteristic – especially for land-based ones – is that they are communally owned, and their primary goal is not to generate profit. The central aspect is green energy production and increasing the energy security of the owner settlement. Below, a hydrogen-producing and utilizing energy island based on the solar electricity production of a small town is presented.

2. Material and method

The study mainly focuses on foreign literature. The referenced literature contains case studies describing systems larger than household size but smaller than power plant sizes. During their processing, a part of the cases is selected, which also appears in the concept discussed in the article. These include, for example, solar farms, sun-tracking processes, energy cells, hydrogen-based transport, Etc., and their applications. A significant part of the literature is related to simulations made with Matlab, PVsyst, System Advisor Model (SAM), and PVGIS programs.

The study was based on a settlement of 2,000 people in central Hungary. Its characteristics, such as households, public buildings, public institutions, public lighting, etc., consider its electricity consumption and the free solar energy capacity that can be produced in the settlement's buildings. The meteorological data consists of the data series of Vecsés and Lőrinci settlements, which serve as input data in the simulations.

The main elements of the system and the connection between them and the energy flow path can be clearly separated. The first is the solar system of households and public buildings, the second is the „energy island" of the settlement's solar field and the hydrogen development plan, and the third is the electrical network connecting them, which is also connected to the national electrical network.

The determination of the number of included buildings was based on an estimate to ensure that the result was underestimated rather than overestimated, ensuring the number of buildings and the amount of solar electricity that can be included in the project provides a solid basis for planning. Based on the KSH database, small and medium-sized settlements have 234 people per hundred residential buildings, so the village of 2,000 people has approx. It has 850 residential properties. [4]

A quarter of the buildings were considered unsuitable for installing a solar system on their roofs due to their location (in a valley, shaded, Etc.) or their condition. For approximately 510 properties, the solar system installed on the building can be included in the project. This is where the estimate, which can contain the most significant error, took place, where I estimated the number of properties at one-third, i.e., 170, where the owners had the entrepreneurial spirit and did not yet have a solar system or, if they had a system, they undertook to expand or convert it. The latter estimate may have a large error because recently (at the time of writing this article, the Russian-Ukrainian war that started on February 24, 2022, which is causing an energy crisis throughout Europe) has increased interest in renewable energies. So, this ratio can be much higher.

2.1 Solar system

Many factors influence the performance of solar systems. First, there are the given factors, such for example, the physical (electrical) characteristics of the solar panels, the orientation and inclination angle, the parameters of the electrical conversion equipment, and there are the changing factors such as the days and seasons, the weather (irradiance, temperature), Etc. All of these must be taken into account during calculations and simulations.

The cell that forms the basis of solar systems can also be understood as a current generator, which generates current depending on the light intensity of the appropriate wavelength (energy) and the cell's temperature. This current is brought to the desired voltage level and current form with the arrangement of the cells and current conversion equipment (inverters). [5]

The PVsyst simulation used for the calculations uses the single-diode Perez-Ineichen model instead of the Hay model. The latter is used when the diffuse irradiation data are not known precisely. [6] In our case, these are available from Meteonorm in the case of PVsyst, from NREL (National Renewable Energy Laboratory), NSRDB (National Solar Radiation Database) in the case of the

System Advisor Model simulation, and from the PVGIS-SARAH2 database in the case of PVGIS. [7; 8; 9]

Single diode model

Shockley's "single diode" model describes the operation of the solar module. The model describes the operation of a cell. In generalizing the entire module – solar panel – we assume that the cells are identical in all respects. For really accurate modeling, two diodes are used. [10; 11]

The monocrystalline solar cell included in the study consists of silicon layers that are joined to each other. During the production of monocrystalline solar cells, a crystal block is first prepared (grown), which is sliced, and surface treated several times. Cells are cut from the cylindrical block to be placed more favorably on the solar panel module. The most economical solution is an octagon design. (Even the layman can recognize it based on the octagonal patterns of the solar panels.) Its efficiency is 15-20%, which is currently the most effective, but you have to pay attention to the orientation and the inclination angel because it utilizes diffused sunlight less than direct sunlight. [12]

The basic equation under reference conditions

For the one diode models, we use the basic equation (Equation (1)). Besides the reference conditions (STC) the parameters given by the producers are at 1000 W/m^2 radiation 25 °C panel and environmental temperature.

$$I = I_{PHref} - I_{0ref}\left(e^{\frac{q\cdot(U+I\cdot R_S)}{N_{CS}\cdot Gamma\cdot k\cdot T_C}} - 1\right) - \frac{U + I\cdot R_S}{R_{SH}} \tag{1}$$

I: module current, A,

U: voltage (can be measured at the module terminals), V,

I_{PHref}: diode reference current, A,

I_{0ref}: diode short circuit current, A,

R_S: series resistance, ohm,

R_{SH}: parallel resistance, ohm,

Gamma: diode quality factor, 1-2 value,

q: electron charge = 1.602·E-19 Coulomb,

k: Boltzmann constant = 1.381 E-23 J/°K,

N_{CS}: number of cells,

T_C: temperature of cells, °K.

After calculating the five parameters, we can draw the I-U curve, and we can define the I=f(U) or the U=f(I) expressions. As the equation is implicit, we need to apply approaches following one another. [11]

The most important factor influencing the electricity production of solar panels is the heeling angle of the light striking them. Maximum production can be achieved when the light strikes the solar panel perpendicularly. If it doesn't, the performance is proportional to the coziness of the angle of incidence. During the sun's path through the sky, there is a daily and yearly cycle; therefore, solar panels need a tracking system to achieve maximum performance. We usually try to set solar panels with optimal orientation and angle of incidence if the location allows it. In the case of the orientation, the South direction is the logical choice, while the heeling angle depends on the latitude of the system. In Hungary, to optimize fix systems, the South orientation and the heeling angle of 30-40 degrees are the standard parameters.

A P50-P90 energy yield calculation

The P50-P90 evaluation is a method based on random variables for which the simulation uses the data of more years. This method assumes that the distribution of yearly production follows the Gauss distribution during more years of usage. The P50 and P90 represent the production level which means the likelihood is that a yearly production exceeds its value by 50 or 90%. You need to define two parameters of the Gauss distribution for this, which are the average value and variance (expected value and standard variation). Meteorological data usually make these parameters more variable.

3. Results

Three different simulation programs and meteorological data series were used to calculate the performance. Meteorological data take into consideration similar geographic positions during a typical meteorological (TMY) Year. Simulations are explicitly based on the electric parameters of the solar panels, which are nearly the same technical parameters. The simulation programs were PVsyst 7.2, the SAM, and the VGIS. The source of the meteorological data for the simulations were Meteonorm 8.0, NREL-NSRDB, and PVGIS-SARAH2.

3.1 Calculation of solar energy

The aim of the first simulation was to examine the orientation and the heeling angle. The System was set up in a field of 250 kWp performance (kWp: the peak performance of a solar panel in ideal conditions). In the case of PVsyst and SAM, the types of the solar panels were 400 kWp LG 400 N2W-A5 monocrystal Si while the Type of the inverters was 20 kW AEG. In the case of the PVGIS, the field's peak performance and the solar panel's crystal type were set. The heeling angle was set between the recommended 35 and 40 degrees on this latitude, except for the tracker System simulating the field of the solar panel of the settlement. The rotation axis is set in the North-South direction with a horizontal heeling angle.

Figure 1 shows the graph of the performance per hour of a solar panel system that lacks shading on an average day at the beginning of June.

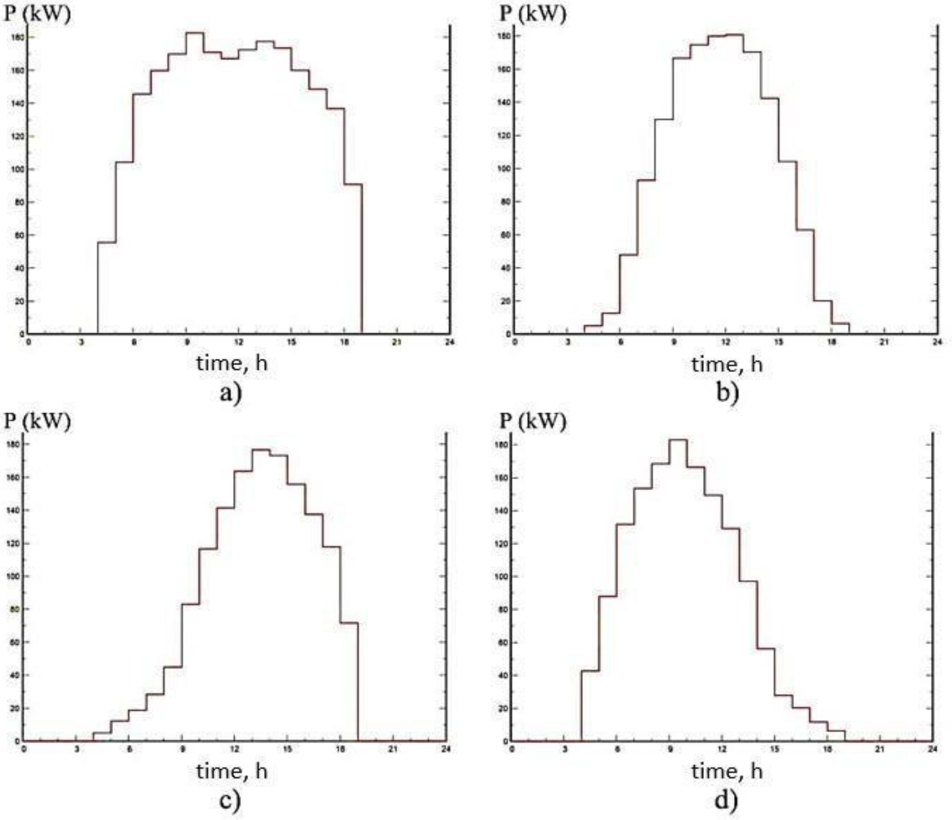

Figure 1.: Hourly performances depending on orientation during the day Source: Matlab 2022a, PVsyst-tools simulation

Figure 1 of the solar tracking system with a north-south orientation and horizontal axis of rotation shows that the daily production (between 8 am and 4 pm) is relatively even thanks to the setting of the panels. Graphs b), c), and d) of figure 1 show the production of solar panels set towards the south, west, and east with a 37-degree heeling angle. You can see the changes in peak production depending on the orientation.

Figure 2 shows the annual solar radiation per hour, indicating the total amount of solar radiation and the direct and indirect solar radiation in W/m^2.

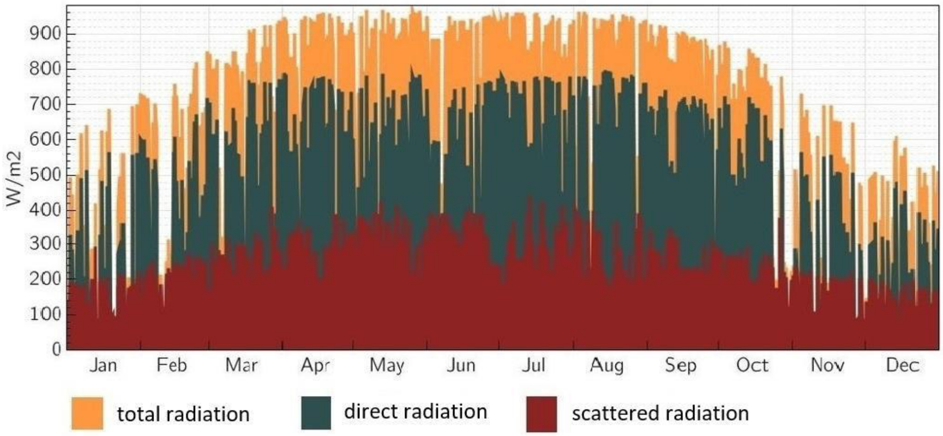

Figure 2.: All solar radiation and its components Source: SAM simulation

Figure 3 shows the performance in kW (also annual solar radiation per hour) of the 250 kWp solar panel shown in figure 2.

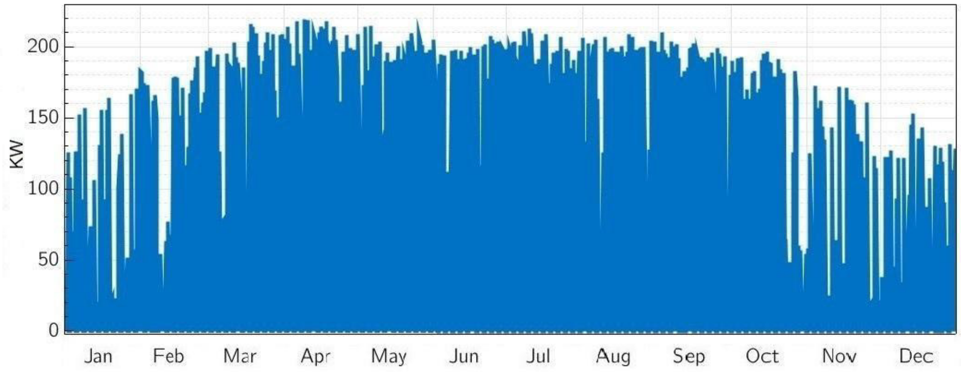

Figure 3.: Annual production in hourly resolution Source: SAM simulation

Figure 4 shows the annual graph of the same field however you can see the daily production in kWh in this figure.

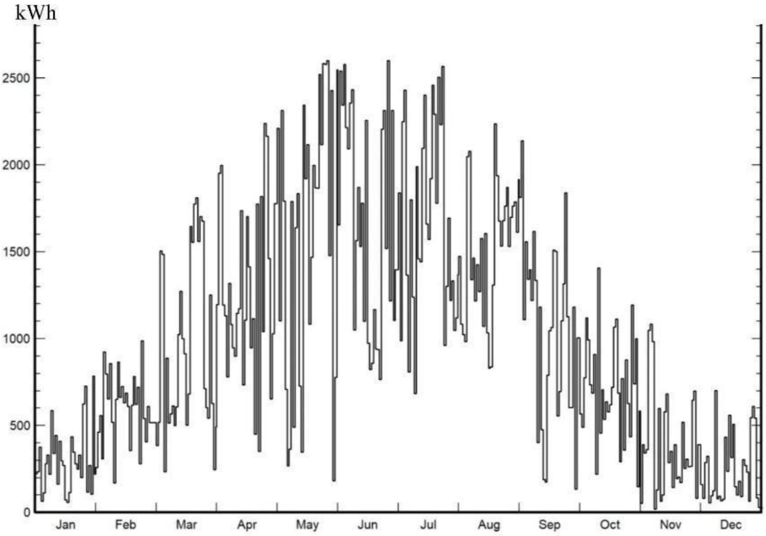

Figure 4. Annual production in daily resolution Source: PVsyst 7.2. simulation

Figure 4 shows the changes occurring during the year. You can see very well the changes in the daylight lengths during the year and the lower production as a consequence. In addition, the performance is lower during the winter period because the sun has a lower celestial orbit, and the number of cloudy days is higher.

Table 1 shows the values given by the simulation. There are different values due to the slightly dissimilar meteorological data and the electrical parameters, which are not entirely the same. It is important to say that the simulations SAM and PVGIS are there to confirm the results given by the PVsyst.

Table 1. Simulation production results depending on orientation and program types on the 250 kWp peak power solar field
**clear weather at beginning of June, (Vecsés, TMY: June.05.)*
*** clear weather at beginning of June, (Lőrinci, TMY: June. 05.)*

	directedness	PVsyst		SAM		PVGIS
		daily*	yearly	daily**	yearly	yearly
a)	North-South	2,216 MWh	366 MWh	2,107 MWh	384 MWh	353 MWh
b)	South	1,497 MWh	311 MWh	1,579 MWh	355 MWh	310 MWh
c)	West	1,448 MWh	251 MWh	1,408 MWh	277 MWh	242 MWh
d)	East	1,443 MWh	249 MWh	1,406 MWh	256 MWh	239 MWh

The simulation of the performance of the solar tracking system indicated a discrepancy of +5% in the case of SAM, and a -3,5% in the case of PVGIS compared to the values given by the PVsyst.

During the simulation, we examined the western and eastern orientations in order to establish the annual production in kWp of the solar panels to be placed on the roofs of the houses of the settlement in these directions. It does not mean that the roofs of the settlement must face west, east, or south, but that we should be able to establish the average annual production in 1 kWp based on the estimated proportional factor.

The annual production for 1 kWp if the orientation is south is 1244 kWh (311 MWh/250 kWp) if the orientation is east, it is 1000 kWh (~250 MWh/250 kWp). The estimation is based on the fact that owners of solar panels can make use of the roofs facing west, east, and south in the proportion of 1:1:2 (Equation (2))

$$P_{average} = \frac{1 \cdot 251\,MWh + 1 \cdot 249\,MWh + 2 \cdot 311\,MWh}{4} / 250\,kW_p = 1122\,kWh/kW_p \qquad (2)$$

The annual performance of each solar panel of 1 kWh installed on the rooftop of buildings is 1122 kWh. I took into consideration 2 extra solar panels of 400 Wp of peak performance per building for my calculations. If we look at an average solar system consisting of 8 solar panels, there is a 25 % increase in production with the two extra panels. Altogether a household can contribute to the energy network of a settlement by producing 20% of the electricity of its system. Thus, the above mentioned estimated 170 estates could produce 153 MWh of electricity per year (Equation (3)).

$$P = 170 \cdot 2 \cdot 0{,}4\,kWp \,\cdot 1122\,kWh/kWp \approx 153\,MWh. \qquad (3)$$

In addition, there are five public buildings that can produce 13 MWh per year with six additional solar panels per building (Equation (4)).

$$P = 5 \cdot 6 \cdot 0{,}4\,kWp \,\cdot 1122\,kWh/kWp \approx 13\,MWh. \qquad (4)$$

The settlement can contribute to the production of the energy island generating hydrogen with 166 MWh of electricity.

In the case of the solar panel field of the settlement, to predict the annual production more precisely, we calculated the P95 value with the help of the P50-P90 function. This means that the calculated estimate value is equal to a 95% probability or exceeds the value belonging to the 995 points.

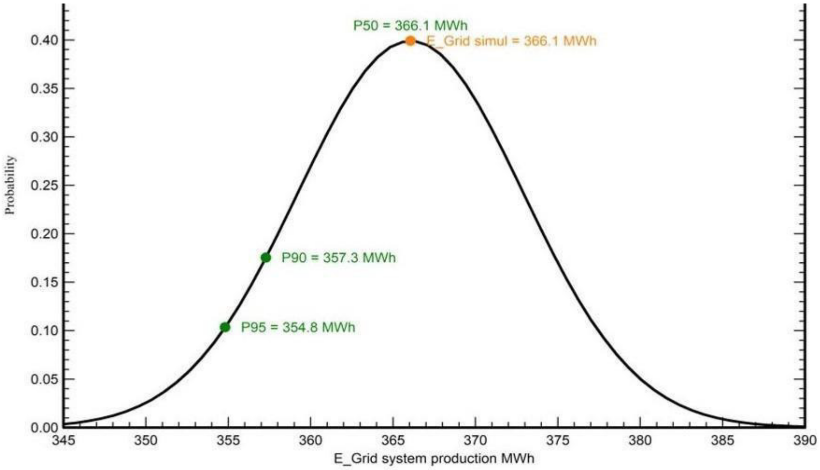

Figure 5. Day tracking values of P50-P90(P95) Source: PVsyst program simulation

Figure 5 shows a 95% probability that the system can produce 354.8 MWh or it can even exceed it. The value per 1 kWp belonging to the annual performance is 1419.2 kWh/kWp/year. For further calculations of the solar panel system of the settlement, an annual electricity production of 355 MWh will be taken into consideration.

3.2 Hydrogen production calculation

Hydrogen annually, 521,000 kWh of electricity is available for hydrogen production. The hydrogen generator converts this electricity into hydrogen gas through electrolysis and stores it compressed in special tanks until use production calculation.

The hydrogen generator can produce nearly 9.5 tons of hydrogen annually from the electricity produced by solar panel systems.

This is produced by the generator 16 hours a day (2 shifts), 52 weeks a year for a total of 5,824 hours of operation, of course, by occasionally using the national grid or the local battery pack as temporary storage.

4. Conclusion

The calculations show that even a small settlement can produce considerable electricity by relying on renewable energy resources without using significant territory (farmland). A field of solar panel system of a settlement can be more efficient by using a solar tracking device. The population can contribute to the production of renewable energy by providing rooftops previously unused. Thus, we can save some valuable territories.

For comparison, the 520 MWh of electricity produced by solar panel systems corresponds to the electricity production per hour of one block of the Paks nuclear plant. Therefore, it is worth using other Systems producing renewable energy, such as wind turbines, which can produce electricity even at night and do not need too much territory. [8]

It is possible to create wind farms consisting of smaller wind turbines (100 kW) similar to the solar panel park of this article. Micro turbines can also be used in the settlement, especially in the premises of institutions and parks, without having any disturbing effects (on the landscape, noise). There is no evidence that the neighboring estates would lose their value due to these wind parks. [9]

5. References

[1] Meyer, N., Magda, R., & Bozsik, N. (2021). The role of renewable energies in the new EU member states. Journal of Eastern European and Central Asian Research (JEECAR), 8(1), 18-25.

[2] Magda, R., Bozsik, N., & Meyer, N. (2019). An evaluation of gross inland energy consumption of six Central European countries. Journal of Eastern European and Central Asian Research (JEECAR), 6(2), 270-281.

[3] Aqachmar, Z., Sassi, H. B., Lahrech, K., & Barhdadi, A. (2021). Solar technologies for electricity production: An updated review. International Journal of Hydrogen Energy, 46(60), 30790-30817. https://doi.org/10.1016/j.ijhydene.2021.06.190.

[4] Központi Statisztikai Hivatal. Lakásállomány. laksűrűség 1990-2022. https://www.ksh.hu/stadat_files/lak/hu/lak0002.html, (letöltve: 2022.10.05.)

[5] Markvart, T., & Castañer, L. (2018). Principles of solar cell operation. In McEvoy's Handbook of Photovoltaics (pp.3-28). Academic Press. https://doi.org/10.1016/B978-0-12-809921-6.00001-X.

[6] Perez, R., Ineichen, P., Seals, R., Michalsky, J., & Stewart, R. (1990). Modeling daylight availability and irradiance components from direct and global irradiance. Solar energy, 44(5), 271-289.

[7] National Renewable Energy Laboratory. https://www.nrel.gov/, (letöltve: 2022.10.05.)

[8] System Advisor Model. https://sam.nrel.gov/weather-data, (letöltve: 2022.10.05.)

[9] National Solar Radiation Database. https://nsrdb.nrel.gov/data-viewer, (letöltve: 2022.10.05.)

[10] John A. Duffie et W.-A. Beckman, Solar Engineering of Thermal process, John Wiley and Sons, N-Y. 2nd ed., 1991

[11] Markvart, T., & Castañer, L. (2018). Principles of solar cell operation. In McEvoy's Handbook of Photovoltaics (pp. 3-28). Academic Press. https://doi.org/10.1016/B978-0-12-809921-6.00001-X.

[12] Sugianto, S. (2020). Comparative analysis of solar cell efficiency between monocrystalline and polycrystalline. INTEK: Jurnal Penelitian, 7(2), 92-100.