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DEVELOPMENT OF PHOTOVOLTAIC CELL EFFICIENCY AND RECYCLING

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ABSTRACT

Photovoltaics are currently experiencing a huge boom in Europe. European policy is focusing on the deployment of renewables in the energy sector and the electrification of the European vehicle fleet. This article focuses on comparing the efficiency of different types of materials and technologies in the construction of PV panels and briefly summarises current technologies for recycling PV panels after the end of their productive life. One of the panels compared was part of a field measurement and its values are partly reported by the manufacturer, partly measured and partly calculated. The other values for the sample of materials used are obtained from scientific literature or annual reports of the manufacturers. The article shows that the original average values of 10% to 20% efficiency of PV panels are still shifting, and some materials and technologies now allow efficiencies of up to 38%. High hopes are especially placed on perovskite materials, GaAs cells, or combinations of these with other materials.

Unfortunately, we have not made much progress in the recycling of photovoltaic panels and, with minor modifications, the methods already used for the first generation of photovoltaic panels are still used. These are mainly the mechanical method, the chemical method and combinations of these.

Keywords: Photovoltaic Panel; Solar Radiation; Recycling Efficiency.

1 INTRODUCTION

The discovery of the photovoltaic effect has a long history. The beginning dates back to 1839 when Edmond Becquerel, Antoine-Cesar Becquerel and Henry Becquerel discovered that two platinum electrodes in a solution flow with an electric current when exposed to sunlight. It was not until 1905 that Albert Einstein was able to describe this phenomenon in more detail in his paper „*Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt*"[1]. A century later, research shows that the efficiency of the Victron Energy 115 Wp/12 V multicrystalline panel is around 20.70% in the measured band [2]. Although this value may appear high, it seems we have not made much progress because energy conversion efficiency of a steam engine is around 15%, or 19% under ideal conditions.

Advances in photovoltaic materials are leading to improvements in their efficiency. This paper focuses on a comparison of 12 PV materials that impart PV efficiencies of up to 37.80%. The paper can serve as a guide to this technology and will facilitate the selection of a suitable panel. Similar issues have also been addressed by the team led by Albert Polman[3] or by Jamil Furqan's team [4].

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2 METHODOLOGY

This multicrystalline Victron Energy 115 Wp/12 V panel was selected for the purpose of my dissertation entitled "Life Cycle Analysis (LCA) of the Photovoltaic Panel Depending on the Energy Performance of the Components Production" and the article "Practical field study of polycrystalline solar cells' efficiency in the conditions of the Czech Republic" published in 2023 in the AIP Conference Proceeding. The measured data was also used for this paper [2]. Other values for the 11 samples of materials used are obtained from the literature or from manufacturers' annual reports.

Based on the values measured (Table 1) on the used photovoltaic panel Multicrystalline solar panel Victron Energy [2], values provided by the PV panel manufacturer (Table 2) and the values obtained by calculating the mathematical relationships below (Table 3), we will compare the data with 11 the most recent results obtained from the scientific literature (Table 4) and will be graphically represented in Figure 1.

Table 1. *Performance characteristics - Measured*

Measured value	Polycrystalline solar panel Victron Energy
Average PV Panel Voltage V_{ave} [V]	16.30
Average PV Panel Current I_{ave} [A]	2.38
Average PV Panel Power P_{ave} [W]	93.40

Table 2. *Performance characteristics - Rated value*

Rated value	Polycrystalline solar panel Victron Energy
PV Cells Area A_c [m^2]	0.579
Maximum Power P_{max}[W]	115
Maximum Voltage V_{max} [V]	18.94
Short Circuit Current I_{SC} [A]	6.56
Maximum Current I_{max} [A]	6.08
Open Circuit Voltage V_{OC} [V]	22.73

To determine the efficiency of the measured panel, the above values were substituted into the mathematical relationships below with a result of ŋ 20.70 %.

$$\text{Power Output Efficiency } \eta = \frac{Pmax}{G \times A_C} \tag{1}$$

$$\text{Fill Factor } FF = \frac{Vmax \times Imax}{V_{OC} \times I_{SC}} \tag{2}$$

$$\text{Average PV Panel Efficiency } \eta_e = FF \text{ x } \frac{Vave \text{ x } Iave}{A_C \times G} \tag{3}$$

Table 3. *Performance characteristics - Calculated value*

Calculated value	Polycrystalline solar panel Victron Energy
Fill Factor FF	0.77
Average Solar Irradiance G [W/m^2]	966
Average Output Efficiency ŋ [%]	20.70
Average PV Panel Efficiency ŋ$_e$ [%]	0.932

Power Output Efficiency ŋ is the fraction of Maximum Power P_{max} generated in the measured time depending on the product of Average Solar Irradiance G and PV Cells Area A_c. Calculation of the efficiency of the measured module $ŋ_e$, i.e. the product of Average PV Panel Voltage V_{ave} and Average PV Panel Current I_{ave} depending on the product of PV Cells Area A_c and Average Solar Irradiance G multiplied by Fill Factor FF. Fill Factor FF is the ratio of Maximum Power P_{max} depending on the product of Short Circuit Current I_{SC} and Open Circuit Voltage V_{OC}. [5]

3 RESULTS AND DISCUSSION

The compared values are measured within the AM 1.5 global spectrum, which corresponds to an Average Solar Irradiance G value of 1000 W/m^2 and a temperature of 25°C according to "*ASTM G-173-03*" global.

Table 4. *Photovoltaic cell values*

Photovoltaic Panel Specification	Efficiency ŋ [%]	PV Cells Area A_c [cm^2]	Open Circuit Voltage V_{OC} [V]	Short Circuit Current J_{SC} [mA/cm^2]	Fill Factor FF [%]	Literature source
Organic solar cells	19.20	0.03	0.91	26.61	79.00	[6]
Multicrystalline solar panel Victron Energy	20.70	0.58	22.73	6.56	77.01	[2]
CdTe (Kadmium tellurid)	21.00	1.06	0.88	30.25	79.40	[7]
CIGS (Copper indium gallium diselenide)	23.35	1.04	0.73	39.58	80.40	[8]
Multicrystalline silicon	23.80	0.02	0.71	40.88	82.20	[9]
InP (Indium fosfid)	24.20	1.01	0.94	31.15	82.60	[10]
Perovskite solar cells	24.35	1.01	1.16	25.60	82.10	[11]
Si (crystalline cell)	26.50	0.03	0.75	41.45	86.10	[12]
GaAs (Gallium arsenid)	29.10	1.00	1.13	29.78	86.70	[13]
Perovskite – Perovskite	29.10	0.05	2.15	16.51	81.70	[14]
Perovskite – Silicon	33.90	1.00	1.97	20.76	83.00	[15]
GaInP/GaAs/GaInAs	37.80	1.00	3.01	14.60	85.80	[16]

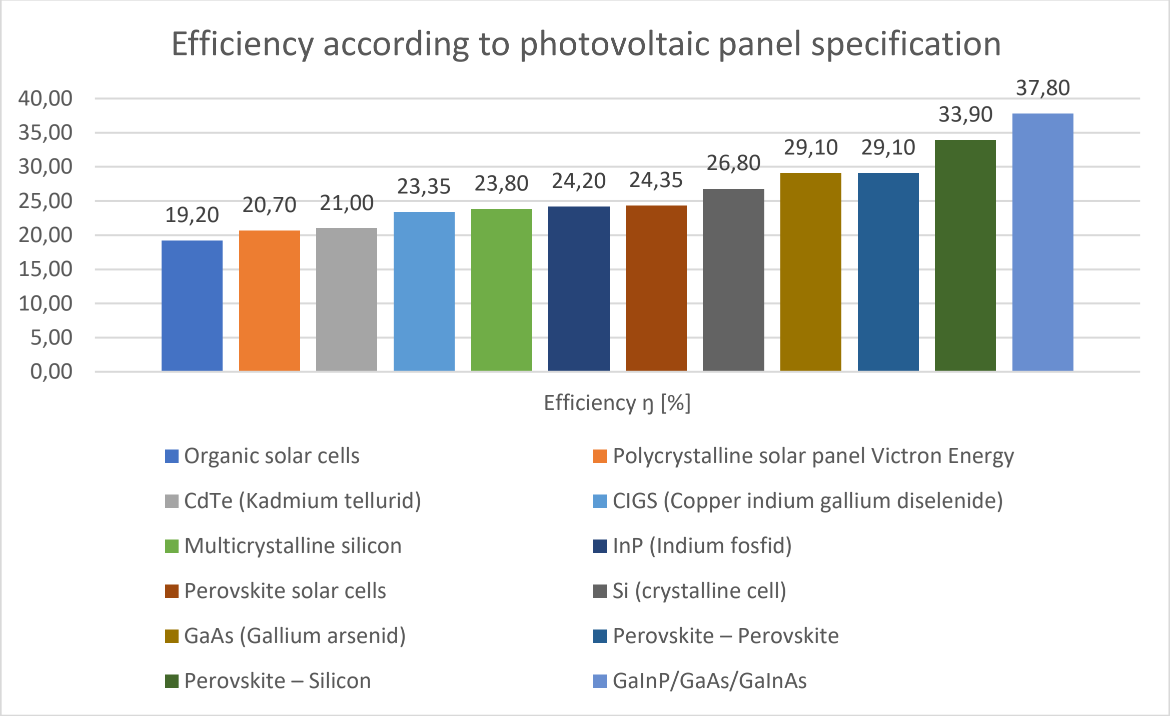

Figure 1. *Efficiency according to photovoltaic panel specification.*

In Figure 1 we can see that the measured Victron Energy Multicrysstal solar panel is the second worst in efficiency compared to the selected comparison panels with a value of 20.70%. This is followed by the panel with CdTe cells with 21.00%. The organic solar cells performed the worst with a value of 19.20%. On the other hand, the GaInP/GaAs/GaInAs panel performed the best with a value of 37.80%. In second place was the panel with cells based on Perovskite - Silicon 33,90%. There is a relatively large difference of 3.9% between the first and second position. On the other hand, the differences between the worst ranked are smaller and from the worst ranked to the middle position #5 i.e. the panel with CIGS cells, the difference is only 4.15%. The middle of the chart is occupied by Multicrystalline Silicone based cells 23.80 %, InP 24.20 %, Perovskite 24.35 % and Silicone 26.80%. The panels based on GaAs and Perovskite - Perovskite are balanced with the same value of 29.10 %. The difference between the cells, however, is not only in the materials used, but in the different manufacturing technology. We will describe the different types of photovoltaic cells in more detail.

Organic solar cells - although the efficiency value of 19.20% is the lowest in our comparison, it is very high for organic cells. Typically, their efficiency value is around 11.50%. [11] In organic photovoltaic cells, controlling the morphology of the donor and acceptor domains in the nanoscale appears to be critical for achieving efficient exciton diffusion, carrier transport and minimizing recombination losses. The team led by Zhu Lei showcased a dual-fibril network, which relies on a ternary donor-acceptor morphology with multiple length scales. This network is constructed by combining ancillary conjugated polymer crystallizers and a non-fullerene acceptor filament assembly. Through this innovative approach, they attained a certified power conversion efficiency of 19,20%. Success lies in aligning the photoelectric parameters with the characteristic lengths of the morphology, allowing efficient utilization of excitons and free charges [11].

Organic cells often show degradation when exposed to sunlight. However, they have several advantageous properties: lightweight construction, ease of processing, non-toxicity, is flexible and can form modules of different shapes and levels of transparency. Organic solar cells are relatively easy to recycle except for the Ag and MoO_3 content in the electrodes [3].

SI (crystalinne cell) – The silicon cells are based on P-N transitions. Silicon has an ideal band gap of $Eg = 1.12$ eV. The efficiency of silicon cells is highly dependent on the correct method of contact wiring, most often by metal deposition or local doping, and on the surface passivation of Si using Al_2O_3 or Si_3N_4. An efficiency value of 26.50% was achieved for IBC Si cells using so-called heterojunctions instead of homojunctions. In this case, a thin layer of doped and hydrogenated amorphous Si is deposited on the crystalline Si surface to form a junction replaced by high-temperature dopant diffusion [3].

The structure of Multicrystalline silicon is very similar to that of single crystals, only due to the effect of boundary crystal grains, internal grain defects and higher concentration of impurities, they have lower electronic quality. The maximum efficiency of multicrystalline cells is 23.80%. In crystalline cell recycling, the yield of precious metals such as Ag, Cu, Te is low.

Multicrystalline solar panel Victron Energy – This is a specific model of a multicrystalline solar panel that is compared to other types of materials used in the construction of photovoltaic panels. Its efficiency value has been calculated to be 20.70% and is lower compared to other [2].

CdTe (Kadmium tellurid) – CdTe is a binary semiconductor with a cubic crystal structure and a near-ideal band gap. It can be deposited at relatively low temperatures using evaporation from CdTe powder and ensures room temperature operation. However, CdTe materials exhibit poor charge carrier transport properties and a disparity between electrons and holes properties. In 2014, First Solar developed the first CdTe cells with an efficiency of up to 21.00%. It was manufactured at the company's Perrysburg, Ohio manufacturing plant and Research & Development Center, using processes and materials designed for commercial-scale production. CdTe is scarce in the Earth's crust and is not used for mass production of solar panels. It may, however, find application in smaller applications in the consumer industry, for example as a solar cell in calculators or as a power supply for navigation and telecommunications equipment or applications in X-ray and gamma ray. The disadvantage is the toxicity of cadmium [17].

Perovskite solar cells – are thin film materials applied by printing or ink coating or vacuum deposition. Perovskites allow adjustment to respond to different sunlight colors by changing the material composition for high performance. This allows the production of tandem Perovskite - Silicone compositions with an efficiency of up to 33.90% or Perovskite – Perovskite 29.10% [18]. In 1989, hybrid organic-inorganic perovskite cells achieved efficiencies of around 20 %. These were an inorganic cation (Pb), an organic cation (CH_3NH_3) and a halide. Depending on the halide used, the band gap of the gas was adjusted from 1.6 eV to 3.2 eV. The smaller the band gap the better the efficiency of the solar cell. In addition, a thick mixed narrowband Pb-Sn_6 subcell was used for the tandem perovskite solar cell , but this is challenging due to the short diffusion length of the carriers in the Pb-Sn perovskites. Here, Lin Renxing's team develops ammonium cation-passivated Pb-Sn perovskites with long diffusion lengths, allowing sub-particles with absorber thicknesses of approximately 1.2 µm. Molecular dynamics simulations show that the widely used phenethylammonium cations are only partially adsorbed on surface defect sites at perovskite crystallization temperatures. By adding a small amount of CF3-PA to the precursor solution, we increase the diffusion length of carriers in Pb-Sn perovskites by a factor of two, to more than 5 µm, and increase the efficiency of Pb-Sn perovskite solar cells to more than 22 %. The certified efficiency is 26.4%. The encapsulated tandem devices retain more than 90 % of their original efficiency after 600 h of operation at the maximum power point under 1 Sun illumination in ambient conditions [15].

This value appears to be very high as it is known that hybrid porous cells degrade rapidly within hours to days. Since perovskite salts are used in the production process and are partially soluble in water, these cells are sensitive to humidity. The use of Pb also makes them toxic and therefore a thorough sealing of the entire system is necessary.

CIGS (Copper indium gallium diselenide) – The efficiency of thin-film solar CIGS cells is currently at 23.35%. CIGS cells have a chalcopyrite crystalline structure and the band gap is continuously adjustable between 1 and 2 eV. Again, the smaller the band gap, the higher the efficiency. The team, led by Motoshi Nakamura, looked at increasing the efficiency of CIGS cells using a $MoSe_2$ interfacial layer and concluded that under the influence of the tunneling effect, the $MoSe_2$ layer changes the nature of the Schottky contact from a chalcopyrite structure to a quasi-atomic structure. This results in better transport of majoritic carriers. The measured height of the Schottky barrier above 0.45 eV affects the filling and stress at no-load. The measured values of efficiency were close to the 24.6 %limit.

The disadvantage of these cells is again the building materials that are considered to be hazardous to health, these are mainly Ag, Al, Cu, In, Mo, Ni, Zn , Fe and Cr [8].

InP (Indium fosfid) – belongs to compound semiconductors with III-V geometry with a band gap of about 1.35 eV and an efficiency at the 24.20% limit. This technology does not currently enjoy much use or research, mainly due to the high acquisition cost of In [3].

GaAs (Gallium arsenid) – Due to the high absorption capability of GaAs cells, the thickness of the cells is relatively small around 2 mm. The design of high-efficiency GaAs cells has layers with a high band gap, which serves to trap minority carriers in the active layer. The maximum efficiency of GaAs cells was achieved by the team led by E, D Kosten, where they worked with the angle of incidence of the emitted light. In direct sunlight, conventional solar cells emit light isotropically, i.e. in all directions, but receive light primarily from angles that overlap with the sun's disk. The wider angular distribution of the emitted light leads to an increase in photon entropy, which unfortunately reduces the overall efficiency of these solar cells. By minimizing the angular dispersion of the light emitted by the cells, we can increase the efficiency of solar energy conversion systems. In other words, by optimizing the way solar cells release light, we can increase their efficiency in harnessing the sun's energy [19]. Recycling of GaSa cells is challenging mainly due to the use of the toxic element As.

GaInP/GaAs/GaInAs – In this technology, thin-film GaAs cells with three junctions are used. This cell has a specific ELO (epitaxial lift-off) design and the efficiency of such cells is 37.80%.

Recycling – This article focused on a comparison of the different technologies and materials used in terms of efficiency. This mainly relates to the ability of each solar cell to convert solar energy into electricity. For each of the materials compared, we briefly mentioned their negative impact on the environment or human health. It is mainly the presence of heavy metals such as lead, cadmium, indium, germanium, gallium, copper diselenide, silver, etc. From this point of view, solar panels are still imperfect, and despite all the advances in the development and successful improvement of the efficiency of individual technologies and materials, we are still at the imaginary beginning of their recycling at the end of their life journey, without much difference worldwide. The individual processes are described in more detail in the Figure 2 below.

The industrially used methods for recycling module separatins include a) Organic solvent method, b) Ultrasonic method using organic solvent, c) Artificial disassembly, crushing, cryogenic breakage method and electrostatic separation, d) Heat treatment and chemical etching methods.

For rare material and silicon recycling, these methods are a) Cement-based thermal insulation system and chemical method, b) Grinding and hydrometallurgy, c) By wet mechanical treatment such as grinding and flotation, or dry mechanical processing methods such as vacuum blasting, d) Heat treatment. [20]

Recycling is still a very lengthy and energy-intensive process. Even today, we cannot effectively recycle all materials to a sufficient extent and the disposal of solar panels is still a major burden on the environment.

The initial idea, involving the development of a recycling process over the lifetime (20 to 30 years) of the first massive onset of PV panel sales and installation, fell short of expectations. The progress of recycling technologies is slow and, above all, still insufficient [21]. The origin of the PV panels themselves, their non-environmental production in Chinese factories, non-environmental transport and inconsistent recycling at the end of the PV life cycle also appear to be major problems [22], [23].

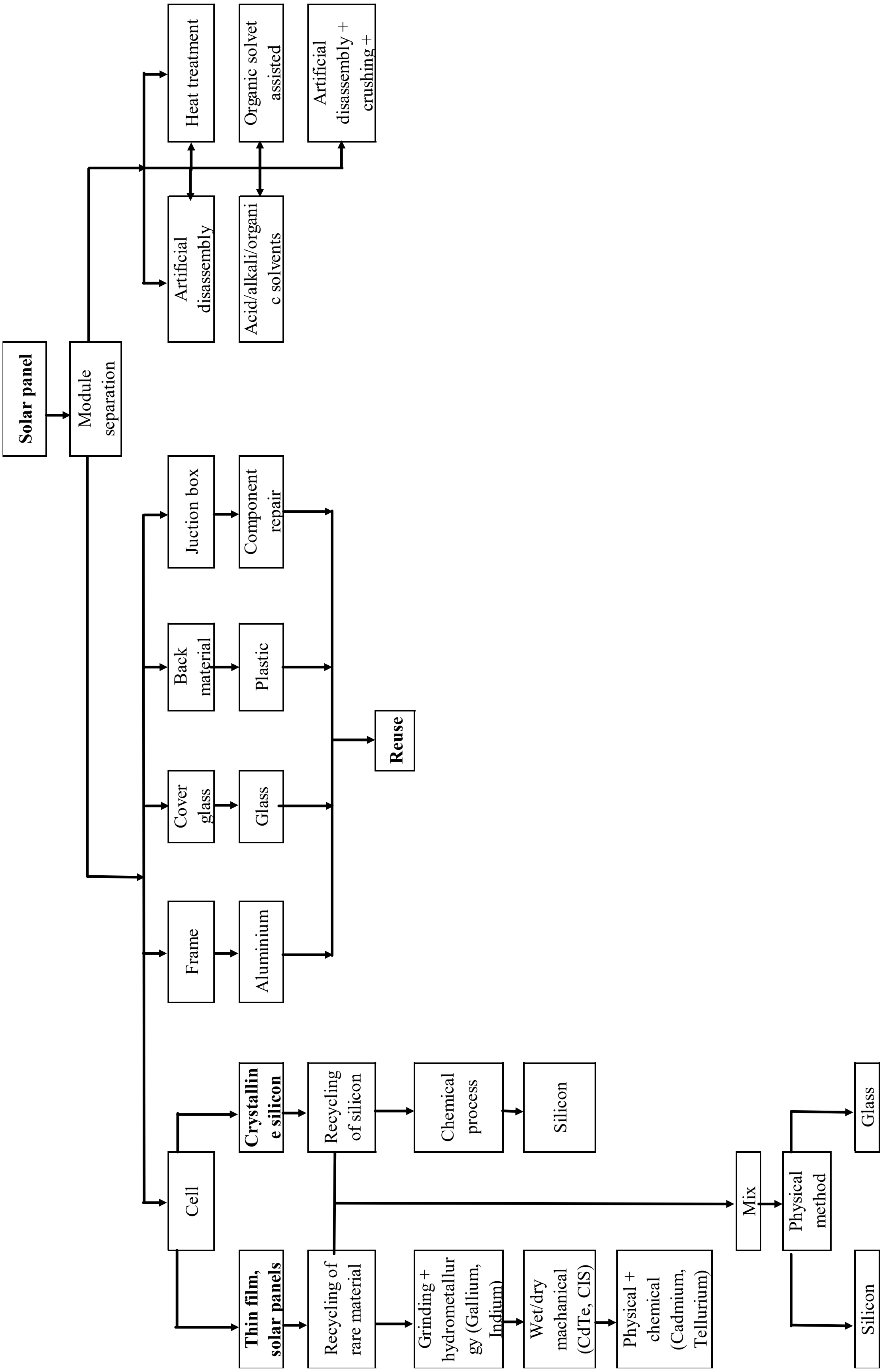

Figure 2. *Diagram –Summary of the PV panel recycling process*

1 CONCLUSIONS

The materials compared showed that their efficiency values currently range from 19.20% to 37.80%. New efficiency values for individual materials and combinations of materials, improvements in manufacturing technology, the development of photovoltaic panels continues to move forward. Values approaching 40% efficiency are certainly impressive and testify to the successful evaluation of the efforts of research teams from all over the world. As efficiency increases, it is also easier to implement photovoltaic systems in electronics, construction, agrovoltaics, power generation systems, mobile devices, space projects and many others. Nevertheless, there is much room for improvement, not only in terms of panel efficiency but also in terms of panel lifetime and, above all, in terms of subsequent recycling, which has lagged far behind the development of efficiency.

As the article pointed out, PV panels unfortunately still contain hazardous substances, heavy metals, chlorofluorocarbons, polybrominated flame retardants, lead, cadmium, indium, germanium, gallium, copper diselenide, silver and others. These substances are not present in large quantities in the panels, but their use cannot be denied. They are still recycled using the same processes (thermal, chemical and combinations thereof) as 20 years ago with minor improvements. Another negative feature of the whole photovoltaic policy is related not only to recycling but also to the production of the panels. Up to 78% [22] of the photovoltaic panels produced come from China and are further distributed worldwide. The energy intensity of PV panel production is not small, especially the production of the cells themselves [22] and China uses up to 50% thermal power (coal) for energy production [23]. Transportation is primarily by shipping, which cannot be described as environmentally friendly. It is therefore important to start producing and recycling panels locally if we want to label solar panel electricity generation as an environmentally friendly source. It is clear that the current state of our planet's environmental policy is fragmented and that there is still a long way to go towards green production and recycling.

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