Photovoltaic: a general overview

And a hypothetical case study

William Colombini
Dipartimento di Fisica,
Università degli Studi Milano-Bicocca,
Piazza dell'Ateneo Nuovo, 1
Milano, Italia
email: w.colombini@campus.unimib.it

Photovoltaic (PV) technology has emerged as a pivotal force in the global pursuit of sustainable energy solutions and the transition towards cleaner energy sources. This brief article provides an insightful overview, aiming to address all the meaningful questions about PV.

In presenting the state of the art, we explore the current efficiency levels achieved by PV technology. From conventional crystalline silicon (c-Si) cells to advanced Thin-Film and cutting-edge Multijunction cells, we traverse the spectrum of materials and technologies, including Concentrated Photovoltaic (CPV) technology and perovskite cells. The article seeks to elucidate the potential and the critical issues associated with these diverse technologies.

While PV technology continues to progress, it grapples with common issues across PV plants, such as intermittency, efficiency limitations, and environmental impact. This article elucidates these problems and suggest some solutions.

The last part of analysis is focused on a hypothetical case study centered on Italy. It will be estimated the energy production that could be harnessed if all roofs across the country were equipped with PV cells. This case study offers a tangible glimpse into the transformative potential of PV technology on a national scale, illustrating the scope of its contribution to the global energy transition.

In essence, this article serves as an broad exploration of photovoltaic technology, assessing its current standing, and envisioning its potential in shaping the future of sustainable energy production

The technical aspects are not described as can be found in specific textbooks as [1]

1 Introduction

The growing interest in climate change and global warning in the last decades makes evident how new methods for producing energy are needed. The population is growing[2], and so is the energy consumption[3].

Over the past few decades, interest in all technologies related to clean energy production has increased[1], as it is possible to see in Figure 1.

PV technology has continued to grow due to several factors, such as the growing interest in climate warming themes, as well as the growing demand for energy and the declining unit cost of silicon-based solar cells[4]. Another important factor is the modularity of the technology: it is possible to create both large PV plants and small groups of PV cells. This allows for a wide range of applications[5].

2 The main technologies

One of the main aims for research about PV is to find the most efficient technology.

The quantity where the majority of studies focus is the conversion efficiency: the percentage of the solar energy shining on a PV device that is converted into usable electricity. The growth of this value is one of the main steps for making PV technologies cost-competitive with conventional sources of energy[7].

For this reason, during the last decades, several materials and techniques have been developed and studied in order to reach the goal:

2.1 c-Si solar cells. The first functional technology developed is the p-n Junction Solar Cell in semiconductor. The operation of a PV cell requires, in fact, three basic steps: the absorption of light that generates electron-hole pairs; the separation of the charge carriers of opposite types at junctions without recombination; the collection of those carriers into an external circuit.

Si cells have been widely studied, and the theoretical maximum efficiency is found to be around 30% [8], being the portion of sunlight that the silicon semiconductor is able to absorb above the bandgap[9].

Nowadays, the efficiency reaches around 27.6%[10], but most of the panels for commercial use have efficiencies around 20%. This value is lower than other technologies we'll see. Despite that, c-Si represents 90% of the worldwide installed PV capacity [4]. One of the main reasons is the continually falling cost of c-Si that has made it difficult for other technologies to compete [11], also thanks to the abundance of the material on Earth[12].

2.2 Thin Film. A thin-film solar cell is typically made by depositing layers of PV material on a substrate such as glass, plastic, or metal[12].

This technology is useful for its adaptability. In fact, it's possible to produce PV panels with elastic properties and position them on curved surfaces, thanks to their reduced dimensions. The range is from a few nanometers (nm) to 10μm, while classical c-Si wafers are up to 200 μm[4]. The main materials used for producing these films are CdTe (Cadmium telluride) and CIGS (Copper Indium Gallium Selenide).

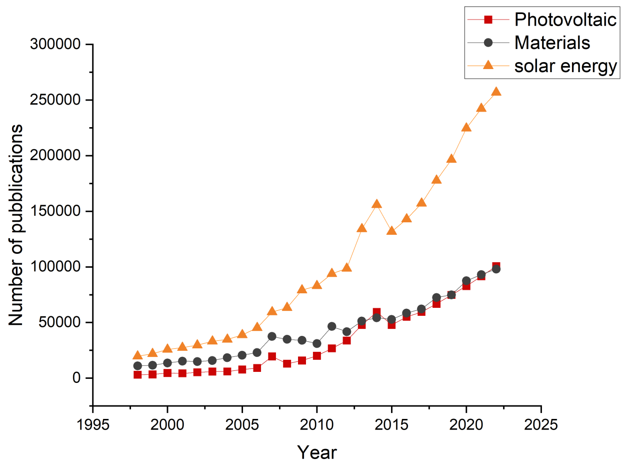
These technologies cover the majority of the PV market, after c-Si. The efficiencies reached are around 20%-22%[10], but for commercial use, it has reached a value of 18% for CdTe[13] and 14% for CIGS[14]. One of the main problems of the technology is due to the toxicity of the components involved in the production of the film[4], followed by the complexity of the process[2] and the lack of cross-industry applicability[3].

September 21, 2023

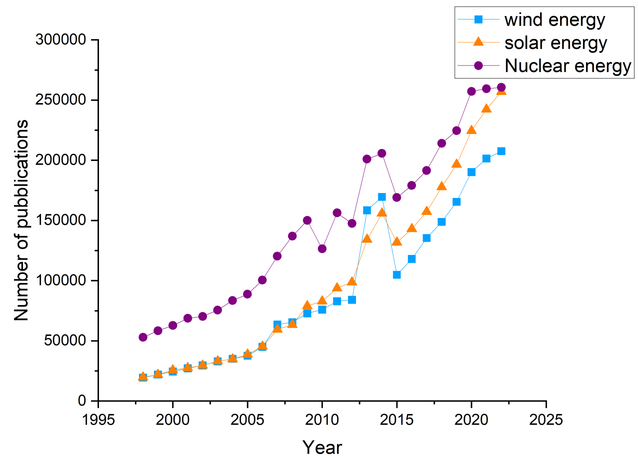
[1]This is just to provide an idea of the interest generated by the topic. The number of reviews and publications doesn't provide a comprehensive measure to evaluate the overall interest; other elements should be considered too.

[2]While c-Si is made in modules, thin-films are not separable, so an error in one point of the production compromises the whole panel

[3]Silicon is used as the main component for the entire electronics industry, so it's more convenient to study it



(*a*) The different interest about various theme related to solar energy.



(*b*) The different interest about different renewable energy technologies.

Fig. 1 On the vertical axes you can find the number of publications about a certain theme in a certain year[6]

2.3 Multijunction cells. Multijunction devices can achieve higher efficiencies than simple single-junction cells. In fact, they are made of several different materials stacked in multiple layers[4]. For this reason, this technology is capable of collecting a larger portion of the broad solar spectrum[15].

These devices use a high-band top cell to absorb high-energy photons, while lower-energy ones pass through the first layer and are absorbed by the subsequent layers[16]. Common materials for this technology are elements from groups III and V[4].

The theoretical efficiency that could be achieved with an infinite number of layers is around 65% for a concentration of 1 Sun and 85% for more Suns. In practical terms, efficiencies between 40% (without Sun concentration) and 48% (with Sun concentration) are achieved[10].

Despite the higher efficiency, the industrial process is much more complex, and the costs increase with the number of junctions. For a simple two-junction[5], it is one order of magnitude greater than common c-Si cells[17]; but for more complex structures, the ratio can reach magnitudes of 10^3[4]. This seems to be the main issue with the technology.

2.4 Concentrated photovoltaic. CPV consists of using lenses and curved mirrors to focus sunlight onto small but highly efficient cells.

This technology is mainly used in solar thermal plants but, as we mentioned in the previous section, it is also used for multijunction cells.

One of the possible advantages of CPV is the reduction in the size of the solar cells. This can lead to a reduction in the BoS (Balance of System) cost, which generally increases with the size of the plant, and the initial installation of PV systems is also cheaper. However, a balance is needed because, in order to maintain the concentration effectively, tracking technologies are required, and not always does this make the investment worthwhile[4].

2.5 Organic photovoltaic. OPV uses transparent or colored molecular or polymeric absorbers.

Despite the appeal of building-integrated PV for aesthetic reasons, their efficiency is still too low to be competitive[18]. Recent studies show efficiencies around 18.2%[19].

2.6 Perovkite. They are named after the eponymous ABX3 crystal structure, with the most studied PV material being methylammonium (MA^+) lead (Pb^{2+}) iodide (I^-), or MAPbI3. Perovskite cells are constructed with layers of materials that are printed, coated, or vacuum-deposited onto a substrate[20].

The interest in these materials is driven by their efficiency, which has reached values around 33% when combined with Si[10]. Despite this, the technology is relatively new, so the manufacturing techniques are expensive, and there is a problem related to the stability of the materials[6] that degrades upon contact with oxygen[4].

3 Problem and issue of PV technologies

Global energy demand is rising each year, and it is forecasted that the demand will have increased by 56% from 2010 levels by 2040[21].

Being an important RES (Renewable Energy Source), it is fundamental to discuss the main issues common to all PV technologies.

For simplicity, here we divide the argument into three parts, but it's important to remember that there is a connection between them, and a complete treatment would require more space than a few pages. An explanatory map of the topics addressed can be seen in Figure 2. For each problem, a solution or a method to reduce the impact of the issue is proposed.

3.1 Ecological issues. It's important to consider the environmental impact of an important method of energy production, such as PV. This impact can manifest in various forms, as follows:

3.1.1 Land and water usage. Studying the land distribution and the need for PV farms is important to avoid competition with other essential activities such as agriculture. It's important to note that as the energy demand is growing, so is the need for food due to population growth.

Despite the fact that the efficiency of agricultural technology is increasing, it's fundamental to find the best way to produce energy with the highest efficiency in terms of land usage. Several

[4]Examples of materials include GaInP, GaInAs, and GaAs

[5]To give an idea, the efficiency record is reached with a six-junction

[6]The material can be functional for approximately 2000 hours

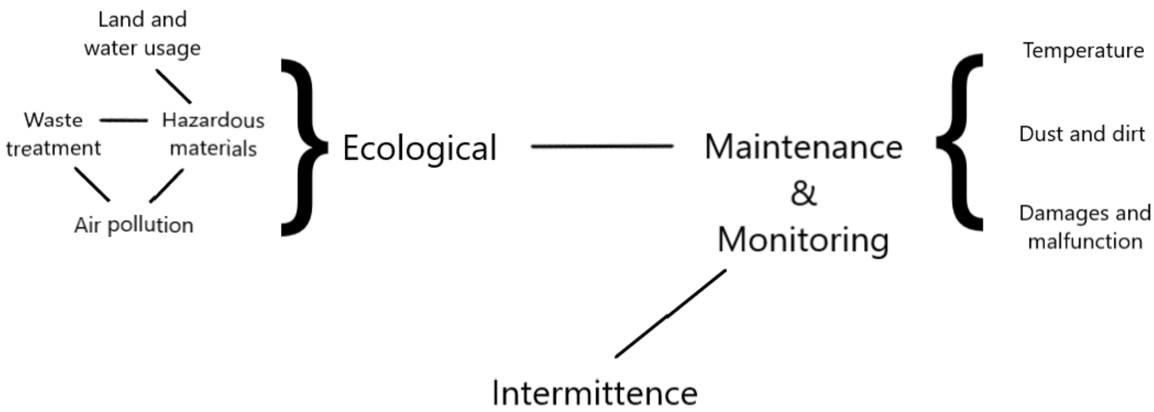


Fig. 2 A map of the issues you will find in the article

studies have shown that solar power systems[7] are the best in these terms[22]. The acres required per MW of power are influenced by the specific PV technology but range from 3.2 acres/MW to 13.9 acres/MW. For comparison, wind farms require 30 acres/MW to 44.7 acres/MW, while a thermal coal plant with a carbon sequestration system occupies 5 to 13 times more land than an equivalent PV farm[22].

The increasing need for land for energy and food production also has an impact on animal habitats and the presence of forests on Earth. Sometimes, animals are removed from their habitats to build solar farms, rendering them unable to be accommodated in the surrounding ecosystem.

The management of surrounding vegetation is an important theme in this context and is also related to the performance of PV plants: reducing vegetation is needed to minimize coverage[8], but protecting trees can reduce dust accumulation over the PV arrays, improving efficiency. Long-term effects on vegetation restoration after the decommissioning of a PV farm are being studied.

Land isn't the only valuable resource used; water is another factor to consider. There are two aspects to consider: usage for maintenance[9] and usage for industrial production and manufacturing. During a PV system's lifetime, water is used for cleaning rather than cooling, thanks to the fact that cooling systems have recycling techniques that prevent waste. Approximately $2.2 \cdot 10^3$ to $2.5 \cdot 10^3$ kg/MWh are consumed during the lifetime[21], while 180 to 470 kg of water for each kg of Si[10] is consumed during production[22].

Despite these challenges, some solutions are already available. For example, it's not necessary to use the terrain where a PV farm is located solely for producing energy. Land originally dedicated to pasture can be used for both PV and breeding. Also, the roofs and windows of buildings can be integrated with PV. This concept is the basis of agrovoltaic, building-integrated photovoltaics (BIPV)[11], and floating solar photovoltaic (FPV)[24]. FPV, in particular, presents challenges due to technical difficulties related to waves and tides and the visual impact of dedicating a water basin to PV farms.

3.1.2 Air pollution. Solar energy is a renewable source of energy. However, building and maintaining solar arrays and plants using modern industrial methods inevitably produce climate-changing gas emissions. Approximately 90% of PV's emissions occur during the fabrication of the arrays and the construction of the farm[22].

Table 1 CO_2 equivalent emission for kWh of electricity

Energy source	CO_2 equivalent production [g/kWh]
PV	14 to 73 [22]
Coal	1025 [25]
Natural gas	440 [25]
Petroleum	1107 [25]

A comparison with other energy sources is shown in Table 1, highlighting the advantages in terms of emission footprint of PV systems.

3.1.3 Hazardous materials and waste treatment. As the installation of PV panels has increased, so has the amount of waste produced when these panels reach the end of their 25-year lifespan. It is forecasted that by 2050, the waste due to PV will reach 80 Mton[26]. In addition to this, during the manufacturing process of solar modules, various hazardous materials are used, potentially causing health issues for humans[27].

Some of the chemical compounds involved in PV cells' manufacturing, such as acetone (C_3H_6O), isopropanol (C_3H_8O), or toluene (C_7H_7)[22], are also used in many everyday products. Studies are ongoing in order to lower the environmental impact of these molecules. The 12 principles of green chemistry provide a chemical approach to industrial production for finding sustainable processes.

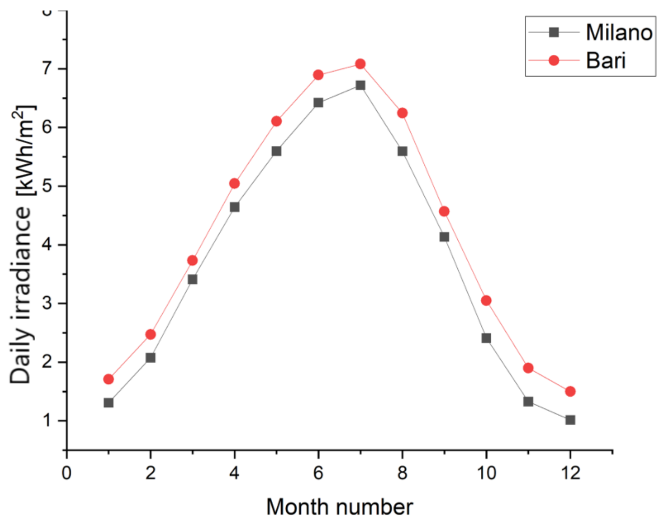
3.2 Maintenance and monitoring. It is fundamental to have real-time monitoring systems and techniques for maintaining the efficiency of PV panels and farms at the highest possible level. Some of the main issues that can hinder the correct functioning of PV cells are analyzed in the following lines.

3.2.1 Temperature. Temperature is one of the factors affecting the efficiency of solar cells and the power output. It is possible to evaluate the relationship between silicon-based PV panel's efficiency and temperature and then examine which environmental and physical factors are involved in the relationship.

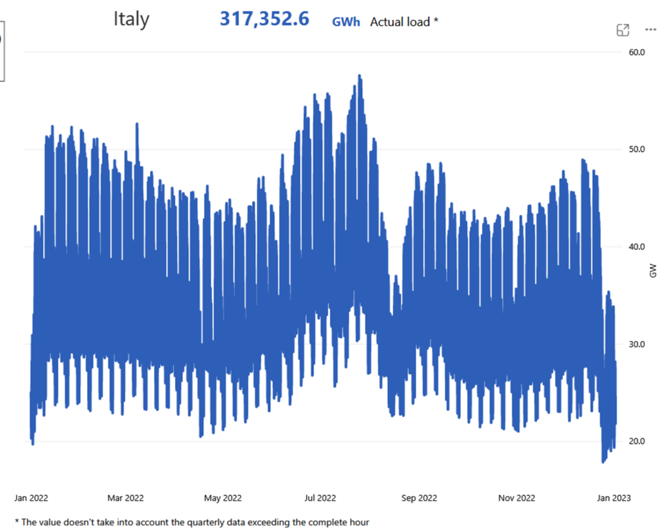
One of the most basic and widely used linear relationships is[30]:

$$\eta_{PV} = \eta_{ref} \left[1 - \beta_{ref} \left(T_{PV} - T_{ref}\right)\right] \quad (1)$$

[7] PV and Concentrated Solar Power
[8] This aspect is more critical in CPV technologies than in others
[9] cleaning and cooling systems
[10] Depending on the type of PV panels produced
[11] Some examples of BIPV can be found around the world in [23]



(*a*) Data taken from [28] and elaborated with Origin



(*b*) Data taken from [29]

Fig. 3 Plots based on daily mean of (a) distribution over the year of the mean daily irradiance based on the location in Italy; (b) distribution over the year of the mean daily energy usage in Italy.

Here, η_{ref} is the PV power conversion efficiency at the reference temperature T_{ref}[12]. β_{ref} $[°C^{-1}]$[13] is a temperature coefficient, and T_{PV} is the operating temperature of the panels. The study analyzed the relationship between T_{PV} and environmental factors such as wind, ambient temperature, and incident irradiance. According to intuition, T_{PV} grows linearly with external temperature and irradiance and decreases with higher wind[14]. The mounting configuration of PV modules also has an influence on PV cell temperature: installing panels lifted up from the ground allows the temperature to be lower and, thus, the efficiency higher[30].

Since temperature is an important working parameter, cooling techniques are being developed based on the required temperature reduction. The main technologies involve water cooling, air cooling, and conductive cooling. Another classification is between active and passive systems: active systems require more external monitoring to automate the cooling process when needed, while passive cooling doesn't involve pumps or fans[31]. These methods require more components and, therefore, affect the cost of the plant when used.

3.2.2 Dust and dirt. Dust deposition can decrease PV efficiency for two main reasons: coverage and temperature. When partial and inhomogeneous, a temperature gradient can be formed on the panel, generating hot spots[31]. Both uniform and non-uniform dust decrease the solar power that reaches the PV cells. The dust problem is more unpredictable than previous ones: dust density doesn't increase linearly with exposure time but strongly depends on climatic conditions during the exposure period[32]. In addition to this, dust can interact with air components, producing mud and solutions that stick to the panels.

For this reason, cleaning systems are needed. One of the simplest methods of cleaning is spontaneous processes: by setting the correct inclination for the PV panels, wind, rainfall, and gravity remove dust. Technologies similar to active cooling systems can mechanically remove dust, supported by real-time monitoring (IRT) systems or programmable devices. More innovative technologies can be found in [32].

3.2.3 Malfunction and damages. Dust, temperature, and other factors due to the harsh environmental conditions surrounding PV panels can cause damage and malfunctions. Detecting and evaluating anomalies requires methods that are more or less automated, depending on the size of the solar plant.

In any case, it is fundamental to have IRT monitoring systems in order to detect important faults that can prevent the arrays from properly collecting incident radiation. In this context, new technology and machine learning techniques can be useful tools when the plant is substantial, and these technologies can assist in multiple tasks beyond fault detection and classification[33].

For example, thermography is a frequently used method to detect underperforming PV modules using drone infrared images[34]. The analysis of hyperspectral images using artificial intelligence algorithms is a branch of study in several fields, and more challenging situations are currently being studied, making the possibility of integrating machine learning techniques in the analysis of drone IR images a reality.

3.3 Intermittence. One of the most considered problems of PV technologies is intermittence and the difficulty in forecasting the power production of a PV plant. In addition to this, the energy demand isn't fixed but changes based on several factors.

Graphical examples can be seen in Figure 3. This problem can't be completely solved, but there are methods to mitigate its impact, such as developing energy storage methods and improving the electrical grid with "smart" systems that can better direct energy where it is needed. These solutions are complex, involve political aspects, and come with high costs.

4 Hypothetical Case study for Italy (an estimation)

The last part of the review is dedicated to answering a hypothetical question: What would happen if all roofs in Italy were covered by commercial c-Si solar panels? In order to make this evaluation, some data are needed: the irradiance of the sun is obtained from [28]. This data provides information on the mean daily irradiance for each month in a specific place and at a specific inclination with respect to the ground. Some assumptions are made to simplify the

[12] typically 25°C

[13] for silicon-based panels, it can be $5 \cdot 10^{-3}$ $°C^{-1}$

[14] Using air is, in fact, one of the cooling methods used in PV panels[31]

evaluation: the solar panels[15] are assumed to be horizontal with respect to the ground. This is an approximation that leads to an overestimate of the power density. The second assumption is that the radiation density is the same for each Italian region, and it's given by the value in the capital of the region[16], which is a reasonable assumption given that the power is of the same order of magnitude, as shown in Figure 3.

The total roof surface in Italy is estimated to be around 763.53 km^2[35][17]. It lacks data about the distribution in each region, so two different models are developed: one considering the roof distribution based on the area of each region and one based on the population density. Data on area and population are obtained from [36] and [37].

The last approximation is about the efficiency: it's assumed to be constantly 20%. This is the most significant simplification, and for a more realistic analysis, environmental factors that affect temperature, as shown in Section 3.2.1, should be considered. The results of the analysis are shown in Figures4 and Figure 5. We can observe that the models based on the area distribution of roofs and population distribution of roofs give similar results: around $2.20 \cdot 10^5 GWh$. The total energy used in Italy in 2022 is shown in Figure 3 (b), and it's $3.17 \cdot 10^5 GWh$. So, in this simplified estimation, it results that an extended BIPV system would produce 70% of the energy needed.

It's important to consider that this estimation is idealistic and not realistic due to the many strong approximations. It's useful to consider it as a high limit of what PV technologies can achieve. Many elements are not considered, such as the cost of PV panels and the need to adapt the electrical system to the intermittence caused by PV.

5 Conclusions

As can be seen, the complete and smart integration of PV into the electrical system is a challenge that must be tackled. Useful new technologies, such as machine learning (ML) approaches, can help provide better control and forecasting capabilities. However, it's impossible to ignore the effect of the environment on PV structures and vice-versa.

6 How to improve this work

Due to time constraints, certain aspects related to smart grids and the potential of machine learning are not thoroughly analyzed in these pages, nor are storage technologies that can help address the intermittence issue.

No attention is given to the economic aspects of innovative PV technologies, but it's important to note that the aim of this review is to provide a summary of the state of the art in various aspects related to PV. It includes methods and technologies that are emerging or currently under study.

Significant improvements can be made in the estimations presented in Section 4. This could involve considering the influence of external temperature on T_{PV}[18]. Additional factors, such as the effects of wind, dust, and rainfall, could be included in the analysis, and economic factors could also be incorporated.

References

[1] 2013, *Energy Science - principles, technologies and impacts*, 2nd ed., Oxford University Press.

[2] Ritchie, H., Rodés-Guirao, L., Mathieu, E., Gerber, M., Ortiz-Ospina, E., Hasell, J., and Roser, M., 2023, "Population Growth," Our World in Data, https://ourworldindata.org/population-growth.

[15] i.e. the roofs

[16] e.g., in the whole of Lombardy, the power density is assumed to be the same as in Milan

[17] This source is unverified and is not from a governmental or official organization

[18] i.e., on the efficiency

[3] "Energy Production and Consumption - Our World in Data," Global Change Data Lab, accessed September 2023, https://ourworldindata.org/energy-production-consumption

[4] Kalkman, J., Merhaba, A., Bose, S., and Bradley, H., 2015, "Emerging technologies in Solar PV: identifying and cultivating potential winners," .

[5] "Solar - IEA," International Energy Agency, accessed September 2023, https://www.iea.org/energy-system/renewables/solar-pv

[6] "Publication - Dimensions," Digital Science and Research Solutions Inc., accessed June 2023, https://app.dimensions.ai/discover/publication

[7] "Solar Performance and Efficiency | Departement of Energy," U.S. Departement of Energy, accessed June 2023, https://www.energy.gov/eere/solar/solar-performance-and-efficiency

[8] Shockley, W. and Queisser, H. J., March, 1961, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells*," Journal of Applied Physics, **32**(3).

[9] "PV Cells 101: A Primer on the Solar Photovoltaic Cell | Departement of Energy," U.S. Departement of Energy, accessed September 2023, https://www.energy.gov/eere/solar/articles/pv-cells-101-primer-solar-photovoltaic-cell

[10] "Best Research-Cell Efficiency Chart | Photovoltaic Research | NREL," National Renewable Energy Laboratory, accessed September 2023, https://www.nrel.gov/pv/cell-efficiency.html

[11] "Evolution of solar PV module cost by data source, 1970-2020 - IEA," International Energy Agency, accessed September 2023, https://www.iea.org/data-and-statistics/charts/evolution-of-solar-pv-module-cost-by-data-source-1970-2020

[12] "Solar Photovoltaic Cell Basics | Departement of Energy," U.S. Departement of Energy, accessed September 2023, https://www.energy.gov/eere/solar/solar-photovoltaic-cell-basics

[13] "Cadmium Telluride | Departement of Energy," U.S. Departement of Energy, accessed September 2023, https://www.energy.gov/eere/solar/cadmium-telluride

[14] "Copper Indium Gallium Diselenide | Departement of Energy," U.S. Departement of Energy, accessed September 2023, https://www.energy.gov/eere/solar/copper-indium-gallium-diselenide

[15] Geisz, J. F., France, R. M., Schulte, K. L., Steiner, M. A., Norman, A. G., Guthrey, H. L., Young, M. R., Song, T., and Moriarty, T., April, 2020, "Six-junction III-V solar cells with 47.1% conversion efficiency under 143 Suns concentation," Nature Energy, **5**, pp. 326–335.

[16] "Multijunction III-V Photovoltaics Research | Departement of Energy," U.S. Departement of Energy, accessed September 2023, https://www.energy.gov/eere/solar/multijunction-iii-v-photovoltaics-research

[17] Baiju, A. and Yarema, M., September, 2022, "Status and challenges of multi-junction solar cell technology," Frontiers in Energy Research.

[18] "Organic Photovoltaics Research | Departement of Energy," U.S. Departement of Energy, accessed September 2023, https://www.energy.gov/eere/solar/organic-photovoltaics-research

[19] Sun, R., Wing, T., Fan, Q., Wu, M., Yang, X., Wu, X., Yu, Y., Xia, X., Cui, F., Wan, J., Lu, X., Hao, X., Jen, A. K.-Y., Spiecker, E., and Min, J., January 2023, "18.2% efficient ternary all-polymer organic solar cells with improved stability enabled by a chlorinated guest polymer acceptor," Joule, **7**, pp. 221–237.

[20] "Perovskite Solar Cells | Departement of Energy," U.S. Departement of Energy, accessed September 2023, https://www.energy.gov/eere/solar/perovskite-solar-cells

[21] Rahman, A., Farrok, O., and Haque, M., February 2022, "Environmental impact of renewable energy source based electrical power plants: solar, wind, hydroelectric, biomass, geothermal, tidal, ocean," Renewable and Sustainable Energy Reviews, **161**.

[22] Tawalbeh, M., Al-Othman, A., Kafiah, F., Abdelsalam, E., Almomani, F., and Alkasrawi, M., October 2020, "Environmental impacts of solar photovolatic systems: A critical review of recent progress and future outlook," Science of the Total Environment, **759**.

[23] Taser, A., Koyunbaba, B. K., and Kazanasmaz, T., December 2022, "Thermal, daylight, and energy potential of building-integrated photovoltaic (BIPV) systems: A comprehensive review of effects and developments," Elsevier.

[24] Vodapally, S. N. and Ali, M. H., December 2022, "A comprehensive Review of Solar Photovoltaic (PV) Technologies, Architecture, and Its Applications to Improved Efficiency," Energies, **16**.

[25] "Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA)," U.S. Energy Information Administration (EIA), accessed September 2023, https://www.eia.gov/tools/faqs/faq.php?id=74&t=11

[26] Health, G., Silverman, T., Kempe, M., Deceglie, M., Ravikumar, D., Remo, T., Cui, H., Sinha, P., Libby, C., Shaw, S., Komoto, K., Wambach, K., Butler, E., Barnes, T., and Wade, A., June 2020, "Research and development priorities for silicon photovoltaic module recycleing to support a circular economy," Nature Energy, **5**.

[27] Rathore, N. and Panwar, N. L., March 2021, "Strategic overview of management of future solar photovoltaic panel waste generation in the Indian context," Waste Management and Research, **40**, pp. 504–518.

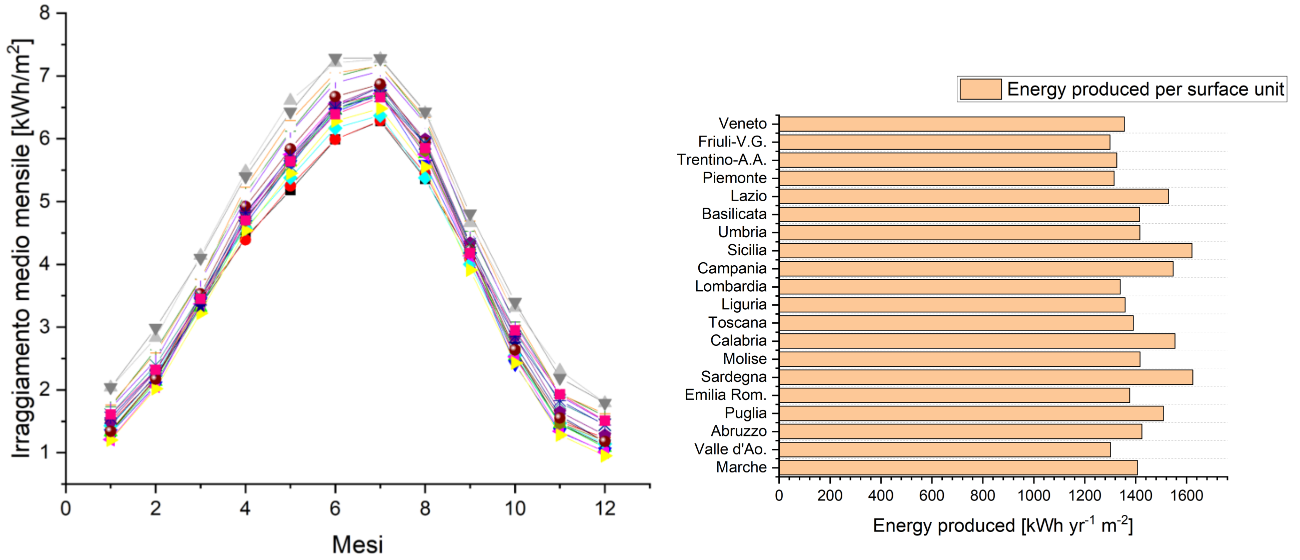
[28] "Atlante italiano della radiazione solare," Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA), accessed June 2023, http://www.solaritaly.enea.it/CalcRggmmOrizz/Calcola1.php

[29] "Total Load - Terna spa," Terna - Rete Elettrica Nazionale S.p.A., accessed June 2023, https://www.terna.it/it/sistema-elettrico/transparency-report/total-load

[30] Aly, S. P., Ahzi, S., and Barth, N., May 2019, "Effect of physical and environmental factors on the performance of a photovoltaic panel," Elsevier.

[31] Dwivedi, P., Sudhakar, K., Soni, A., Solomin, E., and Kirpichnoikova, I., June 2020, "Advanced cooling techniques of P.V. modules: A state of art," Elsevier.

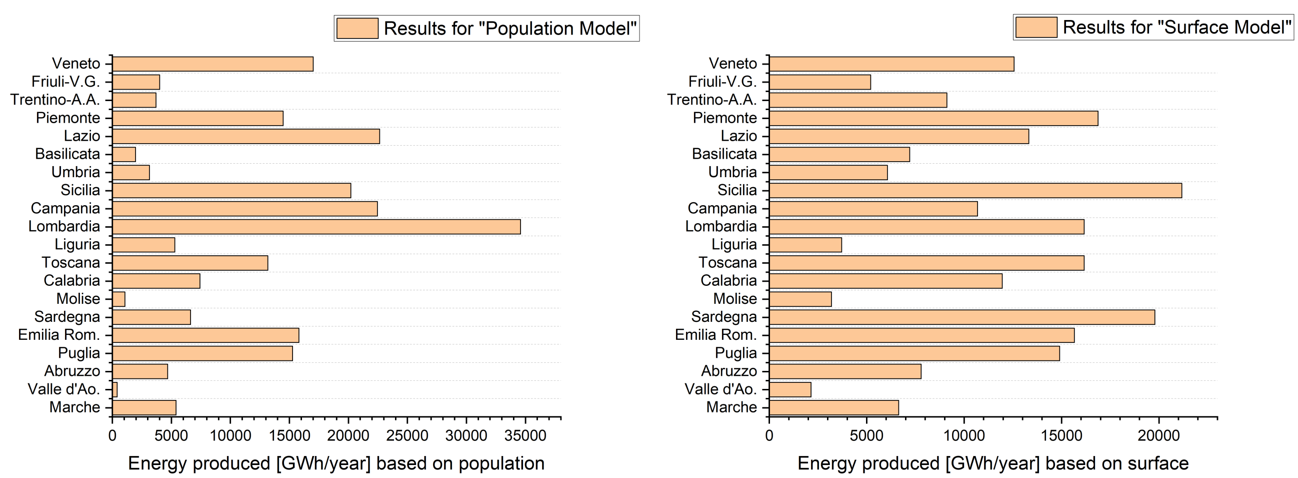
[32] Said, S., Hassan, G., Walwil, H., and Al-Aqeeli, N., September 2017, "The effect of environmental factors and dust accumulation on photovoltaic modules and dust-accumulation mitigation strategies," Elsevier.
[33] Gaviria, J. F., Narvàez, G., Guillen, C., Giraldo, L. F., and Bressan, M., June 2022, "Machine learning in photovoltaic systems: A review," Elsevier.
[34] Buerhop, C., Bommes, L., Schlipf, J., Pickel, T., Fladung, A., and Peters, I. M., September 2022, "Infrared imaging of photovoltaic modules: a review of the state of are and future challenges facing gigawatt photovoltaic power stations," Progress in Energy.
[35] "Potenziale del Fotovoltaico | Energoclub," Energoclub, accessed June 2023, https://www.energoclub.org/page/potenziale-del-fotovoltaico
[36] "Popolazione residente al 1° gennaio," Istituto nazionale di statistica (ISTAT), accessed June 2023, http://dati.istat.it/Index.aspx?DataSetCode=DCIS_POPRES1
[37] "Superfici territoriali," Istituto nazionale di statistica (ISTAT), accessed June 2023, http://dati.istat.it/Index.aspx?DataSetCode=DCCV_CARGEOMOR_ST_COM
[38] "Medie climatiche e dati statistici di diverse città italiane suddivise per regione | Climatologia | Il Tempo in media e agli estremi," Centro Meteo tutto sulla metereologia, accessed September 2023, http://www.centrometeo.com/articoli-reportage-approfondimenti/climatologia/4812-medie-climatiche-dati-statistici-citta-regione



(*a*) Data taken from [28] and elaborated with Origin

(*b*) Total incident energy in a year per region per m^2

Fig. 4 Row data are displayed by (a) while (b) is obtained by calculation. More details in Appendix A.



(*a*) Data considering roof distribution based on area

(*b*) Data considering roof distribution based on population

Fig. 5 Plots of the total energy to roof's surface in a year for each Italian region. More details in Appendix A.

Appendix A: Data tables and calculation details

Table 4 is obtained from Table 3 by using the conversion factor:

$$1MJ = \frac{1}{3.6}kWh \tag{A1}$$

The left part of Figure 4 is a graphical representation of the values presented in Table 4, and the right part of Figure 4 represents data from Table 5.

To find the data in Table 5, the approximation of a commercial year is used[19]. The operation for each capital is:

$$Total\ of\ Capital = (\ Sum\ of\ each\ Month) \cdot 30 \tag{A2}$$

Figure 5 and Table 6 results are obtained using the following equation:

$$E_{tot}\ [GWh\ yr^{-1}] = E_{sur}\ [kWh\ yr^{-1}\ m^{-2}] \left(Sur[km^2] \cdot Perc\right) \cdot \eta \tag{A3}$$

Where E_{tot} is the total energy in the region shown in Table 6, E_{sur} is the energy per year per surface unit per region given in Table 5. Sur is the total available roof surface of 763.53 km^2[35], and $Perc$ is the percentage shown in Table 2. Using the two percentage distributions, the result is different, so there are two "models": the "Surface-based model" and the "Population-based model".

Lastly, η is the efficiency of the solar PV panels, which is fixed at 20%. No multiplication factors are needed because the conversion $[kWh] \rightarrow [GWh]$ is canceled by the conversion $[km^2] \rightarrow [m^2]$. This brings the final result for each region shown in Figure 4.

By summing the energy per region, we obtain the following table:

Total energy produced over a year [GWh/yr]	
Surface Model	220416
Population Model	219448

By comparing these results with the data shown in Figure 3, we find that the "Surface Model" produces 69.45% and the "Population Model" produces 69.15% of the total energy.

A.1 Personal comment. The difference between the "Surface-based model" and the "Population-based model" appears to be quite small in the evaluation. However, with a more accurate description of the efficiency based on Equation 1 and using the data presented in Table 7[38], it's possible that the difference becomes more relevant.

Table 2 Table of region and capital in Italy with population and surface percentage. Data taken from [36] and [37].

Capital	Region	Population [%]	Surface [%]
Ancona	Marche	16.91	7.90
Aosta	Valle d'Aosta	9.70	5.70
Aquila	Abruzzo	9.50	4.53
Bari	Puglia	8.22	6.07
Bologna	Emilia Romagna	8.16	8.55
Cagliari	Sardegna	7.52	7.45
Campobasso	Molise	7.21	8.40
Catanzaro	Calabria	6.63	6.47
Firenze	Toscana	6.20	7.61
Genova	Liguria	3.13	5.04
Milano	Lombardia	2.68	7.98
Napoli	Campania	2.55	1.79
Palermo	Sicilia	2.52	3.09
Perugia	Umbria	2.16	3.59
Potenza	Basilicata	2.03	2.63

[19] Each month has 12 days, so the year is composed of 360 days.

Table 3 Row data table [MJ/m^2 per day]

Anco.	Aost.	Aquil.	Bari	Bolo.	Cagl.	Camp.	Cata.	Fire.	Geno.	Mila.	Napo.	Pale.	Peru.	Pote.	Roma	Tori.	Tren.	Trie.	Vene.	Mesi	Mesi
4.84	4.78	5.80	6.14	4.85	7.36	5.62	7.06	5.17	4.80	4.71	6.35	7.36	5.42	5.78	6.23	5.33	5.16	4.34	4.34	Gen	1
7.80	7.85	8.63	8.91	7.88	10.76	8.31	9.72	8.02	7.66	7.47	9.32	10.20	8.28	8.37	9.51	7.94	8.03	7.27	7.40	Feb	2
12.71	12.01	12.61	13.43	12.24	14.78	12.38	13.80	11.97	11.92	12.28	13.54	14.89	12.46	12.42	13.56	12.35	12.61	11.60	12.13	Mar	3
17.70	15.95	17.10	18.15	16.92	19.43	17.35	18.40	17.03	16.66	16.71	18.82	19.74	17.34	16.91	18.49	15.82	16.46	16.36	17.08	Apr	4
21.03	18.64	20.05	21.98	20.41	23.14	20.57	22.29	20.26	20.28	20.15	22.64	23.81	20.36	20.29	22.04	18.91	19.37	19.60	20.71	Mag	5
24.02	21.56	23.34	24.82	23.53	26.24	23.38	25.15	23.43	23.22	23.12	25.37	25.94	23.57	23.01	25.17	21.58	22.21	22.62	23.63	Giu	6
24.73	22.61	24.21	25.49	24.17	26.20	24.05	25.55	24.56	24.24	24.20	25.78	26.16	24.59	23.97	25.80	22.64	22.94	23.31	24.19	Lug	7
21.40	19.31	21.39	22.48	20.93	23.16	21.32	22.54	21.29	20.74	20.14	22.84	23.07	21.55	21.06	22.64	19.63	19.35	19.99	20.71	Ago	8
15.27	14.83	15.60	16.44	15.16	17.31	15.07	16.59	15.46	15.24	14.88	16.88	16.77	15.62	15.03	16.31	14.74	14.41	14.07	14.92	Set	9
9.52	9.38	10.58	10.98	9.51	12.24	10.25	11.43	9.82	9.15	8.68	11.41	11.91	10.31	10.61	11.10	9.07	9.18	8.73	9.10	Ott	10
5.58	5.26	6.43	6.84	5.31	7.89	6.60	7.58	5.73	5.26	4.78	6.96	8.32	5.92	6.96	6.97	5.36	5.29	4.62	4.84	Nov	11
4.26	4.01	5.22	5.40	4.27	6.43	5.19	6.50	4.21	3.89	3.66	5.83	6.43	4.61	5.45	5.71	4.48	4.09	3.42	3.63	Dic	12

Table 4 Row data table [kWh/m^2 per day]

Anco.	Aost.	Aquil.	Bari	Bolo.	Cagl.	Camp.	Cata.	Fire.	Geno.	Mila.	Napo.	Pale.	Peru.	Pote.	Roma	Tori.	Tren.	Trie.	Vene.	Mesi	Mesi
1.34	1.33	1.61	1.71	1.35	2.04	1.56	1.96	1.44	1.33	1.31	1.76	2.04	1.51	1.61	1.73	1.48	1.43	1.20	1.21	Gen	1
2.17	2.18	2.40	2.47	2.19	2.99	2.31	2.70	2.23	2.13	2.07	2.59	2.83	2.30	2.32	2.64	2.21	2.23	2.02	2.06	Feb	2
3.53	3.34	3.50	3.73	3.40	4.10	3.44	3.83	3.33	3.31	3.41	3.76	4.14	3.46	3.45	3.77	3.43	3.50	3.22	3.37	Mar	3
4.92	4.43	4.75	5.04	4.70	5.40	4.82	5.11	4.73	4.63	4.64	5.23	5.48	4.82	4.70	5.14	4.39	4.57	4.54	4.75	Apr	4
5.84	5.18	5.57	6.10	5.67	6.43	5.72	6.19	5.63	5.63	5.60	6.29	6.61	5.66	5.64	6.12	5.25	5.38	5.45	5.75	Mag	5
6.67	5.99	6.48	6.89	6.54	7.29	6.49	6.99	6.51	6.45	6.42	7.05	7.21	6.55	6.39	6.99	5.99	6.17	6.28	6.56	Giu	6
6.87	6.28	6.73	7.08	6.71	7.28	6.68	7.10	6.82	6.73	6.72	7.16	7.27	6.83	6.66	7.17	6.29	6.37	6.48	6.72	Lug	7
5.94	5.36	5.94	6.25	5.81	6.43	5.92	6.26	5.91	5.76	5.60	6.34	6.41	5.99	5.85	6.29	5.45	5.38	5.55	5.75	Ago	8
4.24	4.12	4.33	4.57	4.21	4.81	4.19	4.61	4.30	4.23	4.13	4.69	4.66	4.34	4.18	4.53	4.09	4.00	3.91	4.14	Set	9
2.64	2.61	2.94	3.05	2.64	3.40	2.85	3.18	2.73	2.54	2.41	3.17	3.31	2.86	2.95	3.08	2.52	2.55	2.43	2.53	Ott	10
1.55	1.46	1.79	1.90	1.47	2.19	1.83	2.10	1.59	1.46	1.33	1.93	2.31	1.65	1.93	1.94	1.49	1.47	1.28	1.34	Nov	11
1.18	1.11	1.45	1.50	1.19	1.79	1.44	1.80	1.17	1.08	1.02	1.62	1.79	1.28	1.51	1.58	1.24	1.14	0.95	1.01	Dic	12

Table 5 Total energy in a year for surface unit [kWh/m^2 per year]

Anco.	Aost.	Aquil.	Bari	Bolo.	Cagl.	Camp.	Cata.	Fire.	Geno.	Mila.	Napo.	Pale.	Peru.	Pote.	Roma	Tori.	Tren.	Trie.	Vene.	Total
1407	1302	1425	1509	1376	1624	1417	1555	1391	1359	1340	1548	1622	1417	1415	1529	1315	1326	1300	1356	28534

Table 6 Total energy per year in each region [GWh/year] based on population and surface distribution of roof.

Marc.	Vall.	Abru.	Pugl.	Emil.	Sard.	Moli.	Cala.	Tosc.	Ligu.	Lomb.	Camp.	Sici.	Umbr.	Basi.	Lazi.	Piem.	Tren.	Friu.	Vene.
5407	415	4695	15273	15811	6639	1066	7430	13181	5298	34595	22459	20206	3141	1971	22648	14475	3700	4020	17018
6647	2146	7802	14906	15658	19791	3196	11966	16168	3720	16163	10697	21178	6063	7208	13323	16882	9120	5211	12571

Table 7 Mean of the max daily temperature for each month an each capital [$^{\circ}C$]

Anco.	Aost.	Aquil.	Bari	Bolo.	Cagl.	Camp.	Cata.	Fire.	Geno.	Mila.	Napo.	Pale.	Peru.	Pote.	Roma	Tori.	Tren.	Trie.	Vene.	Mesi
8	-8	10	12	5	14	6	14	10	11	5	12	15	9	6	12	6	6	7	6	Gen
10	-8	12	13	8	15	7	14	12	12	8	13	15	11	7	14	8	9	9	8	Feb
13	-8	14	15	13	16	10	16	15	14	13	15	16	14	9	16	13	15	12	12	Mar
17	-6	18	18	18	18	14	18	19	17	18	18	18	17	13	19	17	19	17	16	Apr
22	-2	22	22	23	22	19	22	23	20	22	23	22	22	18	24	21	23	22	21	Mag
25	1	26	26	27	27	23	27	27	24	26	26	25	26	22	28	25	27	25	25	Giu
28	4	39	28	30	30	26	31	31	27	29	29	28	30	25	31	28	29	28	28	Lug
28	3	29	28	29	30	26	31	31	27	28	30	29	29	25	31	26	28	27	27	Ago
24	2	25	25	25	27	22	28	27	24	24	26	27	26	21	28	23	25	24	24	Set
20	-1	20	21	19	23	17	24	21	20	18	22	23	20	16	23	17	19	18	18	Ott
14	-5	16	17	11	18	11	19	15	15	10	17	19	13	11	17	11	11	12	12	Nov
10	-7	12	14	6	15	8	16	10	12	5	14	16	9	8	13	7	6	8	7	Dic