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Impacts of different photovoltaic panel technologies on electrical energy production and CO₂ emission reduction

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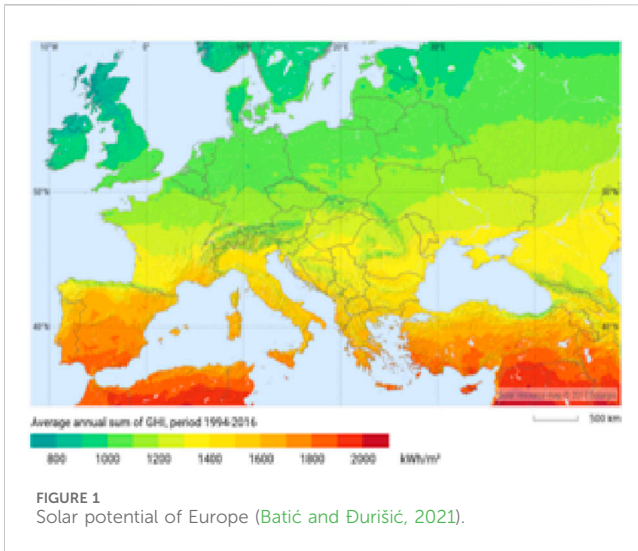
Given the increasing human population on Earth, there is a corresponding increase in the need for energy. One of the ecological and economical methods of meeting such energy needs is through renewable energy sources. Accordingly, this study analyzes the potential for producing electrical energy from solar radiation in Serbia. The Sun is the largest source of renewable energy, and Serbia has very good potential for utilization of solar radiation. In this work, we performed a comparative analysis of the electrical energy production from photovoltaic power plants using different photovoltaic panel technologies; these technologies affect not only the degree of conversion of solar irradiation to electrical energy but also the ecological parameters concerning the use of photovoltaic panels by reducing CO₂ emissions. In this work, the following photovoltaic panel technologies are analyzed: monocrystalline, polycrystalline, thin-layer amorphous (a-Si), and cadmium–telluride (CdTe). The software tool used for the analysis was PVsyst.

KEYWORDS

renewable sources, solar energy, photovoltaic panels, environment, CO₂ reduction

1 Introduction

The global population increase has resulted in increasing need for energy as well as greater energy consumption. Today, energy is mostly produced from non-renewable sources, such as oil, coal, and natural gas, whose supplies are limited, consumed quickly, and concentrated only in a few areas around the world. Oil, coal, and natural gas are currently used to fulfil up to 86.5% of the primary energy demand globally (Babić, 2016). In addition to the extensive economic dependence on fossil energy sources, the problem of protecting the environment from pollution remains a constant concern. The burning of fossil fuels, especially those based on oil and coal, is the one of the main causes of global warming and has resulted in the “greenhouse” effect. This has created problems related to energy provision and environment preservation (obligations to reduce CO₂ emissions and reduce the impacts on climate change, as per the Kyoto Protocol) (Babić and Đurišić, 2015; Carvalho, 2012a). Utilization of renewable energy sources (RES) is one of the methods of meeting the energy needs in an ecologically and economically justifiable manner in the global energy development strategy. Serbia has accepted the COP28 Agreement, whereby the RES capacity must be tripled by 2030, and the transition from fossil fuels to RES in the energy systems should be accelerated in this decade to achieve zero emissions by 2050 (Cop 28, 2023). RESs are energy resources used for the production of electrical energy or heat, whose reserves are found in nature and are fully or partially renewable. The Sun is by far the largest source of renewable and unlimited energy for humans and has great potential. The energy from solar radiation that reaches the surface of the Earth is 1.9×10^8 TWh per year, which is 170 times



the energy from the total known coal reserves in the world. This means that the energy from solar radiation is sufficient to produce an average of 1700 kWh of electricity per year on each square meter of the Earth's surface (Babić, 2016).

Photovoltaic (PV) power systems are used to produce electrical energy from solar irradiation. The quantity of electrical energy that can be obtained from a PV system primarily depends on the radiated solar energy at the location being analyzed. The capacity for solar irradiation on the Earth's surface depends on several factors, such as latitude, cloud cover, season, and time of day. The actual global horizontal irradiation (GHI) for Europe is shown in Figure 1 (Batić and Đurišić, 2021). From Figure 1, it can be concluded that Serbia has a solar radiation energy potential of over 30% higher than that of Germany, which leads the production of electricity from PV systems in Europe. Figure 2 presents a map of the global potential of solar radiation in the Republic of Serbia. The figure shows that the average annual solar energy irradiation per unit of horizontal surface in the open terrain varies from 1,450 kWh/m² in the South to approximately 1,250 kWh/m² in the North of Serbia.

The explosive progresses of PV cell production and technologies have resulted in multiple reductions in the market prices of PV system components (Babić, 2016). Progress regarding technological developments of PV systems has been directed toward the fabrication of more energy efficient and cheaper PV cells, such as thin-film technology, organic PV cells, and perovskite minerals for PV cells (Babić, 2016). The type of PV module used and its operating temperature can impact the electrical performance. Given the various solar cell materials used in PV modules, approximately 6%–20% of the incident solar energy is transformed into electricity. The efficiency of the PV module is also decreased because the remaining solar radiation increases its temperature (Kumar et al., 2020).

2 Comparative analysis of electrical energy production in PV power plants

This work presents a comparative analysis of the electrical energy production of PV power plants using different PV panel

technologies. Differences in the PV panel technologies can affect the degree of conversion of solar radiation to electrical energy. In this work, the following technologies are analyzed and discussed: monocrystalline, polycrystalline, thin-layer amorphous (a-Si), and cadmium–telluride (CdTe). The analyzed PV systems had the same nominal power of 10 kW and were situated in the same geographical location in Belgrade, Serbia, with the same orientation, tilt, and azimuth angle of the PV panels. The geographical coordinates of the PV power plant are N 44°48'14" and E 20°27'54". Figure 3 shows the sun path diagram for the geographical location in Belgrade, Serbia. The PV power plants had similar dimensions and nominal power values. The main differences between the plants were regarding the types of PV panels used, which were fabricated by different manufacturers based on different technologies, as mentioned previously.

The efficiency of a PV power plant can be expressed using different parameters as different indicators of the PV system operation. In this work, detailed calculations of the solar potential of the target location in Belgrade, Serbia, were obtained using the professional software package PVsyst developed by scientists from the University of Geneva in Switzerland. To facilitate comparisons between several PV power plants, the European Joint Research Center introduced a performance index, which is outlined in the IEC EN 61724 norm (PVsyst, 2024). The performance ratio (PR) is the ratio of the effective energy produced to the energy produced if the system was working continuously at the efficiency of its nominal standard test conditions (STCs).

Since the current–voltage characteristic of a PV module changes with the insolation and temperature, the STCs were established to compare different PV modules. The manufacturers of PV modules provide some basic characteristics related to the STCs. The efficiency coefficient represents the part of the solar energy converted to electricity and is defined for the STCs.

The STCs include the following:

- Solar irradiation on the surface of the panel is 1000 W/m² (one Sun);
- the temperature of the PV cell is 25°C;
- the coefficient of air mass is 1.5.

These terms are accepted by the International Electrotechnical Commission (IEC) and American Society for Testing and Materials (ASTM). The reference test conditions are used by the PV module manufacturers to define the specific parameters. The PV modules are then tested indoors, where the temperature and intensity can be adjusted artificially (Batić et al., 2023).

The energy potentially produced under the STCs is equal to $G_{lob}I_{nc} \cdot P_{nomPV}$, where $G_{lob}I_{nc}$ is the hourly value of the incident global irradiance on the PV module and P_{nomPV} is the nominal installed power under STCs as given by the PV module manufacturer (Batić et al., 2023). The energy E_{grid} is calculated the active energy and expressed in terms of kilowatt-hour. This equivalence is explained by the fact that at STC each kWh/m² of incident irradiation will produce 1 kWh of electricity. Therefore for a grid-connected system we have Equation 1 for the Performance Ratio (PR);

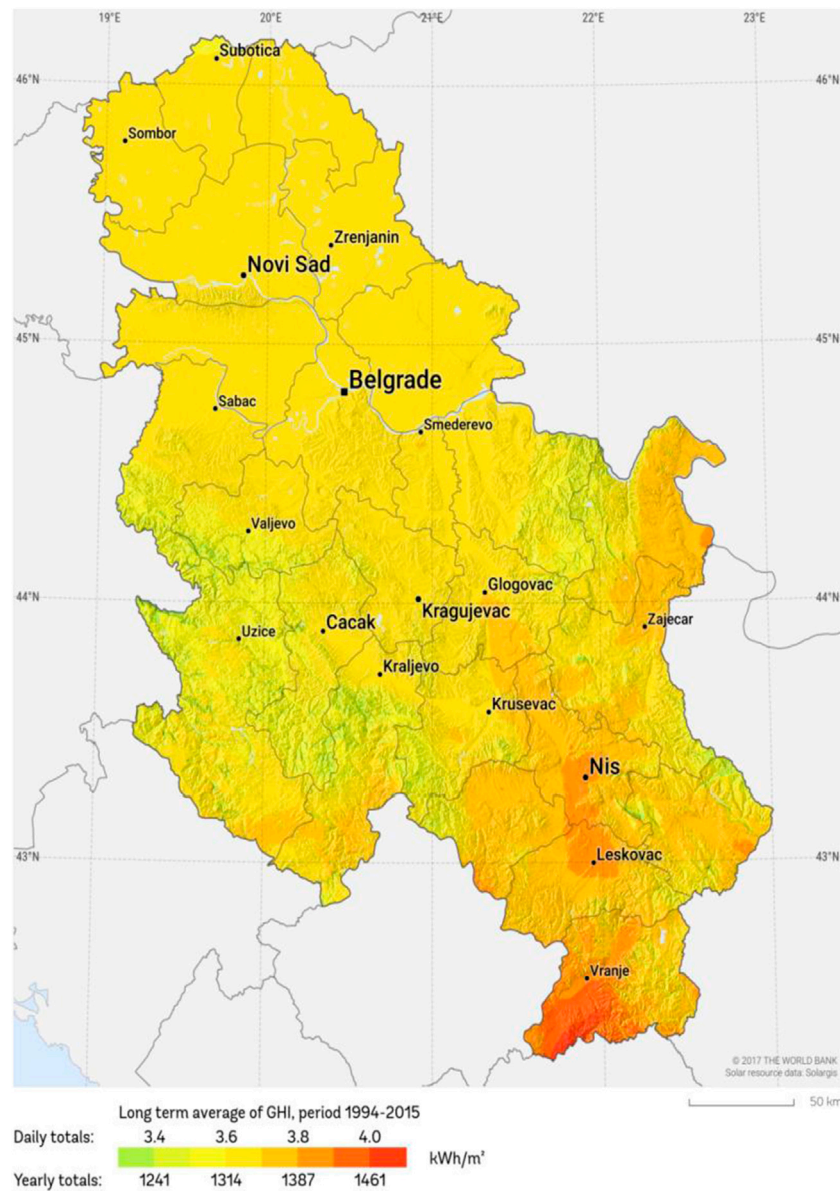


FIGURE 2
Solar potential of Serbia (Batić and Đurišić, 2021).

$$PR = \frac{E_{grid}}{(G_{lob} I_{nc} \cdot P_{nomPV})} \quad (1)$$

Given that the Performance Ratio (PR) is the ratio of electrical energy generated by a PV power plant in a certain time interval, delivered to the power distribution network and the total installed power of PV modules, it can be also defined with Equation 2 (PVsyst, 2024):

$$PR = \frac{Y_f}{Y_r} \quad (2)$$

where Y_r is the reference system yield or ideal array yield according to P_{nom} defined by the manufacturer without any loss. It can be understood as the ideally produced array nominal power P_{nom} by each incident kWh over 1 h; Y_r is numerically equal to the energy

incident on the array plane and is expressed in [kWh/m²/day]. Y_f is the system yield or daily useful energy of the PV system with reference to the nominal power and is expressed in [kWh/KWp/day].

The reference system yield (Y_r) represents the maximum amount of electricity that can be obtained from the given PV panels when illuminated under the most favorable conditions in relation to their nominal power P_{nomPV} . The reference system yield represents the number of sunny hours with maximum irradiation, which in fact defines the solar resources of the PV system for a specific location. All PV systems analyzed in this work are located in the same place in Belgrade, so they have the same value of Y_r . Under the most favorable conditions, Y_r for the analyzed systems with equal nominal power values of 10 kW at the given location is 4.289 kWh/m²/day, as shown in Figure 4. The system yield (Y_f)

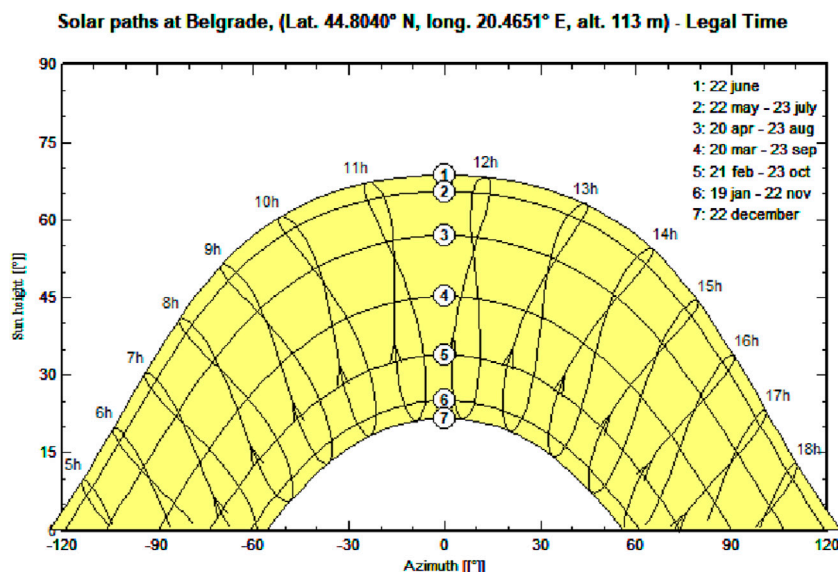


FIGURE 3 Sun path diagram (Meteonorm, 2024).

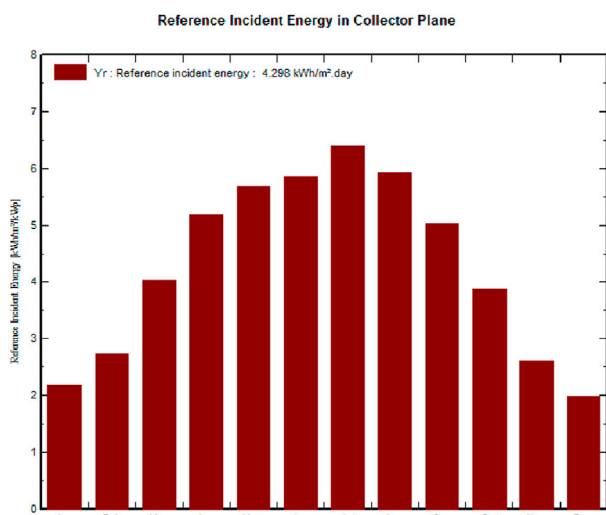


FIGURE 4 Reference incident energies of PV power plants in Belgrade (PVsyst, 2024).

refers to the electrical energy generated by a PV power plant over a certain duration and delivered to the power distribution network. The Y_f values are characteristic for each of the PV systems because they depend on the quality and specifications of the panels, weather conditions, and temperature.

PV modules from different manufacturers were selected in these analyses. For the monocrystalline and polycrystalline technologies, 230 Wp PV modules from Canadian Solar were analyzed. For the CdTe technology, 390 Wp PV modules from First Solar were analyzed. For the a-Si technology, 48 Wp PV modules from Fuji Electric were analyzed. The technical specifications provided by the manufacturers for the analyzed PV modules are given in Table 1.

Each of the four analyzed PV systems has the same rated power and uses the same 2-kW-rated inverter from Fronius International. In these analyses, the best annual performance of 3.69 kWh/kWp/day was obtained for the PV system with monocrystalline technology, followed by the 3.66 kWh/kWp/day performance of the CdTe-based PV system. The lowest value performance was obtained as 3.44 kWh/kWp/day for the a-Si technology.

Figure 5 shows the graphs of the different technologies along with their system yields (Y_f) and losses (L_c and L_s). The losses of a PV power plant are very important parameters with regard to system performance. The PV power plant losses are calculated as a difference between the yields and are presented in terms of kWh/KWp/day; this means that they give the number of working hours per day (or month or year) that the plants were not used. These include the array operation loss (L_c) and system operation loss (L_s). The array operation loss (L_c) is given as the difference between the reference and array yields and represents the panel loss, i.e., loss incurred in the operation of the array of panels (PVsyst, 2024). $L_c = Y_r - Y_a$ is the array loss, which includes thermal, wiring, module quality, module mismatch, incidence angle modifier (IAM), shading, dirt, maximum power point (MPP), and regulation losses as well as all other inefficiencies. Here, Y_a is the array yield or daily output electrical energy of the array with reference to the nominal power [kWh/KWp/day]. The system operating loss (L_s) is the total loss from all other components of the PV system excluding the PV panels; these include losses in the cables, switches, protective equipment, energy converters (DC/DC and inverter), and connecting equipment. These losses show the imbalance between electrical energy production with PV panels and the needs of the energy consumers. The system operating loss is calculated as (PVsyst, 2024) $L_s = Y_a - Y_f$, which also includes the inverter loss in grid-connected systems. The array and system losses for the four types of PV panel technologies are given in Table 2.

From the graphs in Figure 5, it is seen that the largest array and system losses are incurred during the summer months. This can be

TABLE 1 Technical specifications provided by the manufacturers for the PV modules.

Type of PV panel technology	PV module manufacturer	Nominal power (Wp)	Module efficiency (%)	Module area (m ²)	Short-circuit current (A)	Open-circuit voltage (V)
Monocrystalline	Canadian Solar	230	17.65	1.3	9.6	31.6
Polycrystalline	Canadian Solar	230	15.90	1.6	9.1	37.5
Cadmium-telluride (CdTe)	First Solar	390	15.76	2.5	2.5	214.8
Thin-layer amorphous (a-Si)	Fuji Electric	48	6.16	0.8	0.4	218

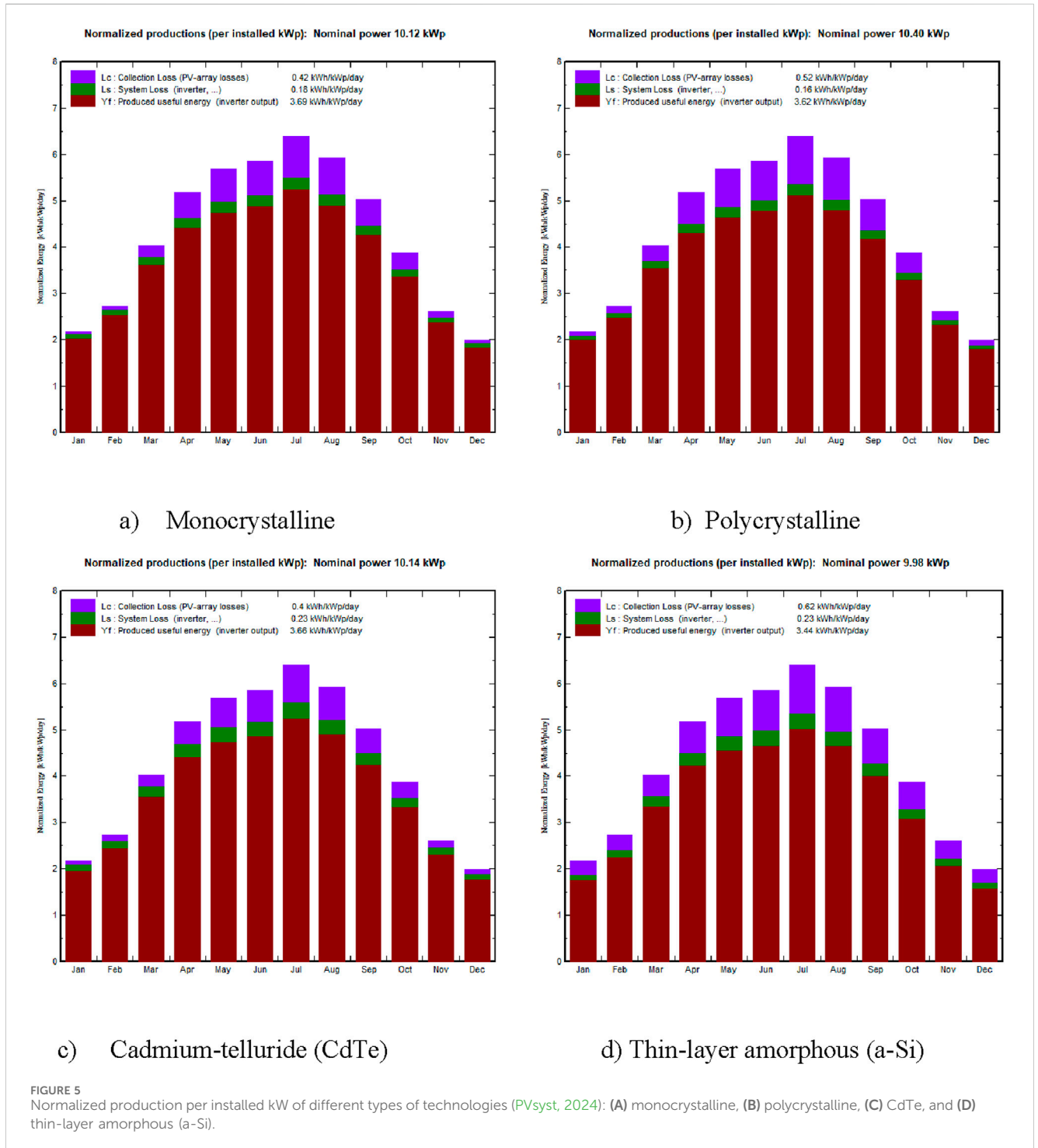
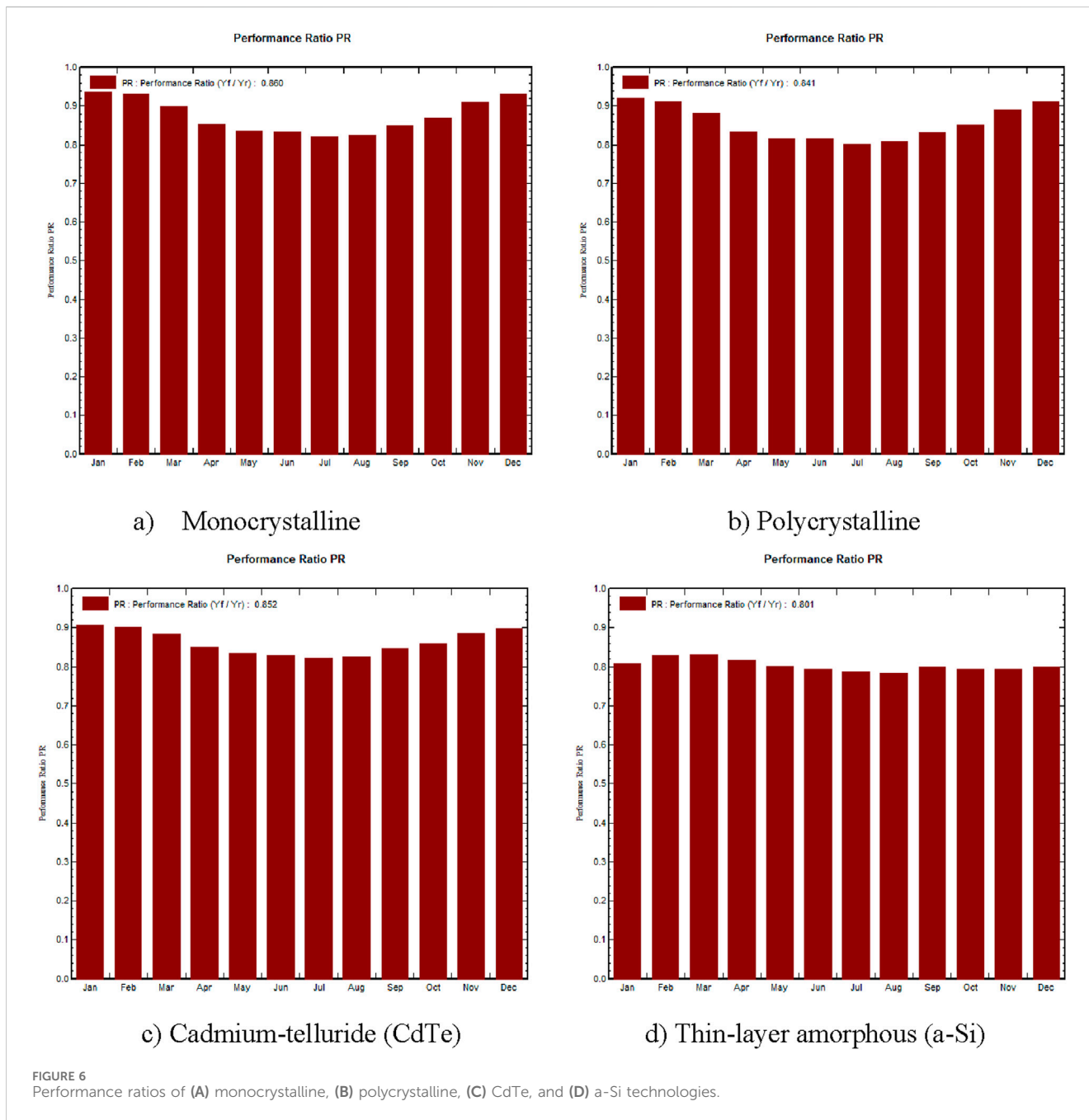


TABLE 2 Losses in the PV systems.

Type of PV panel technology	Array loss L_c (kWh/KWp/day)	System loss L_s (kWh/KWp/day)
Monocrystalline	0.42	0.18
Polycrystalline	0.52	0.16
Cadmium–telluride (CdTe)	0.4	0.23
Thin-layer amorphous (a-Si)	0.62	0.23



explained by the fact that PV panels are exposed to solar irradiation for longer periods of time and very high temperatures during summer. The lowest array losses are noted as 0.4 kWh/kWp/day

and 0.42 kWh/kWp/day for the systems with CdTe and monocrystalline PV panels, respectively. These results are very good and encouraging because monocrystalline PV panels are

TABLE 3 Annual performance ratio (PR).

Type of PV panel technology	Annual performance ratio (PR) (%)
Monocrystalline	86
Polycrystalline	84.1
Cadmium-telluride (CdTe)	85.2
Thin-layer amorphous (a-Si)	80.1

widely used in Serbia. The CdTe-based PV technology is the leading and foremost technology in the rapidly growing thin-film PV industry (Rawat et al., 2018). The highest array loss is noted as 0.62 kWh/kWp/day for the system with a-Si PV panels. The system losses are lower than the array losses for all of the PV technologies analyzed herein. The lowest system loss of 0.16 kWh/kWp/day was noted for the system with polycrystalline PV panels, and the highest system losses of 0.23 kWh/kWp/day each were noted for the systems with a-Si and CdTe PV panels.

Figure 6 shows the monthly results for the PR, which includes all the losses in the PV systems, namely, optical losses (shading, IAM, and soiling), array losses (PV conversion, aging, module quality, mismatch of PV panels, and wiring), and system losses (inverter efficiency in the grid-connected system). The PR is not dependent on the PV module efficiency. As an example, an amorphous module and a crystalline high-efficiency module both have comparable PR. Only low-light performance and temperature dependency can induce differences. The PR is a very important parameter in the PV industry; it is often used as a warranty when commissioning a PV system or for verifying the annual yield. The PR is not constant throughout the year and can change daily or monthly. Usually, the PR is considered over 1 year. The system PR shows the real performance of a PV power plant in relation to the theoretical maximum possible and is expressed as a percentage. Table 3 shows the annual value for each PV panel technology analyzed in this work. It is considered that PV power plants with annual PR values greater than 85% are of good quality (PVsyst, 2024). From Table 2, it can be concluded that the best values for the annual PR of 86% and 85.2% entail plants with monocrystalline and CdTe PV panels, respectively. The lowest annual PR of 80.1% is obtained for a PV power plant with a-Si panels.

3 Impacts of PV power plants on the environment through CO₂ emission reductions

As mentioned previously, electrical energy production from conventional fossil energy sources, especially those based on oil and coal, has a negative impact on the environment. The main negative impact of electrical energy production that creates global problems is the emission of greenhouse gases into the atmosphere. Fossil fuels have higher specific emissions of equivalent gases than RESs. Gases like CO₂, NO_x, and SO₂ that are emitted into the atmosphere can have negative impacts on the environment, such as global warming due to the greenhouse effect, occurrence of acid rain, and unfavorable impact on the ecosystem.

CO₂ is considered the reference gas for global warming and the greenhouse effect. This greenhouse effect represents warming of the planet Earth and is caused by disruption of the energy balance between the amount of radiation received by the Earth's surface from the Sun and that which radiates into space; i.e., it is the result of an increase in the amount of radiation that the Earth's surface cannot emit into space but is absorbed by the greenhouse gases to increase the temperature of the Earth's atmosphere. When 1 kWh of electrical energy is produced in a thermal power plant, 1 kg of CO₂ is emitted into the atmosphere (Babić, 2016).

The use of RESs is very high on the list of priorities of the European Union and occupies a significant place in the European strategy on energy and climate change (Carvalho, 2012b). In 2008, the European Parliament adopted a package of regulations on climate change with the aim of reducing greenhouse gases (European Union, 2017). By ratifying the Treaty on the Establishment of the Energy Community, the Republic of Serbia accepted the obligation to enact and enforce a plan for implementing the directive on promoting electrical energy production from RESs (European Union, 2017).

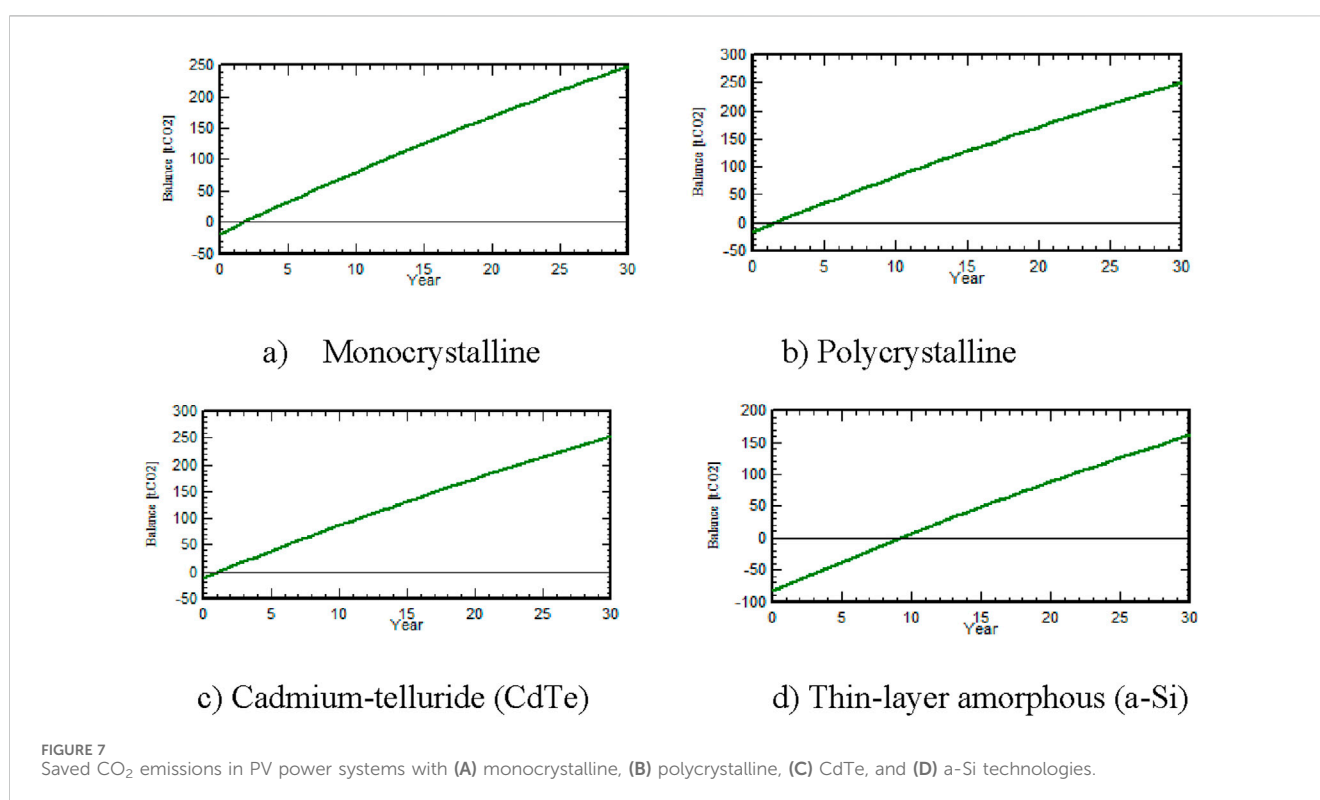
Nowadays, the focus is on renewable-energy-based power generation systems as the basis for achieving the Sustainable Development Goals (SDGs) (Bošnjaković et al., 2023). The SDGs constitute a set of 17 global goals established by the United Nations in 2015 and aimed at addressing various global challenges, including poverty, inequality, climate change, environmental degradation, and peace and justice. The main aims of the SDGs are to eliminate discrimination and inequality, end poverty, and overcome climate change by 2030 (Nooman AlMallahi et al., 2024). Several SDGs are particularly relevant with respect to PV technologies; PV technologies contribute significantly to increase the share of renewable energy in the global energy mix, making energy more accessible and sustainable, which is directly related to SDG7. By reducing our reliance on fossil fuels and lowering greenhouse gas emissions, PV technologies play crucial roles in combating climate change related to SDG13.

PV systems are found as clean and sustainable sources of energy. The electricity generated from solar energy increased from 72 GW in 2011 to 850 GW in 2021 (Nooman AlMallahi et al., 2024). According to numerous projections on the number of installed PV systems by 2050, it is expected that a significant part of CO₂ emissions will be reduced. This goal is very ambitious, but if the integration of PV systems were to continue and if the predicted projections were realized, the reduction of the predicted CO₂ emissions would be easily achieved (Guo et al., 2023; Wang et al., 2024). Bošnjaković et al. (2023) analyzed greenhouse gas emissions based on the installed capacity of a power plant; these power plants were divided into four groups, and the CO₂ eq./kWh emissions ranged from 12.5 to 126. This variability can be caused by differences in the energy requirements during manufacturing and assembly processes as well as the energy mixtures used to manufacture PV modules (Fthenakis et al., 2008). Additionally, variations in module technology (efficiency) and device lifetimes (varying from 15 to 30 years) can be important factors (Sherwani et al., 2010).

Solar energy is one of the most significant RESs that allows production of clean power while significantly reducing CO₂

TABLE 4 Reduction of CO₂ emissions over the 30-year period of exploitation of the PV power plant.

Type of PV panel technology	Total savings of CO ₂ emissions over 30 years (tCO ₂)	Yearly savings of CO ₂ emissions (tCO ₂ /year)	Savings of CO ₂ emissions per installed power plant (tCO ₂ /kWp)	Yearly savings of CO ₂ emissions per installed power plant (tCO ₂ /kWp/year)
Monocrystalline	248.700	8.290	24.575	0.819
Polycrystalline	252.215	8.407	24.251	0.808
Cadmium-telluride (CdTe)	252.036	8.401	24.856	0.829
Thin-layer amorphous (a-Si)	162.286	5.410	16.255	0.542



emissions (Tawalbeh et al., 2021; Shahsavari and Akbari, 2018). According to the IEA tracking report of 2022 (Bojek, 2022), the CO₂ emissions for the production of PV systems ranged from 14 to 73 g of CO₂ eq./kWh depending on the PV technology, location of the power plant, and electricity mix used for production. This is 10–53 orders of magnitude lower than the emissions reported for the burning of oil (742 g of CO₂ eq./kWh). The reported values for CO₂ emissions are roughly in the same range as those for concentrated solar power technologies (8–90 g of CO₂ eq./kWh) (Bošnjaković et al., 2023). It was also noted that the carbon footprint of a PV system could be further decreased by one order of magnitude through the use of novel manufacturing materials (Tawalbeh et al., 2021). PV power plants emit an average of 48 g of CO₂/kWh during their working life, and this is a very coarse global average value.

PV cells are made from different types of semiconductor materials. Most studies in literature have evaluated the greenhouse gas emissions of c-Si cells (monocrystalline and polycrystalline), while thin-film technology has been analyzed to a lesser extent (Bošnjaković et al., 2023). According to Silva and Raadal (2019), the mean estimated values of greenhouse gas emissions for monocrystalline, polycrystalline, and thin films were 61.8, 52.2, and 35.5 g of CO₂ eq./kWh, respectively. The average greenhouse gas emission for a-Si technology is 30 g, CdTe technology is 27 g, and CIGS technology is 53 g of CO₂ eq./kWh. CdTe thin-film technology has the lowest average value of greenhouse gas emissions because the production of CdTe thin-film modules requires a lower amount of energy compared to other technologies (Fthenakis et al., 2008; Fthenakis and Kim, 2011). Greenhouse gas emissions from PV

power plants can decrease over time as the PV modules become more efficient, production of solar cells becomes less energy intensive, and share of renewable energy in the power grid increases (Bojek, 2022).

In the present work, the reduction in CO₂ emission expected from a PV installation is estimated. The basis of this calculation is the so-called lifecycle emission (LCE), which represents the CO₂ emission associated with a given component or energy amount. This value includes the total lifecycle of a component or energy amount, including production, operation, maintenance, and disposal. The LCE methodology used in most studies is the “cradle-to-gate” approach. It should be noted that there may be differences in the methodologies used by different authors and hence differences in the data obtained.

The electricity produced by a PV installation is expected to replace the same amount of electricity in an existing grid. If the carbon footprint of the PV installation per kWh is smaller than that for the grid electricity production, there will be a net saving of CO₂ emissions. Thus, the total carbon balance for a PV installation is the difference between the produced and saved CO₂ emissions and depends on four key factors (PVsyst, 2024):

1. E_Grid: production of the PV installation for 1 year.
2. Lifetime: this is the lifetime of the PV installation in years; together with E_Grid, it determines the total amount of energy that will be replaced by the PV installation.
3. Grid LCE: this is given in grams of CO₂/kWh and represents the average amount of CO₂ emissions per energy unit for the electricity produced by the grid.
4. PV system LCE: this is given in tons of CO₂ and represents the total amount of CO₂ emissions resulting from the construction and operation of the PV installation.

For the analyzed PV power plants based on different PV technologies, Table 4 shows the calculated values of the CO₂ emission reductions. There are four values for these results:

1. Total CO₂ emission savings over the expected lifetime of the PV installation (t).
2. Yearly CO₂ emission savings (tCO₂/year).
3. CO₂ emission savings per installed power plant (tCO₂/kWp).
4. Yearly CO₂ emission savings per installed power plant (tCO₂/kWp/year).

The yearly values are averaged over the entire lifetime by taking into account the annual degradation. The obtained values are graphically shown in Figure 7. These values represent the estimated CO₂ emission savings expected for the PV installation. This reduction in CO₂ emissions is achieved with electrical energy production in the PV power plants by considering that each kWh of energy produced by the PV power plant replaces the average kWh amount of energy from the present thermal power plants in Serbia. The present emission factor for the electrical energy mix in Serbia is 1.099 tCO₂/MWh. It is assumed that the expected lifetime of a PV power plant is 30 years, and this is the period of exploitation of the PV power plants used in the calculations.

In terms of CO₂ emission reduction, the best performance of 252.215 tCO₂ is observed for the PV power plant with polycrystalline panels over the lifetime of the plant and 8.407 tCO₂/year savings of CO₂ emissions. Very similar reductions in CO₂ emissions were obtained for the PV power plant with CdTe panels (252.036 tCO₂ over the lifetime of the plant and 8.401 tCO₂/year savings of CO₂ emissions). The least reduction in CO₂ emission was observed for the PV power plant with a-Si panels, with 162.286 tCO₂ reduction over the lifetime of the plant and 5.410 tCO₂/year savings of CO₂ emissions.

4 Conclusion

This work presents an analysis of the potential for electrical energy production from solar irradiation in Serbia. It is well known that the Sun is the largest source of renewable energy. Serbia has very good potential for receiving solar irradiation, which is over 30% higher than that for Germany that is the leader in electricity production from PV systems in Europe. A comparative analysis of electrical energy production from PV power plants using different PV panel technologies is presented herein. The aim of this research was to determine the manner in which different PV panel technologies impact PV power plant production. Different PV panel technologies can affect the degree of conversion of solar irradiation to electrical energy, and they can also affect the ecological parameters of the use of PV panels by reducing CO₂ emissions from the systems. The following PV panel technologies are analyzed in this work: monocrystalline, polycrystalline, a-Si, and CdTe. The software tool used for the analysis was PVsyst.

For the given types of PV systems, the characteristic parameters, comparisons of the obtained values, and impacts on environmental pollution were calculated. By comparing the obtained values, it was observed that all PV systems analyzed herein showed positive results. In this work, the system yield was calculated for each type of PV panel technology, and this yield is characteristic of the corresponding PV system because it depends on the quality and specifications of the panels, weather conditions, and temperature. The best annual performances were obtained for the PV systems implementing monocrystalline and CdTe technologies. The lowest performance was obtained for the system with a-Si panels. The lowest array losses were noted for the systems with CdTe and monocrystalline PV panels, while the highest array loss was noted for the system with a-Si PV panels.

In terms of CO₂ emission reduction, the best performance was noted for the PV power plant with polycrystalline panels (252.215 tCO₂ over the lifetime of the plant and 8.407 tCO₂/year savings of CO₂ emissions). A similar reduction in CO₂ emission was noted for the PV power plant with CdTe panels (252.036 tCO₂ over the lifetime of the plant and 8.401 tCO₂/year savings of CO₂ emissions). The least reduction in CO₂ emission was noted for the PV power plant with a-Si panels (162.286 tCO₂ over the lifetime of the plant and 5.410 tCO₂/year savings of CO₂ emissions). The expected lifetime of a PV power plant is 30 years.

The monocrystalline and polycrystalline technologies are widely used in Serbia, so analyses of their impacts are very useful and precious. The results obtained in this study for these two technologies are excellent and encouraging. By advancing PV technologies, countries around the world, including Serbia, can initiate significant progress toward achieving these and other SDGs to promote a more sustainable and equitable future for all humans.

Author contributions

IB: writing—original draft and writing—review and editing.

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References

- Babić, I. (2016). *Modeling the influence of the solar radiation time profile on the photovoltaic systems operations effects in a power system*. University of Belgrade, School of Electrical Engineering. Doctoral dissertation. Available at: <https://www.scribd.com/document/332692464/Iva-Babic-Doktorska-Disertacija>
- Babić, I., and Đurišić, Ž. (2015). Impact of daily variation of solar radiation on photovoltaic plants economy at the open market. *Therm. Sci.* 19 (3), 837–844. doi:10.2298/tsci141025009b
- Batić, I., Batić, M., and Đurišić, Ž. (2023). Impact of air temperature and wind speed on the efficiency of a photovoltaic power plant: an experimental analysis. *Therm. Sci.* 27 (1A), 299–310. doi:10.2298/tsci220610160b
- Batić, I., and Đurišić, Ž. (2021). "Analysis of the photovoltaic systems construction capacities and conditions on the preschool buildings roofs in Serbia," in 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), Fort Lauderdale, FL, USA, 0199–0205.
- Bojek, P. (2022). *Solar PV—tracking report—september 2022*. Paris, France: IEA.
- Bošnjaković, M., Santa, R., Crnac, Z., and Bošnjaković, T. (2023). Environmental impact of PV power systems. *Sustainability* 15 (15), 11888. doi:10.3390/su151511888
- Carvalho, M. G. (2012a). EU energy and climate change strategy. *Energy* 40, 19–22. doi:10.1016/j.energy.2012.01.012
- Carvalho, M. G. (2012b). EU energy and climate change strategy. *Energy* 40, 19–22. doi:10.1016/j.energy.2012.01.012
- Cop 28 (2023). COP28 declaration on climate, relief, recovery and peace. Available at: <https://www.cop28.com/en/cop28-declaration-on-climate-relief-recovery-and-peace>.
- European Union (2017). Directive 2009/28/EC of the European parliament and of the council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Available at: <https://eur-lex.europa.eu/EN/legal-content/summary/promotion-of-the-use-of-energy-from-renewable-sources.html#:~:text=This%20directive%2C%20which%20amends%20and%20repeals%20earlier%20Directives,greenhouse%20gas%20%28GHG%29%20emissions%20and%20promote%20cleaner%20transport>.
- Fthenakis, V. M., and Kim, H. C. (2011). Photovoltaics: life-cycle analyses. *Sol. Energy* 85, 1609–1628. doi:10.1016/j.solener.2009.10.002
- Fthenakis, V. M., Kim, H. C., and Alsema, E. (2008). Emissions from photovoltaic life cycles. *Environ. Sci. Technol.* 42, 2168–2174. doi:10.1021/es071763q
- Guo, X., Dong, Y., and Ren, D. (2023). CO2 emission reduction effect of photovoltaic industry through 2060 in China. *Energy* 269, 126692. doi:10.1016/j.energy.2023.126692
- Kumar, R., Deshmukh, V., and Singh Bharj, R. (2020). Performance enhancement of photovoltaic modules by nanofluid cooling: a comprehensive review. *Int. J. Energy Res.* 44 (8), 6149–6169. doi:10.1002/er.5285
- Meteonorm (2024). Meteonorm software worldwide irradiation data. Available at: <https://meteonorm.com/en/>.
- Nooman AlMallahi, M., Al Swailmeen, Y., Ali Abdelkareem, M., Ghani Olabi, A., and Elgendi, M. (2024). A path to sustainable development goals: a case study on the thirteen largest photovoltaic power plants. *Energy Convers. Manag.* X 22, 100553. doi:10.1016/j.ecmx.2024.100553
- PVsyst (2024). Design and simulation software for your photovoltaic systems. Available at: <https://www.pvsyst.com/>.
- Rawat, R., Kaushik, S. C., Sastry, O. S., Bora, B., and Singh, Y. K. (2018). Long-term Performance Analysis of CdTe PV module in real operating conditions. *Mater. Today Proc.* 5 (11), 23210–23217. doi:10.1016/j.matpr.2018.11.052
- Shahsavari, A., and Akbari, M. (2018). Potential of solar energy in developing countries for reducing energy-related emissions. *Renew. Sustain. Energy Rev.* 90, 275–291. doi:10.1016/j.rser.2018.03.065
- Sherwani, A. F., Usmani, J. A., and Varun, (2010). Life cycle assessment of solar PV based electricity generation systems: a review. *Renew. Sustain. Energy Rev.* 14, 540–544. doi:10.1016/j.rser.2009.08.003
- Silva, M., and Raadal, H. L. (2019). *Life cycle GHG emissions of renewable and non-renewable electricity generation technologies part of the RE-invest project*. Aalborg, Denmark: Aalborg University.
- Tawalbeh, M., Al-Othman, A., Kafiah, F., Abdelsalam, E., Almomani, F., and Alkasrawi, M. (2021). Environmental impacts of solar photovoltaic systems: a critical review of recent progress and future outlook. *Sci. Total Environ.* 759, 143528. doi:10.1016/j.scitotenv.2020.143528
- Wang, L., Qiu, T., Zhang, M., Cao, Q., Qin, W., Wang, S., et al. (2024). Carbon emissions and reduction performance of photovoltaic systems in China. *Renew. Sustain. Energy Rev.* 200, 114603. doi:10.1016/j.rser.2024.114603

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