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ORIGINAL PAPER

Assessing the sustainability of solar photovoltaics: the case of glass–glass and standard panels manufactured in Lithuania

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Abstract

The life cycles of glass–glass (GG) and standard (STD) solar photovoltaic (PV) panels, consisting of stages from the production of feedstock to solar PV panel utilization, are compiled, assessed, and compared with the criteria representing energy, environment, and economy disciplines of sustainability and taking into account the climate conditions of Lithuania. The following methods were applied: "*PVsyst*" software, life-cycle assessment (LCA), levelized cost of electricity (LCOE), case studies, comparative analysis, and logical reasoning. The results show that the GG type solar PV panel was more efficient and had better environmental performance than the STD type. During its lifetime, the 1 kW GG type produces 67% more energy and emits 42% less greenhouse gasses (GHGs) than the STD type. The 1 kW GG type could produce 32.75 MWh of electricity and emit 28.0 gCO_{2eq}/kWh. It outperformed the STD type regarding energy and GHG emission payback times, which were estimated to be 3.5 and 3.7 months, respectively. Despite the higher PV panel price of the GG type, its economy is better. Depending on the project financing strategy, the estimated average LCOE of the GG type is 4% lower than that of the STD type. Specifically, the average LCOE of the GG type panels are approximately 0.15 EUR/kWh. These are reduced to 0.13 EUR/kWh, subject to an investment subsidy of 323 EUR/kWp. Overall, the GG type is more sustainable than the STD type. The research results substantiate the relevance of manufacturing and deploying advanced solar PV technologies to meet climatic and sustainable development targets.

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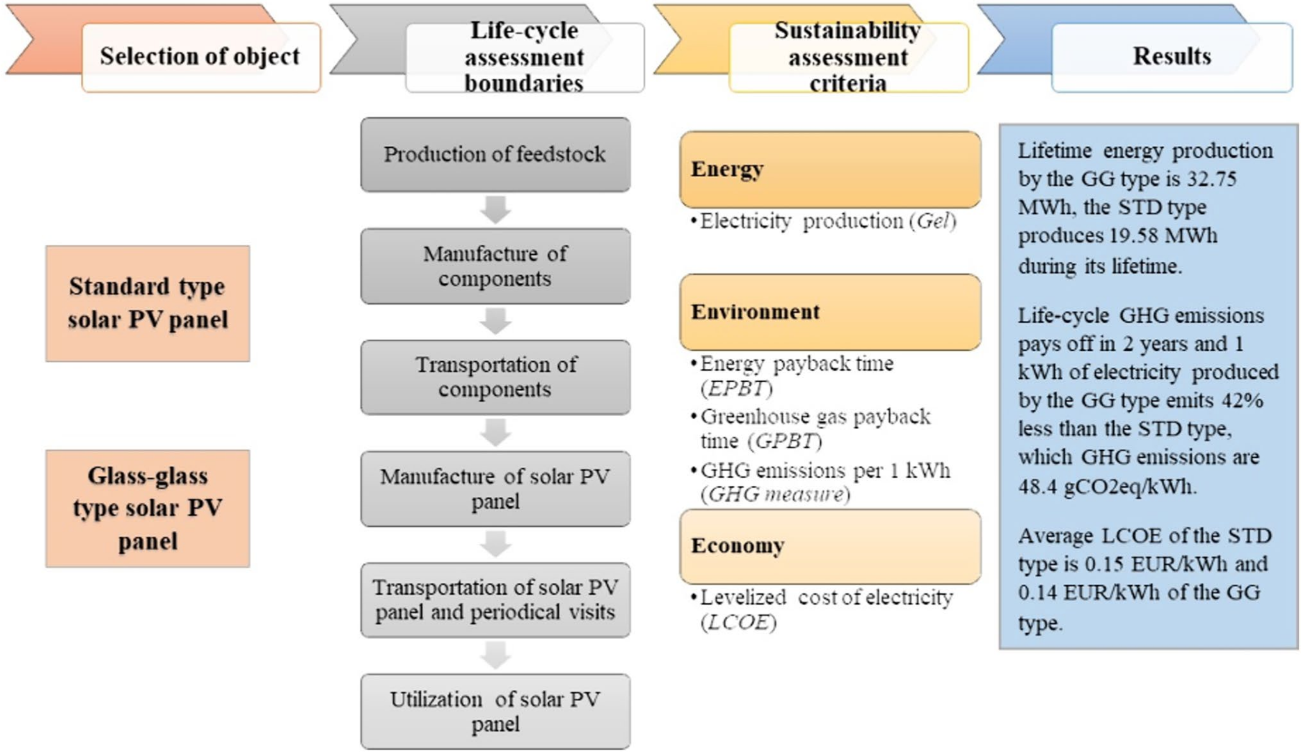
Graphical Abstract



Lifetime energy production by the GG type is 32.75 MWh, the STD type produces 19.58 MWh during its lifetime.

Life-cycle GHG emissions pays off in 2 years and 1 kWh of electricity produced by the GG type emits 42% less than the STD type, which GHG emissions are 48.4 gCO2eq/kWh.

Average LCOE of the STD type is 0.15 EUR/kWh and 0.14 EUR/kWh of the GG type.

Keywords Climate change · Sustainable development · Life-cycle assessment · Levelized cost of energy · Efficiency

Introduction

Worldwide energy demand is increasing by 1% to 6% per year (Ritchie et al. 2022), and is expected to increase by nearly 50% by 2050 compared to 2020 (Energy Information Administration 2021). Energy consumption remains fossil fuel-based, accounting for a share of 81% in 2020, despite shifts to renewable energy sources (RESs), which accounted for 15% (Energy Information Administration 2021). The combustion of fossil fuels to satisfy this increasing demand has led to significant increases in greenhouse gas (GHG) emissions of 2.4% per year, resulting in global warming (Hausfather and Friedlingstein 2022). In 2015, the United Nations (UN) and its Member States (MS) signed the Paris Agreement (United Nations 2015a), in the framework of which they agreed to limit global warming to well below 2 °C and to pursue efforts to limit it to 1.5 °C by undertaking relevant measures to reduce GHG emissions rapidly. In the same year, the MS of the UN agreed on "Transforming Our World: the 2030 Agenda for Sustainable Development" (United Nations 2015b) and announced 17 sustainable development goals (SDGs). Through SDG 13, which required urgent action to combat climate change and its impacts (United Nations 2015b), the UN established clear linkages between development and the climate (Gomez-Echeverri 2018), the latter being implemented in part through the Paris Agreement by applying various strategies (Segger 2016). The deployment of renewable energy technologies is among these.

Solar photovoltaic (PV) systems are among the fastest-growing renewable energy technologies worldwide. The global solar PV installed capacity significantly increased from 0.81 GW in 2000 to 854.8 GW in 2021 (International Renewable Energy Agency 2022). In recent years, global solar PV capacity has outgrown wind energy capacity. Among all renewable technologies, solar PV has the greatest social support (Igliński et al. 2023). The transformation of the global energy system is essential to satisfy SDG 13 and the climate mitigation goals of the Paris Agreement. This transformation is possible by rapidly deploying low-carbon technologies to replace conventional fossil fuel technologies. According to the International Renewable Energy Agency (2019), solar energy will transform the global electricity sector; the cumulative installed capacity of solar PV is expected to rise to 8519 GW by 2050. In light of globally increasing installations, the sustainability of solar PV technologies must be accurately assessed to scale up solar PV electricity to achieve SDGs.

Abu-Rayash and Dincer (2018) argued that a set of disciplines influence the sustainability assessment of solar PV systems, including energy, exergy, economy, environment, society, technology, education, and the size of the energy system, and pointed out that thus far the majority of sustainability assessments focus on the particular discipline. There is a lack of universally adopted sustainability assessment models. Even if such models exist, they prioritize energy, environment, and economy disciplines over others (Abu-Rayash and Dincer 2018). The finding was supported by Yaghoubirad et al. (2022), who performed a multi-criteria analysis comprising energy, exergy, economy, and environment disciplines of solar PV panels to investigate variations in climate conditions on the panel performance. Responding to the conclusions of Abu-Rayash and Dincer (2018) and the choice of Yaghoubirad et al. (2022), in the study, we carry out a sustainability assessment of solar PV panels in terms of energy, economy, and environment disciplines.

Various approaches, methods, and indicators are applied to carry out the sustainability assessment of the solar PV systems according to the prioritized disciplines and make decisions. Energy analysis of solar PV systems consist of an assessment of at least eleven criteria, including energy output, final yield, array yield, reference yield, system efficiency, panel efficiency, inverter efficiency, performance ratio, capacity factor, array losses, and system losses (Owolabi et al. 2023). "*PVsyst*" is a widely used simulation software for estimating the solar energy yield and for optimizing the solar PV system design. Because of its accuracy, flexibility, ease-to use, a rich set of energy indicators calculated, and detailed and explicit study on numerous parameters that influence the efficiency of a system, the software was used by Bansal et al. (2022), Tamoor et al. (2023), Shrivastava et al. (2023) and many others. Bansal et al. (2022) accomplished a detailed performance analysis of a grid-connected utility-scale solar PV plant with three PV technologies. Their findings revealed that the amorphous-Si PV panels have the lowest energy generation, performance ratio, system efficiency, and yearly energy density. The cadmium telluride and the polycrystalline-Si PV panels are the prime PV technologies to be deployed in India's hot semiarid climate. Tamoor et al. (2023) justified that small-scale grid-connected monocrystalline PV panels manufactured in China but installed in Pakistan have energy production potential. Previous studies have demonstrated that solar panels' efficiency and power output have increased significantly over the last few decades. The monocrystalline-Si standard solar panel efficiency ranges from 15 to 24% (Ameur et al. 2021) and is expected to increase. The average efficiency of monocrystalline-Si is lower (12.74%), but this type of panel is more efficient than amorphous-Si (4.52%) or polycrystalline-Si (10.48%) panels (Elibol and Dikmen 2023). Elibol and Dikmen (2023) concluded that monocrystalline-Si is the most suitable PV panel type. The market for monocrystalline PV is expected to grow by 6.3% annually until 2029, considering resource availability, market potential, and cost competitiveness (Data Bridge Market Research 2022). Since the early stages of PV deployment, solar panels have continued to improve in efficiency, design, use of materials, and manufacturing costs. Modern solar PV panels generate significantly more power and have a longer lifespan than early PV panels. The growing demand for lower-cost energy generation has driven innovation at both cellular and panel levels. Bifacial PV (bPV), utilizing both sides of the cell for light absorption and electricity generation, is a promising mature technology (Guerrero-Lemus et al. 2016). Compared with standard PV panels, bifacial panels can be encapsulated in two different module structures: glass–glass (GG) and glass–backsheet (GB) (Singh et al. 2015). However, as Singh et al. (2015) stated, the GG panels can utilize the full potential of bifacial solar panels and provide a much higher energy yield to end users under outdoor conditions. Yin et al. (2021) argued that bifacial GG PV panels provide more than 6% higher energy yield than GB monofacial panels encapsulated with regular solar cells. The energy yield gain of bifacial PV panels can be increased by more than 10% owing to the optically enhanced effects of a reflective coating on the rear glass (Yin et al. 2021). Gu et al. (2020) and other scholars (Luo et al. 2018a, b; Kopecek and Libal 2021; Kumbaroglu et al. 2021) confirmed that a bifacial solar PV with a tracking system installed at an optimal tilt angle can contribute 5–30% more power output than standard PV panels. Additionally, the strengths of bifacial PV panels include their high durability and high resistance levels in compliance with IEC standards (Luo et al. 2018a, b; Kopecek and Libal 2021; Kumbaroglu et al. 2021; Sinha et al. 2021). Owing to the increased durability, the resistance degradation of GG panels is expected to be 0.45% a year, and standard panel degradation is expected to be 0.7% a year over a 30-year lifetime; they can operate at 85% of their capacity (Woodhouse et al. 2020). Modern GG panels are expected to have a lifetime exceeding 20–30, or even 50 years (Venkat et al. 2020). The International Technological Roadmap for Photovoltaics (2021) predicts that the global market share of bifacial PV panels will increase to 85% within the next decade.

Environmental analysis is performed to assess the carbon dioxide (CO_2) emissions, the land use, the pollutant and noise emissions, the water consumption due to expansion of solar PV systems (Bošnjaković et al. 2023), as well as the energy payback time (EBPT) and GHG emissions rate (Peng et al. 2013; de Wild-Scholten 2013; Louwen et al. 2015; Wetzel and Borchers 2015; Chen et al. 2015; Gazbour et al. 2016; Lamnatou et al. 2016; Hou et al. 2016; Akinyele 2017;

Fthenakis and Raugei 2017; El Dabosy and Sheta 2020; Müller et al. 2021; Jia et al. 2021; Li et al. 2022; Alam 2022). Results revealed that the development of PV capacity against the criteria above positively impacts the environment. Life-cycle assessment (LCA) is a comprehensive method used to assess and analyze environmental performance. It is used to identify the maximum impact-generating processes in product manufacturing (Sharma et al. 2020). The number of LCA studies related to various types of PV systems is increasing worldwide. Various studies have considered the differences in data resources, solar radiation, technology characteristics, installation type, electricity generation mix of countries, system boundaries, assessment criteria, and other factors. As part of it, Yaghoubirad et al. (2022) performed the carbon footprint, the ExergoEnvironmental, the EneroEnviroEconomic, and the ExergoEnviroEconomic analysis. The performed comparison of the LCA results for different PV panel types showed that the mono-Si PV standard panels outperformed bifacial GG panels in terms of the energy payback time (EPBT) and the GHG emissions intensity, which were estimated to be shorter and lower, respectively, despite the assumptions and context considered (Peng et al. 2013; de Wild-Scholten 2013; Louwen et al. 2015; Wetzel and Borchers 2015; Chen et al. 2015; Gazbour et al. 2016; Lamnatou et al. 2016; Hou et al. 2016; Akinyele 2017; Fthenakis and Raugei 2017; El Dabosy and Sheta 2020; Müller et al. 2021; Jia et al. 2021; Li et al. 2022; Alam 2022). Furthermore, Hou et al. (2016) observed that approximately 84% of the total energy in the LCA of PV systems was consumed during the PV manufacturing process. Solar-grade silicon production accounts for more than 35% of the total energy consumption; therefore, advanced technologies should be developed and applied to reduce the GHG emissions of PV systems in the future. A sensitivity analysis conducted by Alam et al. (2022) showed that a 10% increase in the lifespan could lead to a 9% decrease in all environmental and human health impact categories. Scientists have argued that the system's lifespan, functional unit, and system boundary could noticeably affect LCA results. Akinyele et al. (2017) determined the significance of geographical location and lifetime on the environmental performance of a solar PV system. A comparative analysis performed by El Dabosy and Sheta (2020) showed no significant difference in GHG emissions between ground- and roof-mounted PV systems. Louwen et al. (2015) observed that silicon heterojunction PV systems outperformed standard mono-Si PV systems in terms of the estimated life-cycle of GHG emissions and EPBT. They found the main reason for the better environmental performance was the higher panel efficiency (18.4%) of silicon heterojunction solar panels compared with the mono-Si panel (16.1%). The specificity of Wetzel and Borchers (2015) is that, in the LCA, they covered all steps from metal-grade silicon refinement to shipping the modules to the customer. Scientists have stated that a comparison performed with data for the same production chains in 2009–2010 showed a 15% reduction in EPBT owing to process energy demand and loss reduction during wafer, cell, and panel production. Lamnatou et al. (2016) demonstrated that reflective films significantly improved the ecological profile of PV systems. De Wild-Scholten (2013) found that moving poly-silicon, ingots, wafers, cells, and panels production to China could result in almost the same EPBT but increase the GHG emissions by a factor of 1.3–2.1 depending on the electricity intensity of manufacturing. Chen et al. (2015) proved that a significantly lower EPBT could be achieved owing to the recent improvements in China's PV industry, which have led to energy savings and decreased environmental pollution. These results confirm the importance of technological improvements. Fthenakis and Raugei (2017) argued that ground-mount installations have a greater balance of systems (BOS) and a longer EPBT. Peng et al. (2013) reported that a mono-Si PV system achieved the worst results due to its high energy intensity during panel manufacturing. They argued that new production technologies, advanced manufacturing processes, reduced consumption of silicon and other raw materials, and increased recycling rates will continue to improve the environmental performance of PV systems soon. Gazbour et al. (2016) performed a comparative analysis of mono-Si standard and bifacial GG panels. In this analysis, only the manufacturing and operational phases were considered. The results showed that the EPBT of the bifacial panel was three times lower than that of the mono-Si PV owing to a 60% reduction in energy demand, and the cumulative energy demand of the open-ground bifacial GG PV installation in Europe amounted to approximately 17.53 GJ/kW. Improvements in the manufacturing process of new PV technology have also led to a 58% decrease in CO_2 emissions. Jia et al. (2021) calculated various environmental impacts, including the global warming potential, of monofacial and bifacial passivated emitter and rear cell modules prepared using 158.75-, 166-, and 210-mm silicon wafers. The estimated environmental impact of the bifacial panels was significantly lower than that of the monofacial panels, mainly because the electricity generation of the bifacial panels was approximately 23% higher during the entire life-cycle. In contrast, the material and energy consumption were similar. They concluded that the greatest contributor to climate change was silicon wafers' manufacturing and supply chains, accounting for approximately 47–51%. Li et al. (2022) conducted a comparative study on bifacial PV systems applied to different building forms in China. Their results showed that the power generation of the bifacial PV increased by 10.7–12.7% compared with the mono-Si panel. Depending on the building form, the estimated EPBT of bifacial PV ranged from 5.0 to 6.6 years. A comparison with mono-Si PV showed that the

EPBT of the bifacial panel was reduced by 5.7–7.4%, although the energy demand during the bifacial PV manufacturing process was higher. Luo et al. (2018a, b) presented a comparative LCA of PV electricity generation in Singapore using three different PV systems, including a frameless double-glass panel structure. The EPBT for silicon–frameless double-glass PV systems in Singapore is approximately one year, and the GHG emissions are approximately 20 gCO_{2eq}/kWh. The results confirmed that long-term PV panel reliability affects environmental performance and that the utilization of frameless double-glass PV panels can significantly increase the environmental benefits of electricity generation. Tawalbeh et al. (2021) reviewed the environmental impacts of solar PV systems in context of fossil fuel technologies. They found that the carbon footprint emission from PV systems were 14–73 gCO_{2eq}/kWh, which is up to 50 times lower than emission reported from the burning of oil. Seeking to reduce emissions from solar PV systems, efforts are requested to optimize its design, development of novel materials, minimize the use of hazardous materials, recycling whenever possible, and careful site selection. Mahmud et al. (2023) studied the environmental impacts of solar PV systems in context of other RES technologies. They showed that PV power system made the highest environmental impact on ozone layer depletion, fresh water aquatic ecotoxicity, and marine aquatic ecotoxicity, while hydropower plant was identified to be more environment-friendly than remaining RES electricity generation systems. The latest review study carried out Cellura et al. (2024) focused on emerging solar cells. Scientists found that they have superior environmental impacts in comparison to conventional silicon but emerging solar cells use toxic materials, therefore their ecotoxicity and human toxicity should be further improved through the design of the technologies. Furthermore, the manufacturing process of emerging solar cells was identified as energy and environmental hotspots. The latest studies (Frehner et al. 2024; Benjamins et al. 2024) expressed interest in shading effects, hydrodynamics, water-atmosphere interactions, benthic ecosystems, mobile species, GHG emissions, and payback time of floating solar power plant. Results demonstrated that life-cycle GHG emissions were 94 gCO_{2eq}/kWh and EPBT was 2.8 years. Wan et al. (2024) studied the sustainability of large-scale solar PV system in Malaysia by taking into account the meteorological uncertainties. The results revealed that the emissions avoided by PV system offset the environmental burden by 12–98 times. LCA of different PV technologies should be performed because their environmental impacts are expected to decrease due to manufacturing process improvements, reductions in energy demand during production, innovative cell development, and recycling. LCA studies must be conducted in the future to address environmental and energy issues and foster the sustainable development of PV technologies (Ludin et al. 2018; Lamnatou and Chemisana 2019). An LCA-related literature review shows that studies have been widely performed on different types of PV systems; however, most of these studies were conducted on the standard (STD) panels, and few LCA studies have been conducted on other types of PV technologies, especially bifacial GG panels.

Economic analysis includes but is not limited to assessing the levelized cost of energy (LCOE) of solar PV systems. In the area, much is done; however, economic analysis is widely used to disclose the economic potential of solar PV systems (Kozlovas et al. 2023). The application of LCOE in the context of comparative analysis of various types of solar PV panels is not plentiful. In the area, the research of Kumbaroglu et al. (2021) and Gu et al. (2020) is worth mentioning. According to the SWOT analysis results performed by Kumbaroglu et al. (2021), the bifacial PV panel has a lower LCOE than standard PV panel. Gu et al. (2020) stated that current LCOE of bifacial PV is 2–6% lower than standard panel.

In relation to findings of and gaps in the literature review, we believe that the "*PVsyst*" software, the LCA, and the LCOE are crucial tools designed to provide relevant information about the solar PV panel's compliance with sustainability requirements to motivate and scale up the development of solar PV. In the context of the research conducted, this work stands out in terms of the assessment of two different types of PV panels (mono-Si standard and bifacial GG) manufactured in Lithuania based on the efficiency, energy, and GHG emissions payback, as well as GHG emissions intensity and cost-effectiveness criteria.

The scientific novelty of this work is defined by the construction of a solar PV panel life-cycle chain structure based on national assumptions and the inclusion of a payment method for the storage of solar energy on the grid in the national LCOE model to assess the sustainability of GG type solar PV panel, which is less researched in scientific literature, in relation to the STD type panel manufactured in Lithuania. Furthermore, it identified the stages of the solar PV panel's life-cycle where it has the most significant impact on the environment and proposed measures to reduce this impact. Moreover, it compared two types of solar PV panels' manufacturing processes. It made informed decisions regarding solar PV panel manufacturing business improvement and its future directions in relation to the types of solar PV panels to be manufactured. In addition, it justified the business continuity due to its profitability, which was ensured by low LCOE. To our knowledge, this is the first study of this kind to be conducted in Lithuania that provides insights into the importance of the country's economic sectors (mining, manufacturing, services, households, etc.) in the global context of sustainable development and climate change when producing and servicing solar PV technologies in the country.

This study aims to answer the following scientific question: How do we assess sustainability of solar PV panels to support and scale up development of solar PV systems worldwide when addressing sustainable development and climate change issues originating from the manufacturing and service of solar PV panels in Lithuania through the application of the "*PVsyst*" software, the LCA and the LCOE based on the criteria of efficiency, energy and GHG emissions paybacks, as well as GHG emissions intensity and cost-effectiveness criteria, which refer to the selected disciplines, respectively?

This study aims to perform a sustainability assessment of the GG and STD types of solar PV panels manufactured in Lithuania, considering criteria of efficiency, energy, and GHG emissions payback and emissions intensity, as well as cost-effectiveness. In this way, it aims to identify the overall sustainability superiorities of advanced solar PV technologies and their significance in the context of sustainable development and climate change.

Four hypotheses are formed related to each sustainability assessment criterion and overall assessment. They are developed in relation to the literature review findings, assuming that solar PV panels' sustainability improves with increasingly advanced PV technologies. In this way:

H_0 The GG type solar PV panel generates more electricity than the STD type; therefore, regarding energy discipline, the GG type is more efficient and sustainable than the STD type solar PV panel.

H_1 The life-cycle GHG emissions and energy consumption of the GG type are lower than those of the STD type; therefore, the energy and GHG emissions payback and emissions intensity of the GG type are better than those of the STD type; in terms of environment discipline, the GG type is more sustainable than the STD type.

H_2 The GG type is awarded with lower LCOE compared to the STD type solar PV panel; therefore, it is more cost-effective than the STD type, and in terms of economy discipline, the GG type solar PV panel is more sustainable than the STD type.

H_3 Overall, the sustainability of advanced solar PV technologies is supreme compared to the standard ones.

To reach this aim, the following methods were applied: literature review, the "*PVsyst*" software, the LCA and the LCOE, case studies, and comparative analysis.

The remainder of this paper is organized as follows. Section 2 describes the specificities of the research object and the method applied, and explains the assumptions and processes. Section 3 introduces the results of the analysis, including the structure of life-cycle energy consumption and related GHG emissions, life-cycle EPBT, life-cycle GHG emissions payback time (GPBT), GHG emissions intensity, and LCOE of two different types of PV panels manufactured in Lithuania. Finally, Sect. 4 presents our conclusions.

Methodology

This methodological section presents the research object, the method applied, and the assumptions.

Research object

Considering Lithuania's climate conditions, the currently most widely used monocrystalline solar PV panels were selected for sustainability assessment. The national producer SoliTek has been manufacturing solar PV panels since 2013. Ten years of successful operations have made the SoliTek the leading manufacturer of solar PV panels in the Scandinavian region. In addition to manufacturing, the company also designs and installs PV for end users and provides maintenance services. The company's extensive experience and certified operations ensure the reliability of the data used for sustainability assessment. The STD and the GG types were selected based on the literature review results. Standard M.60 365 W and SOLID Bifacial Glass–Glass 355 W solar PV panels manufactured by SoliTek were analyzed. The STD panels were fabricated using 60 units of silicon cells (6 × 10), two sheets of 1045 × 1778-mm EVA film, one sheet of 1778 × 1057 × 35-mm glass, one sheet of 1800 × 1060-mm plastic backing, and an aluminum frame. The GG type comprised 60 cell units, two sheets of 1045 × 1778-mm POE film, and two 1778 × 1057-mm glass sheets.

Assessment criteria

A sustainability assessment of solar PV panels was carried out, considering the efficiency, the EPBT, the GPBT, and the intensity of GHG emissions, as well as the cost-effectiveness criteria described below.

Efficiency. The most important criterion for a solar PV panel is its efficiency. The solar PV panel conversion factor, defined as the percentage of incident solar energy converted to electricity (Center for Sustainable Systems 2023), was used to assess efficiency. According to the Center for Sustainable Systems (2023), most commercial panels have efficiencies ranging from 15 to 20%, but researchers have already developed PV cells with efficiencies approaching 50%.

This study analyzed solar PV panels under the same climatic and static conditions. The differences in efficiency were determined by the ability of the GG type solar PV panel to generate electricity from both sides. This implies that, for GG type solar panels, in addition to the direct sunlight per unit area, it is necessary to consider the reflected light from the Earth's surface, which contributes to generating a larger amount of electricity. It is calculated by evaluating the direct sunlight per unit of surface area as well as the surface reflection coefficient, known as albedo (SunMaster 2023), using Eq. (1):

$$\alpha = (1 - D)\bar{\alpha}\left(\theta_i\right) + D\bar{\bar{\alpha}} \tag{1}$$

where (1 – D) is the proportion of direct radiation from a sun angle; $\overline{\alpha}\left(\theta_i\right)$ is the directional hemispherical integral of reflectance; D is the proportion of diffuse illumination; and $\bar{\bar{\alpha}}$ is the bi-hemispherical integral of reflectance.

Owing to the differences in the efficiencies of solar PV panels, different volumes of electricity are generated by the STD and GG types of solar PV. In this research, the software package "*PVsyst*" was used to calculate the electricity generation volume ($G_{el;t}$) during the lifetime of solar PV panels. "*PVsyst*" allows the assessment of the efficiency of solar PV panels and annual meteorological data of a certain region, and provides forecasts of electricity generation volumes with monthly or even hourly accuracy.

Energy and GHG emissions payback times, as well as GHG emissions intensity

To assess the relative environmental impact difference, this study compares the life cycles between the GG and the STD types of PV panels. The LCA methodology used to determine the environmental impacts of the PV panels is based on the International Standards Organization ISO 14040 and ISO 14044 (ISO 14040:2006; ISO 14044:2006). The functional unit, i.e., the reference to which the inventory and impact assessment is done, is defined as 1 kWh of electricity provided to the grid. The data required for a complete analysis of the PV panels concerns the raw materials used, the energy consumed, and the emissions generated at each stage of the life-cycle studied. This study was based on secondary data taken from manufacturing company, various study reports, and other published sources. The production of feedstock, manufacture of components, transportation of components, manufacture of solar PV panels, transportation of solar PV panels for installation, and utilization of PV panels are all included in this study's system boundary. This LCA study examined three main environmental criteria: the EPBT, the GPBT, and the intensity of CO_2 emissions (GHG measure).

The EPBT indicates that the PV panel must produce energy to recover the energy consumed during its life-cycle (Ehara et al. 2022). Gessert (2012) observed that different assumptions can be applied to calculate the EPBT; however, the energy required to manufacture PV panels should be as inclusive as possible. Comprehensive calculations of the EPBT account for the energy consumed to mine, transport, refine, manufacture, and deliver all components of PV panels to those required to deposit/assemble/package PV panels, deploy them, and eventually recycle them at the end of their lifespan. Rahman et al. (2017) observed that the EPBT strongly depends on geographical location; therefore, previous studies have observed a wide range of EPBT values. In this study, the EPBT is calculated using Eq. (2):

$$\mathrm{EPBT} = \left(\mathrm{E_F} + \mathrm{E_C} + \mathrm{E_{TR\ C}} + \mathrm{E_{M\ PV}} + \mathrm{E_{TR\ PV}} + \mathrm{E_U}\right) : \overline{\mathrm{G_{el}}} \tag{2}$$

Where $\mathrm{E_F}$ $\mathrm{E_F}$ is the energy used to produce the feedstocks, kWh; $\mathrm{E_C}$ is the energy used for the manufacture of the components of solar PV panels, kWh; $\mathrm{E_{TR\_C}}$ is the energy used for the transportation of components of solar PV panels, kWh; $\mathrm{E_{M\_PV}}$ s the energy used for the manufacture of solar PV panels, kWh; $\mathrm{E_{TR\_PV}}$ is the energy used for the transportation of solar PV panels to sites and periodic visits, kWh; $\mathrm{E_U}$ is the energy used for the utilization of solar PV panel, kWh; and $\overline{\mathrm{G_{el}}}$ is the average generation of electricity by solar PV per year, kWh.

The energy used in the production of the feedstocks $\mathrm{E_F}$ $\mathrm{E_F}$ and components E_C is calculated considering the norms of energy used for feedstocks (kWh/kWp) and components manufacturing (kWh/kWp) in China.

The energy used for the transportation of components $\mathrm{E_{TR\_C}}$ is calculated by Eq. (3):

$$\mathrm{E_{TR\ C}} = \sum\nolimits_{c=1}^{m} \sum\nolimits_{T=1}^{z} \left(\mathrm{D_{c;T}} \times \mathrm{W_{c;T}} \times \mathrm{EN_{c;T}} : \mathrm{n_{c;T}} : \mathrm{j_{c;T}} \times \mathrm{k_{c;T}}\right) \tag{3}$$

where $\mathrm{D_{c;T}}$ $\mathrm{D_{c;T}}$ is the distance of component *c* transportation from the site of its manufacture to the site of manufacture of solar PV panels by transportation mode *T*, including, air, land, water, and rail (from *1* to *z*), km; m is the number (variety) of components transported; $\mathrm{W_{c;T}}$ $\mathrm{W_{c;T}}$ is the transported weight of component *c*, t; $\mathrm{EN_{c;T}}$ $\mathrm{EN_{c;T}}$ is the energy consumption norm by transportation mode, kWh/tkm; $\mathrm{n_{c;T}}$ $\mathrm{n_{c;T}}$ is the number of containers, units; $\mathrm{j_{c;T}}$ $\mathrm{j_{c;T}}$ is the number of components in a container, units; and $\mathrm{k_{c;T}}$ $\mathrm{k_{c;T}}$ is the number of components used to manufacture one solar PV panel, units. $EN_{c;T}$ was taken from Klein et al. (2021).

The energy consumed to manufacture solar PV panels $\mathrm{E_{M\ PV}}$ is calculated by Eq. (4):

$$\mathrm{E_{M\ PV}} = \sum\nolimits_{K=1}^{k} \left(\mathrm{WC_{l;\ K}} \times \mathrm{t_{l;K}} \times \mathrm{N_{l;K}}\right) \tag{4}$$

where $\mathrm{E_{M\_PV}}$ $\mathrm{E_{M\ PV}}$ is the energy consumed to manufacture a 1 kW solar PV panel, kWh; $\mathrm{WC_{l;\ k}}$ $\mathrm{WC_{l;\ k}}$ is the working capacity of equipment *l* used in manufacturing process *K*, kW; $\mathrm{t_{l;K}}$ $\mathrm{t_{l;K}}$ is the working time of equipment *l* used in the manufacturing process *K* for 1 kW solar PV, h; $\mathrm{N_{l;K}}$ $\mathrm{N_{l;K}}$ is number of equipment *l* used in manufacturing process *K*, units; and K is the manufacturing process of solar PV varying from *1* to *k*.

The energy used in the transportation of a solar PV panel to a site and periodic visits was calculated using Eq. (5):

$$E_{TR\ PV} = \sum_{t=1}^{i} \left(D_{m} \times c\right) : n : C \tag{5}$$

where t is the operation time of solar PV; D_{m} D_{m} is the distance from the PV panel factory to the PV plant, km; c c is fuel consumption, kWh/km; n n is the quantity of PV panels transported; and C is the capacity of one module, i.e., 0.355 kW (GG) or 0.365 kW (STD).

The energy used in the utilization of solar PV panels (cells, ribbons, back sheets, glass, frame, EVA, and POE films) E_{U} is calculated by considering the weight of the utilized components.

The GPBT is defined as a metric to identify the environmental performance of solar energy compared with a fossil energy benchmark, which equals the time (months) it takes for the total GHG emission savings due to the replacement of fossil energy by solar energy to equal the GHG emissions during a solar PV panel's life cycle (Dammeier et al. 2019). GPBT was calculated using Eq. (6)

$$GPBT = GHG_{LCA} : \left(\overline{G_{el}} \times EF_{el}\right) \tag{6}$$

where GHG_{LCA} GHG_{LCA} is the life-cycle GHG emissions of the solar PV panel, gCO_{2eq}; $\overline{G_{el}}$ $\overline{G_{el}}$ is the average generation of electricity by the solar PV panel in a month, kWh/kW/month; and EF_{el} EF_{el} is the emission factor of electricity, gCO_{2eq}/kWh. EF_{el} EF_{el} is taken as 420 gCO_{2eq}/kWh, as it has been approved by the Ministry of Environment of Lithuania (2020) for electricity purchased from the grid in Lithuania.

The GHG emissions intensity (GHG measure GHG measure) are associated with the life-cycle GHG emissions of a solar PV panel (GHG_{LCA}) GHG_{LCA}) and solar PV electricity generation volume during its lifespan ($\sum_{t=1}^{i} G_{el;t}$)($\sum_{t=1}^{i} G_{el;t}$), where t is the operation time of solar PV. It is calculated by Eq. (7):

$$GHG\ measure = GHG_{LCA} : \sum_{t=1}^{i} G_{el;t} \tag{7}$$

The GHG emissions of solar PV panels include GHG emissions from different stages of their life cycle (Tırmıkçı and Yavuz 2020). In this study, the GHG_{LCA} GHG_{LCA} is calculated by Eq. (8)

$$\begin{aligned} GHG_{LCA} = {} & GHG_{F}/, + GHG_{C} + GHG_{TR\ C} \\ & + GHG_{M\ PV} + GHG_{TR\ PV} + GHG_{U} \end{aligned} \tag{8}$$

where GHG_{LCA} GHG_{LCA} is the life-cycle GHG emissions of a solar PV panel, gCO_{2eq}; GHG_{F} GHG_{F} is the GHG emissions from the manufacture of feedstocks, gCO_{2eq}; GHG_{R} GHG_{C} GHG_{C} is the GHG emissions from the manufacture of solar PV components, gCO_{2eq}; GHG_{TR_R} GHG_{TR_C} $GHG_{TR\ C}$ is the GHG emissions from the transportation of components to manufacturer solar PV panels, gCO_{2eq}; GHG_{M_PV} $GHG_{M\ PV}$ is the GHG emissions from the manufacture of a solar PV panel, gCO_{2eq}; GHG_{TR_PV} $GHG_{TR\ PV}$ is the GHG emissions from the transportation of solar PV panels to the installation site and periodical visits, gCO_{2eq}; GHG_{U} GHG_{U} is the GHG emissions from the utilization of the solar PV panel, gCO_{2eq}.

The GHG emissions from the production of feedstocks (GHG_{F} GHG_{F}) and manufacture of components (GHG_{C}) were calculated considering norms of feedstocks (gCO_{2}/kWp) and components manufacturing in China.

The GHG emissions from the transportation of components were calculated by Eq. (9):

$$GHG_{TR\ C} = \sum_{r=1}^{m} \sum_{T=1}^{z} \left(D_{C;T} \times W_{C;T} \times GHGN_{C;T} : n_{C;T} : j_{C;T} \times k_{C;T}\right) \tag{9}$$

where $GHGN_{r;T}$$GHGN_{C;T}$$GHGN_{C;T}$ is the GHG emissions norm, gCO_{2eq}/tkm, which was taken from Klein et al. (2021).

The GHG emissions from the energy consumed in the manufacture of solar PV panels (GHG_{M_PV} GHG_{M_PV}) can be calculated by Eq. (10):

$$GHG_{M\ PV} = EF_{el} \times E_{M_PV} = EF_{el} \times \sum_{K=1}^{k} \left(WC_{l;K} \times t_{l;K} \times N_{l;K}\right) \tag{10}$$

The GHG emissions from the transportation ($GHG_{TR_PV}$$GHG_{TR_PV}$) of solar PV panels to a site and periodic visits were calculated using Eq. (11):

$$GHG_{TR\ PV} = \sum_{t=1}^{i} EF_{G} \times \left(D_{m} \times c\right) : n : C \tag{11}$$

where EF_{G} EF_{G} is the emission factor of the used fuel, tCO_{2eq}/km.

The GHG emissions from the utilization (GHG_{U} GHG_{U}) of solar PV panels can be calculated by Eq. (12):

$$GHG_{U} = \left(m_{U} \times E_{SEP_{PV}} \times EF_{el}\right) + \sum E_{U_{PV}} \times EF_{el} \tag{12}$$

Cost-effectiveness. The cost-effectiveness of solar PV panels was assessed by calculating the levelized of electricity (LCOE). According to the International Renewable Energy Agency (2012), "…the LCOE is the price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate. An electricity price above this would yield a greater return on capital, while a price below it would yield a lower return on capital, or even a loss…". The LCOE is measured by dividing the present value of all expected lifespan costs (including construction, investment, operation and maintenance (O&M), fuel, and taxes) by the present value of the expected volume of energy produced over the energy project's lifetime (Bilgili and Ünal 2023). In this study, an extended approach to the LCOE is applied. This has been presented in detail by Bobinaite and Konstantinaviciute (2018). The LCOE is calculated using Eq. (13):

$$\mathrm{LCOE} = \sum\nolimits_{t=0}^{T} \frac{\mathrm{I_t} + \mathrm{O\&M_t} - \mathrm{IS_t}}{(1+\mathrm{d})^{t}} : \sum\nolimits_{t=0}^{T} \frac{\mathrm{C_I} \cdot 8760 \cdot \mathrm{LF} \cdot (1-\mathrm{DE})^{t}}{(1+\mathrm{d})^{t}} \tag{13}$$

where I_t is the investment at time step t, EUR; O & M_t are the O&M costs at time step t, EUR; IS_t is the investment subsidy, EUR; C_I is the installed capacity, kW; LF is the load factor, %; DE is the degradation coefficient, %; d is the discount rate, %; and t is the time period, years.

I_t includes the cost of a PV panel and the acquisition of the BOS (inverters, cables, structures, lightning protection systems, and others, known as system integration). Elshurafa et al. (2018) reported that the share of the BOS in the structure of capital costs increased from 29 to 51% between 2007 and 2014. After consulting solar PV installers at the beginning of 2023, a BOS of 65% was accepted.

O & M_t costs are calculated using Eq. (14):

$$\mathrm{O\&M_t} = \mathrm{FC_t} + \mathrm{VC_t} \tag{14}$$

where FC_t is the fixed cost (EUR/kW/year) and VC_t is the variable cost (EUR/kWh).

Lee et al. (2018) assumed that FC_t has a capital cost of 1%. This assumption was adopted in this study. VC_t is the cost of electricity storage. Storage costs were calculated considering the billing method of the prosumers. This was the payment for installed capacity.

IS_t is part of a model of public support for the development of renewable energy. In Lithuania, the Environmental Project Management Agency (2023) provides investment subsidies for solar PV. The investment subsidy was 323 EUR/kWp.

The discount rate is calculated using Eqs. (15) and (16).

$$\mathrm{d} = \mathrm{WACC} \tag{15}$$

where $WACC_l$ is the weighted average cost of capital under project financing strategy l, %.

$$WACC_l = R_{E;l} \cdot \frac{E_l}{E_l + D_l} + R_{D;l} \cdot \frac{D_l}{E_l + D_l} \cdot (1 - T_{income}) \tag{16}$$

where $R_{E;\,l}$ is the cost of equity, %; E_l is the amount of equity financing, EUR; D_l is the amount of debt financing, EUR; $R_{D;\,l}$ is the cost of debt financing, %; and T_{income} is the income tax, %.

Overall sustainability. It is decided by comparing values of respective indicators of the GG and the STD types with each other, as it is presented in Table 1.

Table 1 is fulfilled after the specified indicators are calculated by applying "*PVSyst*", Eqs. (2), (6), (7) and (13), respectively; and obtained values of corresponding indicators compared with each other. In detail, if the type of PV panel is determined to be superior according to the selected indicator, it is assigned with 1, but if not, then with 0. Finally, assessments are summed up by considering that the contribution of each indicator to total weight is equal (same). The type of PV panel with the highest cumulative score varying from 0 to 5 is considered more sustainable than that with lower one.

Assumptions *Efficiency*. The "*PVsyst*" software package calculates the generation forecasts of different types of PV panels, taking into account the assumptions summarized in Table 2. Information indicated in Table 2 is obtained from SoliTek datasheets of the STD and the GG type PV panels, as well as the latest installation place of solar PV systems.

Energy and GHG emissions payback, as well as GHG emissions intensity. Energy and related GHG emissions at different stages of the life cycle of the PV panels were assessed considering the following assumptions. In this study, we focused on understanding the role of national climatic conditions described below.

E_F and $GHG_C GHG_F$, as well as E_C and $GHG_C GHG_C$ are calculated by taking into account norms (kWh/kWp and gCO_2/kWp) which were derived by Hou et al. (2016) and de Wild-Scholten (2013). In detail, the following components are assessed on norms: ingot/crystal, wafer, cell, frame, and BOS.

$E_{TR\,C}$ and $GHG_C GHG_{TR\,C}$ are estimated considering the assumptions summarized in Table 3.

Components are transported from China to Lithuania by various modes of transportation, including:

- Long heavy vehicles on a motorway from Yangsu (China) to Qindao Harbor (China) (679 km);
- Maritime shipping in container ships from Qingdao (China) to Gdansk Harbor (Poland) (24,715 km);
- Maritime shipping in container ships from Gdansk (Poland) to Klaipeda Port (Lithuania) (265 km)

Table 1 Overall sustainability assessment (compiled by the author)

Indicator	Assessment	GG type	STD Type
$G_{el;t}$	The higher the better		
EPBT	The lower the better		
GPBT	The lower the better		
GHG measure	The lower the better		
LCOE	The lower the better		
Total		Σ	Σ

- Road container transport from Klaipeda Port to a factory in Vilnius (Lithuania) (300 km).

Distances are set by using Ports.com and Google Maps. Components are transported in 20'DC containers, and factory-ordered components are in heavy- and medium-loaded containers. This affects the $EN_{c;T}$ and $GHGN_{C;T}$selection, which were derived by Klein et al. (2021). Higher $EN_{c;T}$ and $GHGN_{C;T}$ are applied to the transportation of medium-loaded containers. Glass, frames, and films are transported in heavy-loaded containers, while cells, junction boxes, ribbons, and back sheets are transported in medium-loaded containers.

Table 2 Assumptions for electricity generation forecasts (compiled by the authors)

Assumption	STD type	GG type
Geographical site	Vilnius	Vilnius
Situation:		
Latitude	54.69° N	54.69° N
Longitude	25.28° E	25.28° E
Altitude	93 m	93 m
Project settings:		
Albedo	0.20°	0.30
PV field orientation:		
Tilt	35°	35°
Azimuth	0°	0°
System information:		
Number of panels	5 units	5 units
Nominal capacity	1.825 kWp	1.775 kWp
Panels	1 string x 5 in series	1 string x 5 in series
Bifacial model geometry:		
Sheds spacing		10 m
Sheds width		3.04 m
Height above ground		1.5 m
Efficiency	19.42%	19.11%
Degradation coefficient	0.8%	0.4%
Lifetime of PV panel	20 years	30 years

Various pieces of equipment are used to manufacture solar PV panels (Table 4).

As shown in Table 4, manufacturing the STD type panel requires more devices than manufacturing GG type panels. The latter method does not require a panel-edge-trimming machine or an automatic framing device. All items were used for the same amount of time.

Once PV panels are manufactured and sold, they are transported for installation. $E_{TR\_PV}E_{TR\ PV}$ and $GHG_{TR\_PV}GHG_{TR\ PV}$ are estimated taking into account assumptions about the onetime transportation of PV panels for installation and periodic visits (once per year during the lifetime) to the site for maintenance. It is assumed that visits are carried out in a gasoline-powered vehicle with a fuel consumption rate of 12.5 l/100 km and a CO_2 emission factor of 72.77 t/TJ (Konstantinaviciute 2016). An assumption is made that five units of solar PV panels, equivalent to a 1.825 kW STD type or 1.775 kW GG type solar power plant (PP), are installed in Vilnius 20 km away from the factory.

E_U E_U and GHG_U GHG_U are calculated considering the weight of the crushed and recycled components (Table 5), and the amount of electricity required for the crushing of panels, separation of materials, and the recycling of the resulting materials (silicon, plastic, glass, and aluminum) was taken from the scientific articles published by Damgaard et al. (2009), Astrup et al. (2009), Larsen et al. (2009), Fthenakis and Kim (2011), and Mulazzani et al. (2021).

As shown in Table 5, all components, excluding the junction boxes, are recycled by the company. The amount to be recycled corresponded to the weight of outdated components and their defects during the manufacturing process. The defects per solar PV panel are calculated by considering the actual defect data by component for the company in 2021. The amount of CO_2 emitted during the utilization phase is calculated after applying the recycling norms for plastic (0.6 gCO_2 per g of material), metal (0.0526 gCO_2 per

Table 3 Assumptions for the assessment of energy and related GHG emissions from transportation of components (SoliTek 2021)

Component	Weight, t/unit	Number of components per DC'20 container, units	Number of containers transported, units	Number of components used to manufacture a single STD type solar PV panel	Number of components used to manufacture a single GG type solar PV panel
Cell	0.000012	42,240	1	60	60
Junction box	0.000236	2000	1	1	1
Ribbons	0.00019	2632	1	1	1
Back sheet	0.0015	3,389,830	1	1	0
Glass	0.009	2600	1	1	2
Frame	0.003	5022	1	1	0
EVA film	0.00080	21,468,927	1	2	0
POE film	0.00076	21,468,927	1	0	2

Table 4 Assumptions for the assessment of energy and related GHG emissions from the manufacture of PV panels (SoliTek 2021)

Machines, devices, and equipment	Is equipment used in the manufacture of		Capacity, kW	Quantity, units	Time used, s
	STD- type panels?	GG- type panels?			
Cutters of EVA and POE films	Yes	Yes	6	2	10
Devices for glass and back-sheet application	Yes	Yes	9	2	55
Stringer	Yes	Yes	19	1	126
Lay-up	Yes	Yes	8	1	252
Conveyor system before laminator	Yes	Yes	20	1	55
EL testers	Yes	Yes	1.75	2	94
Laminator	Yes	Yes	78	1	375
Conveyor system after laminator	Yes	Yes	20	1	60
Buffer	Yes	Yes	0.96	1	20
Device for turning the panel for visual inspection	Yes	Yes	0.96	1	25
Panel edge trimming machine	Yes	No	2	1	15
Device for automatic framing	Yes	No	8.5	1	31

Table 5 Weights of recycled and crushed components of a single solar PV panel (Solitek 2021)

Recycling and crushing	Utilized weight of STD type, g	Utilized weight of GG type, g
Cells	720.9	720.9
Ribbon	190.0	190.0
Back sheet	1511.6	
Glass	9001.9	18,039.1
Aluminum frame	3000.0	
EVA film	1602.7	
POE film		1531.9
Crushing	16,027.1	20,481.9

g of material), and glass (0.07 gCO_2 per g of material) to the weights of the components. The amount of energy used to recycle the components is calculated by applying an electricity emission factor of 420 gCO_{2eq}/kWh. The company used 0.057 kWh of energy to recycle the cell and 0.094 kWh of energy to crush 1 kg of the components.

Cost-effectiveness. The economic aspects of solar PV panels are assessed considering the assumptions summarized in Table 6 and Table 7.

The analyzed financing strategies and discount rate values used in this study are listed in Table 7.

Results and discussion

This section discusses the results of the sustainability assessment of the GG and STD types of solar PV panels manufactured in Lithuania, considering criteria of efficiency, energy and GHG emissions payback and, emissions intensity, as well as cost-effectiveness.

Energy: efficiency

Based on the "*PVsyst*" estimations, a 1.825 kWp STD type PV system produces 1825 kWh a year. Its performance ratio is 82.96%. Similarly, a 1.775 kWp GG type PV system generates 1986 kWh a year. Its performance ratio is 92.93%. Seeking the "PVsyst" results to be comparable, we recalculate them to 1 kW by taking into account lifetime and degradation coefficient. Results are presented in Fig. 1.

Figure 1 shows that the GG type PV panel is more efficient than the STD type PV panel in terms of the electricity produced annually and during its lifetime. Due to the bifacial feature, which compensates for lower efficiency (19.11%), in the first year of its life cycle, the GG type panel produces approximately 11% more electricity than the STD type. Due to the degradation of the PV panels, the annual efficiency of solar PV panels decreases, resulting in reductions in the amount of electricity produced by both types of PV panels. The GG type degrades slower. Therefore, the decreases in the annual amount of generated electricity are moderately reduced compared to the STD type, whose production curve shows a steeper slope. At the end of the life cycle of the STD type panels, the GG type remains more efficient as it generates approximately 20% more electricity than the STD type. This is in line with the findings of Yin et al. (2021), Gu et al. (2020), Kopecek and Libal (2021), Kumbaroglu et al. (2021), Luo et al. (2018a, b), Guerrero-Lemus et al. (2016), Sinha et al. (2021) who estimated that a bifacial PV system could produce up to 30% more energy than a standard system, with an average value of 6–10%. During its life cycle, a 1 kW GG panel produces 32.75 MWh of electricity, which is 67% more than that produced by the STD panels (19.58 MWh).

Table 6 Assumptions for the economic evaluation of a solar PV (compiled by the author)

Parameters	Indicators	STD type	GG type
Technical	Installed capacity, kW	1.825 (5 units)	1.775 (5 units)
	Efficiency, %	19.42	19.11
	Degradation coefficient, %	0.8	0.4
	Lifetime of PV, years	20	30
Capital cost	Price of PV panel, EUR/unit	198.75	226.51
	BOS, EUR:	1280.40	1254.55
Operational and maintenance cost	Fixed cost, EUR/kW a year	12.46 (1.0% of capital cost)	13.45 (1.0% of capital cost)
	Variable cost, EUR/kW	3.94	3.94
Support measure	Investment subsidy, EUR/kW	323	323
	Investment subsidy, %	27% of capital cost	24% of capital cost
Economical	Inflation, %	1.5	1.5
	Discount rate, %	See Table 7	See Table 7
	Payment for installed capacity, EUR/kW per month	3.94	3.94
Financing	Equity profitability, %	5.0; 5.5; 6.0	5.0; 5.5; 6.0
	Interest rate of long-term debt, %	3.0; 3.5; 4.0	3.0; 3.5; 4.0
	Loan term, years	10	10
	Method of loan repayment	Annuity	Annuity

Table 7 The financing strategies and discount rates (compiled by the author)

Financing strategy	Explanation of financing strategy	Discount rate, %
E100	100% equity	5.0; 5.5; 6.0
E80:D20	80% equity 20% debt	4.5; 5.5; 5.0
E73:IS27 (STD type)	73% equity 27% investment subsidy	5.0; 5.5; 6.0
E53:IS27:D20 (STD type)	53% equity 27% investment subsidy 20% debt	4.3; 5.3; 4.8
E76:IS24 (GG type)	76% equity 24% investment subsidy	5.0; 5.5; 6.0
E56:IS24:D20 (GG type)	56% equity 24% investment subsidy 20% debt	4.36; 4.84; 5.32

Besides, due to a decade-longer lifetime, the GG type produces an additional 10.14 MWh of electricity.

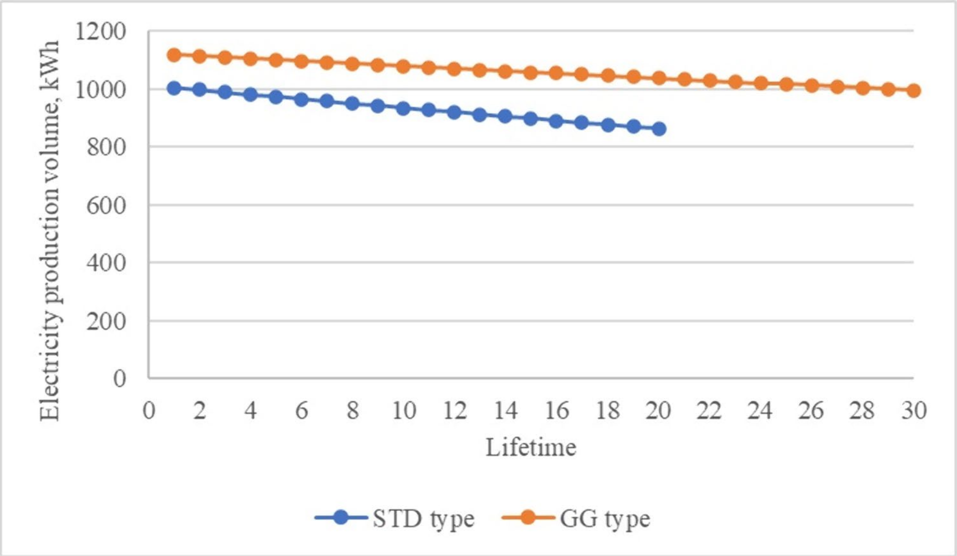
Thus, H_0 that the GG type solar PV panel generates more electricity than the STD type; therefore, in terms of energy discipline, the GG type is more efficient and sustainable than the STD type solar PV panel is approved.

Environment: energy and GHG emissions payback, emissions intensity

During its life cycle, the 1 kW GG type PV panel uses 1.8% less energy than the STD type (Fig. 2).

As shown in Fig. 2, during its life cycle, a 1 kW STD type solar PV panel consumes 2054 kWh of energy, while the GG type – 2016 kWh. The most significant amount of energy is used in the production of feedstock and the manufacturing of components, and the country of origin is China. The energy for feedstocks accounts for 38% of the energy consumption structure, followed by energy for components, which comprises 31% (STD type) and 17% (GG type). The share of energy used to manufacture a 1 kW solar PV panel in Lithuania is low – 1.5%. This is equivalent to 28.7 kWh for manufacturing the STD type and 29.3 kWh for manufacturing the GG type panels. The energy consumption for utilization accounts for 31 (STD type) and 29 kWh (GG type), constituting approximately 2% of the structure. In Lithuania, the transportation of 1 kW solar PV panels to the site for installation and, later on, periodic visits consume

Fig. 1 Annual production volume of electricity by the GG and STD PV panels, kWh (own estimations)



the most energy, 547 kWh (STD type) and 829 kWh (GG type). One should consider that energy use in transportation and periodical visits could be significantly reduced if a large solar PV plant is installed. Besides, a distant solar PV PP will require more fuel to reach it, resulting in higher total energy consumption.

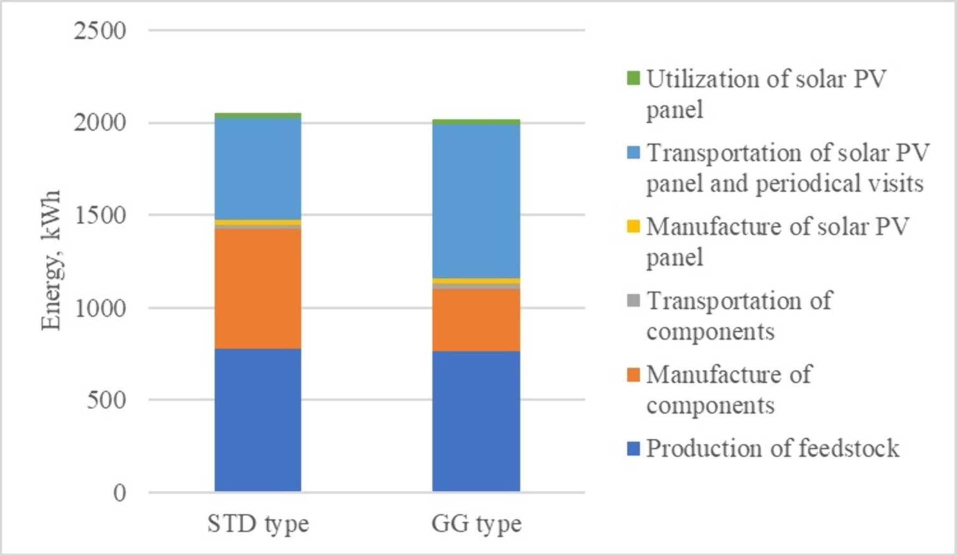
The GHG emissions during the life cycle are shown in Fig. 3.

Calculations revealed that the GG type PV panel emits $0.92tCO_{2eq}$ during its life cycle, 3.3% less than that of the STD type panel ($0.95\ tCO_{2eq}$). Approximately 70–80% of GHG emissions are generated during feedstock production and component manufacturing in China. In Lithuania, 18% (STD type) and 26% (GG type) of the emissions are generated during solar PV panel manufacturing, transportation to the site, periodic visits, and utilization.

Since the most energy is consumed and the most GHG emissions are emitted during the transportation of solar PV panels, we assessed how the latter indicators will change subject to changes in the distance from manufacturer to the site and changes in installed solar PV capacity (Table 8).

Calculations demonstrated that after transportation distances of solar PV panels to the site and periodical visits increase from 20 to 300 km, energy used and related GHG emissions per 1 STD type panel increase by 15 times and 1 GG type panel – by 13 times. In contrast, increase in capacity from 2 to 40 kW transported to the site and periodical visits, reduce energy consumption and GHG emissions of 1 STD type panel by 22 times and 1 GG type panel – by 23

Fig. 2 Total energy consumption during the life cycle of 1 kW STD and GG type PV panels, kWh (own estimations)



times. In Lithuanian side, seeking to mitigate GHG emissions it is recommended to transport more solar PV panels to geographically close sites. Transportation of small number of solar PV panels over long distances causes increase in life-cycle energy consumption and related GHG emissions. Thus, if the STD type panel is installed in Lithuania, its life-cycle GHG emissions from transportation are 0.002–0.78 tCO_{2eq}. Life-cycle GHG emissions from transportation of 1 GG type panel is 0.003–0.96 tCO_{2eq}.

The estimated environmental indicators are summarized in Table 9.

The results reveal that the energy pays off in approximately two years and three months for the STD type of solar PV panel. However, the GG type panels pay off approximately four months faster, as indicated by the EPBT values. The life-cycle GHG emissions pay off in approximately 2 years. In the case of the GG type panel, it pays off GHG emissions four months earlier than the STD type panels. Furthermore, producing 1 kWh of electricity by the GG type produces 42% less emissions than the STD type, which produces GHG emissions of 28.0 gCO_{2eq}/kWh.

Thus, H_1 stating that the life-cycle GHG emissions and energy consumption of the GG type is lower than those of the STD type, therefore the energy and GHG emissions payback, the emissions intensity of the GG type is better than those of the STD type; in terms of environment discipline, the GG type is more sustainable than the STD type, is approved.

Economy: levelized cost of electricity

The average cost of electricity production depends on the financing strategy and discount rate, as shown in Fig. 4.

Table 8 Sensitivity analysis (own estimations)

Assumption	Energy used, kWh per 1 PV panel		GHG emissions, t per 1 PV panel	
	STD type	GG type	STD type	GG type
Distance change				
2 kW/20 km	200	295	0.05	0.08
2 kW/150 km	1496	1841	0.39	0.48
2 kW/300 km	2993	3681	0.78	0.96
Solar PV capacity change				
2 kW/20 km	200	295	0.05	0.08
20 kW/20 km	18	26	0.005	0.007
40 kW/20 km	9	13	0.002	0.003

Figure 4 shows that the highest cost of electricity production occurs after choosing the E80: D20 financing strategy, comprising 80% equity and 20% debt financing. Under this strategy, the average LCOEs of the STD and GG type panels are 0.16 and 0.15 EUR/kWh, respectively. The LCOE has the highest and lowest values. They are defined by the estimated discount rates (Table 7). The difference between the highest and the lowest LCOE values is 0.01–0.02 EUR/kWh. An investment subsidy of 323 EUR/kWp decreases the average LCOEs of the STD and the GG type panels by 13.8% to 0.13 EUR/kWh (E73:IS27 financing strategy) and by 12% to 0.13 EUR/kWh (E76:IS24 financing strategy), respectively. This is the lowest average LCOE among the strategies analyzed. The second-best financing strategy consists of a mix of financing sources. In detail, the E53:IS27:D20 assures the average of 0.13 EUR/kWh for the STD type, and the E56:IS24:D20 defines the average of 0.13 EUR/kWh for the GG type. The average LCOE of 100% equity financing (E100 financing strategy) is similar to 20% debt and

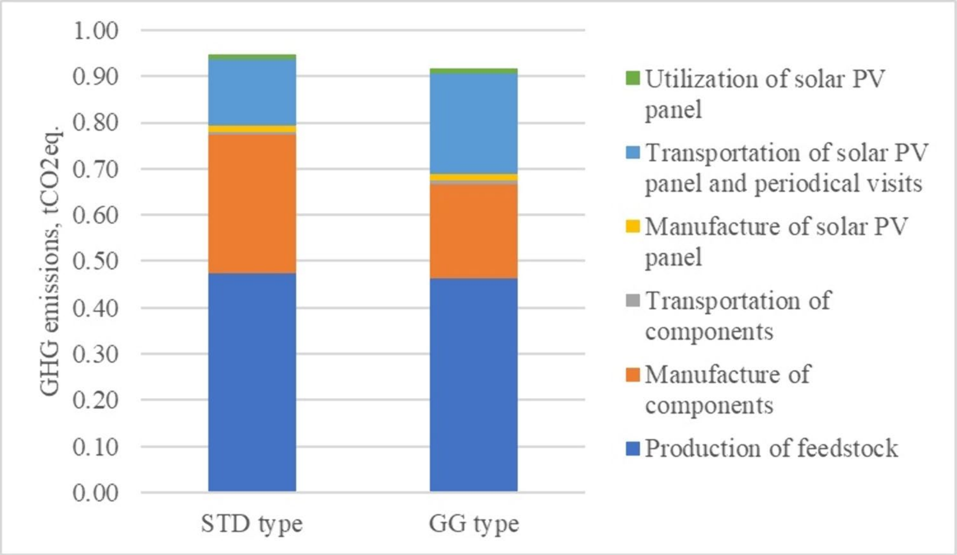


Fig. 3 Total GHG emissions during the life cycles of 1 kW STD and GG type PV panels, $gtCO_{2eq}$ (own estimations)

Table 9 EPBT, GPBT, and GHG measuresEnergy payback time, GHG emissions payback time, and GHG emissions intensity (own estimations)

Indicator	STD type panel	GG type panel
Energy payback time (EPBT), years	2.20	1.91
GHG emissions payback time (GPBT), months	27.68	24.00
GHG emissions intensity (GHG measure), gCO_{2eq}/kWh	48.4	28.0

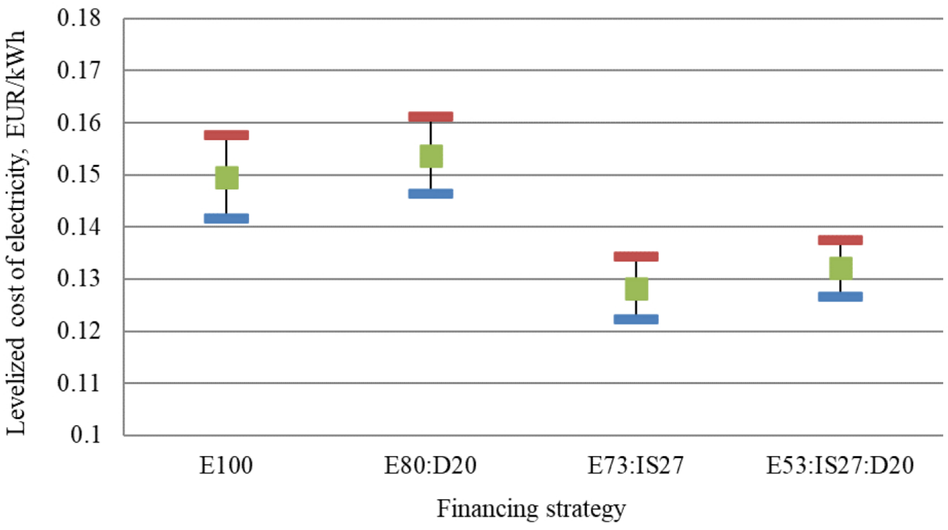
80% equity financing. Under the E100 strategy, the average LCOE for the STD type is 0.15 EUR/kWh and for the GG type is 0.14 EUR/kWh. The estimations reveal that the average LCOE of the GG type solar PV panel is 4% lower than that of the STD type panel.

Therefore, H_2 stating that the GG type is awarded with lower LCOE in comparison to the STD type solar PV panel; therefore, it is more cost-effective than the STD type, and in terms of economy discipline, the GG type solar PV panel is more sustainable than the STD type is approved.

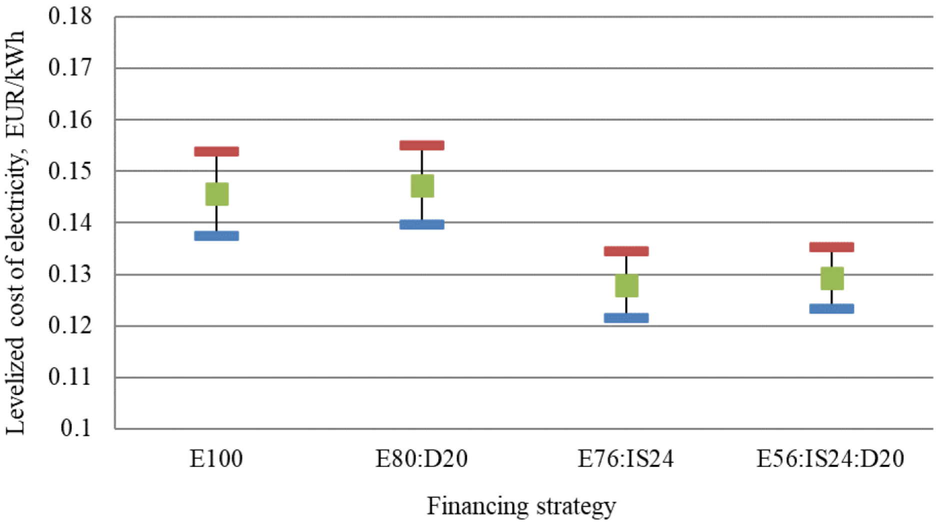
Overall sustainability

Overall sustainability assessment of the GG and the STD types of solar PV panels is given in Table 10.

Fig. 4 LCOE of the STD type **a** and GG type **b** PV panels, EURct/kWh (own estimations)



a) STD type panel



b)GG type panel

As presented in Table 10, the GG type has advantages in all disciplines and indicators. Its sustainability assessment cumulative score is 5 from 5, while the STD type is provided with 0 from 5, which does not suggest that the STD type is not sustainable. It merely states that the advanced solar PV panels are more sustainable than the standard ones in accordance with five indicators representing the key sustainability disciplines: energy, environment, and economy.

Therefore, H_3 states that the sustainability of advanced solar PV technologies is superior to that of standard ones and is approved.

Considerations

In the paper, we conducted a science-based sustainability assessment of the STD and the GG type solar PV panels manufactured in Lithuania based on efficiency, energy, and GHG emissions payback and energy intensity, as well as cost-effectiveness criteria, which correspond to crucial sustainability disciplines of energy, environment, and economy. In Table 11, we summarize our research results with ones provided by global scientists and consider the results below.

We found that over time, the efficiency of solar PV panels improved worldwide due to technological progress. The early studies of de Wild-Scholten (2013), Gazbour et al. (2016), and Fthenakis et al. (2017) demonstrated the efficiency of mono-Si solar PV panels to be around 14–15%, and of the GG type was slightly over 16%. The latest solar PV panels manufactured in Lithuania have an efficiency of 19.42% (the STD type) and 19.11% (the GG type). There are efficiency differences between regions. Müller et al. (2021) argued that, in Europe, an average efficiency of mono-Si solar PV panels was 19.8% and 19.4% of the GG type. Jia et al. (2021) claimed that the efficiency of the mono-Si solar PV panels in China was 20.15–20.24%, but higher (20.18–21.13%) of the GG type. This demonstrates that the efficiency of the Lithuanian manufacturer's solar panels has already reached the EU average but is lower than that installed in China. Thus, observing the trend of improving the efficiency of solar PV panels and the efficiency differences between regions, and wanting to remain the market leader in the Scandinavian countries and aiming to expand markets on a global scale, the Lithuanian manufacturer must maintain the pace of technological progress and accelerate it in order to remain competitive. For this purpose, its R&D department should establish long-term continued collaborations with scientific institutions, universities, and research centers worldwide to research solar PV technologies that contribute to developing more energy-efficient solar PV panels and better application of solar electricity than nowadays. Efforts are requested to improve the efficiency, durability, and resistance of solar PV panels to external factors.

We elaborated that the environmental sustainability of the GG type PV panel is higher than the STD type; therefore, in Lithuania, manufacturers should develop business activities by prioritizing the most advanced PV panels. In the country, the estimated GHG emissions of the STD and the GG type panels are 48.4 and 28.0 gCO_2/kWh, respectively. These results are poorer than the results of research carried out for Europe by de Wild-Scholten (2013), Wetzel and Borchers (2015), Lamnatou et al. (2016), Fthenakis and Raugei (2017), and Müller et al. (2021), but are better than the outcomes received for China by Hou et al. (2015) and countries in Africa by Akinyele et al. (2017) and ElDabosy and Sheta (2020). The efficiency of solar PV panels manufactured in Lithuania is as high as the European average, and the lifetime of STD type is approximately a decade shorter than that of GG panels (Müller et al. 2021). Subject to these assumptions, on average, in Europe, the GHG emissions per 1 kWh is twice as low as that in Lithuania, i.e., 12.9 gCO_2/kWh (GG type) and 29.9 gCO_2/kWh (STD type) (Müller et al. 2021). In Europe, 75 gCO_2/kWh (STD type) and 31 gCO_2/kWh (GG type) are emitted with low efficiency of 14% and 16.4%, respectively (Gazbour et al. 2016). These differences could occur due to the limitations of the studies, including those related to the LCA boundaries analyzed and their details. Instead of comparing our results with the average data for the EU (Gazbour et al. 2016; Müller et al. 2021), it is more precise to introduce differences between regions, as was performed by Wetzel and Borchers (2015). The significantly higher solar radiation in Southern European countries results in higher electricity production volumes and, at the same time, has an impact on the lifecycle GHG emissions, which are twice as low as those in Northern European countries (Wetzel and Borchers 2015). The conditions in Lithuania are more similar to those in

Table 10 Overall sustainability assessment (compiled by the author)

Indicator	Assessment	GG type	STD type
Electricity generation volume ($G_{el;t}$)	The higher the better	1	0
Energy payback time (EPBT)	The lower the better	1	0
GHG emissions payback time (GPBT)	The lower the better	1	0
GHG emissions intensity (GHG measure)	The lower the better	1	0
Levelized cost of electricity (LCOE)	The lower the better	1	0
Total		5	0

Table 11 Comparative analysis of results of global scientific literature and this study (compiled by the authors)

Author	PV type	Country	Solar radiation, kWh/m^2/year	Lifetime, years	Efficiency, %	Energy payback timeEPBT, years	GHG emissions intensity, gCO$_{2eq}$/kWh
Authors of this study	STD type GG type	Lithuania	Lithuania 850–1050 Vilnius 990	20 30	19.42 19.11	2.20 1.91	48.4 28.0
Peng et al. (2013)	Mono-Si	World	–	n. a	n. a	1.7–2.7	29–45
de Wild-Scholten (2013)	Mono-Si	Europe: South	1700	30	14.8	1.96	38.1
Louwen et al. (2015)	Mono-Si	Europe: South	1700	30	16.1	1.8	38
Wetzel et al. (2015)	Mono-Si	Europe: South, Northern Germany	1700 1000	30	15.8	1.09 n. a	22–35 40–60
Lamnatou et al. (2016)	Mono-Si	Europe: Barcelona Dublin, Exeter	1423 987–991	25	15	3.6–5.8 3.7–7.8	n. a
Gazbour et al. (2016)	Mono-Si GG	Europe	1496	30	14 16.4	2.69 1.05	75 31
Chen et al. (2016)	Mono-Si	China (Zhejiang)	778–2117	25	15.7	0.42–0.91	5.60–12.07
Hou et al. (2016)	Mono-Si	China	1200–1600	25	17	1.7–2.3	65.2–87.3
Fthenakis et al. (2017)	Mono-Si	Europe: South	1700	30	14	1.8	29
Akinyele et al. (2017)	Mono-Si	Nigeria	1493–2223	20–30	15.4	0.83–2.83	37.3–72.2
Luo et al. (2018a, b)	GG	Singapore	1580	30	16.2	1.01	20.9
ElDabosy and Sheta (2020)	Mono-Si	Egypt	1900–2200	25	14	2.15–2.3	58–96
Müller et al. (2021)	Mono-Si GG	Europe average	1391	29.9 25.4	19.8 19.4	n. a	29.9 12.9
Jia et al. (2021)	Mono-Si GG	China	1573	25 30	20.15–20.24 20.18–21.13	n. a	26–27 17–20
Alam et al. (2022)	Mono-Si	Canada	913–2117	30	14	n. a	79
Li et al. (2022)	Mono-Si GG	China (Chengdu)	1310	25	n. a	5.4–7.0 5.0–6.6	n. a

Northern European countries (such as Northern Germany) than in Southern European countries. Therefore, when comparing the results under Lithuanian conditions, we compared them with those for Northern Germany, in which the GHG emissions of the STD type were 40–60 gCO$_2$/kWh under a panel efficiency of 15.8%. Considering the differences in efficiency, the comparative analysis shows that the estimated GHG emissions in Lithuania are higher than those in Northern Germany. Lamnatou et al. (2016) and Gazbour et al. (2016) did not agree with the EPBTs of solar PV panels. They varied from one year to almost eight years, with the highest values in Dublin (7.8 years). Lithuanian case demonstrates that if PV panel is installed locally, near to the factory (20 km away from it), its EPBT is better than on average in Europe. However, it deteriorates, if PV panel needs to be transported long distances. For example, if PV panels are transported 150 km away from the factory, the EPBT of the STD type increases. Our results supplement the results achieved by Lamnatou et al. (2016), who demonstrated that low efficiency is related to long EPBT, revealing that, under high efficiency, the EBPT is significantly reduced. Additionally, Gazbour et al. (2016) estimate that STD type panels could pay off longer than the GG type panels. Our results demonstrate that EPBT of the STD type is six months longer than that of the GG type. Thus, environmental sustainability of solar PV panels manufactured in Lithuania is lower than in Europe in terms of EPBT, as well as energy intensity. Seeking to improve environmental sustainability of its solar PV panels, the manufacture should address the issues of improving efficiency of solar PV panels and reducing life-cycle energy consumption. The study demonstrates that, life-cycle energy consumption and GHG emissions are decided by feedstocks and components manufacturing in China. Thus, supply chain management should be a priority in the company. It is hardly possible to replace the import of feedstock and components from China with another source, but the manufacture could carry out the selection of suppliers not only based on price, but also sustainability criteria. In the company, an effective order of sustainable acquisitions should be implemented. Furthermore, even if the company itself is only responsible for around 25% of the life-cycle GHG emission per 1 kW and up to 45% of the life-cycle energy consumption per 1 kW, it should demonstrate a leadership by carrying out business activities based on use of sustainable fuels and energy to manufacture PV panels and their transportation to the site. Indeed, manufacture of solar PV panels should be executed in high-standard facility and undergo careful inspection processes for the purpose assure cost-effective and reliable energy solution.

Finally, economic discipline needs to be discussed for the STD type and the GG type PV panels manufactured in Lithuania. Gu et al. (2020) estimated that the LCOE of bifacial PV is 2–6% lower than that of STD type. Our results confirm this, with an estimated 4% in Lithuania. This proves the company should develop the most cost-effective business activity, manufacturing advanced PV technologies. Besides, further reduction in the LCOE of PV panels is crucial for making solar power more affordable and competitive in the Scandinavian market. A lower LCOE will translate to lower consumer energy costs and increased clean and renewable energy adoption. Again, efficient PV panels will play a relevant role in reducing the LCOE by generating more electricity per kWh, reducing O&M costs, and increasing the overall system performance. Therefore, investments in the manufacture of efficient PV panels are significant to achieve cost-effective and sustainable solar energy solutions.

Conclusions

In Lithuania, a limited variety of solar PV panels is manufactured. These are the STD and the GG type solar PV panels. Thus far, they are mainly supplied domestically and to Scandinavian market to increase the share of RES in the region. Lithuanian solar PV manufacturer strives for the technological progress: products are competitive at regional level as they have achieved efficiency similar to average EU, but needs further significant improvements to be competitive at global level to satisfy the increasing sustainable energy needs worldwide. A sustainability assessment of the STD and GG types of solar PV panels manufactured in Lithuania is conducted based on the criteria of efficiency, GHG emissions intensity, energy and GHG emissions payback times, and cost-effectiveness. Based on the results, the following conclusions are drawn.

- The energy analysis results reveal that, with lower efficiency, longer operation time, less degradation, and bifacial features, the 1 kW GG type panel could produce 67% more electricity than the STD type panel during its life cycle, i.e., 32.75 MWh versus 19.58 MWh, subject to 990 kWh/m^2 a year solar radiation level. Thus, the GG type panel is more efficient than the STD type panel during its life cycle. In order to use the technical potential of solar PV panels, it is important to responsibly select the site. If solar PV panels are installed in Lithuania, the Western (Klaipeda) and Central (Kaunas) part of the country is more suitable, as solar radiation level here is up to 1060 kWh/m^2 a year, which allows increasing electricity production.
- The environmental analysis results show that the GG type panel is superior in terms of life-cycle GHG emissions and energy consumption. It is estimated that the 1 kW GG type panel consumes 2.0 MWh of energy during its life cycle compared to the 2.1 MWh consumed by the STD type panel. The GG type panel emits 0.9 tCO$_{2eq}$, but the STD type emits 31 kgCO$_{2eq}$ more. Approximately 70–80% of GHG emissions are emitted by producing feedstock and manufacturing components in China 18–26% of GHG emissions are produced in Lithuania, where transportation services could emit the largest share of GHG emissions (15–24%). Seeking to mitigate the GHG emissions in hotspots, it is necessary to study the possibilities of components manufacturing in domestic market, using the scientific, technical, and technological potential of the country, as well as exploiting its economic and geographical advantage. Furthermore, GHG emissions from transportation of solar PV system to the site and periodical visits could be reduced by installing large-scale solar PV systems in geographically close markets. Small-scale and scattered solar PV systems will have an impact on the increase in GHG emissions from transportation and periodical visits. The life-cycle GHG emissions of the STD type solar PV panel are 48.4 gCO$_{2eq}$/kWh, compared with 28.0 gCO$_{2eq}$/kWh for the GG type. The advantages of the GG type are its shorter energy and GHG emission payback times, which are about two years. Thus, advanced solar PV panels should be prioritized by manufacturer and businesses as they have better environmental estimates.
- The results of the economics analysis demonstrate that the average energy cost of the GG type is 4% lower than that of the STD type; therefore, the former is more cost-effective than the latter. Without financial support, the average LCOE for the GG type is 0.15 EUR/kWh. Subject to a 323 EUR/kWp subsidy, the average LCOE is approximately 0.13 EUR/kWh. Uncertainty in LCOE is 0.01–0.02 EUR/kWh, which is assessed by considering different discount rates. This demonstrates that subject to 0.18–0.24 EUR/kWh electricity prices for households, small-scale solar PV plants are competitive to grid elec-

tricity. It assures that households can be supplied with electricity at affordable prices.

- Overall, the calculations reveal that the sustainability of the Lithuanian GG type PV panel is higher than the STD type according to efficiency, payback and, energy intensity, and cost-effectiveness criteria. Considering this, the manufacturer should focus its business activity on the most advanced PV panels. Seeking to improve the sustainability of Lithuanian PV panels in a global context, efficiency, durability, and resistance to external factors should be improved. The manufacturer should collaborate with scientific institutions, universities, and research centers to address the issues.
- Our study is limited to estimation of the most common indicators in key sustainability disciplines, and further research could include an extended sustainability assessment according to the diversity of disciplines and an extended set of indicators, as well as validating sustainability assessment on PV panels in the Scandinavian market, which is a crucial market for national manufacturing. Besides, in absence of company and national level data, we applied global estimates. This is especially true for stages of production of feedstock and utilization, which so far remain the least understood by scientists and require special interest and collaboration with material scientists. Furthermore, it is planned mastering the professional LCA tools to assess whether implemented and planned to be implemented new technologies and fuels in the Lithuanian glass industry are sustainable across variety of environmental impact categories. Besides, we have interest in collaboration with scientists when integrating LCA into sustainable procurement procedure for solar PV.

Author contributions Conceptualization was performed by I.K., V.B., V.L., and U.V.; methodology was presented by I.K., V.B., V.L., and U.V.; software was developed by V.B. and U.V.; investigation was done by I.K., V.B., V.L., and U.V.; supervision was conducted by I.K.; writing and review were revised by I.K., V.B., V.L., and U.V. All authors have read and agreed to the published version of the manuscript.

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Data availability Data are available in a publicly accessible repository that does not issue DOIs. Publicly available datasets were analyzed in this study. These data can be found here: https://www.solitek.lt/ (accessed on 4 June 2022). No datasets were generated or analyzed during the current study.

Declarations

Conflict of interest The authors have no relevant financial or nonfinancial interests to disclose.

Consent to participate All authors whose names appear in the submission have made substantial contributions to the conception, design, acquisition, analysis, and interpretation of the work; drafted the work or critically revised significant intellectual content; approved the version to be published; agreed to take responsibility for all aspects of the work; and ensured that issues related to the accuracy or completeness of any part of the work are properly investigated and resolved.

Consent for publication Not applicable.

Ethical approval All authors confirm that the submitted work is original and has not been published elsewhere in any form or language (in part or in whole).

References

Abu-Rayash A, Dincer I (2018) Sustainability assessment of energy systems: a novel integrated model. J Clean Prod 212:1098–1116. https://doi.org/10.1016/j.jclepro.2018.12.090

Akinyele DO, Rayudu RK, Nair NKC (2017) Life cycle impact assessment of photovoltaic power generation from crystalline silicon-based solar modules in Nigeria. Renewable Energy 101:537–549. https://doi.org/10.1016/j.renene.2016.09.017

Alam E, Xu X (2022) Life cycle assessment of photovoltaic electricity production by mono-crystalline solar systems: a case study in Canada. Environ Sci Pollut Res 30:27422–27440. https://doi.org/10.1007/s11356-022-24077-3

Ameur A, Berrada A, Loudiyi K, Adomatis R (2021) Chapter 6-Performance and energetic modeling of hybrid PV systems coupled with battery energy storage. In: Asmae Berrada, Rachid El Mrabet (Eds) Hybrid Energy System Models. pp 195–238. https://doi.org/10.1016/B978-0-12-821403-9.00008-1.

Aplinkos projektų valdymo agentūra (2023). https://www.apva.lt/norite-isirengti-saules-elektrine/. Accessed 6 February-2023.

Astrup T, Fruergaard T, Christensen TH (2009) Recycling of plastic: accounting of greenhouse gases and global warming contributions. Waste Manage Res 27(8):763–772. https://doi.org/10.1177/0734242X09345868

Bansal N, Jaiswal SP, Singh G (2022) Long term performance assessment and loss analysis of 9 MW grid tied PV plant in India. Mater Today: Proceed 60(2):1056–1067. https://doi.org/10.1016/j.matpr.2022.01.263

Benjamins S, Williamson B, Billing SL, Yuan Z, Collu M, Fox C, Hobbs L, Masden EA, Cottier-Cook EJ, Wilson B (2024) Potential environmental impacts of floating solar photovoltaic systems. Renew Sustain Energy Rev 199:114463. https://doi.org/10.1016/j.rser.2024.114463

Bilgili M, Ünal Ş (2023) Technological and dimensional improvements in onshore commercial large-scale wind turbines in the world and Turkey. Clean Techn Environ Policy 25:3303–3317. https://doi.org/10.1007/s10098-023-02582-4

Bobinaite V, Konstantinaviciute I (2018) Impact of financing instruments and strategies on the wind power production costs: a case of Lithuania. Latv J Phys Tech Sci 2:11–27

Bošnjaković M, Santa R, Crnac Z, Bošnjaković T (2023) Environmental impact of PV power systems. Sustainability 15(15):11888. https://doi.org/10.3390/su151511888

Cellura M, Luu LQ, Guarino F, Longo S (2024) A review on life cycle environmental impacts of emerging solar cells. Sci Total Environ 908:168019. https://doi.org/10.1016/j.scitotenv.2023.168019

Center for Sustainable Systems University of Michigan (2023) Photovoltaic energy factsheet. https://css.umich.edu/publications/factsheets/energy/photovoltaic-energy-factsheet. Accessed 06-January-2023.

Chen W, Hong J, Yuan X, Liu J (2016) Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: a case study in China. J Clean Prod 112(1):1025–1032. https://doi.org/10.1016/j.jclepro.2015.08.024

Damgaard A, Larsen AW, Christensen TH (2009) Recycling of metals: accounting of greenhouse gases and global warming contributions. Waste Manage Res 27(8):773–780. https://doi.org/10.1177/0734242X09346838

Dammeier LC, Loriaux JM, Steinmann ZJN, Smits DA, Wijnant IL, van den Hurk B, Huijbregts MAJ (2019) Space, time, and size dependencies of greenhouse gas payback times of wind Turbines in Northwestern Europe. Environ Sci Technol 6 53(15):9289–9297. https://doi.org/10.1021/acs.est.9b01030

Data Bridge Market Research (2022) Global Monocrystalline Solar Cell (Mono-Si) Market. Industry Trends and Forecast to 2029:350

de Wild-Scholten Mm (2013) Energy payback time and carbon footprint of commercial photovoltaic systems. Sol Energy Mater Sol Cells 119:296–305. https://doi.org/10.1016/j.solmat.2013.08.037

Ehara T, Komoto K, van der Vleuten P (2022) 1.35-Very large photovoltaic systems in deserts. Solar Photovoltaic Energy in Comprehensive Renewable Energy (second Edition) 1:743–754

ElDabosy M, Sheta S (2020) Life Cycle Assessment of PV Systems: Integrated Design Approach for Affordable Housing in Al-Burullus Graduates Villages, Mansoura. Engineering Journal: 43. https://doi.org/10.21608/bfemu.2020.94720.

Elibol E, Dikmen o (2023) Long-term performance investigation of different solar panels in the West Black Sea Region. Clean Technol Environ Policy. https://doi.org/10.1007/s10098-023-02658-1

Elshurafa AM, Albardi ShR, Bigerna S, Bollino CA (2018) Estimating the learning curve of solar PV balance-of system for over 20 countries: implications and policy recommendations. J Clean Prod 196:122–134

Energy Information Administration (2021) International Energy Outlook 2021. https://www.eia.gov/outlooks/ieo/narrative/introduction/sub-topic-01.php. Accessed 15-March-2023.

Frehner A, Stucki M, Itten R (2024) Are alpine floatovoltaics the way forward? Life-cycle environmental impacts and energy payback time of the worlds' first high-altitude floating solar power plant. Sustainable Energy Technol Assess 68:103880. https://doi.org/10.1016/j.seta.2024.103880

Fthenakis V, Raugei M (2017) 7 - Environmental life-cycle assessment of photovoltaic systems, Editor(s): Nicola Pearsall. The Performance of Photovoltaic (PV) Systems Woodhead Publishing 209–232. https://doi.org/10.1016/B978-1-78242-336-2.00007-0.

Fthenakis VM, Kim HC (2011) Photovoltaics: Life-cycle analyses. Solar Energy 85(8):1609–1628. https://www.sciencedirect.com/science/article/pii/S0038092X09002345. Accessed 17-January-2023.

Gazbour N, Razongles G, Schaeffer C, Charbuillet C (2016) Photovoltaic power goes green. Electronics Goes Green 2016+ (EGG) IEEE. https://ieeexplore.ieee.org/abstract/document/7829819. Assessed 12-December-2022.

Gessert TA (2012) 1.19 - Cadmium Telluride Photovoltaic Thin Film: CdTe. comprehensive renewable energy 1:423–438. https://www.sciencedirect.com/science/article/pii/B9780080878720001220. Accessed 06 December-2022.

Gomez-Echeverri L (2018) Climate and development: enhancing impact through stronger linkages in the implementation of the Paris Agreement and the Sustainable Development Goals (SDGs). Phil.Trans.R.Soc.A376: 20160444. 1-17. https://doi.org/10.1098/rsta.2016.044. Accessed 15-March-2023.

Gu W, Ma T, Ahmed S, Zhang Y, Peng J (2020) A comprehensive review and outlook of bifacial photovoltaic (bPV) technology. Energy Conversion and Management 223. https://doi.org/10.1016/j.enconman.2020.113283

Guerrero-Lemus R, Vega R, Kim T, Kimm A, Shephard LE (2016) Bifacial solar photovoltaics–A technology review. Renew Sustain Energy Rev 60:1533–1549. https://doi.org/10.1016/j.rser.2016.03.041

Hausfather Z, Friedlingstein P (2022) Analysis: Global CO_2 emissions from fossil fuels hit record high in 2022. https://www.carbonbrief.org/analysis-global-co2-emissions-from-fossil-fuels-hit-record-high-in-2022/. Accessed 15-March-2023.

Hou G, Sun H, Jiang Z, Pan Z, Wang Y, Zhang X, Zhao Y, Yao Q (2016) Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China. Appl Energy 164:882–890. https://doi.org/10.1016/j.apenergy.2015.11.023

Igliński B, Piechota G, Kiełkowska U et al (2023) The assessment of solar photovoltaic in Poland: the photovoltaics potential, perspectives and development. Clean Techn Environ Policy 25:281–298. https://doi.org/10.1007/s10098-022-02403-0

International organization for standardization, environmental management – life cycle assessment - principles and framework. Geneva, Switzerland. ISO 14040:2006.

International organization for standardization, environmental management – life cycle assessment - requirements and guidelines. Geneva, Switzerland. ISO 14044:2006.

International renewable energy agency (IRENA) (2012) Renewable Energy Technologies: Cost Analysis Series. 1 (5/5). https://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-wind_power.pdf. Accessed 15 March-2023.

International Renewable Energy Agency (IRENA) Future of solar photovoltaic. Deployment, investment, technology, grid integration and socio-economic aspects, 2019. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019.pdf. Assessed 11-December-2022.

International Renewable Energy Agency (IRENA) Statistics Data, 2022. https://www.irena.org/Data/. Assessed 11-December-2022.

International technological roadmap for photovoltaics (2021). https://www.vdma.org/international-technology-roadmap-photovoltaic. Assessed 12-December-2022.

Jia X, Zhou Ch, Tang Y, Wang W (2021) Life cycle assessment on PERC solar modules. Solar Energy Mater Solar Cells 227. https://doi.org/10.1016/j.solmat.2021.111112

Klein A, Hilster D, Scholten P, van Wijngaarden L, Tol E, Otten M (2021) STREAM Freight Transport 2020, Emissions of freight transport modes. https://cedelft.eu. Accessed 02-February-2023.

Konstantinaviciute I (2016) Šiltnamio efektą sukeliančių dujų nacionalinių emisijų rodiklių energetikos sektoriuje atnaujinimas. https://am.lrv.lt/uploads/am/documents/files/KLIMATO%20KAITA/Studijos%2C%20metodin%C4%97%20med%C5%BEiaga/Ataskaita_Energetikos_EF_galutine_20160502.pdf. Accessed 7-March-2023.

Kopecek R, Libal J (2021) Bifacial Photovoltaics 2021: Status, Opportunities and Challenges. Energies 14. https://doi.org/10.3390/en14082076.

Kozlovas P, Gudzius S, Ciurlionis J, Jonaitis A, Konstantinaviciute I, Bobinaite V (2023) Assessment of technical and economic potential of urban rooftop solar photovoltaic systems in Lithuania. Energies 16(14):5410. https://doi.org/10.3390/en16145410

Kumbaroglu GS, Camlibel ME, Avci C (2021) Techno-economic comparison of bifacial vs monofacial solar panels. Eng Struct Technol 13(1):7–18. https://doi.org/10.3846/est.2021.17181

Lamnatou Ch, Baig H, Chemisana D, Mallick TK (2016) Environmental assessment of a building-integrated linear dielectric-based concentrating photovoltaic according to multiple life-cycle indicators. J Clean Prod 131:773–784. https://doi.org/10.1016/j.jclepro.2016.04.094.Accessed20-December-2022

Lamnatou Ch, Chemisana D (2019) Chapter 2 - Life-cycle assessment of photovoltaic systems, Editor(s): Sabu Thomas, El Hadji Mamour Sakho, Nandakumar Kalarikkal, Samuel Oluwatobi

Oluwafemi, Jihuai Wu. Nanomaterials for Solar Cell Applications 35–73. https://doi.org/10.1016/B978-0-12-813337-8.00002-3.

Larsen AW, Merrild H, Christensen TH (2009) Recycling of glass: accounting of greenhouse gases and global warming contributions. Waste Manage Res 27(8):754–762. https://doi.org/10.1177/0734242X09342148

Lee M, Hong T, Koo Ch, Kim ChJ (2018) A break-even analysis and impact analysis of residential solar photovoltaic systems considering state solar incentives. Technol Econ Develop Econ 24(2):358–382. https://doi.org/10.3846/20294913.2016.1212745

Li Z, Zhang W, He B, Xie L, Chen M, Li J, Zhao O, Wu X (2022) A comprehensive life cycle assessment study of innovative bifacial photovoltaic applied on building. Energy. https://doi.org/10.1016/j.energy.2022.123212

Louwen A, van Sark WGJHM, Schropp REI, Turkenburg WC, Faaij APC (2015) Life-cycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs. Prog Photovolt: Res Appl 23(10):1406–1428

Ludin NA, Mustafa NI, Hanafiah MM, Ibrahim MA, Teridi MAM, Sepeai S, Zaharim A, Sopian K (2018) Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review. Renew Sustain Energy Rev 96:11–28. https://doi.org/10.1016/j.rser.2018.07.048

Luo W, Hacke P, Terwilliger K, Liang TS, Wang Y, Ramakrishna S, Aberle AG, Khoo YS (2018a) Elucidating potential-induced degradation in bifacial PERCsilicon photovoltaic modules. Prog Photovoltaics Res Appl 26(10):761–884. https://doi.org/10.1002/pip.3028

Luo W, Khoo YSh, Kumar A, Low JSCh, Li Y, Tan YSh, Wang Y, Aberle AG, Ramakrishna S (2018b) A comparative life-cycle assessment of photovoltaic electricity generation in Singapore by multicrystalline silicon technologies. Sol Energy Mater Sol Cells 174:157–162. https://doi.org/10.1016/j.solmat.2017.08.040

Mahmud MAP, Farjana SH, Lang CL, Huda N (2023) Chapter Six - Comparative environmental impact assessment of solar-PV, wind, biomass, and hydropower plants Editor(s): M. A. Parvez Mahmud, Shahjadi Hisan Farjana, Candace Lang, Nazmul Huda. Green Energy. Academic Press: 135–160. https://doi.org/10.1016/B978-0-32-385953-0.00012-4.

Ministry of Environment of Republic of Lithuania (2020). Regulation No D1–315 on Order for Use of Funds of Programme for Climate Change.

Mulazzani A, Eleftheriadis P, Leva S (2021) Recycling of c-Si PV Modules: An Energy Analysis and Further Improvements, 2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe) Bari Italy 1–6. https://doi.org/10.1109/EEEIC/ICPSEurope51590.2021.9584572.

Müller A, Friedrich L, Reichel Ch, Herceg S, Mittag M, Neuhaus DH (2021) A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory. Doi, Solar Energy Materials and Solar Cells. https://doi.org/10.1016/j.solmat.2021.111277

Owolabi AB, Yakub AO, Luqman R, Same NN, Suh D (2023) Performance assessment of four grid-connected solar photovoltaic technologies under similar environmental conditions in nigeria. Int J Energy Res 2023:9458440. https://doi.org/10.1155/2023/9458440

Peng J, Lu L, Yang H (2013) Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renew Sustain Energy Rev 19:255–274. https://doi.org/10.1016/j.rser.2012.11.035

Rahman MM, Salehin S, Sadrul Islam AKM (2017) Chapter Two - Environmental Impact Assessment of Different Renewable Energy Resources: A Recent Development. In Book Clean Energy for Sustainable Development 29–71.

Ritchie H, Roser M, Rosado P (2022) Energy. https://ourworldindata.org/energy-production-consumption. Accessed 15-March-2023.

Segger CMC (2016) Advancing the paris agreement on climate change for sustainable development. Cambridge J Int Comparat Law 5(2):202–237. https://doi.org/10.4337/cilj.2016.02.03.Accessed15-March-2023

Sharma RK, Sarkar P, Singh H (2020) Assessing the sustainability of a manufacturing process using life cycle assessment technique—a case of an Indian pharmaceutical company. Clean Techn Environ Policy 22:1269–1284. https://doi.org/10.1007/s10098-020-01865-4

Shrivastava A, Sharma R, Saxena MK, Shanmugasundaram V, Rinawa Ankit ML (2023) Solar energy capacity assessment and performance evaluation of a standalone PV system using PVSYST. Mater Today: Proc 80(3):3385–3392. https://doi.org/10.1016/j.matpr.2021.07.258

Singh JP, Guo S, Peters IM, Aberle AG, Walsh TM (2015) Comparison of glass/glass and glass/backsheet pv modules using bifacial silicon solar cells. IEEE J Photovolt 5(3):783–791

Sinha A, Sulas-Kern DB, Owen-Bellini M, Spinella L, Uličná S, Ayala Pelaez S, Johnston S, Schelhas LT (2021) Glass/Glass photovoltaic module reliability and degradation: A Review. J Phys D Appl Phys. https://doi.org/10.1088/1361-6463/ac1462

SoliTek (2021). The largest manufacturer of solar panels and batteries in Lithuania. https://www.solitek.lt/lt?_gl=1*x3l72h*_up*MQ..&gclid=CjwKCAjwi_exBhA8EiwA_kU1MnZse4cVnFrE1f0E6Q6bLEAnUJp3-qW-BOMbFA-Kz9nXvVgHM1_AURoC3SAQAvD_BwE.

SunMaster (2023) Solar Light manufacture, Albedo of a PV cell. https://www.solarlightsmanufacturer.com/albedo-of-a-pv-cell/. Accessed 06-January-2023.

Tamoor M, Bhatti AR, Farhan M, Zaka MA, ZakaUllah P (2023) Solar energy capacity assessment and performance evaluation of designed grid-connected photovoltaic systems. Eng Proc 37:39. https://doi.org/10.3390/ECP2023-14729

Tawalbeh M, Al-Othman A, Kafiah F, Abdelsalam E, Almomani F, Alkasrawi M (2021) Environmental impacts of solar photovoltaic systems: a critical review of recent progress and future outlook. Sci Total Environ 759:143528. https://doi.org/10.1016/j.scitotenv.2020.143528

Tırmıkçı CA, Yavuz C (2020) Environmental impact of a 290.4 kWp grid-connected photovoltaic system in Kocaeli. Turkey Clean Techn Environ Policy 22:1943–1951. https://doi.org/10.1007/s10098-020-01927-7

United Nations (2015a) Paris Agreement. https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf. Accessed 15-March-2023.

United Nations (2015b) Transforming Our World: the 2030 Agenda for Sustainable Development. https://sdgs.un.org/2030agenda. Accessed 15-March-2023.

Venkat SN, LiuJ, Bosco NS, Dai J, Gambogi WJ, Brownell B, Gu Y, Carter J, Bruckman LS, Jaubert JN, Braid JL, French R H (2020) Towards 50 year module lifetimes: impact of module architecture and packaging materials. PV Reliability Workshop. https://www.nrel.gov/docs/fy20osti/77317.pdf. Assessed 12-December-2022.

Wan MJ, Phuang ZH, Hoy ZH, Dahlan NY, Azmi AM, Woon KS (2024) Forecasting meteorological impacts on the environmental sustainability of a large-scale solar plant via artificial intelligence-based life cycle assessment. Sci Total Environ 912:168779. https://doi.org/10.1016/j.scitotenv.2023.168779

Wetzel T, Borchers S (2015) Update of energy payback time and greenhouse gas emission data for crystalline silicon photovoltaic modules. Prog Photovolt Res Appl 23(10):1429–1435

Woodhouse M, Repins I, Miller D (2020) LID and LeTID impacts to PV module performance and system economics. DuraMAT

Webinar. https://www.nrel.gov/docs/fy21osti/78629.pdf. Assessed 12-December-2022.

Yaghoubirad M, Azizi N, Ahmadi A, Zarei Z, Moosavian SF (2022) Performance assessment of a solar PV module for different climate classifications based on energy, exergy, economic and environmental parameters. Energy Rep 8:15712–15728. https://doi.org/10.1016/j.egyr.2022.12.070

Yin HP, Zhou YF, Sun SL, Tang WS, Shan W, Huang XM, Shen XD (2021) Optical enhanced effects on the electrical performance and energy yield of bifacial PV modules. Sol Energy 217:245–252. https://doi.org/10.1016/j.solener.2021.02.004