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Solar roof tiles: Unleashing technical advantages and contribution to sustainable society

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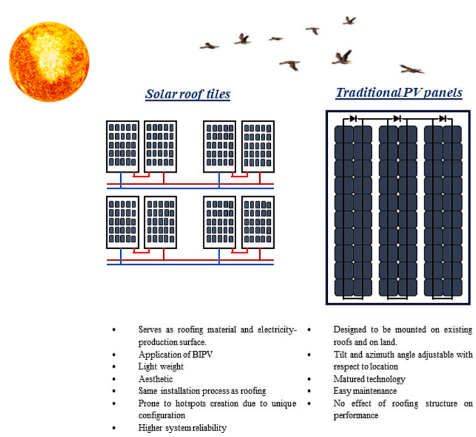
HIGHLIGHTS

- Solar Roof Tiles unique series-parallel connection resists hotspots creation.
- Failure of bypass diode during uncertainty has least effect on performance.
- 1.5 kW system is capable of mitigating 8392.5 kgCO_2 equivalent in its lifetime.

GRAPHICAL ABSTRACT



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ABSTRACT

A solar photovoltaic (PV) system is exposed to multiple environmental stresses such as bird droppings, soiling, and cast shadows during its operation, leading to the formation of hotspots. Traditional PV panels are equipped with a bypass diode to prevent system failure in the presence of such stresses. However, the failure of the bypass diode can lead to system failure and accelerated aging. In contrast, solar roof tiles (SRTs), due to their unique series-parallel configuration, are prone to hotspot creation and system failure, even in the absence of bypass diodes. This paper provides a critical analysis of SRTs, focusing on their technical benefits and potential for mitigating greenhouse gas (GHG) emissions. Using a Simulink model, the performance of a 1.5 kW SRT system is compared with a traditional PV system under various environmental conditions, including standard testing conditions and scenarios where cells are completely or partially shaded. The study concluded that in a 1.5 kW system, SRTs experienced an energy loss of 1.73 %, while the traditional PV system created infinite resistance to the flow of current. This resulted in no energy production when a single panel in both systems was exposed to environmental stress in the event of bypass diode failure. Moreover, findings demonstrate that SRTs can

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significantly contribute to a sustainable society by promoting affordable and clean energy access by generating 1871.72 kWh of clean energy annually. In addition, SRTs advance climate action by mitigating 335.7 kgCO2 equivalent GHG emissions through green energy production, even when taking system and aging losses into account.

1. Introduction

The majority of energy generation worldwide is currently based on fossil fuel-powered plants. These plants are significant contributors to global warming and climate change due to their greenhouse gas (GHG) emissions (Ahmed et al., 2021a). In contrast, solar photovoltaic (PV) systems have the potential to power a sustainable future (Victoria et al., 2021). Therefore, the environmentally friendly nature of PV systems has been leveraged to limit GHG emissions in the energy sector (Ahmed et al., 2021a; Victoria et al., 2021; Virtuani et al., 2023).

In recent years, PV has experienced rapid growth due to technological advancements (Victoria et al., 2021; Killam et al., 2021). PV has emerged as a major energy resource worldwide, offering electricity at a lower cost compared to fossil fuel power plants (Victoria et al., 2021; Rodríguez-Gallegos et al., 2020). Approximately 3000 km^2 of the Earth's surface is covered with light-collecting surfaces, the majority of which are PV systems (Ilse et al., 2019). In 2022, PV production increased by a record 270 TWh (up 26 %), reaching almost 1300 TWh. This showcases that PV is prepared to contribute substantially to CO_2 emissions mitigation (Victoria et al., 2021). By 2050, PV is expected to bridge 48 % of the energy gap among renewable energy resources (Killam et al., 2021).

However, despite the best efforts and multiple commitments, such as the European Union's energy targets (https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-targets_en, n.d.), the Kyoto Protocol (https://unfccc.int/kyoto_protocol, n.d.), and the Paris Climate Accord (https://unfccc.int/process-and-meetings/the-paris-agreement, n.d.), to reduce GHG emissions and limit global temperature rise to 2 °C (with efforts to keep it below 1.5 °C), progress remains insufficient (Virtuani et al., 2023). For instance, to achieve carbon neutrality by 2050, Europe must install 5 to 10 terawatts peak (TWp) of photovoltaic (PV) capacity. However, several limitations hinder this goal. Countries with limited land accessibility, like Malta and Switzerland due to terrain and size, face challenges in installing PV farms on land used for agriculture or forestry. Additionally, countries with available land have encountered resistance from their citizens due to land use conflicts (Victoria et al., 2021).

To mitigate land exploitation, building-integrated PV (BIPV) systems, such as solar roof tiles (SRTs), play a crucial role (Victoria et al., 2021; Virtuani et al., 2023). BIPV involves integrating PV modules into the structural elements of a building envelope, such as roofs, windows, or facades, to harness energy from incoming photons and meet building energy requirements (Gaur et al., 2016). The literature has consistently concluded that BIPV holds the potential to achieve zero-energy building targets (Gaur et al., 2016; Desideri et al., 2013).

Furthermore, individual end-users in the residential sector must actively participate in effective GHG mitigation through the use of PV systems (Ahmed et al., 2021a). Building operations were responsible for 28 % of CO_2 emissions in 2020 (Alim et al., 2022). These operations need to transition their heating, cooling, energy, and mobility requirements to green energy sources via local production (Holzhey et al., 2023). If the cost of PV systems, especially considering their aesthetics, is favorable and they are less susceptible to environmental defects (which contributes to their longer lifespan compared to traditional PV systems), more energy users will be encouraged to make the shift. Despite being prone to specific environmental issues that greatly limit the performance of PV systems and accelerate their aging, PV systems can still yield more than 80 % of their initial power after 25 years of service (Peters et al., 2021).

The significance of this work lies in its comprehensive analysis of SRTs as a viable alternative to traditional PV systems. By addressing the technical challenges and environmental benefits of SRTs, this study contributes to the broader field of renewable energy by providing insights into innovative solutions for sustainable energy production. The findings highlight the potential of SRTs to enhance energy efficiency, reduce greenhouse gas emissions, and promote the integration of renewable energy into urban infrastructure, thereby supporting global efforts to combat climate change.

1.1. Comparison of traditional PV and solar roof tile

Traditional PV systems require home modifications and come with associated issues. These include additional costs and potential damage to the existing roof. Moreover, the use of a metal structure for mounting solar panels covers a large area, resulting in exposed wiring. This arrangement is susceptible to environmental stresses and can adversely affect the visual appeal of residential buildings (Qi et al., 2022; https://www.thomasnet.com/insights/common-solar-panel-installation-issues-and-how-to-avoid-them/, n.d.). Fig. 1 illustrates the metal frame of traditional PV panels installed on the roof of Aalborg University (AAU).

In contrast, SRTs provide an eco-friendly solution by combining traditional building roof tiles with solar laminate. This integration represents an application of BIPV. SRTs provide insulation to homes, similar to traditional roof tiles. They serve as clean energy sources and have an aesthetic appearance (Carvalho et al., 2019). Since SRTs do not require a metal structure (due to its BIPV applications), their installation cost is lower compared to roofing followed by the addition of traditional panels (Qi et al., 2022; Águas et al., 2011). The wires for SRTs are laid beneath the tiles, providing protection from harsh weather, unlike traditional panels. Furthermore, the installation process for SRTs is the same as that for traditional tiles and requires no major alterations (Wajs et al., 2020).

However, the concept of SRTs does have some differences compared to traditional panels. Solar laminates must be compatible with porous and rough-surfaced roof tiles (Águas et al., 2011). It is shown that the type of substrate tile, including its surface properties and material composition, can significantly impact the deposition process and the optoelectronic performance of the solar cells (Águas et al., 2011). Therefore, selecting appropriate materials and conducting thorough compatibility tests are crucial for optimizing SRT performance.

Additionally, roof tile materials exhibit varying heating and cooling characteristics based on their construction material, which can impact the performance of SRTs. Since solar panels absorb infrared radiation, they experience increased panel temperatures, leading to decreased efficiency (Alim et al., 2020), as indicated by the PV panel manufacturer

Fig. 1. Traditional PV system metal structure – AAU.

and datasheets (https://sunceco.com/wp-content/uploads/2017/01/SEP300-320.pdf, n.d.). Alim et al. found that how reflective coatings can reduce the surface temperature of the tiles and improve their electrical efficiency (Alim et al., 2022). Also, Alim et al. found that incorporating phase change materials in solar roof tiles can significantly improve their thermal management by reducing peak temperatures (Alim et al., 2020).

Therefore insulation properties of roof tiles and the lack of proper airflow for cooling can also affect the overall performance of SRTs. In addition, a recent study evaluating the carbon footprint of mono-Si cell photovoltaic ceramic roof tile systems, suggest that traditional PV systems may be more efficient and have a lower carbon footprint compared to BIPV systems (Carvalho et al., 2019). However, implementing strategies such as selecting high-efficiency solar cells, optimizing internal structuring, and integrating advanced materials can significantly reduce the overall carbon footprint of BIPV systems, making them a more sustainable option in the long term. Table 1 provides a comparison of traditional panels and SRTs, highlighting their features, technical advantages, and disadvantages.

1.2. PV cell performance – geographical parameters

A PV system is exposed to geographical factors due to its outdoor operation. Geographical factors such as solar irradiance, ambient atmospheric temperature, precipitation, and wind speed play a pivotal role in the energy production of solar cells (Shaik et al., 2023; Casula et al., 2020; Huld and Gracia Amillo, 2015). A solar cell produces energy by converting the energy of incoming photons, provided it is higher than 1.1 eV (Venkatakrishnan et al., 2023; Le Bris and Guillemoles, 2010). This process is accompanied by heat losses (Huld and Gracia Amillo, 2015; Akinci and Özalp, 2022), and solar cells perform better at lower temperatures (Klychev et al., 2021; Peplow, 2023; Zou, 2021). Therefore, solar irradiance and ambient temperature are the more important factors (Sun et al., 2022; Chan et al., 2019). Consequently, if a PV system with identical specifications is installed at two different geographical locations, each will have a different output (Akinci and Özalp, 2022; Hassan et al., 2022).

Table 1
Comparison of traditional panels and SRTs.

	Traditional panels	SRT
Features	• Designed to be mounted on existing roofs (Dada and Popoola, 2023) and on land. • Tilt and azimuth angle adjustable with respect to location (Ahmed et al., 2021a)	• Serves as roofing material and electricity-production surface (Wajs et al., 2019) • Application of BIPV (Gaur et al., 2016)
Advantages	• Matured technology (https://sunceco.com/wp-content/uploads/2017/01/SEP300-320.pdf, n.d.) • Easy maintenance (https://sunceco.com/wp-content/uploads/2017/01/SEP300-320.pdf, n.d.) • No effect of roofing structure on performance (Wajs et al., 2020)	• Light weight • Aesthetic (Carvalho et al., 2019) • Same installation process as roofing (Wajs et al., 2020)
Disadvantages	• Heavy weight (https://sunceco.com/wp-content/uploads/2017/01/SEP300-320.pdf, n.d.) • Requires additional costly metal structure (Qi et al., 2022) • Exposed wiring, susceptible to environmental degradation (https://www.thomasnet.com/insights/common-solar-panel-installation-issues-and-how-to-avoid-them/, n.d.)	• Not suitable for flat roofs • Requires compatibility with roof material for better performance (Águas et al., 2011) • Roof angles are fixed

1.3. Problematization

The performance of PV technology is based on geographical parameters. In addition, a traditional PV system under environmental stresses such as soiling, bird droppings, and vicinal shadows creates hotspots due to its series connection. Bypass diodes protect the system by bypassing the affected zone with some associated energy losses. In the event of bypass diode failure, environmental stresses compromise the whole system's reliability, energy production, and GHG mitigation potential. Therefore, healthy bypass diodes are important for the healthy operation of a traditional PV system under uncertainties. However, the unique series-parallel structure of SRTs is inherently resistant to hotspot creation, even in the absence or failure of bypass diodes under uncertainties. This aspect is highly neglected in the literature.

This study aims to bridge the gap in the literature by providing a detailed comparison between traditional PV systems and SRTs, focusing on their technical advantages and environmental impact. The research contributes to the broader field by demonstrating how SRTs can mitigate common issues associated with traditional PV systems, such as hotspot formation and system failure. By promoting the adoption of SRTs, this work supports the transition to sustainable energy solutions and aligns with global climate action goals.

In addition, it provides unique insights into the system design of SRTs that existing frameworks fail to address. Unlike traditional PV systems, which rely heavily on bypass diodes to prevent system failure, SRTs utilize a series-parallel configuration that inherently resists hotspot formation. This design not only enhances the reliability and durability of the system but also reduces the need for frequent maintenance and replacement of components. By focusing on the structural and operational differences between SRTs and traditional PV systems, this research offers a novel perspective on improving the efficiency and resilience of solar energy technologies. The main objectives of this study are:

- Evaluation of the impact of geographical parameters on the performance of PV cells through appropriate location selection to ensure technical soundness.
- Investigate the technical advantages of SRTs over traditional PV panels, especially under uncertain outdoor conditions. For this purpose, a Simulink model is developed to compare the performance of traditional panels and SRTs under various environmental conditions, including standard testing conditions and scenarios where cells are completely or partially shaded across one bypass diode.
- Analyze the reliability of SRTs in green energy production by investigating their performance in the event of bypass diode failure due to environmental stress, and comparing this against traditional panels.
- Calculate the GHG mitigation potential of the PV system using RETScreen Expert, considering the fixed slope of SRTs, aging, and the geographical parameters of Aalborg, Denmark (detailed in later sections).

2. Methods

In this section, the location selection and technical comparison between traditional PV panels and SRTs are provided in detail.

2.1. Location selection

Considering the important role of geographical parameters, an optimal location was selected among the top five densely populated areas of Denmark (https://worldpopulationreview.com/countries/

cities/denmark, 2024). This selection was based on the annual average of daily solar radiation on a horizontal surface and the annual mean of ambient air temperature. The geographical factors of each area were extracted from the National Aeronautics and Space Administration's (NASA) database and ground stations using RETScreen Expert (Ahmed et al., 2021b; RETScreen International, 2005; Bourque, 2019). RETScreen Expert, developed by the Ministry of Natural Resources in Canada, is used for the assessment of multiple technologies across various sectors (RETScreen International, 2005). It automatically fetches geographical data from NASA's database and over 6700 ground stations (National Aeronautics and Space Administration, 2014). Due to its robust geographical database and its use in multiple pieces of literature (Ahmed et al., 2021a; Ahmed et al., 2021b), it is utilized for geographical data extraction.

However, it is important to note that the RETScreen extracts information from the station nearest to the project location. For instance, when considering the top 10 densely populated locations in Denmark, it uses data from Billund airport for Kolding, Vejle, and Horsens. This is a limitation of the RETScreen. The annual average geographical factors for the top five populated areas in Denmark are provided in Table 2. The wind speed is provided at a height of 10 m.

Subsequently, a simple PV model was designed in Simulink with a 300 W PV system subjected to a variable load with a ramp rate of 200. The annual average of daily solar radiation on a horizontal surface was converted into annual average irradiance using Eq. (1). Following this, the annual average irradiance and air temperature of all five locations were used as input to calculate the performance of the PV system. The results favor the city of Aalborg due to its geographical factors, as illustrated in Fig. 2. Fig. 3 reflects the monthly average of DSR-h and AT for Aalborg. Aalborg is the 4th most populous city in Denmark, located at 57.02° N, 9.94° E, and with an elevation of 13 m (RETScreen International, 2005). The monthly average geographical factors for the city of Aalborg are provided in Table 3.

$$\mathrm{W}\Big/\mathrm{m}^2 = \frac{\mathrm{kWh/m^2/d} \times 1000}{24} \tag{1}$$

2.2. Traditional PV and solar roof tiles - technical comparison

To maximize the energy output, it is possible to either use more efficient PV cells or through innovative system concepts (Rodríguez-Gallegos et al., 2020). Since the basic working principle of SRTs and traditional solar panels is the same, solar cells convert incoming energy into electricity through the excitation of valence electrons. Also, the efficiency of the PV cell is based on the type of solar cells; mono-crystalline and poly-crystalline, which can be used in either technology.

However, SRTs have a unique series-parallel configuration, where pairs of SRTs are connected in series and then in parallel with the rest of the pairs of SRTs. This unique configuration offers robustness against multiple safety hazards. For instance, it ensures that open circuit voltages always remain below 120 V, providing additional fire and safety protection compared to the traditional series connection of solar panels where operating voltages are between 500 and 1000 V, depending on inverter requirements. Furthermore, the operating current in SRTs is relatively small since each pair contributes a maximum of 330 mA of short circuit current. Multiple parallel pairs can keep this current well below a safe limit, unlike traditional panels where each panel contributes more than 8 A. A detailed datasheet for both an SRT and a traditional panel is provided for reference in Table 4.

In addition, SRTs offer higher durability through robustness against the creation of hotspots. Hotspots limit the power of the entire system, introduce reliability issues, and are responsible for the accelerated aging of the PV system (Ishak et al., 2023). A hotspot is the creation of a localized heating point when a part of a solar panel (i.e., solar cells) is shaded due to environmental stresses such as soiling, bird droppings, neighboring panels, etc. (Bharadwaj et al., 2018). The frequency and intensity of these events vary with the location and are completely random (Killam et al., 2021; Ishak et al., 2023), requiring timely monitoring to ensure safety (Ahmed et al., 2022).

3. Results and discussion

To evaluate the performance of both systems, a Simulink model was developed to observe the performance of traditional panels and SRTs under different environmental stresses. The traditional panel system consisted of a 300 W panel (https://sunceco.com/wp-content/uploads/2017/01/SEP300-320.pdf, n.d.) and 5 panels in series, making a 1500 W system. The SRT system consisted of 57 pairs (114 in total) of 13 W SRTs, making a 1482 W system. Both systems were subjected to the same DC load to overlook the inverter losses for a better comparison. The simplified model is shown in Fig. 4.

3.1. Testing conditions

Initially, traditional panels and SRTs were tested under three conditions:

- Normal operation at Standard Testing Conditions (STC) defined by the International Electrotechnical Commission (IEC) 61215-1-2021 (https://webstore.iec.ch/publication/61345, n.d.)
- When cells across one bypass diode are completely shaded, while the rest of the panel/string and SRT is subject to 1000 W/m^2 irradiance (Case 1)
- When solar cells across one bypass diode operate at 250 W/m^2 irradiance while the rest of the panel/string and SRT operates at 1000 W/m^2 irradiance (Case 2).
- The temperature was maintained at 25 °C to minimize the role of temperature in the performance.

3.2. Traditional PV and solar roof tiles testing – in the presence of bypass diode

Under STC, the traditional solar panel produced 1549.7 W. After experiencing environmental stresses, its energy output reduced by 5.31 % and 4.92 % in case1 and case2, respectively. In addition, a voltage drop in the PV system was observed because of its series connection; the shaded cells' voltage contribution was zero, as shown in Fig. 5.

In contrast, the SRT produced 1454.63 W at STC. Its energy dropped by 1.74 % and 1.26 % respectively when subjected to case1 and case2, respectively. Due to the SRT's series-parallel configuration, no voltage drop in the system was observed, and the system operated at stable

Table 2
Geographical factors of populated Danish cities.

Location	Air temperature (AT) -°C	Relative humidity (RH) - %	Precipitation (Pr) - mm	Daily solar radiation – horizontal (DSR-h) - kWh/m2/d	Atmospheric pressure (AP) - kPa	Wind speed (WS) - m/s
Copenhagen	8.0	79.6	757.1	2.83	101.3	5.7
Arhus	8.1	82.6	756.48	2.92	101.2	4.3
Odense	8.8	81.9	723.99	2.92	101.2	5.1
Aalborg	8.0	81.6	865.66	3.09	101.1	5
Frederiksberg	8.5	85.3	694.99	2.92	101.2	6

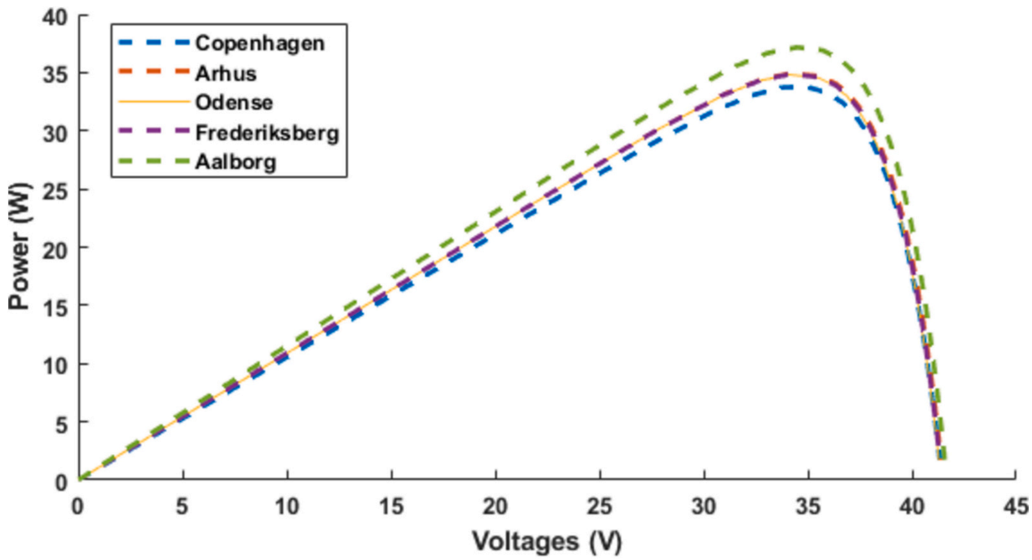


Fig. 2. PV output based on location's irradiance and AT.

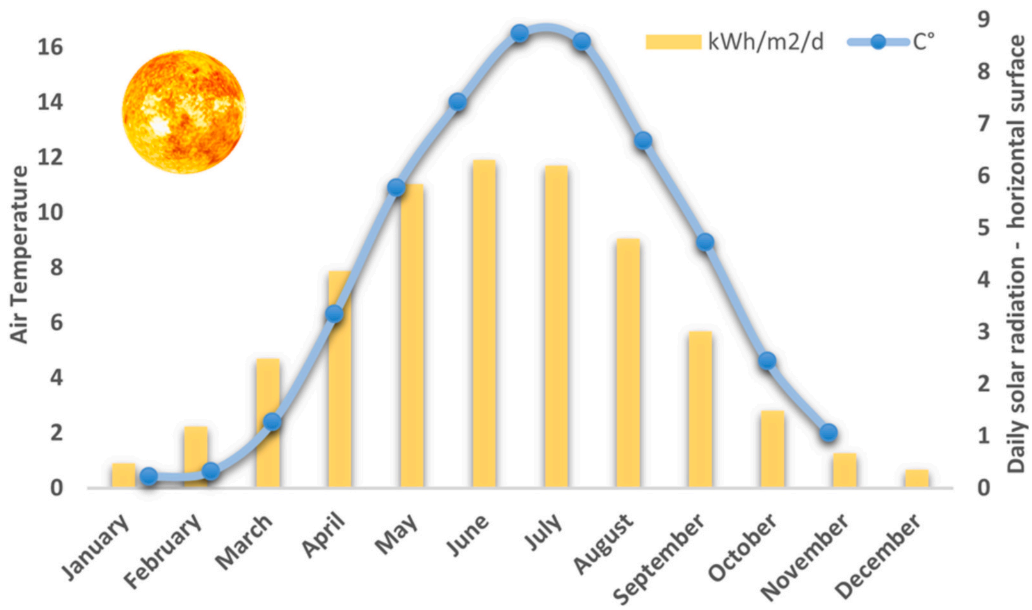


Fig. 3. Aalborg's monthly average – DSR-h and AT.

Table 3
Geographical factors of Aalborg.

Month	AT - °C	RH - %	Pr - mm	DSR-h - kWh/m2/d	AP - kPa	WS - m/s
January	0.4	88.6	76.88	0.48	101	5.7
February	0.6	86.5	57.12	1.19	101.1	5.5
March	2.4	82.3	56.73	2.49	101.1	5.5
April	6.3	76.8	50.10	4.17	101.2	5.0
May	10.9	74.2	55.18	5.84	101.3	4.8
June	14.0	76.2	75.30	6.31	101.1	4.8
July	16.5	75.6	73.47	6.20	101.1	4.7
August	16.2	77.8	84.32	4.79	101.1	4.6
September	12.6	81.3	83.4	3.01	101.1	4.8
October	8.9	84.6	95.79	1.49	101.1	5.1
November	4.6	86.8	77.70	0.67	100.9	5.0
December	2.0	88.5	79.67	0.36	101	5.1

voltage levels. However, in these cases, the bypass diode was active and contributed to a healthy PV system output.

A bypass diode is a protective measure used in PV systems, and it is not designed to carry the entire current for extended periods (Coetzer et al., 2019; Shiradkar et al., 2018). The bypass diode provides a pathway for the current to flow if some cells are partially shaded, thereby avoiding the hotspot problem and increasing the maximum power point (MPP) (Shiradkar et al., 2018; Vieira et al., 2020). However, if the bypass diodes are activated for a long time, they have a higher chance of burning out or getting damaged. This is because they are typically weakest in reverse bias when the reverse current reaches a critical threshold (Coetzer et al., 2019). Therefore, while bypass diodes play a vital role in the functioning of the modules during shadowing (Satpathy et al., 2022), their continuous use can lead to potential issues (Coetzer et al., 2019). Considering the bypass diode as faulty or inactive due to continuous usage, Case1 and Case2 of shading without the bypass diode were re-simulated.

Table 4
SRT and traditional panel comparison.

Parameter	SRT	Traditional panel (https://sunceco.com/wp-content/uploads/2017/01/SEP300-320.pdf, n.d.)
Nominal power (P_{mpp})	13.0 W	300 W
Short circuit current (I_{sc})	0.330 A	8.947 A
Open circuit voltage (V_{oc})	49.0 V	44.71 V
Nominal current (I_{mpp})	0.315 A	8.06 A
Nominal voltage (V_{mpp})	41.0 V	37.23 V
Temperature coefficient	−0.40 %/K	−0.45 %/K
Solar module size	420 × 265 mm	1956 × 992 × 50 mm
Operating temperature	−40 to +85 °C	−40 to +85 °C
Weight	5.3 kg	23.20 kg
Solar cells	Monocrystalline	Polycrystalline
Glass thickness	3.2 mm toughened, structured solar glass	3.2 mm
Encapsulation	Ethylene vinyl acetate, polyolefins, silicone	Ethylene vinyl acetate
25 years warranty	80 % power output	80 % power output

3.3. Traditional PV and solar roof tiles testing – in the absence/failure of bypass diode

In the absence of a bypass diode, the traditional PV system dissipated all energy across shaded cells, creating hotspots in case 1. This compromised the system's reliability and performance. In Case 2, its output reduced to 482 W, representing a loss of 68.9 % in output power, resulting in major hotspot creation.

In contrast, SRTs, due to their unique structure and configuration, experienced a drop of 1.73 % in Case 1 and 1.3 % in Case 2 under similar conditions. The 1.73 % drop in the SRT output is approximately 25.1 W, which is approximately equivalent to the output of a pair of SRTs (approximately 26 W). The unique structure and configuration of SRTs allow them to be decoupled from the healthy system to protect it. This is unlike traditional PV systems. Fig. 6 provides the results of the performance of the traditional system and SRTs in the absence of bypass diodes.

3.3.1. Visualization of hotspot effect on traditional panel

Bodies with a temperature above absolute zero Kelvin possess thermodynamic energy and emit electromagnetic radiation in the infrared region (8 to 12 mm wavelength) (Ahmed et al., 2021c). Infrared thermographs are used to examine the heat dissipation and defects of the PV system based on thermal properties such as hotspots (Ahmed et al., 2021c). Fig. 7 shows a hotspot on a traditional solar panel (infrared thermograph) due to a block fault caused by long-term environmental stresses. This affects one-third of the solar panel (Ahmed et al., 2021c). The bypass diode failed to bypass this region, negatively impacting the performance of the entire system and introducing durability and reliability issues. As a result, the panels need to be replaced urgently. It is important to emphasize that monitoring of the PV system is mandatory to ensure the continuous accessibility of energy at a reasonable cost (van Sark, 2023).

3.4. Performance analysis of the systems – traditional panel and solar roof tiles

Under any uncertainty that arises due to environmental stresses or any other factor, which leads to the blockage of effective photon transmission to part or the complete PV system, it impacts its energy output. Bypass diodes effectively bypass the affected area to ensure healthy panel/surface performance. However, in the absence or failure of a bypass diode in a traditional PV system, power production will be limited by the weakest link, the shaded panel that can lead to durability and reliability issues in the whole system. The flow of current in the traditional PV system, in the presence and absence of a bypass diode under uncertainties, is shown in Fig. 8. This aids in better understanding the behavior of the system.

In contrast, the unique series-parallel configuration of SRTs avoids the creation of hotspots by decoupling shaded or underperforming SRTs from the PV array in the presence or absence of bypass diodes. This

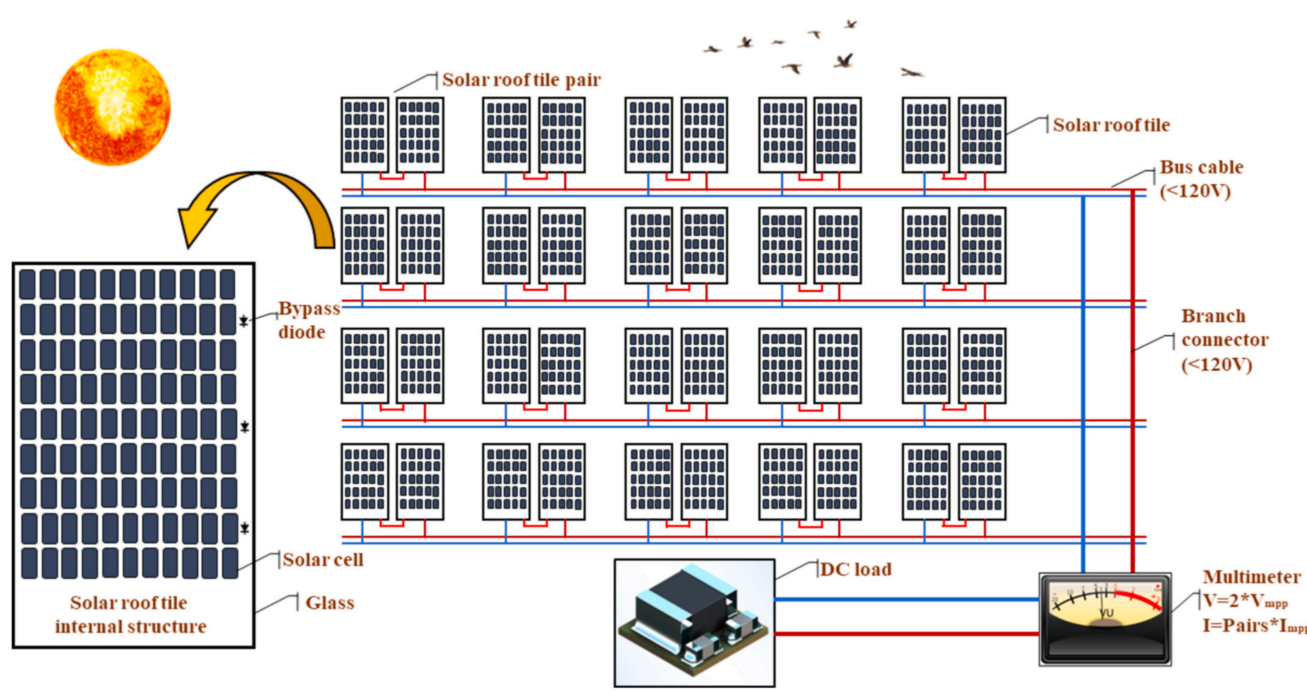
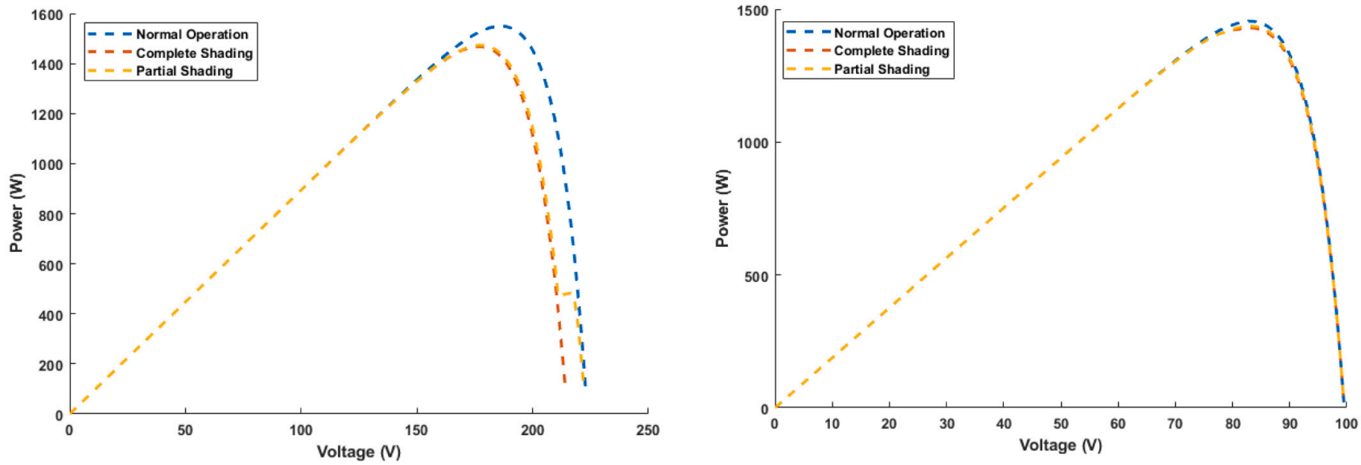


Fig. 4. SRT simplified model.



a. Traditional panel b. Solar roof tile

Fig. 5. Performance under normal, complete and partial shading of solar cells.

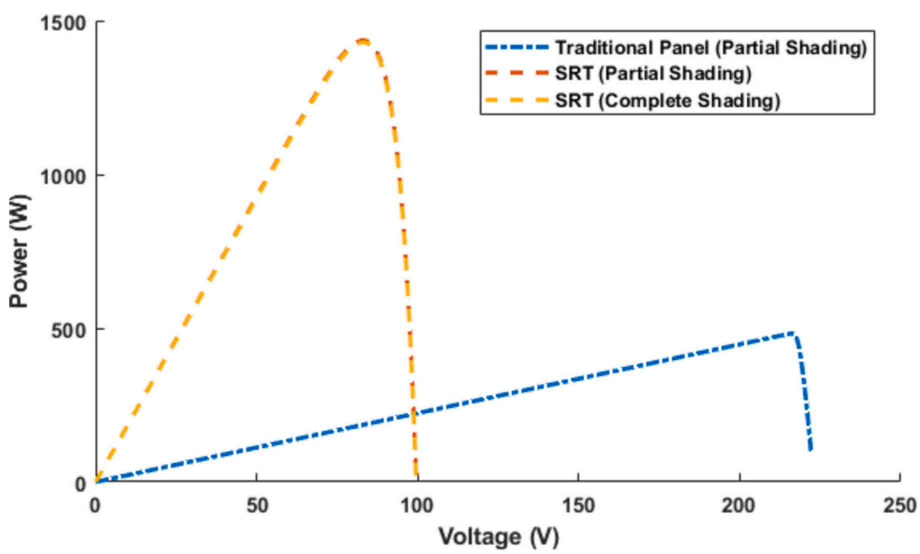


Fig. 6. Performance under stress and without bypass diode.

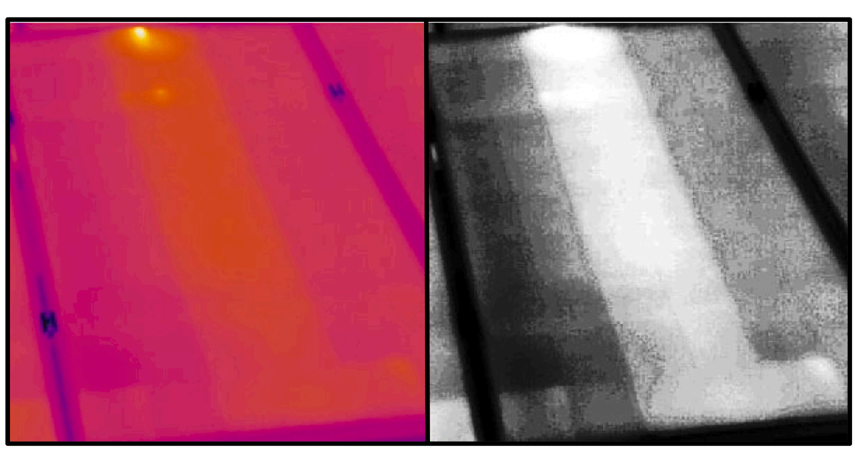


Fig. 7. Block fault (actual on left and binarized on right for impact) – traditional panel (Ahmed et al., 2021c).

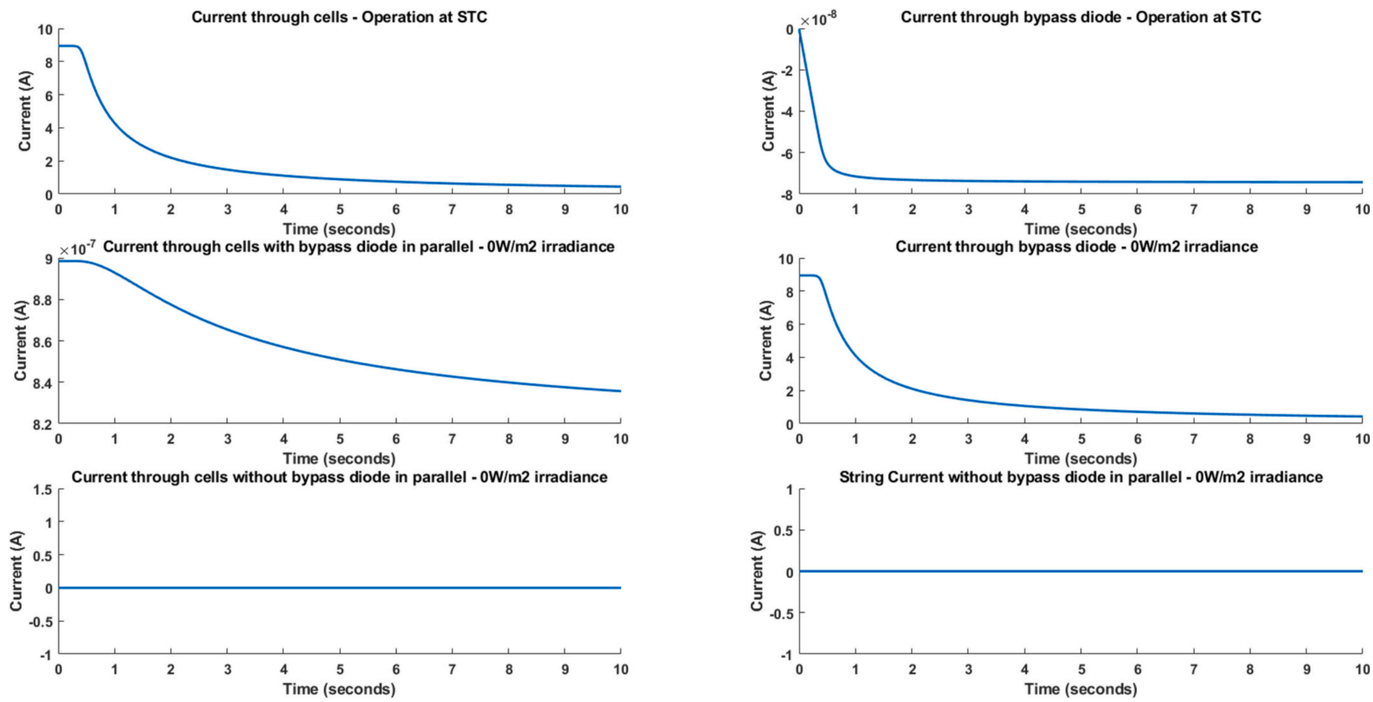


Fig. 8. Traditional PV system with defective/without bypass diode.

design ensures that the operating voltages of the system are not compromised at the same time, unlike a traditional panel (due to their series connection). The current flow in SRT, in the presence and absence of bypass diodes under uncertainties, is shown in Fig. 9 for a better understanding of SRT working. This unique property of SRT offers robustness against the creation of hotspots and power loss.

The results of this study demonstrate that SRTs offer significant advantages over traditional PV systems, particularly in terms of energy efficiency and reliability under environmental stresses. The unique series-parallel configuration of SRTs reduces the risk of hotspot formation and ensures stable energy production even in the absence of bypass diodes. These findings underscore the potential of SRTs to enhance the

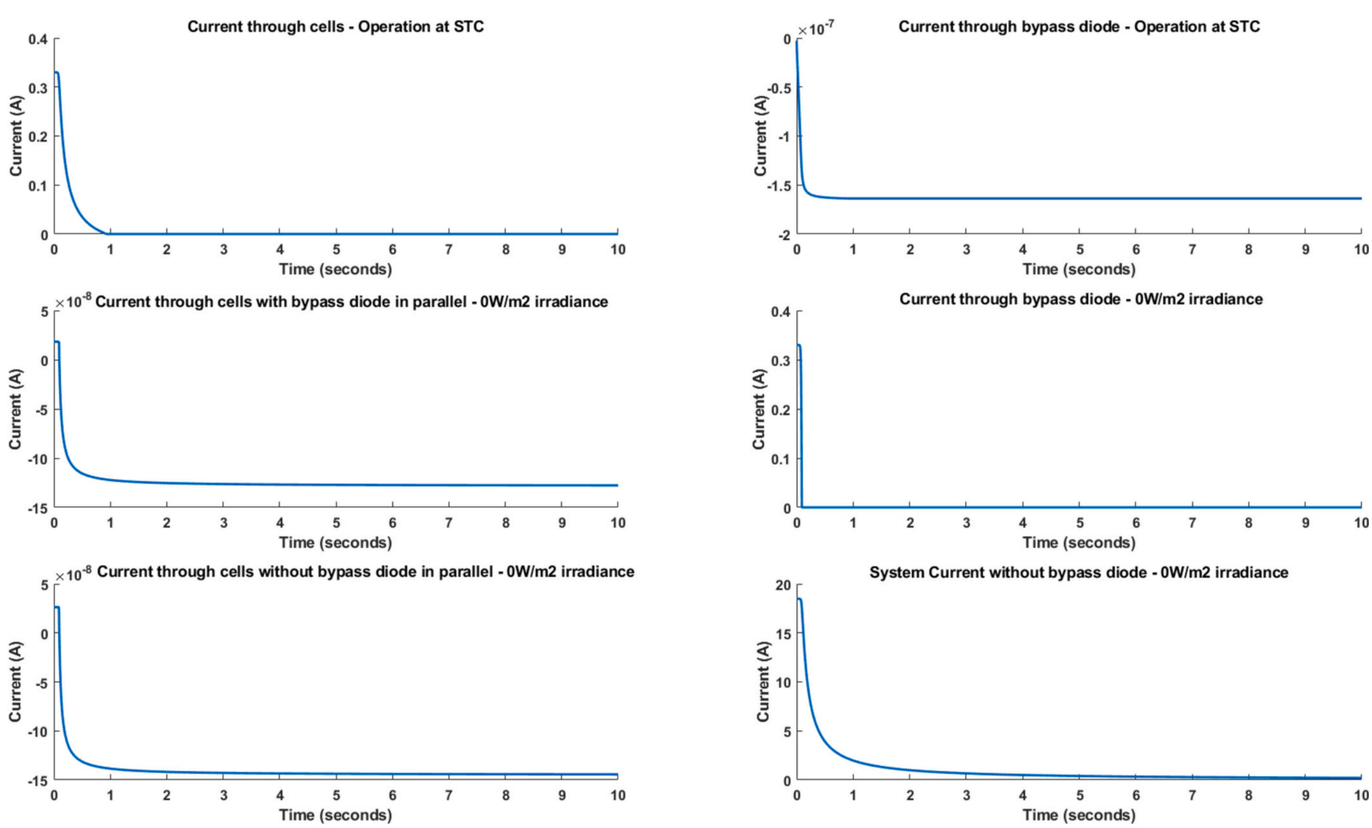


Fig. 9. SRT with defective/without bypass diode.

resilience of renewable energy systems and contribute to the reduction of greenhouse gas emissions.

The significance of this work lies in its demonstration of the superior performance and reliability of SRTs compared to traditional PV systems. The potential of SRTs to overcome common challenges associated with solar energy systems, such as hotspot formation and system failure. By providing empirical evidence of the benefits of SRTs, this research informs future discussions on the development and implementation of advanced solar technologies. The insights gained from this study can guide policymakers, engineers, and researchers in designing more efficient and resilient renewable energy systems.

The implications of this study are far-reaching, particularly in the context of urban energy infrastructure and climate action. The adoption of SRTs can significantly reduce the carbon footprint of buildings by integrating renewable energy generation into the existing architectural framework. This not only promotes energy efficiency but also enhances the aesthetic appeal of buildings, encouraging wider acceptance and adoption of solar technologies. Furthermore, the resilience of SRTs to environmental stresses ensures consistent energy production, contributing to the stability and reliability of the energy grid. These factors collectively support the transition to a sustainable energy future and align with international climate goals.

This study acknowledges several methodological limitations and assumptions. The performance evaluation of SRTs and traditional PV systems was conducted using a Simulink model, which may not capture all real-world variables and uncertainties. Additionally, the study assumes a fixed orientation angle for SRTs, which may not reflect the variability in actual installations. The geographical parameters were based on data from Aalborg, Denmark, and may not be generalizable to other locations with different climatic conditions.

4. Contribution to sustainable society - solar roof tiles

Due to the green energy nature with potential to outlast traditional PV panels under environmental uncertainties through their unique structure, SRTs has a positive impact on the society. For instance, SRTs are installed on the existing buildings with any additional infrastructure required, offering aesthetics to the homes as well. In addition, SRTs GHG mitigation potential compared to traditional PV panels is higher due to lack of accelerated aging due to environmental uncertainties.

4.1. Greenhouse gases mitigation potential – solar roof tiles

For energy production and GHG emissions mitigation potential of SRTs (detailed below), a 1.5 kW system (as discussed in Section 3. Results) was utilized and evaluated in RETScreen Expert (RETScreen International, 2005).

4.1.1. Energy production potential

Aalborg, city of Denmark was considered to calculate the green energy potential of SRTs (geographical parameters of Aalborg are provided in Fig. 3 and Table 3). Over time, the performance of the solar cells degrades, a phenomenon defined as aging (Lindig et al., 2021). Therefore, aging effect was also considered. In addition, roof tiles are installed at specific roof pitches, ranging between 23°–60°, a fixed orientation angle was also assumed. Table 5 provides more detailed parameters considered for SRT's energy production.

Considering the orientation angles (slope and azimuth), annual average daily solar radiation increased from 3.09 kWh/m^2/d (provided in Table 3, monthly data) to 3.75 kWh/m^2/d annual average. It resulted into in an annual energy production of 1871.72 kWh, considering SRT's parameters in Table 6. The monthly average daily solar radiation at 35°, along with the approximated kWh produced per month through 1.5 kW SRT, is furnished in Table 6. Considering all parameters, it is estimated SRT system will produce 46,793 kWh in its 25 years of service.

Table 5
SRT parameters.

Location	Aalborg, Denmark
Slope tracking	Fixed
Slope	35°
Azimuth	0°
SRT capacity	1.482 kW (57 pairs)
Efficiency	20 %
Temperature coefficient	−0.40 %/K
Aging loss	5 % (every year)
Miscellaneous losses	1 % (every year)

Table 6
Daily solar radiation average and electricity production – SRT.

Month	Daily solar radiation – tilted 35° (kWh/m^2/d)	Electricity produced (kWh)
January	1.16	52.55
February	2.21	89.51
March	3.58	157.61
April	4.95	206.05
May	6.12	256.50
June	6.25	250.78
July	6.30	258.08
August	5.39	221.80
September	3.97	161.86
October	2.49	107.82
November	1.54	66.05
December	0.96	43.09

4.1.2. Greenhouse gases mitigation potential

To calculate the GHG emissions mitigation potential of 1.5 kW SRT system, it is compared against Danish national grid's equivalent GHG emissions factor per kWh production considering all the energy resources in the country. Excluding transmission and distribution losses, GHG emissions factor per kWh is 0.169 kgCO_2 equivalent (RETScreen International, 2005). Considering 6 % transmission and distribution losses in Denmark (https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?locations=DK, n.d.), GHG emission factor per kWh increases to 0.179 kgCO_2 equivalent. As SRTs are installed on the end user/load premises, 0 % transmission and distribution losses were assumed for 1.5 kW SRT system.

A 1.5 kW SRT system, capable of producing 1871.72 kWh green energy per annum is capable of mitigating 335.7 kgCO_2 equivalent. The 25 years- service of 1.5 kW SRT system equivalent GHG mitigation potential is furnished in Table 7.

It's important to note that GHG emissions involve different types of gases such as carbon dioxide, carbon monoxide, methane, nitrogen oxide, etc. The greenhouse potential of these gases is used to translate them into carbon dioxide equivalents. For example, 28 t of CO_2 is equal to 1 t of CH_4, and 265 t of CO_2 is equal to 1 t of N_2O as per IPCC 2014 (Intergovernmental Panel on Climate Change, 2014).

4.2. Contribution to sustainable society – global perspective

The United Nations' Sustainable Development Goals (SDGs) are a

Table 7
Equivalent GHG mitigation potential – 25 years' service of SRT.

SRT's GHG mitigation potential	8392.5 kgCO_2 equivalent
Cars and light trucks not used	1.54
Liters of gasoline not consumed	3606.18
Barrels of crude oil not consumed	19.52
People reducing energy use by 20 %	8392.5
Acres of forest absorbing carbon	1.91
Hectares of forest absorbing carbon	0.77
Tonnes of waste recycled	2.90

universal call to action to ensure that by 2030 all people enjoy peace and prosperity (https://www.undp.org/sustainable-development-goals?utm_source=EN&utm_medium=GSR&utm_content=US_UNDP_PaidSearch_Brand_English&utm_campaign=CENTRAL&c_src=CENTRAL&c_src2=GSR&gclid=EAIaIQobChMIstT4iJbg8gIVmMx3Ch25EAB1EAAYAyAAEgLCE_D_BwE, n.d.). The SDGs have identified potential problems and targets. For instance, some identified fields of action are:

- The energy sector contributes to 73 % of human-caused GHGs, hence it is the main contributor to climate change (SDG 7: Affordable and Clean Energy).
- Cities occupy just 3 % of Earth's land, yet account for 60–80 % of energy consumption and 70 % of carbon emissions (SDG 11: Sustainable Cities and Communities).
- There is a need to reduce global net CO_2 emissions by 45 % by 2030 and reach net zero around 2050 to limit warming to 1.5 °C (SDG 13: Climate Action).

Based on the identified problems, some of the potential defined targets are:

- Increase the share of renewable energy in the global energy mix.
- Enhance international cooperation to facilitate access to clean energy research and technology.
- Increase the number of cities and human settlements adopting and implementing integrated policies towards mitigation and adaptation to climate change.
- Promote mechanisms for raising capacity for effective climate change-related management.
- Integrate climate change measures into national policies, strategies, and planning, etc.

SRTs, due to their green energy nature, contribute effectively to these SDGs targets. For instance:

- A 1.5 kW SRT produces approx. 46,793 kWh in its 25 years of service, considering aging and miscellaneous losses. In addition, the unique structure of SRTs protects the whole system in case of uncertainties by effectively decoupling the compromised SRT pair, unlike in traditional PV systems. This is possible due to technology research, hence increasing the renewable energy share in the global energy mix.
- With the potential of SRTs to integrate with existing building structures without major alterations, unlike traditional PV systems, they can provide clean renewable energy to more than 4.2 billion people living in cities alone.
- A 1.5 kW SRT system effectively mitigates 8392.5 $kgCO_2$ equivalent in its lifetime. One million homes will contribute towards 8,392,500,000 $kgCO_2$ equivalent, bringing down carbon emissions and achieving net-zero targets well before 2050.

5. Conclusion

The study found that the performance of solar cells, which is influenced by geographical parameters, can be partially compromised by environmental uncertainties such as shadows from bird droppings, snow, and dust. These uncertainties can create hotspots and reduce system performance. Defective bypass diodes can further affect the system's performance, reliability, and long-term durability due to accelerated aging.

However, SRTs, which consist of solar cells with a unique series-parallel configuration, can mitigate these issues. Even under uncertainties and in the case of defective bypass diodes, SRTs can decouple the unhealthy pair, allowing the rest of the system to operate as usual without any voltage loss. This increases the system's reliability, durability, and robustness against environmental stresses by 98.37 %, leading to higher energy yields, compared to standard PV panels.

SRTs not only enhance the resilience of green renewable energy systems but also ensure their reliable and long-term performance. This is significant as it enables these systems to mitigate greenhouse gas emissions (8392.5 $kgCO_2$ equivalent per 1.5 kW) throughout their lifetime, despite environmental uncertainties. This underscores the potential of SRTs in strengthening the robustness of renewable energy systems against environmental stresses.

This study underscores the importance of innovative design in enhancing the performance and reliability of renewable energy systems. The findings demonstrate that SRTs offer a viable solution to the limitations of traditional PV systems, providing a pathway for more sustainable and resilient energy infrastructure. By highlighting the technical and environmental benefits of SRTs, this research contributes to the broader discourse on renewable energy technologies and supports the global transition to a low-carbon future.

In conclusion, this study highlights the technical and environmental benefits of SRTs, emphasizing their potential to improve the performance and reliability of renewable energy systems. By addressing the limitations of traditional PV systems, SRTs can play a crucial role in advancing sustainable energy solutions and supporting global efforts to mitigate climate change. The insights gained from this research can inform future discussions and guide the development of more efficient and resilient renewable energy technologies.

However, the delimitations of the present study include the investigation of the compatibility of solar roof tiles with porous and rough-surfaced insulated roof tiles for cooling and heating. Moreover, airflow to cool down the SRTs due to roof tile insulation characteristics is not evaluated. Future work includes the experimental validation of SRTs' performance under various environmental stresses, such as soiling, bird droppings, and partial shading, to better understand their robustness and reliability. Additionally, evaluating the impact of different geographical parameters, such as atmospheric pressure, ambient temperature, and wind speed, on SRT performance will provide a more comprehensive understanding of their efficiency across diverse climates. Specific experiments could involve long-term field tests in multiple locations, coupled with advanced monitoring techniques like infrared thermography and real-time performance analytics.

CRediT authorship contribution statement

Waqas Ahmed: Writing – original draft, Methodology, Investigation, Conceptualization, Formal analysis, Software, Writing – review & editing. **Jamil Ahmed Sheikh:** Visualization, Supervision, Investigation, Conceptualization. **Tamas Kerekes:** Supervision, Software, Resources, Project administration, Validation. **M.A. Parvez Mahmud:** Visualization, Validation, Supervision, Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Bing AI, Grammaly, and Quillbot to address the grammatical errors. After using these tools/services, the author(s) reviewed and edited the content as necessary.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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