Replace or retain? Timing PV panel replacement for maximum life cycle carbon savings

Citation for the original published paper (version of record):

Galimshina, A., McCarty, J., Ghaida, H. et al (2025). Replace or retain? Timing PV panel replacement for maximum life cycle carbon savings. IOP Conference Series: Earth and Environmental Science, 1554(1). http://dx.doi.org/10.1088/1755-1315/1554/1/012119

IOP Conference Series:
Earth and
Environmental Science

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To cite this article: A Galimshina *et al* 2025 *IOP Conf. Ser.: Earth Environ. Sci.* **1554** 012119

Replace or retain? Timing PV panel replacement for maximum life cycle carbon savings

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Abstract. Driven by innovations in cell materials and manufacturing techniques, photovoltaic (PV) technology has advanced rapidly, with panel efficiencies increasing from around 5-10% to over 25% in recent designs. These efficiency gains raise questions about optimizing the replacement of PV panels in a system as they degrade; could upgrading an older, less efficient panel provide environmental benefits even if it hasn't reached its full lifespan? This study investigates the optimal timing for PV panel replacement by examining the embodied and operational trade-offs between maintaining panels until their technical end of life and upgrading to high-efficiency panels earlier.

We develop a parametric model that assesses embodied impacts, carbon payback times, and the impact of the regional electricity grid's carbon intensity for two types of PV panels: monocrystalline and Cadmium telluride. Results reveal threshold conditions where early replacement aligns with carbon reduction goals. A case study of a residential building in Switzerland with full building-integrated PV coverage provides insights into real-world applications. The findings provide a framework for policymakers and industry stakeholders to make informed decisions on PV replacement, balancing carbon payback across scenarios. This approach enables a strategic use of PV technology, aligning decisions with long-term sustainability goals.

1. Introduction

Greenhouse gas (GHG) emissions remain high, and according to UNEP [1], they have not decreased in recent years. One of the most effective solutions for decarbonization is renewable energy generation, which reduces dependence on fossil fuels and significantly lowers GHG emissions.

Photovoltaic (PV) technology has been widely recognized for its potential to mitigate GHG emissions, particularly in regions with favorable solar conditions. Studies have demonstrated that PV deployment on roofs and south-facing facades in Switzerland is especially beneficial in terms of GHG emissions savings [2]. Over the years, PV technology has advanced considerably, with the rated panel efficiency of monocrystalline panels improving from 18.2% in 1993 to 25.4% in 2025 and from 8.1% to 19.9% for Cadmium-telluride (CdTe) panels [3], [4]. The deployment of PV systems in Switzerland has also increased significantly, reaching 5.2 MW of installed capacity (4,602 GWh in generation) in 2023 [5]. The growth in PV installations has been driven by a combination of policy incentives, declining costs, and improvements in panel performance.

Despite the widespread adoption and technological progress of PV systems, a crucial challenge persists: the embodied GHG emissions associated with PV panel production. The manufacturing, transportation, and installation of solar panels generate significant upfront GHG emissions, raising concerns about their overall environmental impact throughout their life cycle. While operational carbon savings from high-efficiency panels are evident, the embodied carbon cost must also be considered when evaluating the sustainability of PV deployment.

Given the fact that many PV systems were installed in the early adoption of renewable energy and that panels have seen increased efficiency in the recent years, the question arises: does it make sense to replace existing PV panels before they reach their technical end of life to leverage the benefits of newer, more efficient models?

This question has received far less attention in the literature so far. One of the few studies that look into this calculates the repowering time for monocrystalline silicon modules for rooftop and open-field installation [6]. However, they do not look at building integrated PV (BIPV) and the solar irradiance in different settings.

Therefore, this paper addresses this question by developing a detailed, parametric model to assess the environmental trade-offs of PV panel replacement. The model evaluates embodied impacts, operational efficiency gains, and carbon payback times for monocrystalline and CdTe panels, considering the specific location conditions, such as solar irradiance and the local electricity grid.

2. Methods

The analysis of the carbon payback time takes into account the efficiency of the old system, the lost benefit in saved carbon emissions from the old panels, the efficiency improvement of the new system, the local electricity grid´s carbon intensity, the upfront carbon of the new system, and solar irradiation. Each of the parameters is described in detail below.

The analysis of the payback time has been calculated using the following equation:

$$EPT = \frac{E_{new} + E_{grid} * G_{old} * t_{remaining}}{E_{grid} * (G_{new} - G_{old})}$$

Where:

E_{new} - Embodied environmental impact of the new PV panels (kgCO$_2$e).

E_{grid} – Carbon intensity of the electricity grid ($kgCO_2e/kWh$).

G_{old} - Annual electricity generation of the old panels (kWh/year).

$t_{remaining}$ - Remaining lifetime of the old panels (years).

G_{new} - Annual electricity generation of the new panels (kWh/year).

For the analysis, two photovoltaic replacement options were considered: 1) a first generation monocrystalline silicon panel as it is the most widely used option, and 2) a second generation CdTe as it has been shown to be the lowest embodied impact when assessed in kgCO2eq/kWh. The PV panel efficiencies were considered as 25.4% for the monocrystalline panel and 19.9% for the CdTe (4).

The embodied carbon of these PV technologies was assessed using the Acacia tool [6]. The results indicate that monocrystalline panels have an embodied impact of 305 $kgCO_2eq/m^2$, whereas CdTe panels have a significantly lower impact of 97 $kgCO_2eq/m^2$. These values are based on production in Europe.

To estimate the annual electricity generation, the building was modeled in Rhino3D and simulated using Grasshopper and plugin Ladybug, incorporating detailed geometry, solar irradiance, and shading effects. Rhino3D (Rhino) is a 3D computer-aided design (CAD) software widely used for architectural and engineering modelling. Grasshopper is a visual programming language integrated into Rhino, enabling parametric design and automation of modeling processes. Ladybug is a plugin used to evaluate the outdoor climate analysis [7].

For the analysis of the payback time, the Zurich electricity grid mix from 2023 was considered [8]. Along with the embodied impact of the new panels, the lost benefit of the old panels was calculated. To do that, the remaining operating lifetime of the existing panels was multiplied by the annual emissions that would have been avoided in one year of their operation.

2.1. Case study

As a case study, a residential building in Zurich was selected. Located on Hofwiesenstrasse, the building has full BIPV coverage (See Figure 1). Originally built in 1982, a renovation of the multi-family house was completed in August 2016 [9] supported by the Swiss Federal Office of Energy. As a part of the refurbishment, the old plastered exterior walls were replaced with a gray-green glass façade with integrated PV panels. The BIPV system utilizes monocrystalline silicon cells with an efficiency of approximately 10%; lower than the expected cell efficiency of 24.4% [4] at the time due to a coloured tint on the front glass cover. This raises the albedo of the panel and reduces overall efficiency as calculated against irradiance at the front of the panel.

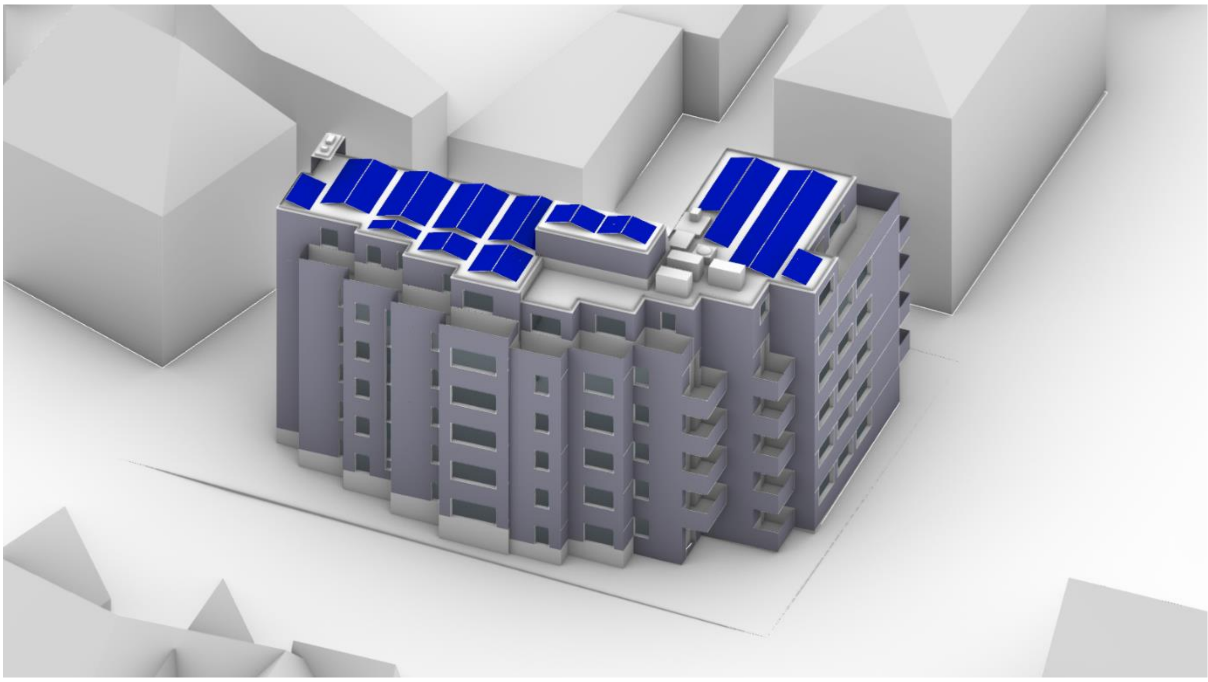

Figure 1: Model of the Hofwiesenstrasse case study building.

Three scenarios for early PV replacement were developed for this case study:

1. Replacement of the older and less efficient BIPV panels across the entire façade with new BIPV panels.
2. Installation of new panels on the roof and façade, assuming no previously installed BIPV.
3. Replacement of the older and less efficient BIPV panels across only the south-facing façade with new BIPV panels.

The payback time was calculated for the three scenarios for monocrystalline panels with a conversion efficiency of 25.4% and cadmium telluride panels with a conversion efficiency of 19.9%. The service life of the newly installed panels was assumed to be 25 years, while the lost benefit of the replaced panels, having been in operation for 16 years, was also accounted for.

3. Results

The results of the replacement analysis for the entire façade area of the building in Scenario 1 indicate that the payback time for CdTe panels after replacement is approximately 43 years, whereas for monocrystalline panels, it is around 65 years. This is due to the high embodied environmental impact of the new panels, the lost remaining environmental benefits of the old panels upon replacement, and the relatively clean electricity grid mix in Zurich with an average of 0.1 kgCO2e/kWh in 2023. The curves in Figure 2 illustrate the required irradiance and efficiency levels for both technologies to achieve a payback period within the 16-year remaining lifetime of the replaced panels. The crossover point for the CdTe panels and the available average irradiance across the façade is 36.6% and the monocrystalline panel curve never crosses line of average façade irradiance.

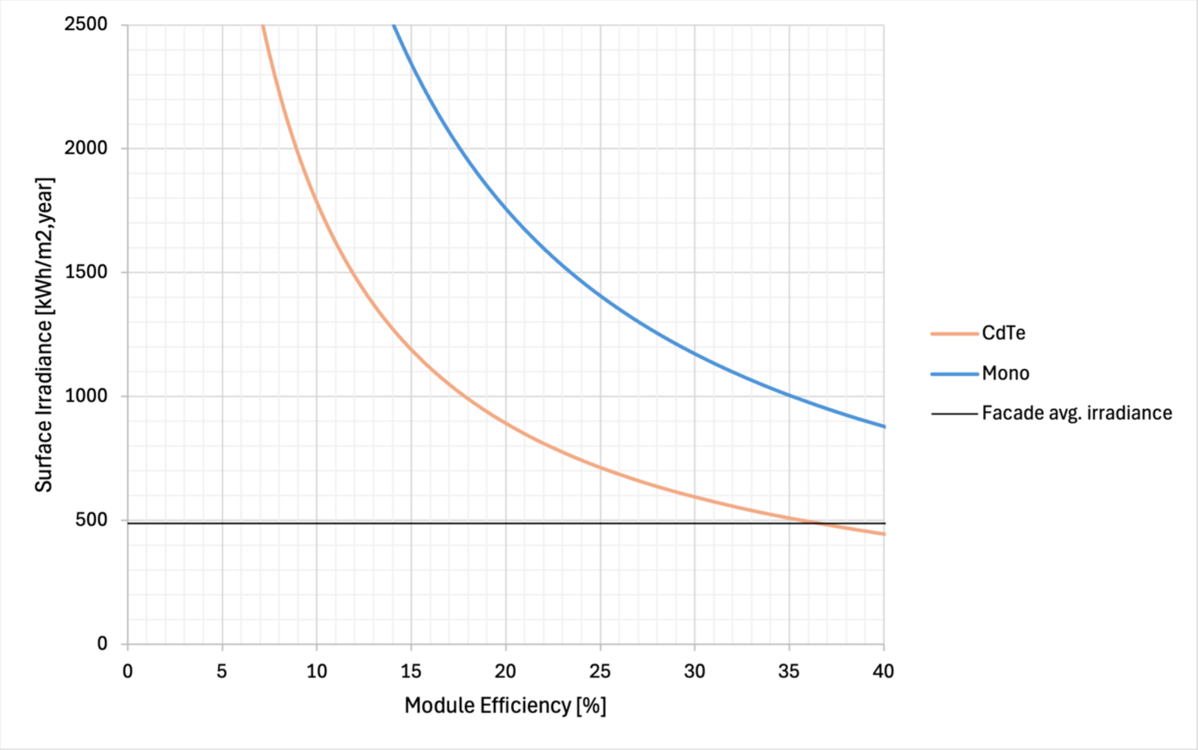

Figure 2: Required irradiance and efficiency levels for Monocrystalline and CdTe technologies to achieve a payback period within the 16-year remaining lifetime of the replaced panels when analysing the entire building façade.

As the average irradiance in the considered case study is approximately 487 kWh/m^2 per year, replacing the existing PV panels is not an environmentally favorable option in this case study. The irradiance level is significantly lower than the required values for both monocrystalline and CdTe panels, meaning the environmental benefit from replacement is minimal compared to the substantial embodied carbon impact of producing new panels.

The environmental payback time of BIPV installed on a building that previously had no PV system was analyzed in Scenario 2. The payback time was evaluated under different conditions, with payback values set at 10, 20, and 40 years (see Figure 3).

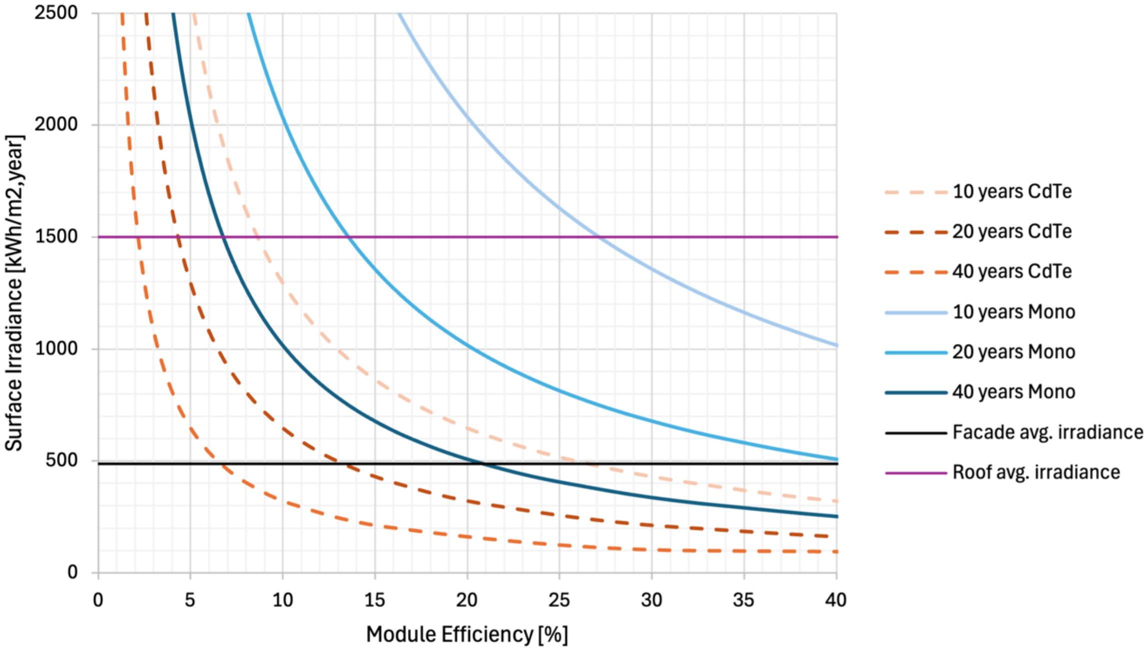

Figure 3: Feasibility of BIPV installed on the roof and façade

When considering monocrystalline panels installed on the facade, the payback time varies significantly, ranging between 20 and 40 years, depending on the efficiency of the panels. However, when Monocrystalline panels are installed on the roof, the payback time is reduced to a range between 10-20 years, making it a more favorable option. For CdTe panels, achieving a 10-year payback period on the facade requires an efficiency of at least 26.6%, the performance is also considerably improved when installed on the roof. If installed on the roof, CdTe panels with the expected present-day efficiency of 19.9% achieve a payback time of less than 5 years, making them a more environmentally viable choice in this scenario.

Previous studies show the benefit of the installation of panels primarily on the Southern façade [2]. Therefore, Scenario 3 considers only the replacement of the panels on the Southern façade. The results shown in Figure 4 indicate that the payback time for the panels is lower, but still unreasonable for contemporary systems, being 36 years for CdTe and 50 years for monocrystalline silicon panels. Looking closer at the curve and the relationship with the annual irradiance on the façade, it can be seen that the required efficiency for CdTe panels to be environmentally beneficial would be around 32%, which is above the expected efficiency for available panels, but is close to the theoretical limit of 32.1% conversion efficiency of CdTe cells [10].

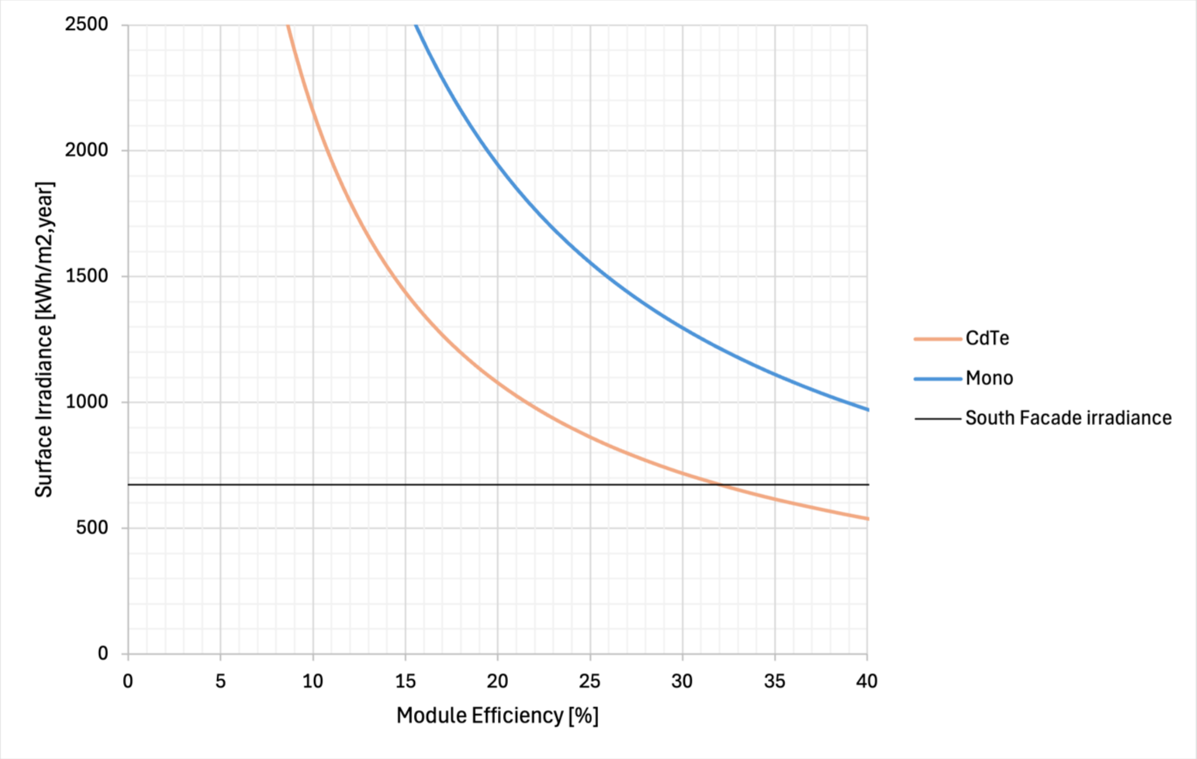

Figure 4. Required irradiance and efficiency levels for monocrystalline and CdTe technologies to achieve a payback period within the 16-year remaining lifetime of the replaced panels when analysing only the south-facing façade area.

4. Discussion

As the efficiency of the new panels is continuously improved, the question of the replacement of ageing panels is becoming important to analyze. While replacing older, less efficient panels with newer, high-efficiency models may seem beneficial, it is crucial to assess the environmental burden of the new technology and the lost benefit of the older panels. Our analysis shows that in Zurich, the replacement of the panels will never be beneficial, considering the available irradiance, possible PV panel efficiencies, and when the system competes with the low-carbon electricity grid. However, our analysis shows that CdTe panels are more beneficial from the environmental point of view, even though the efficiency is lower than for the monocrystalline panels. This aligns with previous work in the field where CdTe and other thin-films (i.e. Copper indium gallium selenide) performed better than crystalline systems from the perspective of global warming potential [11], [12].

Another LCA study has evaluated the carbon payback time (CPT) of monocrystalline PV panels installed on the MFH Hofwiesen-/Rothstrasse complex, with the 3D model displayed in Figure 1 [13]. This study also considers the avoided emissions from the cladding materials excluded from the building's façade in the discounted category. Overall, the CPT results are consistent, though slight differences exist due to variations in the efficiencies applied, embodied impact, and grid emissions in Zurich (Figure 5).

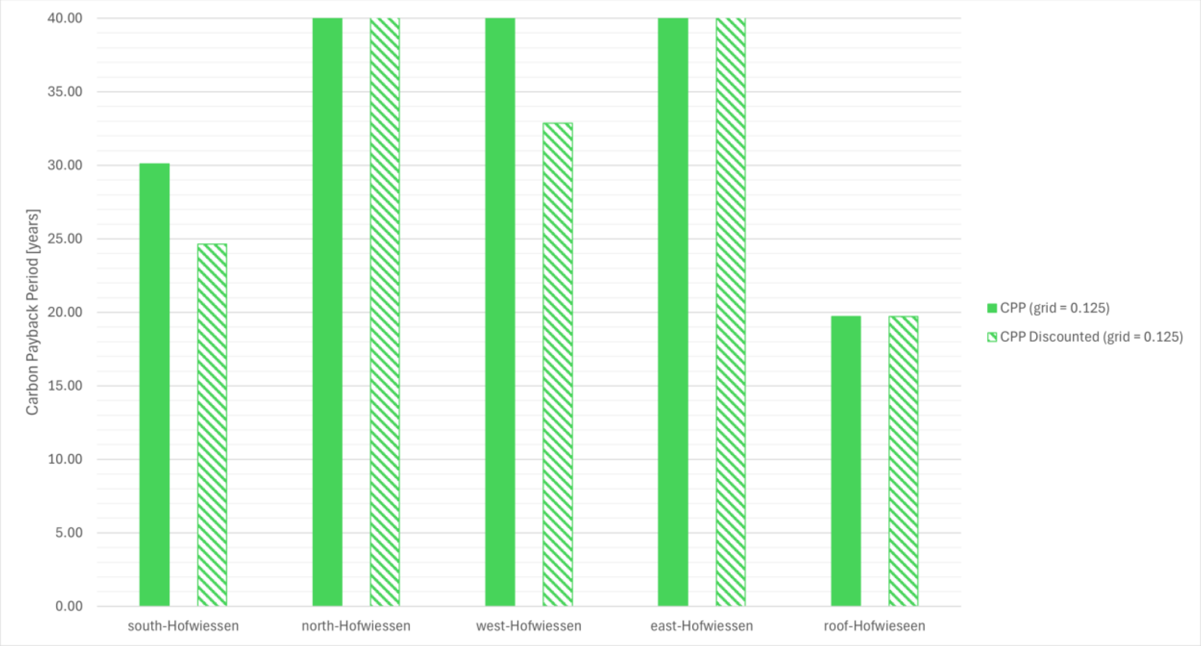

FIGURE 5: Comparison of the carbon payback time for the surfaces of the case study building [13]

Additionally, factors such as site-specific solar irradiance play a crucial role in determining whether early replacement is environmentally beneficial. Locations with high irradiance levels can offset the embodied impact of new panels more quickly, whereas in low-irradiance environments, the carbon payback time may be significantly extended. For example, Zurich, with its moderate irradiance and a relatively low-carbon electricity grid, presents a scenario where replacing older panels may not bring substantial environmental benefits. In contrast, a location like Singapore, with high solar irradiance and a fossil-fuel-dominated grid mix, could justify early replacement more readily. A more dynamic approach that considers degradation rates, local energy generation potential, and evolving grid emissions could provide a better understanding for future decision-making.

Lastly, we point out the importance of the results of the replacement only on the southern-façade. As the required efficiency of the CdTe panels would be near the level of the theoretical limit to achieve net environmental benefit, it is perhaps more important to focus on manufacturing methods for solar cells that perform at the level they do now but require less energy input to manufacture or are manufactured using low-carbon energy sources.

Limitations

One key limitation of the current assessment is the exclusion of End-of-Life (EoL) considerations in the CPT calculation. The analysis includes only the embodied emissions related to the production of the panels, omitting the potential environmental burdens or benefits associated with the disposal, recycling, or recovery of PV panels at the end of their service life. Including the EoL phase would likely increase the CPT, as additional emissions may be incurred through dismantling, transport, and treatment processes. However, if efficient recycling technologies are developed—the net impact of the EoL phase could become beneficial. As such, future assessments should aim to include more comprehensive lifecycle stages, especially as circular economy solutions for PV systems continue to evolve.

5. Conclusion

In this study, a parametric model was developed to evaluate whether upgrading older, less efficient PV panels is environmentally beneficial when considering embodied impacts, operational gains, and carbon payback times across two different types of panels: monocrystalline and CdTe. Our findings indicate that early replacement is unlikely to yield environmental benefits in a setting like Zurich, where relatively low irradiance and a decarbonized grid extend payback periods. Although newer systems produce more electricity, the embodied impact of manufacturing replacement panels, combined with the lost carbon savings of the old ones, often outweighs these gains. CdTe panels, despite lower efficiency, emerged as a comparatively favorable choice from a life cycle perspective. Overall, we suspect that replacing older panels prematurely would be appropriate in regions with either higher solar irradiance, more carbon-intensive electricity grids, or a combination of the two. The context of Zurich, Switzerland with respect to these two categories is likely the most difficult to justify premature replacement. Lastly, further research into lower-impact production processes, as well as panel deployment on rooftops or sun-rich façades, can help realize shorter payback times and improve the overall carbon balance of PV systems. This is of particular importance due to the results of the analysis showing that for premature replacement to be beneficial, the efficiency of the solar cells must be close to or exceed the theoretical limits of the cell technologies.

6. Acknowledgements

This research was conducted at the Future Cities Lab Global at ETH Zurich. Future Cities Lab Global is supported and funded by the National Research Foundation, Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) program and ETH Zurich (ETHZ), with additional contributions from the National University of Singapore (NUS), Nanyang Technological University (NTU), Singapore and the Singapore University of Technology and Design (SUTD).

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