Original Research Article

The Promise and Possibilities of Perovskite: A Comparison to Monocrystalline Solar Cells and Guidelines for the Future

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ABSTRACT

The world would be better if solar energy not only achieved high efficiency but also minimized its environmental impact across its entire life cycle. While monocrystalline silicon (mono-Si) solar cells dominate the market with proven efficiency and durability, and perovskite solar cells (PSCs) have surged forward with rapid efficiency gains, there remains a gap in understanding how their global warming potential (GWP) compares, especially given the much shorter lifespan of PSCs. This systematic review of life cycle assessment (LCA) studies of monocrystalline silicon and perovskite solar cells using the PRISMA framework evaluates and compares the GWP of mono-Si and PSCs in terms of gCO_2eq/kWh. It finds that mono-Si solar cells generally range between 19–210 gCO_2eq/kWh depending on technology and energy mix, whereas PSCs can achieve values as low as 6–12 gCO_2eq/kWh. These findings suggest that PSCs have strong potential, but only if their lifespans can approach the durability of mono-Si cells.

Keywords: Monocrystalline solar cells; Perovskite solar cells; Life cycle analysis; Global warming potential; Break-even lifespan

INTRODUCTION

In 1954, Bell Labs invented the first ever silicon solar cell, though it reached an efficiency of only 6% (1). Today, these same silicon solar cells – specifically, monocrystalline (mono-Si) solar cells – have more than quadrupled in efficiency, reaching 25% efficiency in commercial settings, and 27.6% under ideal laboratory conditions (2). This efficiency, coupled with long lifespans and a declining cost of production, has made mono-Si solar cells the dominant solar cell with a market share of nearly 98% (2).

Recently, however, a new contender has come to light: perovskite solar cells (PSCs). These PSCs have made an incredible jump in power conversion efficiency (PCE) from 3.5% to 25.8% in just a decade, and have the added benefit of a relatively low production cost (4). The rapid development and seemingly endless potential of PSCs have garnered interest across the scientific community, leading many to wonder if these could be a viable contender against the market-dominating mono-Si solar cells.

However, PSCs are not without their drawbacks: PSCs are highly sensitive to moisture, UV light, heat, and oxygen. These sensitivities mean that PSCs, even when encapsulated, have an extremely short lifespan compared to mono-Si solar cells. While mono-Si solar cells have a

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lifespan of around 30 years, the lifespan of PSCs ranges from a few weeks to a year (4).

The drastic difference in lifespan makes it clear that PSCs, for now, remain a laboratory curiosity. Unfortunately, no study so far has estimated a break-even lifespan for PSCs with regards to global warming potential (GWP). Thus, this review paper asks the question: at what lifespan will PSCs be a serious competitor with mono-Si solar cells? Given that the goal of renewable energy is to reduce the emissions of greenhouse gases, this review paper will explore its question by focusing specifically on GWP in terms of gCO_2eq/kWh.

METHODS AND MATERIALS

To understand this question, it is essential to first derive an equation that allows mono-Si solar cells and PSCs to be compared. In order to find the breakeven lifespan, the GWP of PSCs should be compared to the GWP of mono-Si cells. Because mono-Si cells are so prolific, their GWP is easily available, leaving only the GWP of PSCs to be calculated. To find this value, the total electricity generated by a PSC over its lifespan should be divided by all the CO_2eq generated in its production. A measure of how much electricity the PSC generates in total can be found by multiplying by the solar irradiance, which is the power per unit area received from the sun in the form of electromagnetic radiation, the PCE, the performance ratio (a measurement of how much energy remains after losses due to factors such as temperature and shading), and the lifespan. By dividing the reported gCO_2eq/m^2 by this value, setting it equal to the median GWP of the mono-Si cells, and rearranging with basic algebra, one can determine the break-even lifespan for PSCs.

This is summarized in Equation 1, where L_B is the break-even lifespan that PSCs need to attain, $G_{m^2}^{PSC}$ is the GWP of PSCs per m², eff^{PSC} is the median efficiency of the PSCs studied, S is the solar irradiance, PR is the performance ratio, and $G_{mono-Si}$ is the median GWP of the mono-Si solar cells studied.

$$L_B = \frac{G_{m^2}^{PSC}}{\text{eff}^{PSC} \cdot S \cdot PR \cdot G_{mono-Si}} \tag{1}$$

Equation 1. Formula for calculating the environmental break-even lifespan based on cumulative GWP.

For this data analysis, only the cradle-to-gate studies of mono-Si were used to find the median, due to the fact that all but one of the PSC studies were cradle-to-gate. Although this limits the answer found in terms of the number of data points, this decision also increases the accuracy of the answer found, as including cradle-to-grave studies would make the two answers incomparable. It also assumes the global average solar insolation of 1500W/m² (5). A performance ratio of 0.8 is assumed, as a conservative average that accounts for seasonal variation (6). These assumptions allow for a more streamlined analysis and for impacts to be normalized worldwide.

RESULTS

In conducting this literature review, the goal was to extract the GWP of manufacturing, efficiency, and lifespan of PSCs as to utilize them within Eq. 1. To accomplish this, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, a standardized and transparent framework for reporting systematic reviews, was followed. By utilizing the PRISMA method, this review paper searches the ScienceDirect database, the Environmental Science and Pollution Research database, and the International Energy Agency's published works, focusing only on journal articles published from 2020 and onward as to highlight the most recent developments in photovoltaic technology. The search string "solar cell" AND "life cycle" AND "global warming potential" AND ("silicon" OR "perovskite") was used, returning 1062 results. The titles were further filtered to only show results that had ("solar" OR "photovoltaic") AND ("silicon" OR "perovskite"). Finally, by looking at each paper, results were narrowed down to only research articles that followed ISO 14040 and 14044 (international standards for LCAs) and reported results in gCO_2eq/kWh. This left 6 papers on mono-Si solar cells and 4 papers on PSCs to be selected for data extraction, presented in the PRISMA flow chart in Figure 1.

The papers on mono-Si cells tended to be cradle-to-grave, while the papers on PSCs tended to be cradle-to-gate. This discrepancy could be due to the fact that PSCs are so new, accurate data on disposal does not exist. The characteristics of all included studies are summarized in Table 1.

Life Cycle Assessment of Monocrystalline Silicon Solar Cells

Mono-Si solar cells are quite energy intensive to make. The silicon that they are made from needs to be purified not just once, but twice, before it can be

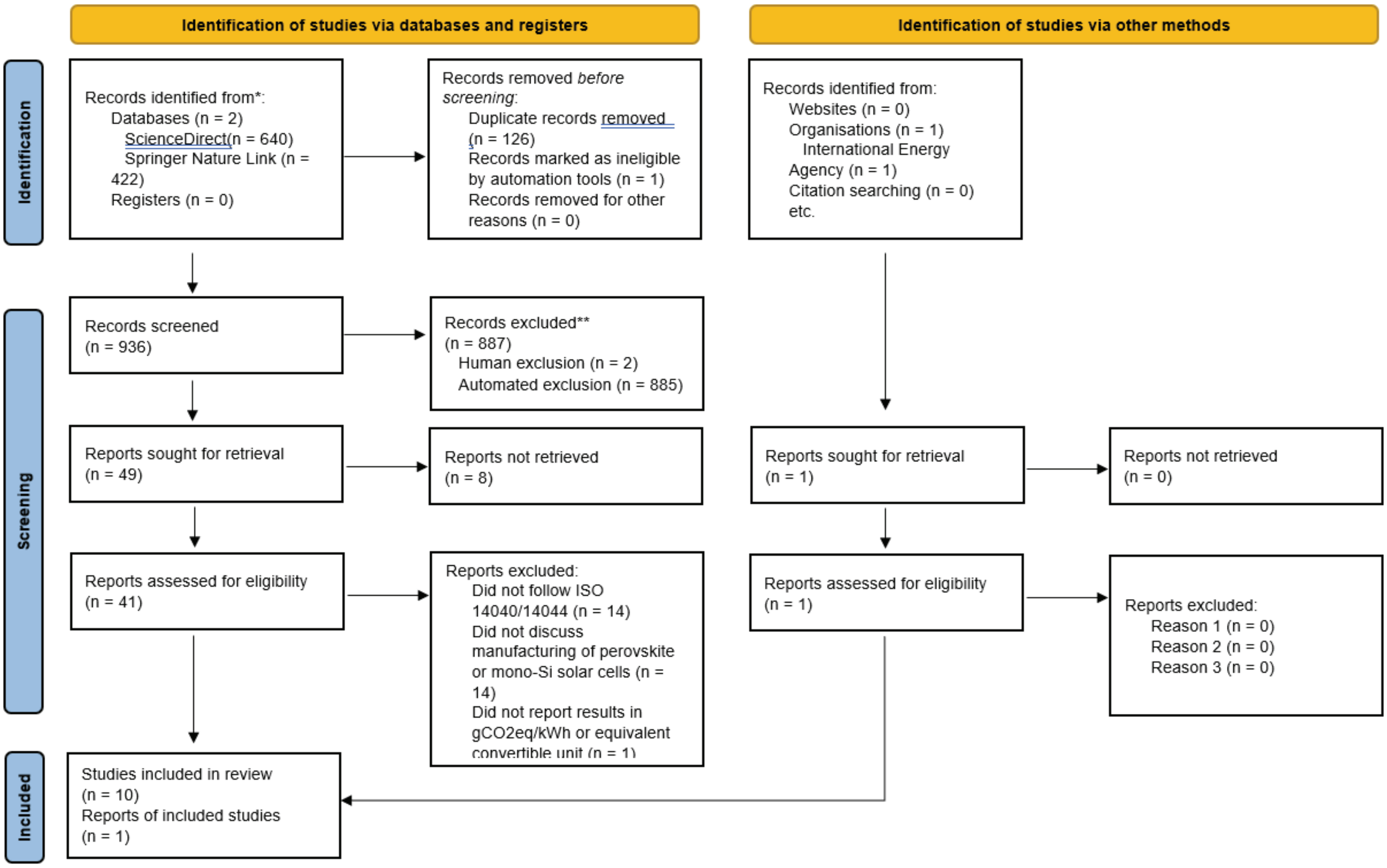

Figure 1. PRISMA flowchart.

Table 1. Characteristics of included studies

References	Year	Location	System Boundaries	Functional unit	Lifespan	Methodology	Energy mix
7	2024	China, Germany, Norway	Cradle to gate	gCO2eq/k Wh	25, 30, and 45 yrs. Data extracted from 30yr analysis.	Conducted with Umberto v11	Grid mix of China, Germany, and Norway
8	2022	Canada	Cradle to gate	gCO2eq/k Wh	30 yrs	Conducted with OpenLCA v1.11	Ontario grid mix
9	2025	Pakistan	Cradle to grave	kgCO2eq/k Wh	25 yrs	Conducted with SimaPro 9.4.0.2	China grid mix for the PV panel production, Pakistan grid mix for battery, inverter, and charge controller production
10	2025	Türkiye	Cradle to grave	gCO2eq/k Wh	25 yrs	Conducted with Ecoinvent v3.7	China grid mix for the PV panel production, Türkiye grid mix for maintenance and disposal

Continued Table 1. Characteristics of included studies

References	Year	Location	System Boundaries	Functional unit	Lifespan	Methodology	Energy mix
11	2025	China	Cradle to grave	gCO2eq/k Wh	25 yrs	Conducted with OpenLCA	Nanjing grid mix
12	2021	China	Cradle to grave	gCO2eq/k Wh	25 and 30 yrs. Data extracted from 30 yr analysis.	Conducted with SimaPro 9.0	China grid mix
13	2024	United States	Cradle to grave	gCO2eq/k Wh	25 yrs	Conducted with GaBi ts 10.0	United States grid mix
14	2024	United Kingdom	Cradle to gate	gCO2eq/k Wh	2 yrs	Conducted with GaBi	United Kingdom grid mix
15	2023	India	Cradle to gate	kgCO2eq/k Wh	5, 10, 15, 20, and 25. Data extracted from 5 yr analysis.	Conducted with SimaPro v9.0	India grid mix
16	2024	Thailand	Cradle to gate	gCO2eq/k Wh	2 yrs	Conducted with Sima Pro 9.3.0.2	Thailand grid mix

crystallized, cut into wafers, and doped to create the cell (6). Thus, the GWP of mono-Si solar cells is quite heavily dependent on the energy mix used to create them, with values of GWP ranging from 19.0 to 210. gCO_2eq/kWh. The impact of energy mix is best demonstrated by one study which conducted a cradle-to-gate LCA using the energy mix of Norway vs. China, and found that the resulting GWP varied between 23.1 and 54.8 gCO_2eq/kWh respectively (7). The solar irradiance of the location where the solar panel is installed also plays a role, as seen in a different cradle-to-gate study conducted in Canada, where they found a value of 79.0 gCO_2eq/kWh, even though the grid mix of Ontario incorporates significantly more renewables (8).

Cradle-to-grave LCAs tend to have a higher GWP, given their expanded boundaries. In fact, a study conducted in Pakistan found a GWP value of 210. gCO_2eq/kWh (9). Other cradle-to-grave LCAs of mono-Si solar cells, conducted in Istanbul and China, found a value of 55.1 gCO_2eq/kWh (10) and 150.-180. gCO_2eq/kWh (11) respectively.

Finally, the inclusion of emerging technologies for mono-Si solar cells plays a role in their GWP as well. One cradle-to-grave study that utilized passivated emitted rear cell (PERC), which increases efficiency by reflecting lost light back into the cell and reducing electron recombination, found a GWP of 19.3 gCO_2eq/kWh (12). This significantly lower GWP is consistent with the increased efficiency of PERC solar cells. All in all, the difference between the two can be summarized by their medians: the median GWP for cradle-to-gate LCAs is 54.8 gCO_2eq/kWh, while the median GWP for cradle-to-grave LCAs is 150. gCO_2eq/kWh.

Life Cycle Assessment of Perovskite Solar Cells

Just like PERC cells, PSCs are also able to achieve a fairly low GWP by virtue of their high PCE. In addition, their production methods are much more energy efficient than mono-Si. Instead of needing to be crystallized, they can be made using spin coating, blade coating, or slot-die coating, and can even be printed with inkjet printing. The benefits of high PCE and manufacturing efficiency can be seen in the range of the gCO_2eq/kWh values, which goes from 6.00 to 180. gCO_2eq/kWh – both the minimum and maximum are less than the respective values for mono-Si cells. Unfortunately, their short lifespans mean that many of these benefits are negated once their active lifespan is factored in.

One can observe the impact of lifespan on GWP in a cradle-to-grave study testing out low dimensional materials used to make PSCs. Although they found a very low GWP value of 6.1 gCO_2eq/kWh, they used a lifespan of 25 years, which is at the very high end of the scale for expected lifespan of PSCs (13). A different study, this one using a more reasonable lifespan of 2 years, found a GWP value of 12 gCO_2eq/kWh (14). Although these two are not directly comparable, since the second study is cradle-to-gate and does not use low dimensional materials, one can still observe the effects of lifespan on GWP.

The manufacturing process used to create the solar cell also has an impact on the GWP of the PSC. Both of the above studies used slot-die coating techniques, but one cradle-to-gate study that used inkjet printing found a much higher value of 126-180 gCO_2eq/kWh (15). This significantly higher GWP due to manufacturing is fairly unique to inkjet printing, however – a final cradle-to-gate study that used blade coating found a GWP of 8.61 gCO_2eq/kWh (16), which is more in line with the other values found through the manufacturing technique of slot-die coating.

Break-Even Lifespan Analysis

From the above findings, it is clear that PSCs have the capability to be extremely competitive with mono-Si – in fact, some of the above GWP values for PSCs already beat those of mono-Si solar cells. Unfortunately, the ones that beat those of mono-Si solar cells tend to use more unrealistic lifespans. Nearly all PSCs have lifespans of a few weeks to a year (17), yet these studies use lifespans of various lengths (some much higher than 1 year) in their calculation. Thus, this review paper first normalizes the GWP values by testing various lifespans for each of the above PSCs, presented in Figure 2. By the decaying slope of the graph, it is clear that the GWP decreases as lifespan increases. This is because the CO2eq generated by manufacturing, the most carbon intensive process throughout the life of a solar cell, is spread out over a

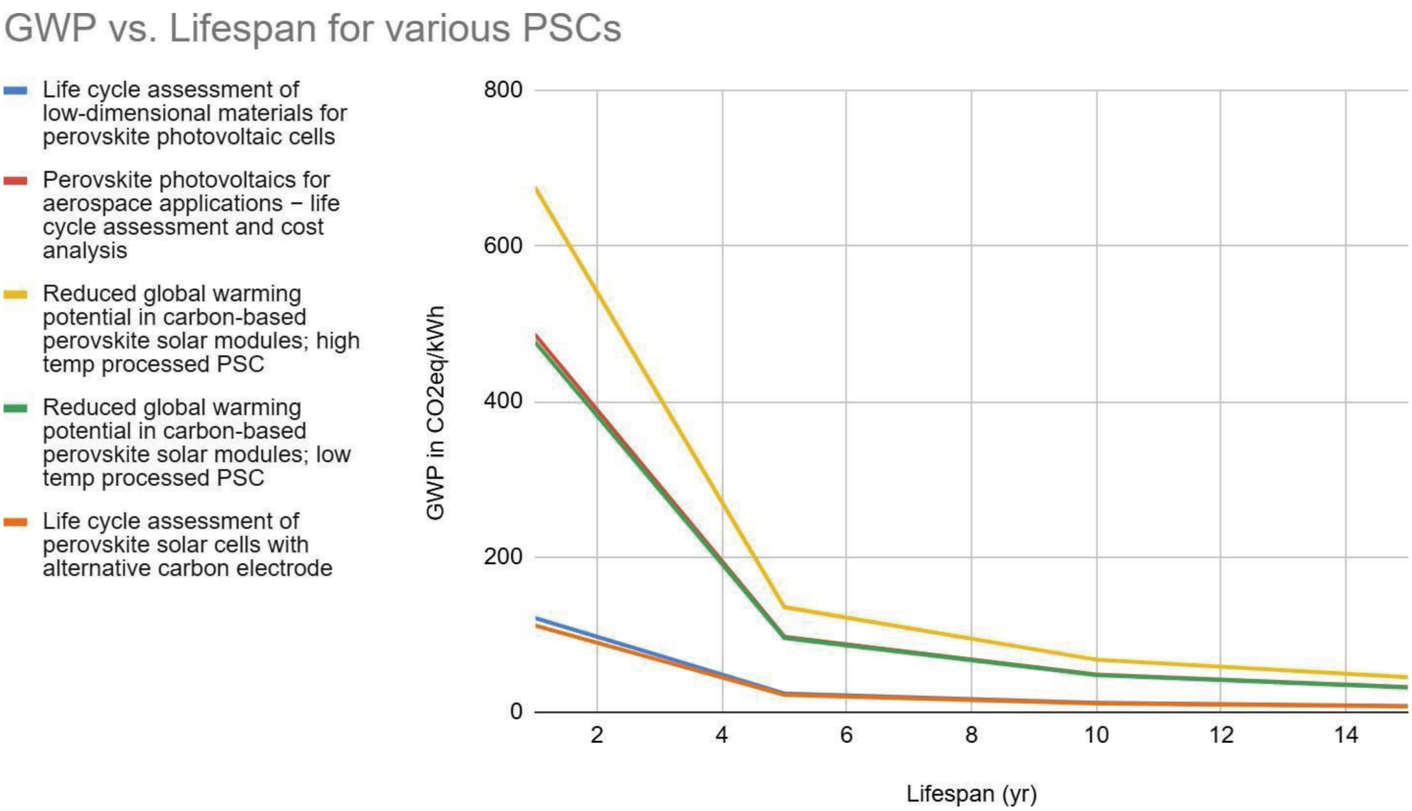

Figure 2. A graphical representation of how the GWP of the different types of PSCs in this study changes as the lifespan of the cell increases. Data compiled from sources [12–15].

higher number of kWh produced.

Next, by using Equation 1, it calculates the break-even lifespan that PSCs need to achieve to be competitive with mono-Si, in the terms of gCO_2eq/kWh. By plugging in the GWP of manufacturing, efficiency, and lifespan of PSCs, break-even lifespans for each study are found, and presented in Table 2. The lowest value found was 2 years 7 months, and the highest was 15 years 6 months. The median value is 10 years 11 months. The large difference between the lowest value and the median is because the study was researching PSCs that utilized carbon-based materials that have lower GWPs of production. Otherwise, the rest of the studies agree that PSCs need to reach a lifespan of at least 10 years before they break-even with mono-Si.

DISCUSSION

This value means that PSCs need to attain a break-even lifespan of at least 10 years and 11 months before their GWP, in terms of gCO_2eq/kWh. This lifespan is less than half of mono-Si, likely due to the decreased energy needed during manufacturing and the increased efficiency of PSCs (17). This benchmark is important, as it gives a value at which the scientific community should pivot from increasing lifespan and efficiency to increasing manufacturability. While the current lifespans still fall far short, with most values in literature using values of 2-24 months, it is important to remember that PSCs are still a new technology.

A best-of-both-worlds scenario could potentially be found in perovskite-silicon hybrid solar cells, which include a PSC layer stacked atop a mono-Si cell. The combination of the two aims to make the most of the PSCs high efficiency as well as the long lifespan of mono-Si. These tandem cells have demonstrated remarkably high PCEs of nearly 30%, though they too are still in early stages of research (19). From a GWP perspective, they seem to provide a middle ground, but the final result will depend on how the increased efficiency compares to the more intensive manufacturing process.

Limitations

Going back to PSCs, it is important to note that this value of 10 years and 11 months is not strict, given the lack of available data of the GWP of PSCs as well as mono-Si. Furthermore, given that PSCs have not yet reached commercial production, these values are simply an estimation. Included studies also have different system boundaries. Finally, manufacturing technique, material, and lifetime assumptions all vary widely between studies, especially with regards to PSCs. However, given that no such value existed before, this value still provides use, given that a best guess estimation is still better than none at all.

Future Work

Future research should focus on furthering the stability and lifespan of PSCs so they can better compare to mono-Si. Furthermore, another avenue of research should be focused on resolving toxicity issues with PSCs. The materials and organic solvents that are used to produce PSCs are hazardous to human health and the environment, and climate friendly replacements do not have as high of a PCE (18). Finally, the wide-scale production potential of PSCs should be further investigated, including manufacturing techniques and recyclability, in order to further decrease environmental

Table 2. Utilizing Equation 1 to determine the break-even lifespan of the different types of PSCs in this study

Application of Eq. 1	
Study	**Break-even lifespan**
Life cycle assessment of low-dimensional materials for perovskite photovoltaic cells	2 years 9 months
Perovskite photovoltaics for aerospace applications − life cycle assessment and cost analysis	11 years 1 month
Reduced global warming potential in carbon-based perovskite solar modules: Cradle-to-gate life cycle analysis; high temp processed PSC	15 years 6 months
Reduced global warming potential in carbon-based perovskite solar modules: Cradle-to-gate life cycle analysis; low temp processed PSC	10 years 11 months
Life cycle assessment of perovskite solar cells with alternative carbon electrode	2 years 7 months
Median value: 10 years 11 months	

impact. If these processes occur, PSCs could quite possibly become a promising contender against the current market dominance of mono-Si solar cells.

CONCLUSION

This systematic review set out to determine at what lifespan PSCs would rival mono-Si solar cells in terms of global warming potential, measured in gCO_2eq/kWh. Through a comprehensive analysis following the PRISMA framework, this study identified and evaluated 10 life cycle assessment studies—6 examining mono-Si cells and 4 examining PSCs. After reviewing the most current literature and normalizing their values, it was discovered that the break-even lifespan for PSCs lies at the 10 year 11 month mark (median value, with a range of 2 years 7 months to 15 years 6 months depending on manufacturing approach and materials).

This finding reveals that PSCs need to achieve less than half the lifespan of traditional mono-Si cells before they become competitive from a climate impact perspective, due to their lower manufacturing energy requirements and higher efficiencies. Notably, carbon-based PSCs achieved break-even lifespans as low as 2-3 years. However, current PSC lifespans remain in the 2-24 month range, representing a substantial gap that must be bridged.

In future LCAs, considering the impact of regional energy mixes, incorporating recycling potential and end-of-life scenarios, and drawing upon a wider variety of studies with standardized system boundaries could improve the accuracy of break-even predictions. Additionally, expanded research into perovskite-silicon tandem cells may reveal hybrid approaches that combine favorable attributes of both technologies.

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CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this work.

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