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Organic Photovoltaics: Where Are We Headed?

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Organic photovoltaics (OPV) is an emerging technology that combines semitransparency and flexibility in lightweight, ultrathin solar modules. The record power conversion efficiencies for OPV are approaching 20%, with reported lifetimes ranging from months to several years. Despite these attributes, OPV has not yet been commercialized on a large scale. Here, we critically examine the commercial potential of OPV. We begin by surveying feasibility studies in the literature to identify threshold values for performance that would enable OPV to be commercially competitive with conventional electricity production. We discuss how these parameters alone are not sufficient to predict the success of a photovoltaic technology, as there is still significant discrepancy between performance in the laboratory and in the field. Even if this gap can be closed, it is unlikely that OPV will ever compete in the conventional electricity market. Instead, the unique properties may make OPV an interesting candidate for niche applications with less rigid demands on performance, but stricter requirements on aesthetics, flexibility, weight, and transparency. In this case, application-specific requirements on efficiency and stability must first be established. Ultimately, even the most optimistic scenarios for OPV identify poor stability as the biggest challenge for general market entry.

1. Introduction

Photovoltaics (PV) has recently become the cheapest source of electricity in history.[1] Over the past 20 years, the PV market has expanded tremendously, increasing from just 252 MW installed per year in 2000 to 115 GW installed per year in 2019[2,3] to a total of 740 GW installed capacity. This corresponds to a steady growth of 40% per annum over nearly 20 years; in addition, it is expected that the total installed capacity worldwide will reach 2840 GW in 2030.[4] The remaining PV market share is distributed over several thin-film technologies. Silicon wafer-based PV consistently has been the most dominant commercial PV technology, representing over 95% of the entire market in 2018.[5]

Due to the potential advantages inherent to thin-film fabrication, such as flexible, high throughput, and low-cost production, it was predicted that thin-film PV would gain increasing market share to eventually compete with, and even overtake, silicon.[6,7] However, though thin-film PV market volume has increased along with the total PV market, it has not increased relative to the silicon PV market share. The decline in the price of crystalline silicon solar cells over the last two decades[5,8] has made it difficult for thin-film PV technologies to gain competitive traction.[9–12]

These dynamic and unexpected developments in the PV market raise interesting questions about how to assess the commercial feasibility of emerging technologies. Much research is currently devoted to developing new PV technologies with the perspective of lowering processing costs, and material usage, as well as increasing the flexibility of PV production and installation. However, the market potential of these emerging technologies with respect to the current market is unclear. It has become nearly impossible to compete with the price of silicon PV. Therefore, emerging PV may only have a chance for commercialization if it either contributes to the existing PV market, for example, by increasing silicon PV efficiency as in the case of silicon–perovskite tandems,[13–15] or if it satisfies the demands of an emerging or niche market that cannot be met with existing technologies.[16–19]

Organic photovoltaics (OPV) is an emerging technology with a unique combination of attributes, such as low-cost solution processing with nontoxic materials, low material usage due to the ultrathin absorber films, and tunable optical absorption for harvesting a wide range of the solar spectrum. Together, this offers the perspective toward large-scale, low-cost PV with attractive properties such as semitransparency, flexibility, and ultralight-weight modules. Decades of research on OPVs[20–24] has resulted in record power conversion efficiencies (PCEs) exceeding 18%,[25–28] with reported device lifetimes ranging from months to several years.[29,30] However, despite the rapid development and interesting potential, OPV has not yet succeeded as a commercial technology on the large scale.

OPV refers to a class of solar cells and not a single device technology. An organic solar cell comprises a molecular donor–acceptor heterojunction, and research over the last decades has resulted in a library of donor and acceptor molecules and therefore a multitude of potential absorber layers.

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Breakthroughs in OPV performance have been largely driven by advancements in molecular design,[31–33] and especially recent developments in nonfullerene acceptors,[24,34–36] as well as control over the donor–acceptor active layer morphology.[37–39] There have been many recent reviews that address the scientific and technological developments and challenges toward the commercialization of OPV.[40–43] Here we address the question of the commercial feasibility of OPV in today's PV market.

To do this, we critically assess results from feasibility studies in the literature to determine requirements on efficiency and lifetime that would make OPV commercially competitive with conventional electricity production. OPV performance in the lab has already exceeded these thresholds; however, it is nontrivial to provide guarantees on commercial OPV modules. This is because there is a gap between the efficiency and lifetime of modules in the lab and in the field. In particular, the complex, interdependent degradation pathways in OPV mean that lifetimes strongly depend on the conditions that the module is exposed to.[44–48] Together, the efficiency and lifetime of a module determine the overall cost. So, while OPV is generally believed to be a low-cost PV technology due to the favorable fabrication processes, the cost of commercial OPV modules will ultimately be determined by the application-specific conditions. It seems unlikely that OPV can compete with conventional PV technologies in the current market. However, the unique attributes of OPV may make it a contender for clean energy production in emerging and niche markets.

2. Commercial Feasibility of OPV

PV technologies are considered to be commercially feasible when they reach grid parity, that is, when the cost of electricity production is equal to (or lower) than the cost of electricity from the grid. A common strategy to evaluate this is to estimate the levelized cost of electricity (LCOE). The LCOE of a technology is defined by the net cost of the system, that is, PV module (including installation and maintenance), divided by the net electricity produced by the system over its lifetime.

$$\mathrm{LCOE} = \frac{\text{Total module cost over lifetime}}{\text{Total energy production over lifetime}}\,[\$\mathrm{kWh}^{-1}] \tag{1}$$

A well-known issue for assessing the LCOE of immature technologies, such as OPV, is the discrepancy between the PCE of laboratory-scale devices measured under standard testing conditions and those of modules operating in location-specific, potentially highly variable, conditions.[49] The module lifetimes of noncommercial technologies are poorly defined. Together, inaccuracies and uncertainties in estimations of both efficiency and lifetime will have a nontrivial impact on the estimation of total energy produced by the module. Therefore, although production and maintenance costs may be known, the poor predictability associated with OPV performance over time makes reliable LCOE calculations challenging. It should be noted that in the case of emerging technologies like OPV, module lifetimes are certainly shorter than the lifetimes of silicon PV modules and therefore represent a bottleneck for commercialization.[9,44]

3. From Lab Scale to Commercial Scale: Challenges in Assessing OPV Efficiency

The discrepancy between PCEs of PV cells fabricated in the laboratory and PCEs of commercial-scale PV modules is an indication for the degree of maturity of a PV technology.[50–52] Scaling-up PV technologies from the lab requires the development of new, commercially relevant fabrication protocols. In the lab, OPV solar cells are fabricated on small substrates (typically glass), and the deposition steps are executed under controlled atmospheres. Soluble active layers can be spin cast to form homogeneous thin (from several tens to several hundred nanometer) layers, with areas usually much smaller than 1 cm^2. In contrast, upscaling OPV toward industrial processing targets the fabrication of larger-area modules on flexible substrates. Module fabrication consists of continuous, sequential deposition and drying steps to produce the functional layers, often in ambient conditions with techniques such as roll-to-roll (R2R) and printing.[53–55] Industrial-scale OPV processing is associated with thicker active layers with reduced PV performance as well as lower-quality functional layers and substrates.[51,55–57] OPV module areas in the literature range from smaller than 1 cm^2 to larger than 100 cm^2, and module efficiency generally decreases with increasing size.[55]

The difference between the efficiencies of lab-scale PV cells and commercial modules is known as the "scaling gap." To facilitate the comparison of the scaling gap between different technologies with different efficiencies, we define the scaling gap as

$$\text{Scaling gap} = 1 - \frac{\eta_{\text{module}}}{\eta_{\text{lab}}} \tag{2}$$

The scaling gap of crystalline silicon PV is between 20% and 40%.[58] The scaling gap results due to differences in the fabrication routes and materials used to produce lab-scale versus commercial PV devices. In the laboratory, OPV is fabricated with time and cost-intensive production steps to ensure high-quality layers with minimized exposure to environmental stress factors. Upscaling toward industrial applications, in contrast, involves lower cost and faster throughput steps with lower-grade materials and a higher probability for defect formation and material degradation.[43]

The scaling gap does not necessarily follow a clear trend over time. It decreases as factors limiting quality during commercial production are identified and mitigated. Research breakthroughs resulting in increased solar cell efficiencies, in contrast, can cause an increase in the scaling gap, as it takes time to translate new insights from the laboratory into module fabrication. In the case of OPV, increases in solar cell efficiency have been driven largely by the design of new high-performance donor and acceptor molecules[31,34,36,59] combined with the optimization of the active layer morphology.[39,60] In contrast, research devoted to the development of OPV modules often targets the processing of well-studied donor–acceptor systems for large-area coating,[61] processing from nonchlorinated solvents,[62,63] and deposition on flexible substrates,[64] with focus on strategies to optimize continuous layer-by-layer deposition.[57,65]

There are few commercial OPV installations.[43] Therefore scaling gap estimates for OPV are based on reports in the literature that compare record OPV cell efficiencies to demonstrator OPV modules. Carlé et al.[51] estimated the scaling gap for OPV between 2008 and 2017 by comparing record efficiencies for lab-scale cells from the NREL efficiency charts and efficiencies of OPV modules produced at the Technical University of Denmark (DTU). In 2008, the efficiency of R2R OPV modules was reported at 4.3%[66] and the record efficiency of OPV was 6.4%,[67] resulting in a scaling gap of 33%. In 2015, the record efficiency for OPV cells was 10.1%,[68] and R2R OPV modules were reported with an efficiency of 5.7%.[69] Subsequently, the scaling gap was 44% at this time. The current record PCE for OPV cells (18.2%) was reported in 2020,[28] and the record module efficiency in 2020 was 10.1%.[70] This corresponds to an increase in the scaling gap to around 44%, slightly higher than that in 2015, despite the overall increase in OPV performance. In 2021, Brabec and coworkers reported a module efficiency of 12.6%,[54] resulting in a significant decrease in the scaling gap to 31%.

We note that the scaling gap values reported here are likely underestimated. There are very few commercial OPV installations, but these have efficiencies closer to 5%. The efficiencies of commercial modules are lower than demonstrator modules due, in part, to additional stress factors during integration and installation.[43]

The large and variable scaling gap between current lab-scale OPV efficiencies and estimates of industrial-scale OPV efficiencies means that LCOE calculations may lead to overly optimistic, or even contradictory, assessments of the commercial potential of OPV. This is shown in **Figure 1**, where the record OPV solar cell efficiencies[71] (orange circles) are shown between 2008 and 2021. Values for OPV module efficiencies (blue circles), and the corresponding scaling gap values (dashed blue lines), are indicated for 2008, 2015, and 2021.[51,54] The gray diamonds represent LCOE estimations from the literature (plotted according to year of publication) for the minimum efficiency values required for OPV. The error bars represent the spread in these values between different publications from the same year.[45–47,72–78]

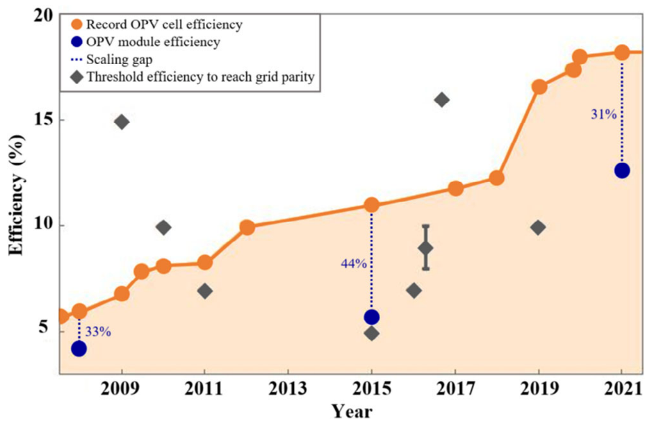

Figure 1. Comparison of record PCEs (orange symbols) for OPV cells.[71] The record efficiencies for OPV modules (blue symbols) along with the corresponding scaling gap (blue dashed lines) are included for the years 2008, 2015, and 2021.[51,54] The gray stars represent the minimum OPV efficiency (gray symbols) predicted by LCOE studies to achieve grid parity and the error bars represent the spread in the values between different publications from the same year.[45–47,72–78]

First, there is considerable discrepancy between the predicted threshold values for efficiency to enable grid parity from the LCOE studies. This is attributed to the different approaches used to estimate lifetime and cost that have a non-negligible impact on the LCOE assessment.[45,75] We note that this discrepancy is not related to variations in electricity price, as the energy cost from the grid has increased 0.2 ¢ kWh^{-1} in the USA, over the timespan (from 2008 to 2020) represented in the graph,[79] and is therefore negligible compared with the discrepancies in the LCOE results. Second, the record OPV efficiencies are frequently comparable or even higher than the required threshold efficiencies for commercial feasibility predicted by the LCOE assessments.[45,74–76,78] However, after we account for the scaling gap, OPV module efficiency estimates (even optimistic ones) are clearly lower than these threshold efficiencies. This underlines that the scaling gap remains a hurdle for OPV commercialization.[17,18,46,80] Further, it highlights that more insights into OPV lifetime and cost are required to make realistic predictions about market feasibility.

4. OPV Lifetimes: Undefined, Unpredictable, and Ultimately Too Short

The lifetime of a PV module is estimated using standardized testing that applies high-stress conditions to accelerate module deterioration. For commercial technologies, such as crystalline silicon, the International Electrotechnical Commission (IEC) 61215 protocol[81] is used. This protocol consists of thermal cycling between −40 °C and 85 °C and a damp heat test at 85 °C and 85% relative humidity. The module lifetime is determined by the T80, that is, the time it takes for the efficiency to drop to 80% of its initial value. IEC has developed a protocol specifically for thin-film PV modules, the IEC 61646.[82] This protocol was motivated by the fact that each thin-film technology has specific failure mechanisms. However, these commercial protocols are not suitable for assessing lifetime values for emerging technologies such as OPV, as the specific failure mechanisms, and their complex interdependence, are not yet well understood.[83–85]

Degradation mechanisms in OPV devices are related to 1) degradation of the conjugated molecular backbone of the absorber layer materials due to photo-oxidation,[86,87] 2) changes in the active layer morphology induced by heat, light, or thermodynamic instabilities in the blend,[88,89] and 3) physiochemical changes at the device interfaces.[90] The situation is complicated further, as OPV refers to a class of materials, so degradation mechanisms associated with the organic active layer are specific to the donor and acceptor molecules used, as well as processing parameters.[85,91]

Identifying and mitigating performance loss is an active area of OPV research, with focus ranging from the design of stable donor and acceptor molecules, transport layers, and contacts, to cell and module encapsulation strategies.[92–95] As a result, the research community, specifically the International Summit on OPV Stability (ISOS), developed standardized test procedures that are based on the IEC 61646 but that focus on specific issues related to OPV.[85] The ISOS test procedures have recently been extended to perovskite PV,[84] another emerging PV technology that promises excellent PV performance at low cost but suffers from stability issues. The main goal of the ISOS procedures is to standardize testing conditions to facilitate comparisons of PV performance between different laboratories around the world, thereby improving the reliability and reproducibility of reported values, as well as identifying degradation pathways (which may have a complex interdependence on a variety of stress factors). The ISOS testing procedures are therefore designed to provide insight into the specific stress factors (and codependence of these stress factors) that limit device stability via a series of tailored testing protocols. More specifically, the ISOS protocols define parameters for a set of successive stress tests, that is, in the dark, in outdoor conditions, and exposed to laboratory weathering, thermal cycling, and solar–thermal–humidity cycling conditions. This facilitates the identification of major factors limiting stability in OPV, as well as correlations between stress factors. To account for differences in the sophistication of available laboratory infrastructure for OPV testing, the ISOS protocols are subdivided into three levels (Basic ISOS D-1, Intermediate ISOS D-2, and Advanced ISOS D-3).[85] In other words, the ISOS procedures are not made for assessing the commercial lifetime of PV modules, but rather, the aim is to provide strict guidelines for successively sophisticated aging tests to obtain a comprehensive collection of parameters that impact lifetime.

Despite differences in the microscopic mechanisms leading to performance loss between OPV devices, a general trend has been identified. The "burn-in" effect refers to rapid performance loss of 10–50% during early testing.[96] After the burn-in phase, the efficiency decreases roughly linearly over time, that is, the "long-term" degradation. The timescales and magnitude of burn-in and long-term degradation depend on cell composition and architecture, as well as testing conditions.[83,85] Based on this trend, the ISOS community has proposed the Ts80 lifetime. The Ts80 is defined as the time when the efficiency of the OPV has dropped to 80% of its value at the start of long-term degradation, thus after the burn-in effect took place.[85] The burn-in effect differs between OPV technologies; therefore, the Ts80 is technology specific.

It is generally nontrivial to estimate PV module lifetime based on standard testing protocols, as the variability of different stress factors in the field, that is, temperature, humidity, and illumination, is unknown.[29,97] Specifically, in the case of OPV, the permeation of water and oxygen through encapsulation barriers, ultimately leading to module failure, is critical. Delays between module fabrication and installation, for example, may have a significant impact on module lifetime in the field.[83] It is not possible to account for this simply by combining the shelf and operational lifetime to determine the application lifetime, as the ingress of water and oxygen depends on multiple parameters and does not increase linearly over time. It is accepted by the OPV community that the encapsulant is the limiting factor for module lifetime, and therefore a detailed understanding of the ingress of water and oxygen under specific storage and operating conditions is required to make accurate lifetime assessments.[98]

Analogously to the case of OPV efficiency, there is a wide range of predictions for required minimum threshold lifetime

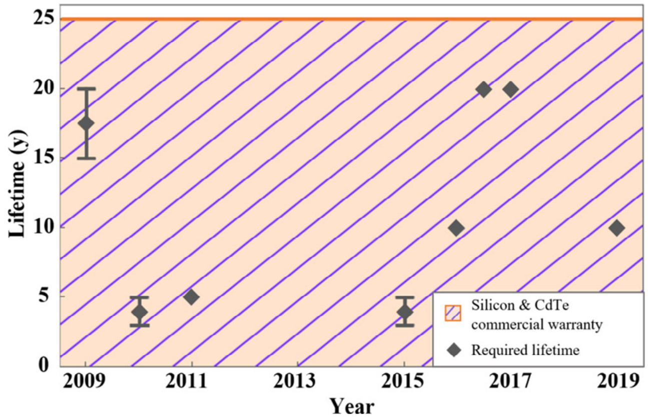

Figure 2. The predictions of the required minimum lifetime, in years, to achieve grid parity shown per year of publication. Some publications state a range of lifetimes, which is indicated by error bars.[45–47,72–78]

values for OPV to achieve grid parity. This is shown in **Figure 2**, where threshold lifetimes for OPV commercialization predicted by LCOE studies are plotted according to the year of publication. The shaded area corresponds to the 25-year commercial warranty for silicon and CdTe solar cells[99–102] and was added for reference.

There is a large discrepancy in the predicted threshold values for OPV lifetime, and no clear trend can be observed between the predictions. However, a lifetime of at least 10 years appears to be a requirement for OPV to achieve grid parity. Therefore, OPV may still be commercially relevant even if module lifetimes are considerably lower than the commercial warranty of silicon and CdTe. We note that most of the studies included in Figure 2 conclude that the current OPV lifetime is the limiting factor for commercial feasibility.[45–47,72–75,77,78] It is therefore unlikely that OPV will compete with Si PV in the near future in the conventional energy market, such as for large-scale installations on, for example, rooftops.[103] Nevertheless, OPV may be a contender in niche markets that require autonomous, lightweight energy sources.

5. OPV in Emerging and Niche Markets

In niche or emerging markets, value may be derived from the unique attributes of a technology rather than from conventional performance parameters. In the case of energy production, this means that as long as device performance is sufficient to provide required functionality,[46,103–106] then aspects, such as aesthetics, weight, flexibility, and nontoxicity, may outweigh the importance of efficiency and lifetime and in some cases, even cost. Therefore, the commercialization roadmap of an emerging technology like OPV may be intrinsically different than those of other PV technologies. Decisive OPV parameters may, for example, include transparency,[46] low power requirements and limited warranty,[73] a high indoor and low-light efficiency,[106] flexibility and washability for wearable purposes,[46] and a high power-to-weight ratio.[105] The threshold for cost is then defined by the consumer's willingness to pay for specific functionality,[107–109] rather than by grid parity.

An accurate assessment of the potential of a PV technology in niche and emerging markets requires an understanding of the market's size and prospective growth,[110–112] the investment costs, and the maturity of the PV technology. For each market, overall product specifications, such as warranty, geometry, fixed versus mobile, indoor versus outdoor usage, location-specific illumination conditions, and other factors that may influence OPV efficiency and lifetime, must be known. Ultimately, feasibility studies will be application driven.

With the current state-of-the-art OPV performance, relevant potential markets that have been identified in the literature are consumer electronics,[19,46,73,113,114] wearables,[46] and indoor PV.[17] The global consumer electronics market is projected to reach 365 billion US$ in revenue, in 2020, and is expected to keep on growing to 450 billion US$ in 2024.[115] In 2020, the worldwide revenue of wearable devices, which consists mostly of devices that are explicitly intended for fitness, is projected to reach 18 billion US$.[116] The global market for indoor PV was around 140 million US$ in 2017, and it has been predicted that this market has the potential to grow to 1 billion US$ globally by 2024, making it the fastest growing, nontraditional PV market.[117] Further, with increasing technological maturity, it is expected that OPV will become commercially feasible in future markets, such as building integrated PV (BIPV),[46,73,113,118–120] military,[19,73,114] and greenhouses.[73,113,121] The BIPV market is likely to expand to 32.2 billion US$ by 2024.[122] As the military and greenhouse markets are strongly dependent on local government support, data on global projections of market growth are not available. To put things in perspective, in 2018, the global solar energy market was valued at 52.5 billion US$, and it is projected to reach 223.3 billion US$ by 2026.[123] Therefore, of all the niche and emerging markets discussed here, only the global consumer electronics market is of comparable size with the global solar energy market. The potential commercialization roadmap of OPV is shown graphically in **Figure 3**.

6. Summary and Outlook

We surveyed LCOE studies of OPV in the literature between 2008 and 2020 to assess the commercial feasibility of OPV. We observed considerable discrepancy between individual estimations for the threshold efficiency and lifetime values required for OPV commercialization. These discrepancies could be attributed to the immaturity of OPV, including the large scaling gap and poorly defined module lifetimes. However, even the most optimistic studies agree that the current performance parameters are still too poor for the use of OPV in large-scale energy generation,[17,18,46,80,124,125] and ultimately poor stability has been recognized as the main issue. The large scaling gap between laboratory cells and commercial modules can be attributed to successive performance loss during fabrication, integration, and installation.[43] New interdisciplinary and dedicated approaches from other research areas, for example, machine learning,[126] may shed light on the complex issues related to performance loss during the scaling-up of OPV fabrication.

Emerging and niche markets such as consumer electronics, indoor PV, and BIPV, however, may provide a unique opportunity for OPV commercialization. If OPV performance is sufficient for product-specific demands, then requirements on, for example, aesthetics, weight, mechanical properties, may become more relevant than the total efficiency and lifetime of the technology. However, commercializing a new technology requires investments to enable the transformation from the laboratory toward large-scale fabrication and distribution. Silicon PV could initially profit from the existing global electronics industry, as pipelines for wafer processing and device manufacturing were already been developed for other silicon-based technologies. However, in the case of emerging PV, these pipelines must still be developed. Considering the broad spectrum of commercially available energy-conversion and storage devices, it is not obvious, first, that OPV can uniquely satisfy the demands of a market and second that the market has considerable size and/or potential for growth

Figure 3. The potential roadmap for OPV commercialization.

to warrant these initial investments. In this case, the customer's willingness to pay is decisive and must be assessed and quantified. This is a tough task, as application-specific values of OPV efficiency and lifetime must be well defined before the cost of the technology can be established. While existing protocols and testing standards provide a good basis for assessing performance, each niche application will have its own unique demands. These become more difficult to assess in the case of applications that are subject to unpredictable fluctuations in illumination and temperature, nonstandard illumination conditions, and/or mechanical stress. In other words, the customer may prefer an existing, established technology (even a battery) over an emerging PV technology as long as the functionality of the application is not significantly impacted or changed. For this reason, market entry for emerging PV likely will require initial support from public institutions, for example, in the form of demonstrator applications, to support upscaling of fabrication and the development of certified testing protocols. This would help to increase customer awareness and acceptance, as well as provide important insight into the long-term performance of new technologies.

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Conflict of Interest

The authors declare no conflict of interest.

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