# Revolutionizing Indoor and Outdoor Photovoltaics with 2D Materials: Boosting Efficiency, Stability, and Scalability

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The advancement of 2D materials-based photovoltaic (PV) technologies, including organic photovoltaics (OPVs) and perovskite solar cells (PSCs), is significantly propelling progress in both indoor and large-scale outdoor solar energy applications. The IntoPV project is pioneering OPV cells tailored for indoor environments, emphasizing enhanced efficiency under various lighting conditions and improved long-term stability. By integrating Transition Metal Dichalcogenides (TMDs) such as $MoS_2$, $MoSe_2$, $WS_2$, and $WSe_2$ as hole transport layers (HTLs) in OPVs, the project leverages these materials' unique optical and electronic properties. Through advanced photophysical characterization and innovative fabrication techniques, including liquid-phase exfoliation and spray coating, we demonstrated that $MoS_2$-based HTLs match or surpass traditional materials like $MoO_3$ in inverted structures, achieving high power conversion efficiency (PCE) and exceptional stability under both artificial indoor light and solar illumination. Further exploration of $MoS_2$ and $WS_2$ as HTLs in standard OPVs led to significant performance enhancements, with $WS_2$ achieving a remarkable PCE of 28.9% under dim indoor light, outperforming traditional materials like PEDOT. This PCE improvement, coupled with an enhanced fill factor (FF) and short-circuit current ($J_{SC}$), is attributed to $WS_2$'s superior surface coverage on indium tin oxide (ITO) and reduced recombination losses. The optimized OPV devices also demonstrated excellent stability, retaining 86% of their initial efficiency after 1,000 hours in ambient air. These findings underscore the potential of TMDs in advancing OPVs for practical applications, particularly in low-energy electronic devices like those powering the Internet of Things (IoT), where consistent performance under dim indoor lighting is crucial.

Simultaneously, substantial progress has been made in scaling up perovskite solar technology for outdoor use. The development of large-area perovskite solar modules (PSMs) integrated with 2D materials such as graphene and functionalized $MoS_2$ culminated in the creation of GRAPE (GRAphene-PErovskite) solar panels The 2D materials enhance charge dynamics at the interfaces and protect the perovskite layer from environmental factors like oxygen, moisture, and metal ion migration. In this context, five square meters of perovskite PV panels were installed at a solar farm on the HMU campus in Crete for outdoor field testing. The solar farm's energy output was continuously monitored using custom-built maximum power point trackers, correlating the farm's performance with environmental conditions recorded by a weather station. The solar farm achieved a peak output exceeding 260 W, demonstrating the scalability of the proposed system. During the twelve-month monitoring period, the energy output exhibited a 20% decline in performance after eight months of operation ($T_{80}$ of 5,832 h). Further analysis revealed that high temperatures, solar irradiance, moisture, and oxygen infiltration, due to lamination failure, were primary factors in the degradation of the panels. Unique light-soaking behaviours were also observed before and during the degradation process, affecting power output. The study showed that the perovskite modules developed optical defects over time, illustrating the detrimental effects of lamination failure. Despite these challenges, the data indicated that perovskite panels hold significant promise for outdoor operations in high-temperature, high-irradiance environments. These efforts underscore the transformative potential of 2D materials in both indoor and outdoor PV applications. The use of TMDs and graphene-based materials not only enhances the efficiency and stability of PV devices but also supports the scalability of these technologies from lab-scale prototypes to real-world solar farms. This research paves the way for the broader commercial adoption of 2D materials-based photovoltaics, offering sustainable and efficient energy solutions across diverse applications.