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Controlled quasi-diffuse light characterisation of photoelectrochemical devices and low concentration photovoltaic optics using an integrating sphere

George H Creasey^{1,2,*} , Andreas Kafizas² , Anna Hankin¹ and Katie Shanks^{3,*} ¹ Department of Chemical Engineering, Imperial College London, South Kensington, London SW7 2AZ, United Kingdom² Department of Chemistry, The Molecular Science Research Hub, Imperial College London, White City, London W12 0BZ, United Kingdom³ Environment and Sustainability Institute, University of Exeter, Penryn Campus, Cornwall TR10 9FE, United Kingdom

* Authors to whom any correspondence should be addressed.

E-mail: g.creasey22@imperial.ac.uk and k.shanks2@exeter.ac.uk**Keywords:** solar water splitting, solar photovoltaics, diffuse irradiance, solar hydrogen production, solar fuels, photoelectrochemical systemsSupplementary material for this article is available [online](#)

Abstract

Testing photoelectrochemical (PEC) and photovoltaic devices under realistic operating conditions is a critical phase of system development. However, most studies still focus on standard AM 1.5 G tests at one sun (1000 W m^{-2}) irradiance with direct collimated light beams, which does not capture outdoor operation under broad angular illumination from diffuse skies and low solar elevation. Outdoor field trials are difficult to benchmark reproducibly due to the unpredictable nature of outdoor environments. Herein, we demonstrate a simple, laboratory-based method for generating controlled, angularly broad ‘quasi-diffuse’ illumination by coupling a continuous solar simulator to an integrating sphere. By positioning a PEC device at the integrating sphere exit aperture, we produce a controlled quasi-diffuse illumination geometry and demonstrate its use in two case studies involving $\text{WO}_3|\text{BiVO}_4|\text{NiFeOOH}$ photoanodes: one with a planar architecture and another coupled with a crossed-compound parabolic concentrator (CCPC) with wide-angle acceptance, designed to harvest diffuse and off-normal light. After normalisation to one-sun equivalent irradiance, the non-concentrating (planar) configuration performed similarly under direct and quasi-diffuse irradiance, whereas the CCPC-coupled configuration retained 26.3% of the direct-illumination photocurrent under quasi-diffuse conditions, consistent with acceptance-angle limited concentration. Whilst demonstrated here for non-concentrating and CCPC-coupled $\text{WO}_3|\text{BiVO}_4|\text{NiFeOOH}$ photoanodes, this method is in principle extendable to other compact planar photo-absorbers and low concentration non-imaging optics, provided that their dimensions are compatible with the exit aperture of the integrating sphere and their operation remains meaningful at the reduced irradiance available after sphere losses. This work provides a practical, controllable and transferable framework for quasi-diffuse light characterisation that complements AM 1.5 G measurements and can be benchmarked across different research teams. It offers a simple way to assess diffuse light tolerance and to validate ray tracing models using readily available laboratory equipment, before embarking on more challenging field trials.

1. Introduction

Competition in global renewable energy markets is rapidly driving down cost of solar technologies, with the economics of solar fuel production—either by electrolysis driven by photovoltaics (PV) or by photo-electrolysis using photo-electrosynthetic cells—becoming increasingly attractive, particularly for decentralised or off-grid settings [1,2–5]. With the rapid expansion of technology, the importance of reliable,

reproducible methods for characterising photo-absorbing materials such as PV cells or photoelectrodes is critical to enable continual development and improvement in photoelectrochemical (PEC) technology.

For PEC systems, which will ultimately operate outdoors, the challenge is to replicate inherently variable weather conditions that can diverge greatly from controlled laboratory environments. Laboratory PV and PEC cells are typically characterised under standard ‘one sun’ conditions with solar simulators that produce an irradiance of $\approx 1000 \text{ W m}^{-2}$. The spectral output is typically calibrated, or optical filters are used, to enable a spectral match close to reference Air Mass 1.5 Spectra, as defined by the American Society for Testing and Materials [6]. Internationally recognised protocols exist for PV characterisation under direct one-sun illumination and PEC benchmarking guidance has also been proposed [7–9]. However, no established protocol yet addresses photo-absorber characterisation under controlled quasi-diffuse illumination. Although AM 1.5 is a very useful standard for comparing solar driven chemical and electrochemical reactions, it does not capture variability in global irradiance levels, proportions of direct to diffuse light, and cloud cover that results in a broad angular field. These are challenging and complex phenomena to replicate reproducibly in a laboratory.

Whilst the effect of different, single incident angles can be examined under a solar simulator, by using tilt tables or similar, solar simulators typically produce uniformly direct irradiance, which therefore cannot reliably represent the effects of clouds. With PV and PEC devices designed to operate at one sun, AM 1.5 conditions, shifts in the spectral output under partly cloudy or low solar elevation can drive the system away from their design operating points, which can have detrimental effects on both performance and stability [10, 11]. Angular effects are already well recognised in the concentrating PV and concentrated PEC communities [12, 13]. High concentration imaging optics systems require precise tracking and largely reject diffuse rays [13–15], whilst low concentration, non-imaging optics can tolerate larger acceptance angles. However, beyond ray tracing simulations and experimental characterisation under direct irradiance at individual incident angles, there is limited analysis of the effects of angular or diffuse light on different optical systems [13].

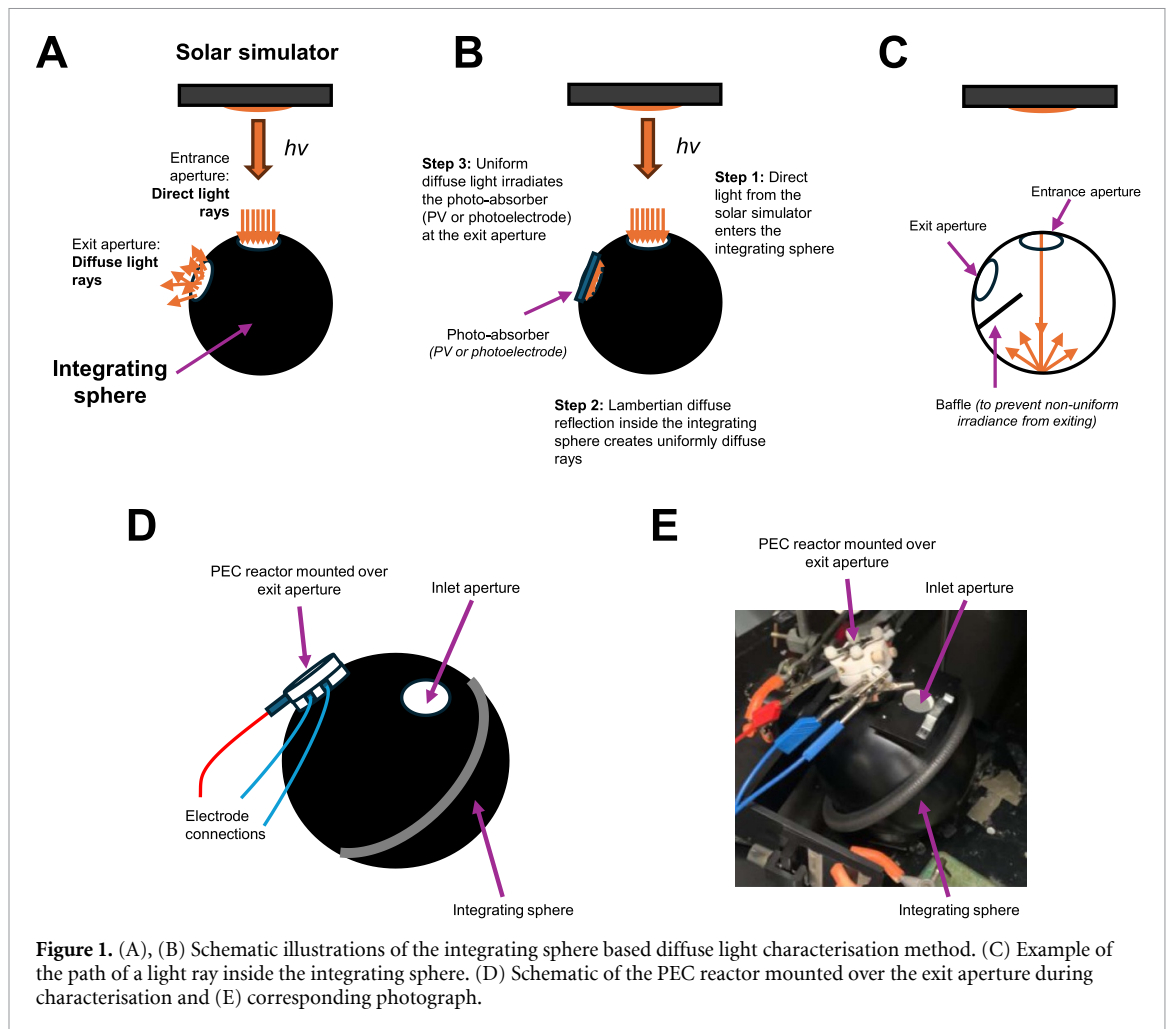
Current methods to vary simulated sun intensity using solar simulators, involving beam attenuation via neutral density filters or lamp current adjustment, preserve a narrow, typically highly direct, angular distribution that cannot reproduce broad quasi-Lambertian distributions associated with cloudy or highly diffuse weather conditions. As a result, the response of photo-absorbers, electrochemical interfaces, PV and PEC systems remains poorly quantified in controlled laboratory settings, while outdoor benchmarks differ wildly between studies, and often focus on clear sky periods that maximise device performance.

Herein, we address this methodological gap by introducing a simple laboratory-based approach for simulating quasi-diffuse, angularly broad illumination. We achieve this by coupling a solar simulator to an angularly redistributing optical element that converts the collimated input beam into a broad angular distribution at the device plane. In this work, we use an integrating sphere, typically employed as a spectrophotometry accessory, to perform this role. We use the term ‘quasi-diffuse’ to describe illumination with a broad angular distribution approximating a ‘Lambertian-like’ field, as produced by the multiple internal scattering events within the integrating sphere [16–19]. Whilst demonstrated here for $\text{WO}_3/\text{BiVO}_4/\text{NiFeOOH}$ photoelectrodes, this framework is designed to be extended to other photo-absorbers, including single or multi-junction PV devices, PEC devices or PV-coupled PEC systems, provided the dimensions of the photo-absorber are compatible with the exit aperture of the integrating sphere.

The central aim of this work is therefore to establish and demonstrate this framework as a controllable, transferable method that can extend existing laboratory characterisation standards to include quasi-diffuse illumination conditions. This method offers a simple extension to standard laboratory solar simulator setups using hardware that is commonly found in many laboratories. It enables quantification of diffuse light tolerance, validation of wide-angle optical performance and ray tracing simulations, and hence provides an indication of device performance under cloudy day operation without relying on outdoor field trials.

2. Methodology

A WACOM Class AAA continuous solar simulator (model: WXS-210 S-20) equipped with an AM 1.5 G filter was used to produce simulated sunlight in a controlled laboratory with ambient temperature of 20°C . Prior to any measurements, the Xe lamp was switched on and allowed to warm up and equilibrate for 30 min. A reference monocrystalline solar cell, generating a short circuit photocurrent of 127 mA at 1000 W m^{-2} irradiance, was used to calibrate the light intensity prior to measurements. The



light spectrum of the solar simulator at 1000 W m^{-2} irradiance was measured using a StellarNet black comet UV/Vis (280–900 nm) and a StellarNet Dwarf star NIR (900–1700 nm) spectrophotometer. A representative spectrum is shown in figure S1.

Diffuse-like illumination was generated using an integrating sphere (UV-vis-NIR accessory, Bentham DTR6 150 mm diameter integrating sphere), with a BaSO_4 diffuse coating providing high hemispherical reflectance across the UV-vis-NIR spectral range. The term ‘quasi-diffuse irradiance’ in this study is fundamentally supported by the known optical properties of the Bentham DTR6 integrating sphere, namely the high-grade BaSO_4 coating, which is an industry standard for near-ideal Lambertian reflectance and spectral neutrality [16, 17, 19]. Researchers adopting this framework with alternative hardware should therefore confirm that the internal scattering geometry, coating reflectance and port configuration produce a near-Lambertian distribution equivalent to the BaSO_4 coating and consistent relative irradiance at the device plane.

The integrating sphere was equipped with a front entrance port that was aligned to the output beam of the solar simulator, as shown in figure 1(a). The photo-absorber receiving the diffuse irradiance was mounted at the circular exit aperture which had a diameter of $\approx 2 \text{ cm}^2$ (as shown in figure 1(b)). Figure 1(c) provides an illustration of the first reflection of a single ray inside the integrating sphere. Figures 1(d) and (e) show a schematic drawing and photograph of the setup during the demonstration with the PEC reactor. This simple arrangement can be implemented using any light source with a known irradiance at the entrance port of the integrating sphere. Additional photographs of the setup with the PEC reactor mounted at the exit aperture of the integrating sphere are shown in figures S2 and S3.

A bare, unencapsulated flat 1 cm^2 monocrystalline Si reference cell (Talesun) placed directly at the exit aperture was used to compare the relative irradiance after internal reflective losses by comparing the total flux leaving the integrating sphere with the flux irradiance at the entrance aperture (calibrated at 1 sun, 1000 W m^{-2}). Spectral measurements using the optical fibre-based spectrophotometers at the exit

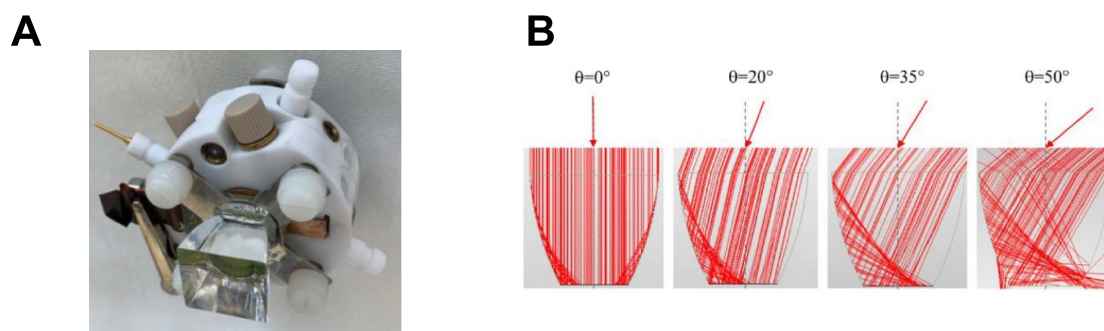


Figure 2. (A) Photograph of the CCPC-integrated PEC reactor. (B) Ray-tracing diagrams of a CCPC optic at selected angles between 0° and 50° . Reproduced from [24]. CC BY 4.0.

aperture were not considered quantitatively reliable, as their narrow angular acceptance prevents them from capturing the broad range of angles present under diffuse-like illumination [20, 21]. To account for the increased surface reflectance of the silicon reference cell at wide angles of incidence, the potential underestimation of irradiance under diffuse illumination was assessed using the cell's incidence angle modifier (IAM) profile. The flux-weighted mean IAM was computed by integrating the IAM profile over a Lambertian angular distribution, corresponding to a relatively small reflective loss correction of $\approx 1.5\%$. The use of a bare, unencapsulated silicon cell minimised additional wide angle reflection losses that would otherwise arise from a glass cover or encapsulant. When measuring the relative irradiance factor, it is recommended to use a planar PV cell without light management techniques (such as texture, surface patterning or anti-reflective coatings) and to report the IAM profile of the cell used. It should further be noted that the relative irradiance factor will depend on the integrating sphere used, meaning that clear and transparent reporting of equipment specifications is needed. This will avoid confounding results and enable reproducibility and replicability across different research teams.

Electrochemical measurements were made using an Autolab PGStat302N potentiostat (Metrohm), interfaced with Nova 2.1 software. PEC measurements were conducted in a Redox.me PTFE PECF cell (adapted for quiescent measurements), equipped with a Pt coil auxiliary electrode (Redox.me) and a refillable Ag/AgCl reference electrode (sat. KCl, $0.197\text{ V}_{\text{SHE}}$ at 25°C , Redox.me). The electrolyte used was a 1 M sodium borate buffer (1 M H_3BO_3 , $\sim 17\text{ g L}^{-1}$ NaOH titrated to pH 9.3), prepared with Milli-Q-water (Millipore Corp., $18.2\text{ M}\Omega\text{ cm}$ at 25°C). This electrolyte selection was informed by previous experiments in which analogous $\text{WO}_3|\text{BiVO}_4|\text{NiFeOOH}$ photoanodes exhibited the highest stability in borate buffer [22]. The exposed (photoactive) area of the photoanodes in the PEC cell was 0.8 cm^2 . The photoanodes were characterised under continuous illumination, at the entrance aperture (facing the solar simulator) and at the exit aperture (facing the inside of the integrating sphere), by linear sweep voltammetry from the open circuit voltage to $1.0\text{ V}_{\text{Ag/AgCl}}$ (scan rate 10 mV s^{-1}).

$\text{WO}_3|\text{BiVO}_4|\text{NiFeOOH}$ electrodes were fabricated on TEC-15 FTO substrates (Pilkington, UK) using aerosol-assisted chemical vapour deposition (AA-CVD) procedures previously established by the authors [22, 23]. The CVD reaction was carried out using a purpose-built reactor (shown in figure S4). UV-vis (shown in figure S5) and XRD (shown in figure S6) analysis showed that the materials fabricated in this work exhibited optical and structural properties consistent with those reported previously, indicating that the electrodes are representative of our established $\text{WO}_3|\text{BiVO}_4|\text{NiFeOOH}$ photoanode structure.

For concentrated light experiments, a crossed-compound parabolic concentrator (CCPC) optic was mounted onto the surface of the photoanode using an epoxy resin, as shown in figure 2(a). The geometric concentration ratio, C_g of the CCPC was 3.6, which was determined by the ratio of its entrance and exit apertures the effective optical concentration ratio is typically a lower value due to optical losses which reduce the energy at the exit aperture. For the CCPC used in this study, the optical concentration ratio is 2.9 and the optical efficiency $\approx 80\%$.

The properties of the CCPC used in this study were established in prior literature via validated ray tracing simulations [24, 25]. These included a half-angle acceptance of $\pm 30^\circ$ and an optical concentration ratio (C_{opt}) of 2.9. Ray-tracing diagrams of a CCPC optic at selected angles between 0° and 50° are shown in figure 2(b) [24].

Table 1. Relative irradiance at the entrance and exit aperture of the integrating sphere for a calibrated irradiance at the entrance aperture of 1000 W m^{-2} (i.e. 1 sun, AM 1.5 G spectrum). The relative irradiance was quantified by comparing the short circuit current of a 1 cm^2 monocrystalline solar cell positioned at the entrance and exit apertures. The locations of the entrance and exit apertures on the integrating sphere can be seen in figure 1(a).

Illumination condition	Measurement plane	I_{sc} (mA)	Relative irradiance
Direct (collimated)	Entrance aperture	44.7	1.000
Quasi-diffuse	Exit aperture	10.6	0.237 ± 0.004

3. Results & discussion

3.1. Quantification of optical losses in the quasi-diffuse illumination module

To enable the comparison of PEC performance under irradiation of quasi-diffuse light with the predominantly collimated, direct illumination provided by the solar simulator, it was necessary to quantify the optical losses within the integrating sphere arising from internal reflectance and port losses through the entrance aperture. The effective irradiance delivered at the exit aperture of the integrating sphere was quantified by comparing the short circuit current of a 1 cm^2 monocrystalline solar cell with a linear current-irradiance response characteristic of silicon PV devices under standard operating conditions. As summarised in table 1, reflectance losses and port losses resulted in a 76.3% reduction in the relative irradiance at the exit aperture (to 0.237) compared with the entrance aperture. Reporting the relative irradiance at the exit aperture will enable reproducible comparison between different implementations of this method. Subsequent current densities were scaled according to the relative irradiances in table 1, to enable the comparison between direct and diffuse illumination conditions, with raw (unscaled) data provided in the supplementary information as appropriate.

3.2. Effect of quasi-diffuse irradiation on PEC performance

To examine the effect of the quasi-diffuse irradiation from the integrating sphere on PEC performance, current densities generated during linear sweep voltammetry under predominantly collimated, direct illumination and quasi-diffuse irradiation (at the integrating sphere exit aperture) were compared. These data are illustrated in figure 3. The irradiance under direct illumination (at the entrance aperture of the integrating sphere) was 1000 W m^{-2} (1 sun, AM 1.5 G). The effective irradiance under quasi-diffuse illumination at the exit aperture was 237 W m^{-2} and current densities in figure 3 have therefore been scaled to one-sun equivalent. Some minor differences in current density (up to 10%) were observed, particularly in the range $0.6 V_{RHE}$ to $1.0 V_{RHE}$. This may reflect differences in mass transport due to distinct mounting requirements of the quasi-diffuse and direct light measurements, which necessitated different orientations for the LSV measurements [5, 26]. Nevertheless, the differences remained limited and consistent with typically observed variability seen in successive LSV measurements in PEC systems [9, 27, 28]. The corresponding as-measured LSV curve from the measurement at the exit aperture is shown in figure S7.

The comparable performance under direct and quasi-diffuse irradiation after intensity scaling to one sun equivalent indicates that the PEC performance of the $\text{WO}_3|\text{BiVO}_4|\text{NiFeOOH}$ without concentrating optics is primarily governed by the total photon flux, rather than the angular distribution. This conclusion is further supported by the angular photocurrent response of the $\text{WO}_3|\text{BiVO}_4|\text{NiFeOOH}$ photoanodes (shown in figure S9), which is in line with theoretical cosine projected area at different incidence angles, with minor deviations at some angles consistent with expected transmission and reflection losses [29, 30].

This further suggests that under non-clear sky conditions the primary driver of decreased PEC performance is the reduction in irradiance associated with cloud attenuation and atmospheric scattering or absorption [31].

Although demonstrated here for a $\text{WO}_3|\text{BiVO}_4|\text{NiFeOOH}$ photoanode, similar irradiance-dominated behaviour is expected for other planar photoelectrodes and conventional flat-plate PV cells lacking selective optical elements [32]. This irradiance-dominated behaviour is characteristic of planar photo-absorbers. Device architectures that incorporate concentrators or other optics are expected to respond differently, as will be demonstrated in the following subsection.

3.3. Quasi-diffuse light concentration using a non-imaging CCPC optic

In contrast to imaging optics, which offer high optical concentration ratios but have very narrow angular tolerances, non-imaging optics can enhance effective irradiance whilst retaining wide acceptance angles

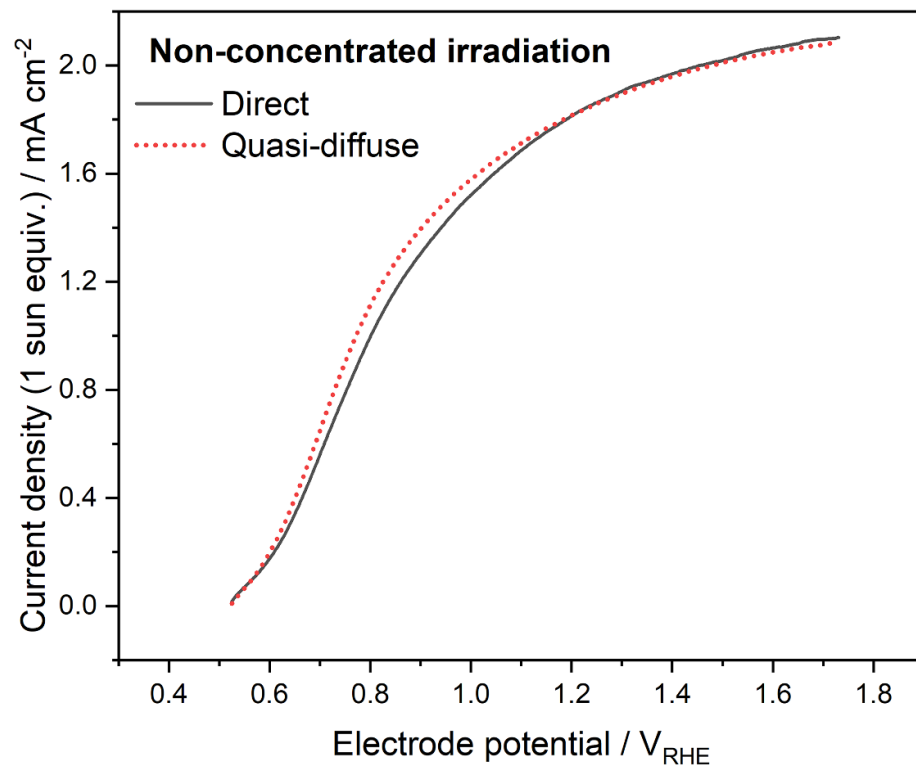


Figure 3. Effect of direct illumination and quasi-diffuse illumination (delivered at the exit aperture of the integrating sphere) on the photoelectrochemical performance of $\text{WO}_3|\text{BiVO}_4|\text{NiFeOOH}$. To enable comparison of direct and quasi-diffuse performance, the quasi-diffuse current density was normalised to one sun equivalent, with the original curves available in figure S7.

[13, 14]. CCPCs have a geometric concentration ratio, C_g of 3.6, an effective optical concentration ratio, C_{opt} of 2.9 (accounting for optical losses in the CCPC), and a half-acceptance angle of $\pm 30^\circ$ [24, 33]. When integrated with a PEC reactor, the benefits of increased effective irradiance can be realised, even with diffuse or indirect light, whilst avoiding detrimental device heating that occurs under higher solar concentration [11].

Due to their very narrow angular acceptance, the efficiency of imaging optics is severely limited by non-clear sky conditions when there is a greater degree of diffuse irradiance and when the incident angle distribution broadens at low solar elevation. Non-imaging optics, such as CCPCs, continue to deliver a concentration benefit under these conditions, enabling device operation beyond ideal clear-sky illumination.

Figure 4 illustrates a comparison of the effect of direct and diffuse CCPC light concentration on PEC performance. Under direct light, the CCPC-integrated PEC photocurrent was approximately 2.7 times higher than the non-concentrated PEC. This slight reduction from the measured optical concentration ratio of the CCPC (2.9) was attributed to additional optical losses arising at the mounting interface with the PEC. Such losses, including reflections and scattering from bubbles trapped within the epoxy resin, are well documented to reduce performance in photo-absorbing systems [34, 35]. As with the non-concentrated light example, the effective irradiance under quasi-diffuse illumination at the exit aperture was 237 W m^{-2} and current densities were therefore scaled to one-sun (1000 W m^{-2}) equivalent. The corresponding LSV curve for the CCPC condition under quasi-diffuse irradiation is shown in figure S8.

Under quasi-diffuse irradiance, the CCPC retains a useful, acceptance angle limited concentration effect. Over the range of the LSV test, the normalised current density was on average 26.3% of the value under direct light (ranging between 23.6% and 31.5%). To determine the expected performance over an entirely uniform diffuse field, numerical integration was performed on the measured angular response of the CCPC-integrated PEC reactor (shown in figure S10), which yielded a theoretical retention of 34.1%. The theoretical retention was determined by normalising the CCPC-integrated photocurrent (taking the maximum value achieved at 0° as 1.0), then integrating under the curve to determine the average fraction retained across the range 0 – 90° , with all angles given equal weighting. The measured angular response confirms that the effective half acceptance angle of the assembled CCPC|PEC system is approximately 20° , somewhat below the design value of 30° , consistent with the assembly-level optical losses at the CCPC|PEC interface discussed above. The further departure from 34.1% to the measured average

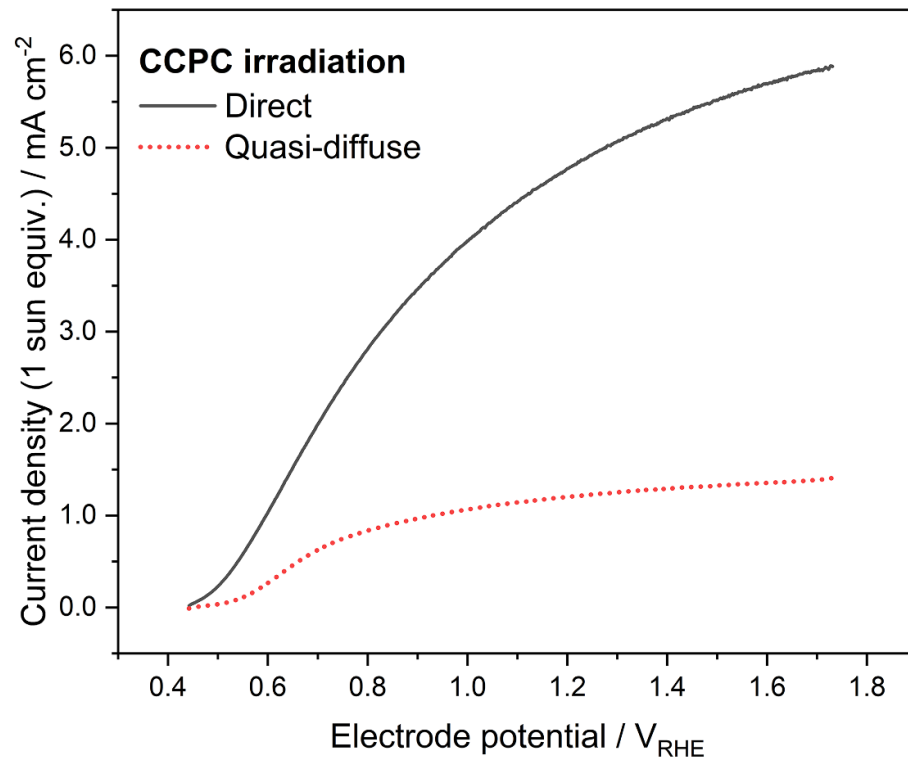


Figure 4. Effect of direct illumination and quasi-diffuse illumination (delivered at the exit aperture of the integrating sphere) on the photoelectrochemical performance of $\text{WO}_3|\text{BiVO}_4|\text{NiFeOOH}$ coupled with a CCPC optic. To enable comparison of direct and quasi-diffuse performance, quasi-diffuse current density was normalised to one sun equivalent, with the original curve available in figure S8.

of 26.3% is consistent with the supralinear photocurrent response of BiVO_4 . This phenomenon, which reportedly occurs due to kinetic limitations, is most notable at lower light intensities, particularly when scaling up to approximately three suns [36, 37].

This demonstrates that wide-angle non-imaging optics can retain a measurable concentration benefit under diffuse-rich illumination. In contrast, imaging optics, such as convex lenses, have very narrow angular acceptance (typically to the order of 1 or 2°), and under uniformly diffuse irradiation cannot form a focused spot [13–15]. For small focal receivers (typical in such systems) this results in negligible irradiance delivered to the photo-absorber and thus negligible photocurrent.

3.4. Implications for evaluating devices and optics under diffuse light conditions

The non-concentrated $\text{WO}_3|\text{BiVO}_4|\text{NiFeOOH}$ PEC demonstration showed that, at matched one sun equivalent irradiance, the PEC performance was comparable under both direct and quasi-diffuse irradiance, indicating an irradiance-dominated response. This flux-dominated behaviour is expected to extend to other photo-absorbers with similar, planar geometries, consistent with flat-plate PV studies and PEC benchmarking protocols, which treat total irradiance as the primary driver of performance [8, 38].

In contrast, our use of a CCPC showed that optical and device architectures can have a markedly different effect on device performance, driven here by the wide acceptance angle of the CCPC optic [24, 25]. This method therefore offers a comparatively straightforward and controllable route for ray tracing and other optical model validation, without the need for complex procedures or the use of facilities that many solar energy research groups may not have access to [11, 15, 39].

Whilst these insights could also be gathered from outdoor field trials, these can be complex to organise, and experiments are subject to unpredictable weather conditions and temperature fluctuations [11, 15]. Furthermore, variation in weather conditions, even in the same testing locations, can lead to different results, making it more difficult to compare performance across different research teams. This work provides a framework to complement existing standards for testing solar PV and PEC devices, which are typically focused on AM 1.5 G one-sun characterisation conditions, by adding a controllable quasi-diffuse test which is more representative (in terms of broad angular irradiance distribution) of climates with high proportions of diffuse irradiance [8, 9]. Used alongside AM 1.5 G characterisation,

this provides a clearer picture of the performance of different photo-absorbers and optical architectures across a wider range of conditions.

3.5. Method applicability and limitations

The method presented here is intended to be applicable to most PEC devices, which predominately employ macroscopically planar photoelectrode and reactor geometries [5, 9, 28], and to low concentration non-imaging PV optics such as CPCs and CCPCs [13, 40]. The two case studies using benchmark $\text{WO}_3/\text{BiVO}_4/\text{NiFeOOH}$ photoanodes in a PEC reactor with and without a CCPC are representative of these device classes and illustrate the practical scope of the method.

Several limitations should be considered when developing this method for quasi-diffuse light characterisation of other device classes. Firstly, geometric compatibility; the device must fit within the exit aperture and changes to port geometry may affect internal scattering in the integrating sphere. Secondly, the reduced irradiance at the exit aperture should be considered. The method as presented is most directly applicable to photo-absorbers with a linear response to irradiance, and which are able to operate at the reduced irradiance available at the exit aperture [41–43]. Whilst this method can be applied to devices with non-linear responses, this should be considered to ensure accurate comparison between direct and quasi-diffuse performance. A third limitation concerns bifacial photo-absorbers. Since this method only illuminates a single face, it is not applicable to bifacial device characterisation [44]. However, future adaptations to this method could deliver collimated light from the solar simulator to one face, whilst illuminating the other face with quasi-diffuse irradiance from the integrating sphere.

Wider adoption of this testing framework will require validation across different laboratory setups and devices to establish the reproducibility needed for it to serve as a community standard [7, 9, 27, 28]. This work and the case studies presented herein provide the foundation for this process.

4. Conclusions

In this work, we developed a framework for characterising photo-absorbing materials under broad angular, ‘diffuse-like’ irradiance by coupling a solar simulator with an integrating sphere typically used in UV-vis-NIR spectrophotometry. By directing the primarily collimated light of the solar simulator into the integrating sphere, we irradiated the photo-absorber with broad angular light scattering at the exit aperture. To demonstrate the use of this technique, we contrasted two device architectures, using a $\text{WO}_3/\text{BiVO}_4/\text{NiFeOOH}$ photoanode-based PEC reactor. First, we compared the effects of direct and diffuse light on the planar photoanode surface. At normalised solar flux, the performance of the direct and quasi-diffuse conditions was very similar, indicating an irradiance-dominated response for planar geometries. Next, we coupled the PEC reactor with a CCPC, a non-imaging optic with wide-angle acceptance. In this case study, there was a 26.3% retention in photocurrent in the diffuse condition, showing the effect of the angular acceptance of the CCPC optic.

This study provides a framework for diffuse light testing that complements existing standards centred around direct light, relatively high irradiance conditions, but may not necessarily represent realistic operating conditions. It enables simple validation of ray tracing and other optical models and provides a practical way to benchmark photo-absorber performance over a wider range of illumination conditions than are typically characterised in the laboratory, without dedicated field trials.

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Data availability statement

all data that support the findings of this study are included within the article (and any supplementary files).

Supplementary Information available at <https://doi.org/10.1088/2515-7655/ae6e6e/data1>.

Conflict of interest

There are no conflicts of interest to declare.

Author contributions

George H Creasey  0009-0002-9327-3253

Formal analysis (lead), Funding acquisition (equal), Investigation (lead), Methodology (equal), Project administration (lead), Visualization (lead), Writing – original draft (lead), Writing – review & editing (equal)

Andreas Kafizas  0000-0002-2282-4639

Resources (supporting), Supervision (equal), Writing – review & editing (equal)

Anna Hankin  0000-0001-8358-2349

Funding acquisition (equal), Resources (equal), Supervision (equal), Writing – review & editing (equal)

Katie Shanks  0000-0002-6645-0181

Conceptualization (lead), Investigation (supporting), Methodology (equal), Resources (equal), Supervision (equal), Writing – review & editing (equal)

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