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AN ARTIFICIAL SUN FOR BUILDING SYSTEMS RESEARCH

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Summary

To address the particular challenges of testing full-scale prototypes and products under global climates in building systems research, a novel Artificial Sun has been developed. A 3.5 m by 2.5 m array of LED sources with attached Compound Parabolic Concentrators (CPCs) produces an irradiance of $\geq 1100\,\mathrm{W\,m^{-2}}$ on the facade of a test chamber. Mounted on a rotating 90° arc-rail, this illuminator array can produce directional irradiance in the visible and near-infrared range of the solar spectrum from any direction above the horizon. By controlling the emitted power of three types of LEDs individually, the mixed spectrum can be tuned according to the emulated solar conditions. Systematic testing confirmed the high degree of collimation achieved by the CPCs and the stable provision of the specified irradiance over extended measurement periods. Initial experiments demonstrated applicability in building systems research, e.g., in assessments of building-integrated photovoltaics, thermal and total solar transmittance, and daylight research. A current limitation is the spectral match in the near infrared, that may lead to a future modification.

Keywords: Solar simulator, building envelopes, full-scale testing, solar gains, daylight

Field of application for the findings: Development and testing of building systems

Addressed audience: Building scientists, facade industry, architects and engineers

1. Introduction

The response to and management of solar radiation is one key aspect in the design of innovative building systems, aiming for reduced operational energy demand, occupant health and comfort, and the utilisation of renewable energy sources. The research and development of novel concepts and models of such systems and their components, including their demonstration, as well as the applying existing solutions under different current and future climates, relies on the thorough experimental research and testing of prototypes.

Common approaches to characterise building systems combine standardised methods for few laboratory measurements on small specimen with simplified mathematical models. An example is the determination of the solar-optical properties of fenestration comprising multiple layers (Abolghasemi Moghaddam et al., 2023). Direct measurement of these properties is challenging. On the other hand, rapid characterisation of the individual layers' transmission and reflection properties requires little specialised equipment, and allows to compute the effective properties of any combination of these layers using established solar-optical models. However, the development and validation of such models requires a (measured) ground-truth, and in some cases they are not applicable at all. One example is the non-destructive testing of an existing building component of unknown internal composition, that may be further affected by unknown deterioration mechanisms that are not accounted for by established models. Novel building components aiming for refined optical and thermal characteristics may rely on entirely new approaches and methods, e.g., digital fabrication, for which models may not have been sufficiently validated or are under development (Piccioni et al., 2024).

Measurements on full-scale specimen and under standard conditions are performed in laboratories. Strict adherence to these conditions, e.g., assuming standardized solar geometries (normal incidence) and spectral

Fig. 1: Left: PCB with 26 LEDs in its centre, emitting in the visible (cold and warm white) and near infrared ranges. Right: Array of C-CPCs with attached PCBs forming the illuminator of the Artificial Sun (image courtesy Girts Apskalns).

power distributions (e.g., AM 1.5 spectrum), warrants comparability but does not reflect realistic conditions. This can be addressed by outdoor testing. However, outdoor testing conditions cannot be controlled but require extended monitoring periods to produce representative results, that are valid only for the local climate.

Therefore, testing at full scale and under realistic but controlled conditions is desirable, in particular if building components are not adequately described by existing models. However, implementing such an approach in a laboratory environment imposes particular challenges, i.e., the typical dimensions of full-scale prototypes in building systems research, the wide range of boundary conditions that may significantly diverge from what is specified by standards and norms (Zhang et al., 2025), and the complex interaction with other components of building systems as well as occupants. Furthermore, to reach comparability and produce results that are applicable in planning decisions, may ultimately call for new standardisation efforts.

We present a setup for full-scale testing, which comprises of a test chamber situated in a climatic shell and an Artificial Sun, and its applications in building systems research. The design and implementation process is reported in detail by Baur et al. (in prep). The reconfigurable test chamber is equipped with state-of-the art systems for heating, cooling, and lighting and with one wall exposed to an artificial climate. It is set up to allow for testing under realistic conditions. The artificial climate is controlled in terms of air temperature, humidity, and solar irradiance. The latter is implemented by an Artificial Sun, i.e., a solar simulator that can produce dynamic sunlight conditions in terms of geometry (directionality and incident direction), spectral composition (ratio of infrared and visible light, correlated colour temperature of the latter), and uniform irradiance on the exposed wall of the test chamber (up to $1200\,\mathrm{W\,m^{-2}}$).

2. Design and Implementation of the Artificial Sun

The aim to produce irradiance from any incident direction above the horizon and of variable spectral composition led to an early decision for an LED-based design. In contrast to, e.g., Xenon arc-lamps, LEDs enable stable operation during movement and rotation (Tawfik et al., 2018). The combination of LEDs featuring different peak wavelengths allows to tune the emitted spectral composition (Watjanatepin et al., 2023). Different to illuminators that aim for optimum spectral match and coverage through dozens of individually controlled spectral channels, we chose a design employing only three types of LEDs to meet the irradiance requirement on a large area and to limit the complexity of the control system. The phosphor-converted LEDs were selected for emission in wide wavelength ranges in the visible (warm-white and cold-white) and near infrared spectrum.

The radiation emitted by groups of 26 LEDs, sharing one PCB, is mixed and collimated by an attached Crossed Compound Parabolic Concentrator (C-CPC) (Sellami and Mallick, 2013). Based on an initial parametrization of the profile (Winston et al., 2005), the truncated C-CPC was optimised using optical ray-tracing and prototype testing, aiming to constrain the half-opening angle to less than 5°. Such solution provided a light-weight optics, that could be partially manufactured in-house, and in which one PCB and one C-CPC form one basic unit.

25 of such units form a module, that is supplied with electrical power and cooling. This design allowed to operate individual modules to tune the combined performance of multiple units in terms of collimation, as well as irradiance and uniformity on a test target.

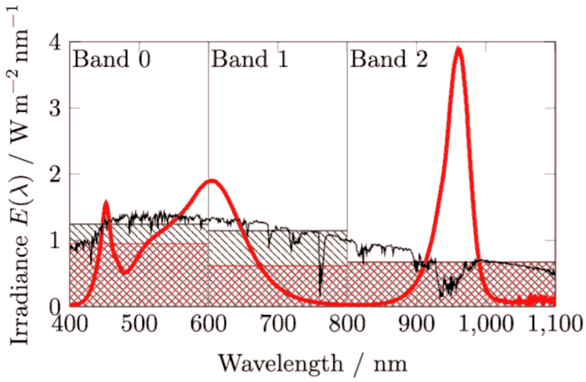

Fig. 2: Effective illuminator (red) and AM 1.5 standard spectrum (black) in the range 400 nm to 1100 nm, and integrals in three coarse band (hatched grey and red bars for illuminator and AM 1.5 integrals, respectively).

Tab. 1: Preliminary performance summary of the Artificial Sun's illuminator.

Parameter	Performance
Collimation (half opening angle)	± 4.7°
Irradiance, continuous operation	1200 W m^{-2}
Spatial irradiance non-uniformity	13.6 %
Spectral coverage & match (3 bands AM1.5G)	76.6 %, 53.8 %, 101.6 %
Vis/IR balance (maximum optical output)	50.0 % – 50.0 %
Target area with uniform irradiance	7.3 m^2

Grouped to 35 modules, in total, 875 units are assembled in a source array of 3.5 m by 2.5 m (Figure 1, right). This illuminator is attached to a 90° arc-rail to form the Artificial Sun that can be rotated across two axes to emulate different azimuth and elevation angles (Figure 3).

3. Performance Testing

The absolute irradiance, its spectral composition, and its distribution, were tested after completion of the Artificial Sun's setup.

Pyranometer measurements at coarse grid of positions in front of the test chamber confirmed that the illuminator outperformed the target irradiance of ≥ 1100 W m^{-2} during stable operation over extended periods.

Spectrophotometric measurements monitored the spectral composition for different combinations of set points controlling each LED channel. The measurements describe the optical output of each channel's LEDs as a function of set-points, and thereby inform the Artificial Sun's configuration to match a given solar spectrum. Figure 2 illustrates the summed output of the three channels (red) configured to match an Air Mass (AM) 1.5 spectrum (black). The spectral coverage of the LEDs proved to be constrained to the range of 400 nm to 1100 nm. It shows significant deviations from the solar spectrum but it fits reasonably to the integral irradiance when summarized in broader wavelength channels (red and black hatches).

A refined irradiance distribution was acquired with the help of a reflective target, that was installed between the Artificial Sun's illuminator and the test chamber (Figure 3). Calibrated by the previous pyranometer measurements, irradiance maps on the target were produced by relating the vignetting-corrected radiance map acquired by a camera to the reflection properties of the screen. This refined irradiance map was employed for the subsequent characterization of the spatial distribution and uniformity of the irradiance, as well as to verify that the effective collimation of the Artificial Sun's 375 C-CPCs achieved the prediction based on the measurements on an individual module during the development.

After the confirmation of the stable operation of the Artificial Sun, first experiments demonstrated the applicability of the setup.

Fig. 3: The artificial sun, comprising the illuminator mounted on a rotating 90 degrees arc-rail, illuminates a screen in front of the test chamber during testing (image: Girts Apskalns).

4. First Applications of the Artificial Sun

4.1 Testing Photovoltaics with the Artificial Sun

Prior to the construction of the Artificial Sun and its climatic chamber, the testing of Photovoltaic (PV) systems larger than two modules was relegated to exterior test sites. This is a particularity problematic condition to be in with the advent of Building Integrated PV (BIPV), which require a host building to be tested thoroughly. This can become a costly and difficult endeavour to approve, given the experimental nature of BIPV and the perceived risks of electricity-related fires within the thermal envelope of a building. Therefore, a facility in which building-scale installations of PV modules (and specifically BIPV modules) can be tested under real-life controlled conditions would be a significant benefit for research and industry.

Given the spectral composition of the Artificial Sun and the collimated beam, it was suspected that the LED array would be capable of replicating outdoor conditions for full solar days, but detailed validation was required to ensure the claim for future research. To suit this, a 1.32 kWp BIPV array was constructed at the wall of the test chamber, representing the building, and facing the climatic shell. Wall construction followed the Swiss Society of Engineers and Architects (SIA) standards for a timber infill wall, replacing the rain cladding with twelve small format BIPV modules (110 Wp capacity) in three columns of four rows.

Validation of the electrical response was carried out at the single-module scale. One module was measured within the chamber at a sequence of solar positions and compared against measurements of the same module outdoors at the times the real sun occupied those positions. Across thirteen matched pairs, spanning solar azimuths of 174° to 229° and vertical-plane irradiances of $211\,\mathrm{W\,m^{-2}}$ to $751\,\mathrm{W\,m^{-2}}$, indoor and outdoor irradiance agreed to within 5 % and the current residual along the aligned current-voltage curves averaged approximately 5 % of the reference short-circuit current, with maximum-power differences of 3 % to 4 % once the differing thermal boundary conditions of the two mountings were corrected for. At the array scale, the measured curves departed from the response of a uniformly illuminated series string reconstructed after McCarty et al. (2024). A positional sweep of a single module across the target area attributed this to spatial non-uniformity of the illumination field rather than to module-to-module variation, with agreement between

Fig. 4: A still shot from the transit of the sun across the 1.32 kWp BIPV facade used for the validation experiments. Source: McCarty et al. (in prep.)

the co-located reference sensor and the module-integrated response closest at the centre of the target area and degrading toward its edges. This finding allowed for the definition of a tight operating boundary on the target area at different positions of the Artificial Sun. Future research is being directed towards the effects of the spectral mismatch of the Artificial Sun's illuminator on various PV cell types.

4.2 Measuring Thermal and Total Solar Transmittance

Employing the Artificial Sun in the measurement of solar gains through extended fenestration components addresses two challenges. First, the performance of full-scale prototypes, accounting for, e.g., scale-dependent fabrication effects, can be directly determined and inform further development iterations. Second, the performance of fenestration elements that cannot easily be disassembled can be determined. One example for the latter is the non-destructive performance evaluation of fenestration modules from existing buildings, for example in the case of retrofit.

A first experiment aimed to test the performance of a double-glazing unit from the 1970's in terms of total solar energy transmittance (g-value) and thermal transmittance (U-value), accounting deterioration of gas infill, sealing, and coatings. The test chamber was equipped with a highly insulated wall toward the Artificial Sun, with an aperture matching the dimensions of the specimen. A 'cold box' (Kuhn, 2014) was set up inside the test chamber (Figure 5, left), turning the latter into a 'guardian box' (Chen et al., 2012). Electric fans controlled convection and stratification in the inside. Monitoring the mass flow rate and temperature increase through five absorber panels (covering the surface of the internal walls of the cold box, towards the test chamber), under steady state conditions one could determine the gains through the specimen. To correct for residual heat fluxes by the fans and through the opaque walls of the cold box, the former's effective power demand was monitored and the latter were equipped with heat flux sensors.

The initial experiment allowed to determine the glazing unit's thermal and total solar energy transmittances, although standard conditions could not be met yet, in particular with respect to convection on both sides of the specimen. The data-set produced by the experiment, however, not only informs about the condition of the tested

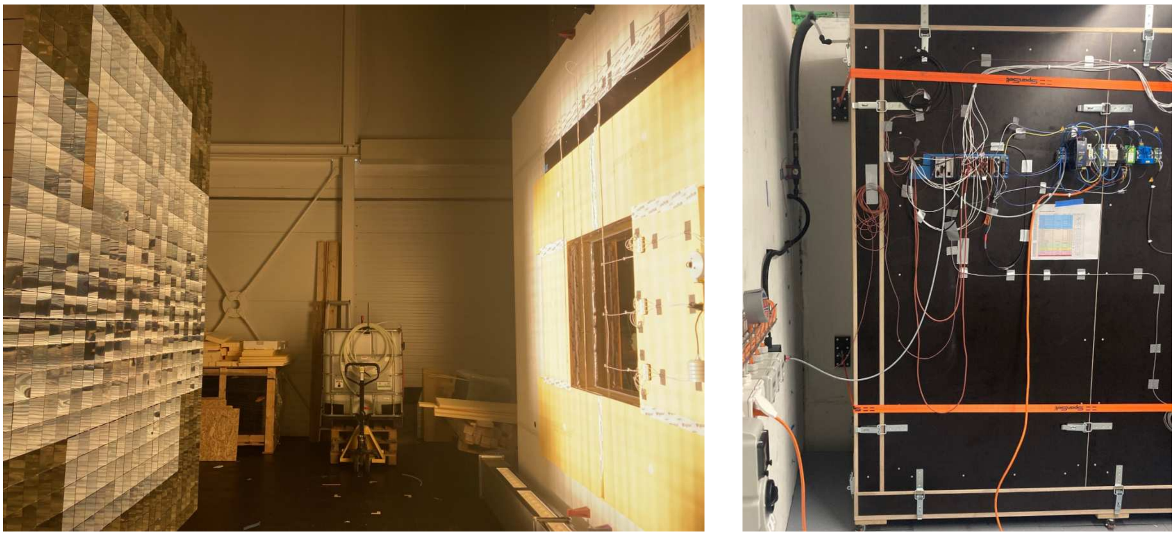

Fig. 5: Measurements of solar gains through a double-glazing unit. Left: Prototype of 1 m^2 under oblique illumination. Right: 'cold box' seen from the inside of the testing chamber.

specimen, but also about the ongoing development of the cold box setup for future applications (in particular for dynamic solar gain assessments, e.g., testing with oblique incident directions).

4.3 The Artificial Sun in Daylight Research

The test chamber can be equipped with sensors to monitor photometric variables (illuminance, luminance) under controlled direct illuminance. Other than determining photometric properties at the facade layer (Geisler-Moroder et al., 2024; Hoffmann et al., 2026), this allows the direct observation of the lighting conditions in the attached space. The chamber was further designed so that it can represent an architectural space in subject studies. For this, the chamber is furnished according to the specific experiment's requirements.

To test the effects of a 3D-printed facade element (Piccioni et al., 2024), the test chamber's wall facing the Artificial Sun was equipped with a full-scale prototype. The aim of the experiment was to test computational models of the facade's solar-optical performance, its effects on spatial daylight supply, and to identify potential glare conditions. Upward-facing illuminance sensors were installed at work-plane height to record horizontal illuminance for different incident sun directions. At the back wall of the chamber, a calibrated camera captured the luminance of the facade element (Figure 6, left). One daily sun-path was reproduced by the Artificial Sun for each of the two visible light channels. Due to light's additivity, illuminance and luminance under any spectrum could then be forged by a weighted sum of two corresponding measurements.

A first human subject study employing the Artificial Sun is currently prepared as part of the Daylight Integration Nexus Fellowship project 'Humes'. For this study, the test chamber will be furnished as a typical cellular office. The participants of the study will rate sunlight patterns (Figure 6, right) produced by different configurations of the Artificial Sun in conjunction with a shading system. The study shall improve the understanding of the perceptual effects of sunlight beyond summary metrics.

5. Conclusions, Future Applications and Possible Modifications

The expansion of the laboratory's capabilities and in particular the further tuning of the Artificial Sun are ongoing. Yet, it has already become a central infrastructure for building systems research. The presented studies are examples for completed, ongoing, and planned research. The completed experimental studies demonstrated the potential to combine the Artificial Sun with different sensor configurations in a wide range of research areas, such as the performance of building-integrated devices for power conversion (e.g., PV or thermal collectors) or the solar-optical properties of fenestration. Accounting for human response, e.g., in daylighting research, necessitates human subject studies, that will tap into the design of the test chamber as full-scale architectural space.

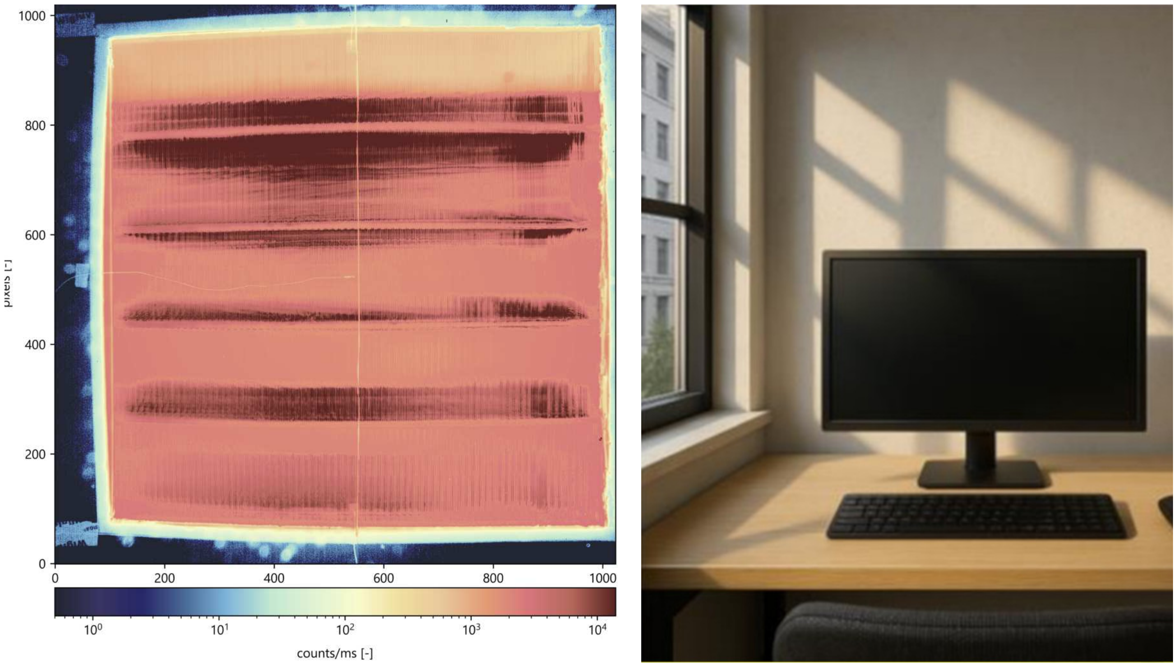

Fig. 6: The Artificial Sun in daylight research. Left: Radiance map of the 3D-printed prototype from the inside of the testing chamber for one LED channel. Right: Example for a sunlight patterns to be evaluated in a human subject study.

Besides purely academic research, the laboratory offers unique opportunities for research and development collaborations with industry and practice that go beyond small-scale experiments. The current configuration in particular lends itself for the accelerated testing of full-scale components of building envelopes under controlled conditions, that would otherwise require extended measurement periods to arrive at representative results under outdoor conditions. Facade prototypes for new construction or retrofit, which are often created for visual inspection only, could additionally be tested for building performance, thus mitigating implementation risks.

The design of the laboratory, which exposes a test chamber to an emulated global climate, was driven by the aim of testing building components at full scale and under realistic conditions. This diverges from setups primarily aiming to the implementation of current standards, but may inform future standardisation efforts expanding from comparable to realistic testing conditions.

Despite the demonstrated applicability of the Artificial Sun for building systems research, some limitations(mostly resulting from deliberate design decisions) are addressed by the development of future enhancements. One example is the spectral mismatch in the infrared, that was accepted to improve the efficiency of the illuminator and to reduce complexity but is problematic for BIPV research especially. This could be addressed by small changes in the design of the illuminator.

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References

Abolghasemi Moghaddam, S., Simões, N., Gameiro da Silva, M., 2023. Review of the experimental methods for evaluation of windows' solar heat gain coefficient: From standardized tests to new possibilities. Building and Environment 242, 110527. doi:10.1016/j.buildenv.2023.110527.

Baur, M., Hischier, I., Kreuzer, G., Grobe, L.O., Schlueter, A., in prep. Design and development of an artificial sun for full scale building systems research .

Chen, F., Wittkopf, S.K., Khai Ng, P., Du, H., 2012. Solar heat gain coefficient measurement of semi-transparent photovoltaic modules with indoor calorimetric hot box and solar simulator. Energy and Buildings 53, 74–84. doi:10.1016/j.enbuild.2012.06.005.

Geisler-Moroder, D., Lee, E.S., Apian-Bennewitz, P., de Boer, J., Bueno, B., Deroisy, B., Fang, Y., Grobe, L.O., Hauer, M., Hoffmann, S., Jonsson, J.C., Maurer, C., Plörer, D., Subramaniam, S., Tian, Z., Wang, T., Ward, G.J., Weitlaner, R., Wilson, H.R., 2024. BSDF data generation for daylight applications: A call for international standardization. Lighting Research & Technology , 14771535241291838doi:10.1177/14771535241291838.

Hoffmann, S., Pfau, C., Subramaniam, S., Deshaboina, S., Turek, M., Hagendorf, C., Alwalidi, M., Geisler-Moroder, D., Grobe, L., 2026. A new approach to measuring angular-dependent transmittance values of extended complex fenestration systems with a near field goniophotometer. Measurement 257, 118751. doi:10.1016/j.measurement.2025.118751.

Kuhn, T.E., 2014. Calorimetric determination of the solar heat gain coefficient g with steady-state laboratory measurements. Energy and Buildings 84, 388–402. doi:10.1016/j.enbuild.2014.08.021.

McCarty, J., Waibel, C., Leow, S.W., Schlueter, A., 2024. Towards a high resolution simulation framework for building integrated photovoltaics under partial shading in urban environments. Renewable Energy 236, 121442. doi:10.1016/j.renene.2024.121442.

McCarty, J., et al., in prep. Artificial sun PV characterisation for building-scale PV testing .

Piccioni, V., Grobe, L.O., Hischier, I., Schlueter, A., 2024. From layer to building: Multiscale modeling of thermo-optical properties in 3D-printed facades. Energy and Buildings 314, 114222. doi:10.1016/j.enbuild.2024.114222.

Sellami, N., Mallick, T.K., 2013. Optical efficiency study of PV crossed compound parabolic concentrator. Applied Energy 102, 868–876. doi:10.1016/j.apenergy.2012.08.052.

Tawfik, M., Tonnellier, X., Sansom, C., 2018. Light source selection for a solar simulator for thermal applications: A review. Renewable and Sustainable Energy Reviews 90, 802–813.

Watjanatepin, N., Wannakam, K., Kiatsookkanatorn, P., Boonmee, C., Sritanauthaikorn, P., 2023. Improved spectral mismatch and performance of a phosphor-converted light-emitting diode solar simulator. International Journal of Electrical and Computer Engineering (IJECE) 13, 4931–4941. doi:10.11591/ijece.v13i5.pp4931-4941.

Winston, R., Miñano, J.C., Benitez, P.G., et al., 2005. Nonimaging optics. Elsevier.

Zhang, X., Saelens, D., Roels, S., 2025. Quantifying dynamic solar gains in buildings: Measurement, simulation and data-driven modelling. Renewable and Sustainable Energy Reviews 212, 115221. doi:10.1016/j.rser.2024.115221.