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Solar power windows: Connecting scientific advances to market signals

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Recent materials advances have enabled researchers to envision and develop highly efficient, partially transparent photovoltaic (PV) prototypes, exposing a potentially large and untapped market for solar energy: building integrated (BI) solar powered windows. In this perspective, we assess the case for market deployment of BIPV windows, specifically intended for commercial U.S. high-rise buildings. Research and development on solar powered windows has been predicated on the hypothesis that sunlight-to-electrical power conversion efficiency (PCE) and device cost per unit area are the key figures of merit that might drive market adoption. Here we investigate the market landscape and desirability for solar powered windows by identifying and evaluating the customer needs for the commercial high-rise building window market. In the course of this assessment, we performed 150 interviews with experts across the value chain for commercial windows. We found that the market forces are complicated by a misalignment of incentives between the end users of BIPV windows and the key decision makers for building projects that could incorporate this technology. Our assessment leads us to frame new figures of merit for BIPV windows that address the underlying needs of prospective customers as well as technical metrics for energy generation. We finally discuss one possible direction for BIPV window technology in which photovoltaics are integrated with switchable windows. Here, the integrated PV converts visible and infrared light transmission into useable electricity enabling standalone, self-powered active windows that can potentially address market needs for smart windows, thereby enabling a pathway for BIPV window deployment.

1. Building-integrated photovoltaic energy

In the past two decades, global solar photovoltaic (PV) capacity has grown more than 600-fold [1]. One driver for this market growth stems from the more than 99.9% cost decrease in crystalline Si (c-Si) PV cells since 1980 [2]—where c-Si cells currently comprise approximately 93% of total installed PV [3]. During this same time frame, record c-Si cell power conversion efficiency (PCE), a second driver for this specified market growth, has doubled from 13% to 26.1% [4]. As a result of these rapid reductions in cell and module cost per Watt, approximately 57% of the costs in 2019 for utility-scale PV systems come from soft costs (e.g. installation labor, sales tax, overhead) and balance of systems (BoS) costs [5].

With this shift in PV system economics, new application areas and market opportunities are being explored. Building integrated PV (BIPV) technology enables traditional building materials (e.g., walls, windows, roof shingles) to be equipped with PV power generation capability—where PV BoS and soft costs can be minimized or even absorbed into the construction costs of a building. Shown in Fig. 1a, the number of U.S. high-rise buildings (>125 ft in height) continues to increase every year, as indicated in blue, with over 3,000 new projects developed since 1980 [6]. While U.S. PV capacity in this same time frame has grown at a near exponential rate, reaching over 70 GW of installed systems by the end of 2019 (Fig. 1a, red), BIPV installations have significantly lagged their utility c-Si counterparts, with less than 0.50 MW capacity in 2019 (Fig. 1a, green).

Buildings alone are responsible for approximately 28% of global CO_2 emissions in the US, and when building-related construction is also considered, that number jumps to over 40% [8]. Given limited rooftop areas of most urban high-rise buildings, typical commercial

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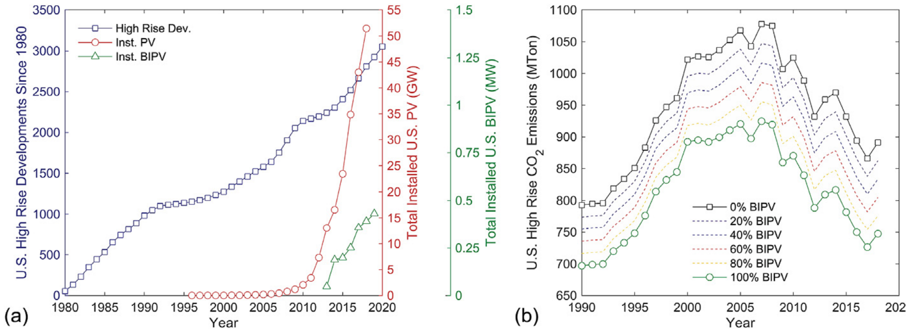

Fig. 1. (a) A comparison of the number of U.S. high-rise developments since 1980 (left y-axis, blue) against the total installed U.S. PV capacity (right y-axis, red) in gigawatts (GW) and the total installed U.S. BIPV capacity (far right y-axis, green) in megawatts (MW). (b) An estimate for the amount of CO_2 emissions in megatons (MTon) resulting from U.S. high-rise buildings with respect to varying total amount of BIPV integration. Here we assume energy production of a BIPV module operating at 5% power conversion efficiency at a temperate, sunny climate comparable to Los Angeles, CA [5,6,47–50]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

rooftop PV installations cannot economically offset electricity demands of the building [9]. And while utility-scale solar PV offers off-site generation to urban centers, up to 10% of generated PV electricity can be lost due to electric power transmission losses [10]. It is thus interesting to consider how direct integration of PV components into the building façade (i.e., curtain wall and windows) can enable a reduction in installation and systems costs [11], while also providing on-site electricity and mitigating building-related CO_2 emissions, shown in Fig. 1b.

While BIPV installations currently occupy less than 0.001% of the overall solar market share, as shown in Fig. 1a, active research and commercialization efforts are underway to develop integrable BIPV technology [12–17]. Given the historical trends for utility-scale PV, BIPV researchers commonly assume that the most influential figures of merit for increased market adoption are those related to on-site electricity generation and, consequently, avoided use of grid electricity. Thus, figures of merit have often considered technical performance factors, such as power conversion efficiency (PCE) and cost per unit area. However, as has been suggested in previous reports, BIPV must also incorporate non-technical factors (e.g., aesthetics, business models) when evaluating the marketability of a new technology [18–21]. In this perspective, we evaluate whether the currently assumed BIPV figures of merit are the most influential factors to assess market deployment of this technology. We limit the scope of our analysis to BIPV power-generating window technology intended for commercial, high-rise building applications within the U.S. We first discuss current electricity-generating window technologies, both under research and commercially available. We then evaluate the glass and window markets, identifying customer segments and decision makers. The outcome of this analysis provides a challenge to the BIPV research community to redefine the key figures of merit to include metrics that take into account customer segment needs as well as technical performance. Finally, we provide an outlook for a BIPV window design that may address these new figures of merit, which combine both market and technical factors.

2. A survey of electricity-generating window technology

Unlike conventional utility PV modules, BIPV window applications must respond to aesthetic requirements (e.g., color, average visible light transparency (AVT), image clarity) in addition to power production. Consequently, a variety of power-generating window technologies have been developed over the past several decades to address these features. Despite a myriad of BIPV window concepts, each share at least one operating characteristic: one or more surface(s) of the insulated glass unit (IGU) window absorbs a portion of incident sunlight for electrical power conversion. Given that a portion of visible light must pass through the window to reach the building occupant, a reduced spectrum of light is useable for power conversion in BIPV windows. As a result of this reduced amount of useable light, the power production of the device is limited, creating a trade-off between window AVT and PCE [16]. Fig. 2a depicts PV power generation by light absorption and electron-hole pair generation at the inside surface of the exterior glass pane (S2).

While BIPV windows share a common feature of incident sunlight to electrical power conversion in semi-transparent modules, the underlying PV technology varies widely, as shown in Fig. 2b–e. Among others, organic PV (OPV) [14,22], luminescent solar concentrator PV (LSC-PV) [9], thin-film PV [14,23], and perovskite PV [14] all enable partial light absorption and have been researched for power-generating window applications. Fig. 2b–e illustrate typical components found for thin film structures for each of these

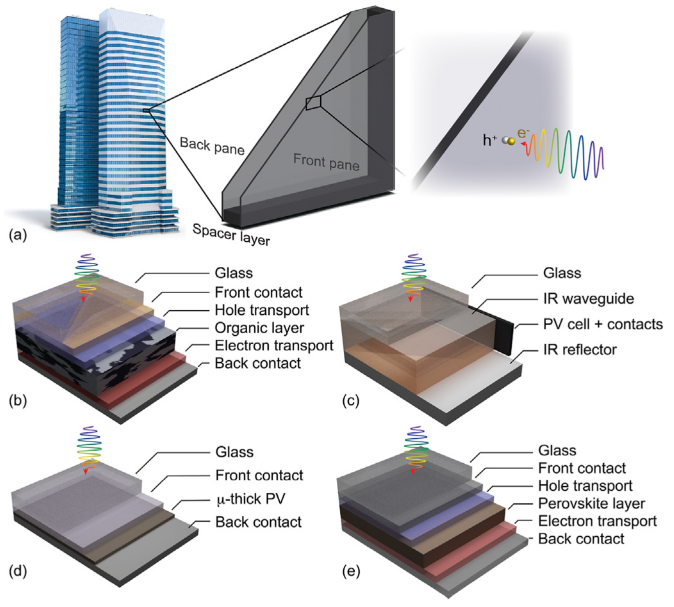

Fig. 2. An overview of various technologies and their respective structures for a BIPV window IGU. (a) An illustration of the structure for a double paned IGU with the front pane layer containing the PV technology resulting in a photogenerated exciton (h^+,e^-). (b), (c), (d), and (e) Renderings of four commonly-employed BIPV window devices including organic PV, LSC-PV, thin-film PV, and perovskite PV structures, respectively.

PV technologies. As shown, each design includes at least one glass surface serving as either the front or back pane. OPV and perovskite PV include electron and hole transport layers encasing the organic/perovskite material, respectively. Recent advances in these devices exhibit PCEs beyond 8% and 10% under 1-sun illumination at over 25% AVT for OPVs and perovskite devices, respectively [14]. For the case of thin-film PV technology (e.g., thin films of a-Si), PCEs can surpass 5% at more than 30% AVT [17]. Finally, LSC-PV prototypes demonstrate recent milestones such as beyond 2% PCE at more than 44% AVT for large-area (100 cm^2) module sizes [24].

Despite decades of device research and product development, the amount of installed BIPV (e.g., BIPV windows) technology has not experienced the same growth, or even the same trend, as its utility PV counterpart (Fig. 1a). Moreover, research into how to further integrate BIPV windows into the commercial buildings market remains an active area of study in both academia and industry [18–21]. One possible reason is that BIPV window modules have not yet achieved sufficiently high PCE and annualized energy production in order to meaningfully offset building electrical loads. Yet, despite advances in PV efficiency and durability, BIPV window adoption remains limited in this commercial, high-rise market. This could indicate that conversion efficiency is not the sole driving factor for widespread BIPV window adoption. A second possibility is that the customers' needs and associated value propositions for the BIPV market are significantly different from those of the utility-scale PV market, such that the same norms do not apply. If such is the case, then PCE and AVT alone may not be sufficient to meet customer needs for BIPV adoption.

3. Commercial glass and window market

In order to assess how BIPV window technology could enter into the commercial glass and window market, we must first develop a comprehensive understanding of the value chain for a traditional window – a double-paned IGU – from cradle (i.e., initial manufacturing) to end-use (i.e., use in a commercial high-rise building). While the building load electrical generation for BIPV windows is applicable for all building sizes, in this paper we specifically address a subsegment of the commercial market, considering only large-scale (≥100,000 ft^2), high-rise buildings [25]. Such large-scale high-rises typically exhibit larger window-to-wall ratios than other commercial building market subsegments [26]. We traced this IGU cradle-to-end-use value chain (see figure S2 in the Supporting Information) by conducting nearly 150 in-person interviews across the commercial building value chain during the fall of 2019. We categorize these 150 interviews as: 37% within the glass and IGU manufacturing chain; 15% from IGU suppliers and distributors; 28% from real estate developers, architects, engineers, and contractors (general and sub-); 12% from city and building regulators; and 8% from building occupants and end-users.

The cradle-to-end-use value chain of a double-pane IGU describes how solar powered windows would be transferred from BIPV window manufacturers, to window suppliers and distributors, to large-area building developers, and eventually to the end-users—either as the building owners or occupants, as shown in Fig. 3. We can subcategorize roles of the various parties within this value chain as the direct economic buyer(s) of BIPV window coating technologies; decision maker(s) who determine whether or not to adopt a particular IGU product; influencer(s) that can sway buyers or decision makers; and saboteur(s) that can impede or prevent BIPV window technology from entering into the market.

From our collected data, we can identify a singular economic buyer within the first stage of the value chain—BIPV window manufacturing. We also find that key decision makers, BIPV window influencers, and emerging window technology saboteurs all occupy distinct roles within the third stage of the value chain, building development. In contrast, none of these roles (e.g., economic buyer, key decision maker, influencer) exists within the end-use stages (e.g., ownership or occupancy) for such a BIPV window process flow. Fig. 3 depicts the five stages of the BIPV window value chain, highlighting the key roles spanning from cradle-to-end-use, and specifies how each role relates to one another with respect to product flow.

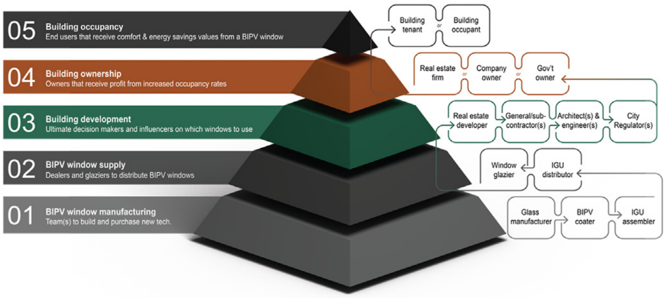

Fig. 3. A conceptualization of the value chain for a commercial building IGU. (left) Five major categories of product development from window cradle to end-use. (right) Subcategorization of roles within these five categories, explicitly showing the product flow between subsequent customers in the chain. For such a BIPV technology, the primary economic buyer for this setup lies in the initial window manufacturing process, between the glass manufacturer and IGU assembler. The key decision maker to adopt BIPV window products for a building owned by the real estate developer, as is common, lies in the third stage with the real estate developer itself. Here we show that the end-user and primary beneficiary of PCE or low cost per area units lies at the very top of the pyramid, thereby not substantially influencing either the economic buyer or key decision maker.

Within the value chain, we identify specific needs for each of the major roles that impact market adoption for BIPV window technology—influencers, key decision makers, and economic buyers. Influencers (in this case architects) are motivated to create aesthetically attractive building designs to increase project acquisition. As such, BIPV windows need to meet the aesthetic needs (material, color, clarity, flexibility) of architects. The key decision makers (here commercial real estate developers) are motivated by an increased return on investment (ROI) to turn a greater profit [27]. For a real estate developer, the primary purpose for a window simplifies to increasing the availability of natural daylight, allowing unobstructed views, and enabling comfort through temperature control, all in order to attain higher building occupancy rates and therefore heightened ROIs. Finally, the economic buyers (IGU manufacturers) are incentivized to maintain the status quo; i.e., to produce windows whose production costs and installation procedures and costs do not disrupt the current practice of window production and installation. Therefore, electrically connected windows, which incur additional installation costs, are intrinsically at odds with the economic buyers' primary need.

While electricity generated by BIPV windows may appear to be the most obvious added value for high-rise buildings, this value is only appreciable to the end-user (building occupant or owner), who occupies the top stage of a value chain pyramid and accordingly has no significant decision making role in the value chain. Moreover, the real estate developer's greatest need (i.e., increased ROI) doesn't necessarily align with that of the building occupant's or end-user's. From nearly 150 qualitative interviews, large-scale building developers most commonly rely upon higher degrees of comfort, increased views, or other "soft" values to attract more tenants. While lower utilities costs may attract a certain number of tenants, our interviews show currently most developers rely upon other methods (e.g., soft values) to achieve increased ROI.

4. Re-defining the figure of merit

As shown in this market analysis, there exists more than one customer role, each of which are separated along the value chain. The separation of roles (e.g., decision maker, economic buyer, and end-user/beneficiary) suggests that the key figure of merit to spur market adoption may not stem solely from power conversion efficiency. Given the interview data, we find that the specific needs of each role; 1) the key decision maker, 2) the economic buyer, and 3) the end-users; must be addressed. Thus, BIPV windows must first work to enable increases in building occupancy rates and in turn ROI. Second, BIPV windows must also feature designs that simplify or eliminate the need for integration into the building electrical infrastructure. Finally, while optimization for PV electrical performance (e.g., PCE) are still considerations to meet end-user's needs (e.g., reduced utilities bills), our interviews suggest these factors are less important to the key decision makers and economic buyers. As has been concluded in related market studies [28], an inclusive figure of merit to capture each of these three features of a BIPV window (ROI impact, installation/integration, PCE) could enable researchers to more efficiently develop technology deployable to this market.

5. An outlook for BIPV window research and development

Given the disparity between the power-production capabilities of current BIPV window concepts and the market needs (identified through this interview process) of high-rise building developers and IGU manufacturers in the United States, we identify several strategies to enable BIPV window technology to meet such market needs. One strategy, as has been discussed by previous studies [28–31], involves an increase in policy and regulation of required on-site PV production and energy efficiency of such building markets in order to create a demand for the key decision makers. As introduced in the previous section, another such strategy could be to align building developers' current needs of increased ROI with BIPV window technology. From interviews conducted throughout this study, dynamic windows (e.g., electrochromic) represent one such technology that provides the "soft" values needed for increased occupancy rates. An example of how to introduce BIPV window technologies could be to hybridize dynamically transparent IGUs with PV power-generating components [32–41]. As shown in Fig. 4a, a dynamic glazing window transmits visible and infrared radiation (light and heat) when configured in its off (clear) state. However, when switched to the on (dark) state, such windows reflect solar heat at the first glass surface (S1), thereby optimizing the daylighting and heating within a commercial building.

To date, most commercially deployed active window technologies rely upon switching mechanisms driven by externally supplied power from the building's electric infrastructure [42]. The high labor-related installation costs for replacing traditional IGUs with externally-powered dynamic windows creates a limited market size, in which dynamic windows would only be practical in new building projects [43,44]. However, retrofitting projects far outnumber those of new builds [6]. Fig. 4a shows a 3D rendering of a dynamic, electrochromic double pane IGU coupled with transparent BIPV technology in order to illustrate a self-powered tinting window [36,41,43,44]. Given this design, the PV component absorbs a small portion of light, in both the on and off states, to enable the power production needed for switching. This standalone self-powered window unit would not incur any labor costs related to integration into the building electrical infrastructure. Fig. 4b estimates the impact that self-powered dynamic window technology could have for U.S. high-rise CO_2 emissions if widely adopted. In this figure, we assume an average energy savings of 10% when replacing standard double-pane, low-E windows with dynamic windows [45]. From this, we can expect a comparable decrease in CO_2 emissions resulting from widespread adoption of self-powered active windows as from on-site electricity generation by power-generating BIPV windows (Fig. 1b), owing to decreased HVAC use in buildings featuring self-powered dynamic window technology [46]. The above suggests BIPV window technology has untapped potential to transform energy use in high-rise commercial buildings.

Despite its potential, total BIPV installation in the US lags far behind conventional utility-scale PV. From the 150 interviews with experts in the high-rise building value chain, we learned that the market case for BIPV technology cannot be made by applying the same figures of merit as are used for the utility-scale PV market. Researchers investigating BIPV technology need to define appropriate figures of merit that can quantify the BIPV aesthetics, enabled comfort values, and ease of installation. While such attributes are less commonly considered or emphasized by the photovoltaics or broader renewable energy technology communities, in comparison to technical merits, the emergence and market adoption of innovative PV forms demands equally innovative and evolving metrics for market evaluation.

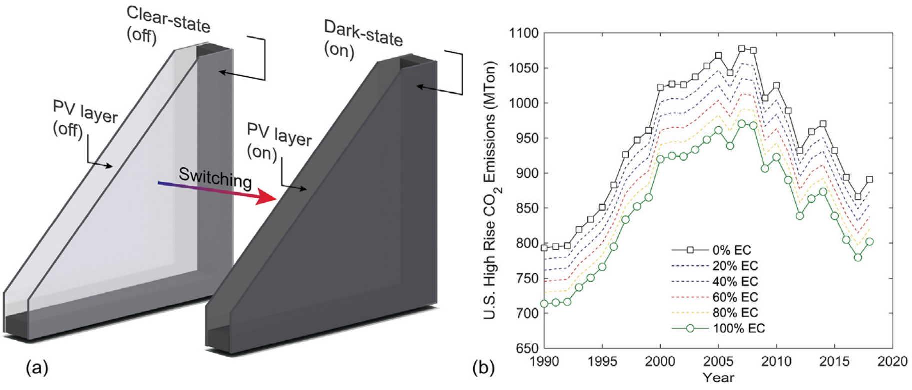

Fig. 4. (a) 3D rendering of a dynamic, double pane insulated glass unit (IGU) coupled with transparent BIPV window technology, conceptually illustrating the effect of self-powered switching from the off, clear state to the on, dark state. (b) An estimate for the amount of CO_2 emissions in megatons (MTon) resulting from U.S. high-rise buildings with respect to varying the total amount of BIPV-powered, dynamic IGU integration. Here we assume energy production of a BIPV module sufficient to operate the switching energy demands of the dynamic component, geographically set to a temperate, sunny climate comparable to Los Angeles, CA [5,6,45,47–50].

Author contributions

David R. Needell, Conceptualization, Methodology, Data collection, Writing – original draft preparation. Megan E. Phelan, Conceptualization, Methodology, Data collection, Writing – original draft preparation. Jason T. Hartlove, Data collection, Writing-Reviewing and Editing. Harry A. Atwater, Data collection, Writing-Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no competing interests with respect to this manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2020.119567.

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