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System-Scale Modeling of a Building-Integrated, Transparent Concentrating Photovoltaic and Thermal Collector

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Abstract. The buildings sector is a principal contributor to global greenhouse gas emissions, but consistently falls short of targets for harnessing on-site energy resources towards sustainable operation. Emerging integrated solar technologies could transform buildings and urban settings into resilient, self-sufficient, and healthy environments. But if effects of these technologies are not understood in the multiple contexts in which they operate (human-scale, building-scale, district-scale), their potential is difficult to project. To explore building-scale metabolization of solar energy, a previously-developed analytical model of a Building Envelope-Integrated, Transparent, Concentrating Photovoltaic and Thermal collector (BITCoPT) was run to project electrical and thermal energy and exergy production (cogeneration) in a range of orientations and operating temperatures. Simulated annual cogeneration efficiency was noted at 27% (exergy) at an operating temperature of 55°C, and up to 55% (energy) at 25°C. Exergetic efficiency remained nearly constant as operating temperatures increased through 75°C, indicating the thermal energy collected would be some heat-engine-based applications. Although the scope of this study excludes broader architectural benefits of daylighting (lighting load reduction), and reduction of solar gains (cooling loads), these results suggest BITCoPT merits further investigation for on-site net-zero and energy-positive commercial building design, and might contribute to expanding net-zero and energy-positive architecture opportunities.

1. Multiple utilities of envelope-integrated concentrating solar collection

To sustainably meet our societies' future energy needs, a fuller range of the forms and qualities of energy available from the natural environment might be more effectively harnessed. The built environment is an ideal focus for novel energy strategies, as approximately one-third of the primary energy produced in the world is consumed in the non-industrial building sector [1], but most of this energy is sourced from fossil fuels, and it is delivered to end users in easily used forms: refined fuel and electricity. A building's service demands, however—lighting, heating, cooling, and ventilation—can be addressed, at least in-part, with the resources and potentials available locally in the natural environment. If harvested



and delivered correctly, solar energy could be a prime resource to simultaneously provide high quality daylighting, electricity and thermal power. If architecturally desirable systems are available that transform solar into these inherently useful forms, while spatializing and temporalizing them appropriately to deliver the end products when and where they are needed, then the built environment system would *both* consume less energy and generate more power on-site, unlocking the potential for both net-zero and energy-positive operation for a broader range of buildings.

It is traditionally beneficial to limit solar gains in many commercial building settings, as cooling demands are driven by the sum of these gains with day-time internal gains. A revised paradigm for the built environment—metabolization—develops from redirecting unwanted climatic energy towards useful ends. This potential motivated development of a Building Envelope-Integrated, Transparent, Concentrating Photovoltaic (PV) and Thermal collector (BITCoPT), proposed and explored in previous research [2][3]. BITCoPT is a dual-axis tracking collector, integral to an envelope's glazed components, that employs concentrating optics and multi-junction concentrator PV cells (CPVs), a configuration demonstrating (in non-building-integrated designs) module efficiency over 36% relative to direct insolation [4], and potentially provides material life-cycle benefits over non-concentrating PV [5].

1.1. Precedent and related studies and technologies

Active integrated façade (AIF) technologies with which BITCoPT shares core concepts continue to be actively explored. Building-integrated, photovoltaic AIFs (BIPV) potentially improve on shading-only devices, by collecting solar energy otherwise rejected to the environment, and are widely available [6]. But a performant envelope is a result of a multi-variate optimization, and because BIPV systems inherently compromise between energy collection and other primary design criteria (views, daylighting, and management of heat and moisture), their performance is limited. It is possible, for example, that if a BIPV envelope's heat transfer and daylighting characteristics are not appropriate for a building's context, power generation is less than the marginal cooling, heating, and lighting power the design incurs [7]. Likewise, BIPV's potential benefits to urban heat island (UHI) effects from reducing energy imports are complicated by factors such as trades with UHI mitigation strategies such as cool roofs [8]. To gain acceptance, an AIF's energy generation must not impinge on (and should support) other primary criteria.

By incorporating optical concentration and thermal control, AIFs can realize additional value streams [8], and improvements to exergetic efficiency with combined PV and thermal collection are noted [10]. High-temperature collection with concentrating building-integrated systems enables solar cooling (or other heat engine-driven processes) [12]. Availability of a façade-integratable system activates more area than roof-only installations, with greater potential benefits, such as daylighting and reduced gains in perimeter spaces. BITCoPT is an optically concentrating AIF that transmits diffuse insolation for daylighting (and low glare), harvesting direct insolation for electrical generation and thermal collection (through active, hydronic heat exchangers). The novel contribution of BITCoPT is in the optical/mechanical design, which allows a large active area, and cogeneration of thermal energy at a range of temperatures. In previous simulation studies, BITCoPT showed a 50% reduction in gain over baseline solar-control glazing, with parallel reductions in glare probability [13], while an operational prototype demonstrated 43.6% cogeneration energy efficiency at 58°C [3], when installed in occupied space with live solar input. This current study investigated the system's potential at a larger scale.

2. Methods: technology description, analytical model, experimental setup

To investigate BITCoPT's potential energy and exergy generation and efficiencies, simulations were run of a full-scale installation, using an existing analytical model [14] that was calibrated to results from an experimental prototype, and adjusted to reflect expected installation characteristics [3]. Ranges of operational temperatures and collector orientations were investigated. The BITCoPT technology and analytical model are summarized here for convenience. Specifics to this study are also described, such as exergy calculations (which have not yet been documented), and simulations setup.

2.1. Technology description

BITCoPT demonstrates envelope-integrated metabolization of solar energy, preserving its value (specifically daylight and exergy) as possible. BITCoPT comprises closely-packed optically concentrating modules suspended internal to a deep-mullion unitized glazing cassette (figure 1).

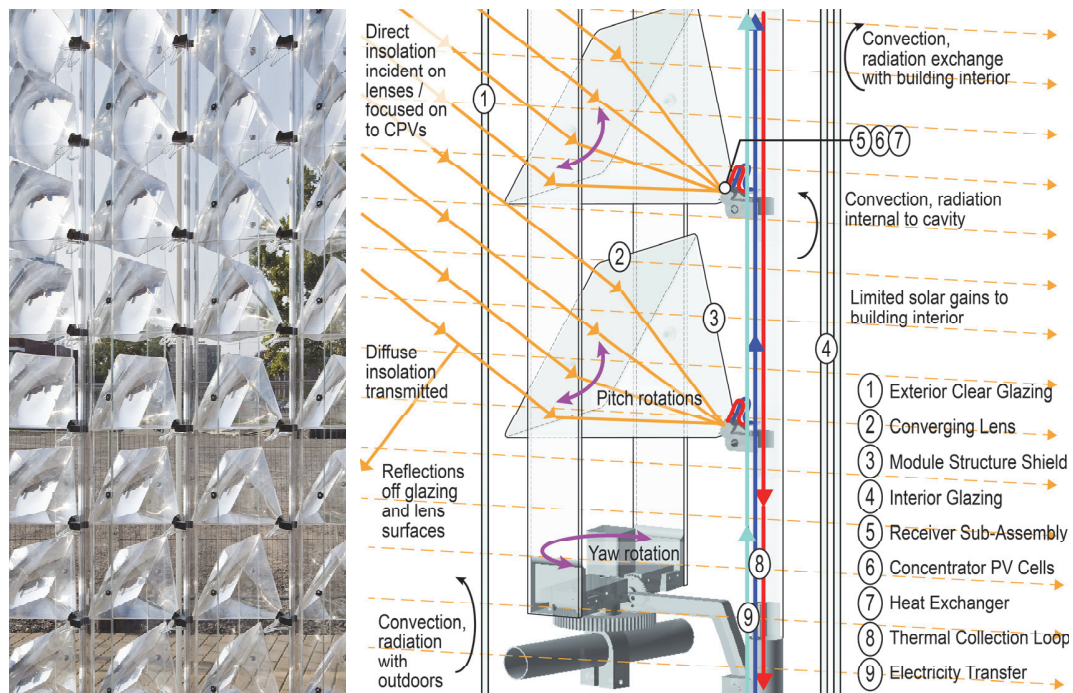


Figure 1. BITCoPT: Visual transparency of a constructed prototype, and operational diagram indicating functionality for simultaneous reduction of building lighting and cooling loads, alongside high efficiency collection and distribution of high temperature heat and electrical power.

The modules are rotated through two degrees of freedom via linkages, to dynamically track the sun, focusing insolation onto 1cm^2 -format concentrator photovoltaic cells (CPVs) at roughly 600X. The CPVs are cooled by hydronic circuits, transferring thermal energy to storage, which, at between 40°C and 100°C , can be applied to building processes. As desired, the modules can also be “off-tracked” to re-direct and spread additional light into the indoors [15].

As with other unitized systems, the cassettes can form vertical, horizontal, or tilted envelope facets. Glazing material would be glass or ETFE, modelled in this study with a solar heat gain coefficient (SHGC) of 0.95. While exterior glazing should be transmissive to solar energy, the interior glazing spec is driven by requirements of the occupied space, such as multi-pane with low-e coatings (reducing thermal transfer). The SHGC of the modelled interior glazing was 0.65. As possible, the modules and tracking structure are constructed of slim members and transparent materials to permit diffuse daylighting and views through the system (noted in figure 1).

2.2. Analytical model details

The analytical model of BITCoPT is a quasi-steady state, lumped-capacitance representation of relevant physical relationships. Energy balances are constructed for each module, and for a whole cassette, and solved iteratively at time steps. The model was described in earlier studies, and key relationships are highlighted here, as well as parameters and functions specific to the full-scale simulation.

As a basis for efficiency, the direct power available to be converted (incident on the collector's primary optical elements), $G_{DN,POE}$ (W), is a function of direct irradiance, glazing transmittance, lens geometry, and dynamic shading characteristics (Equation 1):

$$G_{DN,POE} = I_{DN} T_{glaz,\theta} A_{POE} \sum_{i=1}^n F_{POE} \quad (1)$$

I_{DN} is direct normal irradiance (W/m^2), $T_{glaz,\theta}$ is the angularly-dependent transmittance across glazing, A_{POE} is the active area of one module's primary Fresnel lens optic (constant at $0.0626m^2$), and n is the array's module count. F_{POE} is the unshaded fraction of the primary optic, a function of array pitch and yaw, which varies with a module's position in the array. Modules are shaded by: optics of adjacent modules, tracking structures, and the cassette's frame. F_{POE} functions were generated through geometric ray tracing for unique module positions within an array (left, right, top edges, corners, and central), confirmed with measurements taken during prototype operation, and represented as look-up tables.

Modules at an array's edge are shaded, on average, 10% more than the center, by the cassette frame. Although stacks might comprise any number of modules, the projected model setup is a stack of ten modules (roughly 3m tall, and occupying $1m^2$ of glazing area), corresponding to one story of a typical office building. It can be assumed a BITCoPT array would be at least 12 stacks wide, and at 10 modules tall, the edge shading would be negligible, so in simulation, all modules were assigned the central F_{POE} .

Limits to BITCoPT's dynamic range of motion, as determined by its mechanical design, are represented in the model. Because limits are hit at high incidence angles (θ_{AOI}) where Fresnel reflections from exterior glazing are already significant, overall efficiency is not impacted as greatly as with a stand-alone tracker. In this study, the array rotated up to 60° in either pitch or yaw direction (see figure 1).

The primary performance metric for BITCoPT is cogeneration exergetic efficiency (ϵ_{cogen}): the fraction of solar exergy incident on modules' primary optics that is captured either as thermal exergy or electricity. Energy efficiency (η_{cogen}) is likewise important, as both the quality and quantity of collected energy are useful (for driving processes and providing heat) in the built environment.

The exergy-energy ratio of solar irradiance was assumed constant at 0.933. Exergy of generated electricity is equal to energy. Thermal exergy is defined as the power drawn from a system as it equilibrates with a heat reservoir at a reference temperature, with minimum entropy generation. The reference state was set to the time-dependent wet bulb temperature (from weather data), in keeping with other exergy studies [16], to represent an ideal sink that could be achieved with cooling towers.

Two parasitic electrical losses were included: tracking servo motors, and pumps. Based on measurements of a maximum torque of 4Nm required to change pitch angle in the prototype, -2.5W per stack was applied to represent servo power. Pumping power is the sum of: pressure losses across the heat exchangers; hydraulic head; and friction losses in piping and fittings, assuming nominal flow rates. Pumping power was set constant at -1.8W per stack of 10 modules.

Two parametric studies were run. Firstly, the simulations were run in multiple orientations, with hourly annual inputs (I_{DN} and outdoor temperatures) from a seasonally variable, continental climate at a moderate latitude (New York, NY, USA, using TM3 data). Tilt angles used were: horizontal roof (0°), lifted (30°), inclined (45°), tilted (70°), and a vertical wall (90°). East, southeast, south, southwest, and west orientations were used. A constant indoor space temperature ($23^\circ C$) was set, and heat transfer fluid inlet temperature ($T_{HTF,in} = 45^\circ C$), and volumetric flow rate (5 ml/s per stack) were set for the system.

In the second study, to explore exergetic efficiency relative to operating temperature, annual simulations were run with a range of constant $T_{HTF,in}$ (from $35^\circ C$ to $85^\circ C$) that represent useful thermal collection for space heating, service water heating, and thermally-driven processes such as adsorption chilling. The array was oriented south and lifted 30° from horizontal for this study.

3. Results: normalized cogeneration energy and exergetic efficiencies

Annual projected efficiencies were calculated relative to $G_{DN,POE}$ in each orientation (Table 1). Of the simulated orientation and tilt variations, the instance oriented south and lifted at 30° from horizontal generated the most electrical and thermal energy (expected at the modeled latitude of $\sim 40^\circ N$). Inclining

to 45° performed similarly, but it is noted this angle does not conform well to standard building designs. Relative to the horizontal instance, lifting the system 30° improved annual cogeneration by 28%. Relative to the vertical instance, tilting 20° (to 70° from horizontal) increased cogeneration by 49%.

Table 1. Annual electricity and thermal production, cogeneration energy and exergy efficiencies, relative to array orientation (45°C inlet temperature).

	Electricity ($kWh(m^2\text{-yr})^{-1}$)					Thermal ($kWh(m^2\text{-yr})^{-1}$)					Energy efficiency					Exergy efficiency					
	E	SE	S	SW	W	E	SE	S	SW	W	E	SE	S	SW	W	E	SE	S	SW	W	
Roof (0°)			187					206						46%							27%
Lifted (30°)			233					269						48%							27%
Inclined (45°)	150	204	233	206	151	163	233	268	237	168	46%	47%	48%	48%	46%	27%	27%	28%	27%	27%	
Tilted (70°)	113	171	197	172	114	118	187	218	191	123	44%	46%	47%	46%	45%	27%	27%	27%	27%	27%	
Wall (90°)	80	125	139	127	81	77	126	139	132	83	42%	44%	44%	45%	43%	27%	27%	27%	27%	27%	

BITCoPT generated electricity at 21.5% and thermal energy at 26.1% (with inlet temperature of 45°C) for a maximum annual η_{cogen} of 47.6%. ϵ_{cogen} was nearly constant across instances, peaking at 27.5% with the array oriented south and tilted to 45° C, but never falling below 26.5%. For comparison, a current PV glazing product simulated in the lifted orientation produced 148 kWh/m²a (ONYX PV Glass, per California Electrical Commission database, through PVWatts v1), while BITCoPT generated 233 kWh/m²a—an over-50% increase in output, without considering the thermal component.

The sensitivity of ϵ_{cogen} to $T_{HTF,in}$ was studied through a set of year-long hourly simulations at different constant inlet temperatures (figure 2).

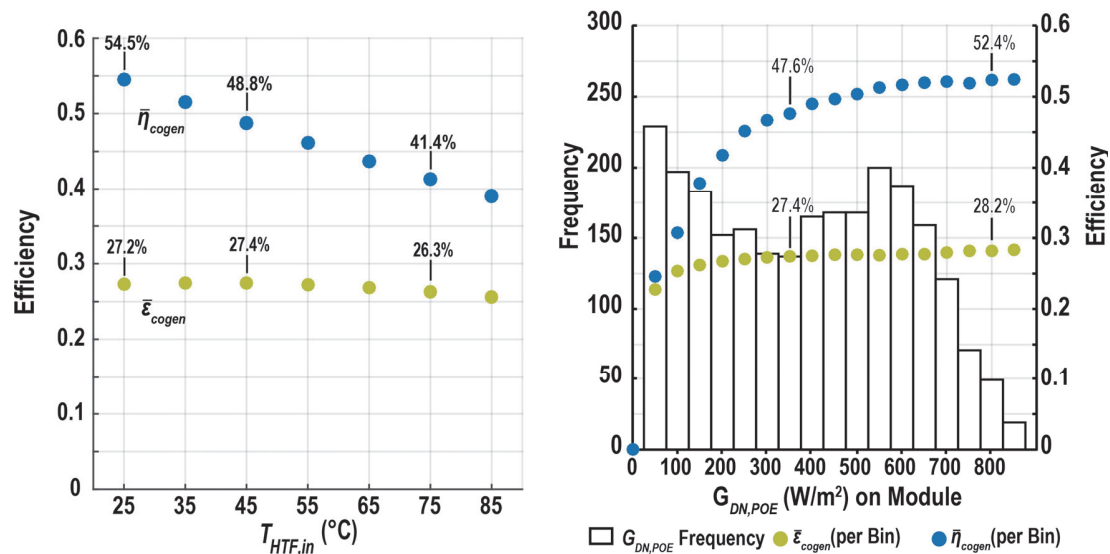


Figure 2. (Left) Efficiencies relative to inlet fluid temperature ($T_{HTF,in}$), summed annually. Exergetic efficiency (ϵ_{cogen}) shows a smooth peak of 27.4% at $T_{HTF,in} = 45^\circ\text{C}$, and only 1 to 2% loss through 85°C. ϵ_{cogen} of 27.4% comprises 23.1% electrical and 4.3% thermal. (South-facing, lifted 30°, New York City climate.) **(Right)** Energy and exergetic efficiencies increase with irradiance ($T_{HTF,in} = 45^\circ\text{C}$).

Notably, increasing irradiance correlated to increases in both energy and exergy efficiencies (figure 2). Both measures rose steadily with respect to insolation levels experienced in the annual simulation, although exergy achieved 97% of its ultimate efficiency with $G_{DN,POE}$ as low as 350 W/m².

3.1. Diurnal and annual response

A prototypical diurnal relationship between available insolation and BITCoPT output is shown, for strong-solar days representing low, medium, and high-angle periods of sun in the simulated year (January 24th, October 17th, and May 20th), for south vertical wall, lifted roof, south wall tilted, and east wall tilted orientations (figure 3).

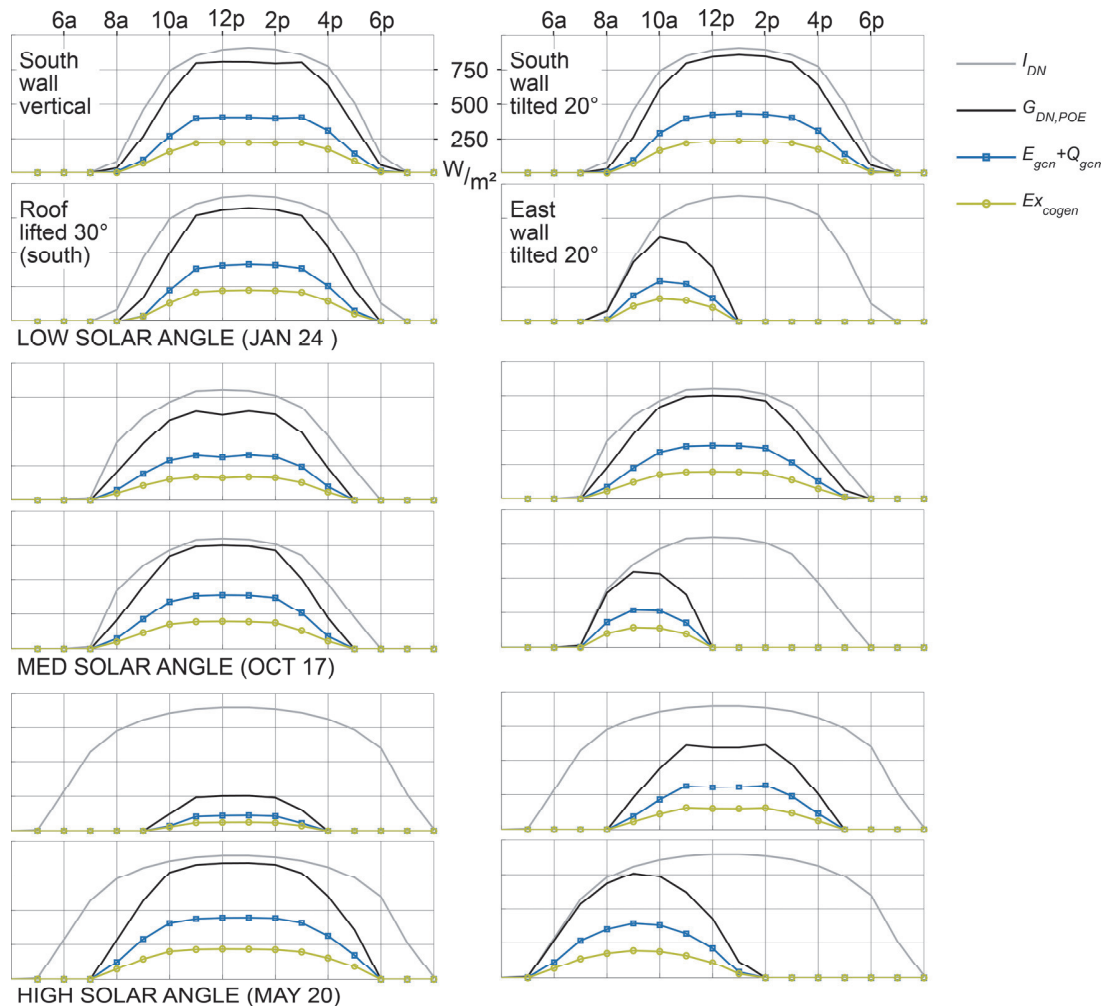


Figure 3. Simulated single-day power and exergy production, for strong direct solar conditions in three distinct seasons/solar altitude regimes, with four example orientations shown.

With lower solar altitude in January, production from the south wall was on-par with the optimal lifted roof orientation (fig 3) and outpaced the flat roof orientation (not shown). For middle-solar elevation cases (October data) the vertical wall performed similarly to tilted cases, although output sagged mid-day (due to high θ_{AOI}). With high summer sun, less $G_{DN,POE}$ was available for vertical and titled instances, due to view factor, and high θ_{AOI} producing Fresnel reflection losses off exterior glazing. Per Table 1, however, the benefits of these orientations (particularly in electrical generation) in other seasons meant no more than 15% loss in annual η_{cogen} , and no overall decrease in ϵ_{cogen} .

Overall exergy benefits of high-temperature thermal collection can be observed. Although full simulations were not run for an electrical-only system, the CPV sub-model (explained in [3]) was run, comparing performance at CPV temperatures of 95°C (for thermal collection) and 45°C (an assumption

for passive cooling), improving output by 11%. If that factor were applied to the simulated annual electrical efficiency ($\varepsilon_{Egen} = 23.1\%$) it would increase to 25.6%, suggesting high-temperature thermal collection (simulated at $\varepsilon_{cogen} = 27.4\%$) boosts overall exergy collection by 7%.

4. Discussion: Ramifications of Simulated Results

The projected exergy efficiency showed a slight local maximum, in the middle of the tested temperature range (fig 2), which spans from process heating at the low end (45°C) to driving heat engines (over 55°C). This maximum confirms expected solar thermal collector behavior, as temperature increases cause linear increases in thermal energy losses, but only proportional increases in exergy.

In precedent studies the increase in exergetic efficiency from combined heat and power systems was shown for opaque [11] and semi-transparent non-concentrating systems [10]. Results of this analysis suggests a system which centers daylighting (such as BITCoPT) might provide similar benefits, in useful temperature ranges. The exergetic advantages of solar cogeneration are unique in the building context, as daylighting and solar gain reductions would further improve a building's net energy use. To fully leverage the effects of BITCoPT, the collector would be integrated with building systems designed to take advantage of both the quantity and the potential of the collected thermal energy.

The different responses to temperature of energy and exergetic efficiency (decreasing and flat, respectively) suggest another benefit of building-integrated cogeneration: control options. Depending on service demands (current or predicted), the operating temperature could be varied to preference either energy or exergy. This control question might be studied further through whole-building modeling.

The increase in efficiencies with increasing irradiance demonstrates a dependence on solar exposure, which varies both by climate and building context. High solar gains typically drive cooling loads in medium and larger buildings, so this efficiency ramp is another potential benefit specific to the building-integrated context. This relationship is influenced by several factors, however, and as with all integrated systems, the full system effects are only explorable as a subsystem of a building, as investigated in related studies [7][12]. Nevertheless, the simulated performance of BITCOPT relative to comparable systems (over a 50% gain in electrical output relative to commercial BIPV, without considering thermal collection) are encouraging of further investigation.

5. Summary

Towards exploration of synergistic and efficient metabolization of climatic resources in the built environment, a building envelope-integrated, transparent, concentrating photovoltaic and thermal solar collector was simulated over annual cycles. BITCoPT is conceived to provide daylighting, views, and cooling load reductions, with electrical generation and thermal energy collection at magnitudes significant to commercial buildings. Using an analytical model developed previously through comparison to an operational prototype, exergetic cogeneration efficiency of 27.4% was demonstrated, and energy cogeneration efficiency of up to 54.5% at 25°C (41.4% at 75°C). The exergetic efficiency was stable through elevated temperatures (75°C), demonstrating suitability for driving heat engine-based processes. With the analytical model so exercised, investigations might be done into building systems strategies that incorporate BITCoPT. The simulations and results were presented and discussed.

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