FAÇADE BIPV
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THE ENVIRONMENTAL LIFE-CYCLE VALUE PROPOSITION

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ABSTRACT

The value of Building Integrated Photovoltaics (in façade applications) lies in the fact that these systems entirely replace façade-cladding systems that do not have the added benefit of generating power that offsets expensive, non-renewable and polluting sources from the surrounding electrical grid. This study quantitatively demonstrates this value through the lens of process-based life-cycle analysis via the following metrics:

- Energy pay-back time (EPBT),
- Energy Return on Investment (EROI),
- Global warming potential (GWP) and
- Carbon-equivalent payback time (CPBT)

Lower incident radiation from sub-optimal orientation and shading obstructions notwithstanding, façade-integrated BIPV is shown herein to have an environmental impact comparable to that of optimally-oriented roof or ground-mounted PV systems. This relatively high environmental benefit stems from the avoided environmental burden associated with the materials that façade BIPV replaces.

Furthermore, we determine functional relationships between environmental impacts of façade-BIPV under a range of incident radiation conditions and under a range of applications—in terms of the types of façade systems the BIPV system replaces.

This study leverages first-hand life-cycle inventory data sourced directly from the designer, architect, and supply chain partners involved in the construction of curtain-wall façade arrays in Manhattan, New York. Operational performance metrics of façade-BIPV systems have been derived from publicly-available IEA-PVPS data and validated via on-site monitoring and recording of the prototypical façade-array at the Solaire Building in the Battery Park City area of Manhattan. Time-synchronized, extensively-validated, satellite-derived meteorological data for the site was obtained from Clean Power Research and used to measure performance ratios over the system's operating lifetime. The quality of data and 'avoided impact approach' to accounting for the façade systems the BIPV arrays replace makes this study novel among previous analyses and further demonstrates unique value-proposition offered by these PV applications.

1. INTRODUCTION

The PV array which forms the basis for our analyses of BIPV life-cycle impacts, is a completely integrated curtain-wall façade spanning 12 floors of the *Solaire Building* in New York City and was installed in early 2004. The Solaire's array was the first BIPV application of it's kind installed in New York City and it has a capacity of 11.3 kW_{DC}. This study builds upon previous research on the life cycle impacts of BIPV with a wealth of detailed data on material composition, structure and performance of the Solaire array and of the other façade systems cladding the building. [Fig.1, 2-4]

Covering ~153 m^2 of façade-space, the array was designed and engineered by altPOWER, Inc and Pelli-Clarke-Pelli Architects. To achieve the building architect's aesthetic parameters, five distinct varieties of custom solar modules were manufactured for the array, each differing in shape and capacity but using the same materials. Facing the Hudson River waterfront, the array's azimuth is 275° (95° west of south). While this orientation is less than optimal, it remains largely unobstructed aside from a few trees lining the adjacent street. The array is divided into four sub-arrays, each running to a dedicated potted junction box (J-Box) via conduit-encapsulated power cables. From these J-Boxes, larger conduits drop inside the building to the first floor where they interconnect to four separate inverters and associated switchgear. [5]

Employed in the array is a 300µm-thick monocrystalline Silicon AstroPower 'AP-105' cell built on a 127-mm quasi-square wafer. The cells, no longer in production, are unique because the wafers were recovered from the waste stream of the Si microchip industry, and at the time of manufacture represented negligible economic value. Accordingly, we did not allocate any life cycle impacts from the wafers' production to the life-cycle impacts of the Solaire array as-is. However, with the rapid growth of the PV industry, solar cells whose wafers are sourced in a similar manner to the Solaire Array are becoming increasingly rare. Therefore, we also analyze the BIPV array's lifecycle impacts in a realistic scenario which includes the lifecycle impacts stemming from a 180-µm monocrystalline wafer production of the same 127-mm quasi-square dimensions as the Solaire system. [6]

BIPV systems are a rapidly growing application of solar PV technology, especially in Europe where governmental incentives directly benefit this particular application. While most PV systems installed in the United States are sited on the roof of low-height structures, an increasing number are integrated directly into the vertical facades of commercial and residential towers. As architects, developers, and their clients realize the aesthetic and environmental appeal of such designs, technological advancement and targeted incentives will likely yield continued expansion in this segment of the solar market. [7]

A significant solar resource impinges on the facades of urban structures and offers the potential to add substantial ultra-localized renewable energy capacity to the world's power-hungry urban centers. BIPV offers two main advantages over traditional PV system applications: it does not require any 'virgin' land for its operation, and it replaces other facade systems that do not as productively use the incident radiation. The infrastructure the BIPV replaces as a design choice has a large impact on the life-cycle CO_2 and energetic burden of the BIPV array as a whole. The key drawback to vertical façade-systems is their non-optimal orientation and corresponding lower incident solar radiation. In this paper, we detail how the replacement of different types of traditional cladding materials can offset this drawback in terms of environmental burden and Energy Payback time, a fact which differentiates Façade-BIPV systems other PV system archetypes. Furthermore, we demonstrate functional relationships between environmental impact parameters and annual incident radiation on the BIPV system for multiple façade architectures the BIPV system could replace. [8]

2. BIPV SYSTEM CHARACTERIZATION

This section describes in brief the construction of the BIPV array and the alternative façade claddings it has the option of replacing. Particulars of construction and material balances comprising the LCI are tabulated in an appendix available upon request from the authors. Development of the LCI employed in this study is consistent with previous accounting methods for BIPV LCI in that materials replaced by the BIPV are credited back to the system. [1-4]

2.1 BIPV Laminates:

Affixed to the building's façade, the array contains 76 custom laminates of five different sizes. We analyze these five varieties of BIPV laminate by examining their primary constituent components. Although they vary by size and rated capacity, each of these modules share a common cross-section: a 6.35 mm thick layer of solar float glass, a 1 cm thick layer of EVA Photocap encapsulating the cells and bussing elements, with a multilayer backsheet laminate. Bound to the laminates' backs with silicone sealant are injection-molded polyamide junction boxes. These j-boxes are 'potted,' or filled with silicone to meet NYC electrical code requirements for outdoor interconnections—a regulation that is mirrored in other urban municipalities. [5, 9]

A mass-based compilation of material balances was performed by analyzing specification sheets and corollary documentation provided by the system's engineer, the building architect and component suppliers along the supply chain. Any auxiliary material compositions unavailable from these sources were adapted from the latest Environmental Center of the Netherlands (ECN) Crystal Clear database and scaled to match each BIPV laminate's mass and volume characteristics. [5, 10, 11]

2.2 AP-105 Solar Cell:

The 1.988 WDC AstroPower AP-105 Cell was fabricated on a 127 mm x 127 mm quasi-square, 300 µm-thick monocrystalline reject wafer weighing 12.4 g. Being of waste-stream origin and assumed as being of no economic value, only processes and materials downstream from the acquisition of the reject wafer are included in our analysis of the system as-is. The primary production processes involved in the cell's creation, from acquisition of the reject wafer to the complete cell include: texturization, de-oxidation, N-doping, chemical attack, chemical vapor deposition (CVD) of the antireflection (AR) coating, contact metallization, RTC cooking and cell testing. [6, 10-12]

To generalize these LCA results to other BIPV facades, it was necessary to show the impact of the energy and material burden associated with refining silica to polysilicon, growth of the wafer and the subsequent processing steps. In a second scenario—which we will henceforth refer to as the 'realistic scenario,' we scaled all LCI data available from the ECN on mono-crystalline silicon wafer manufacture to simultaneously match the footprint of the AP-105 cell and reflect a wafer thickness of 180 µm. [10, 11] This wafer thickness was chosen as it represents the low bound of today's monocrystalline wafer thicknesses and thus is a good estimate for near-future BIPV systems. Additional LCI components added to the realistic scenario include the material and energetic balances associated with: the input solar-grade silicon, scraps washing, casting, ingot squaring and cutting, washing and wafer thickness testing. Increases in EPBT and GWP between the 'as-is' and 'realistic' scenarios stemming from the LCI additions are quantified in the discussion.

2.3 Balance of System (BoS) Components:

Balance of System components comprise every component essential to the structural, electrical, thermal or aesthetic integrity of the array excluding the solar laminates themselves but forming part of the overarching power-generating facility. For semantic simplicity, the BoS category is divided into two logical sub-categorizations: Façade BoS components and Electrical BoS components.

Only two components comprise the Façade BoS category and these are called out in the cross section of Fig 1: aluminum framing (known as mullions in the architect's jargon) which wraps along the exterior edges of the array and holds the laminates in place, and a layer of 5 cm- thick fiberglass insulation that directly abuts the back edge of the array. Any components to the exterior of the dotted line in Fig 1, aside from the solar laminates, are included in the LCI for the BoS.

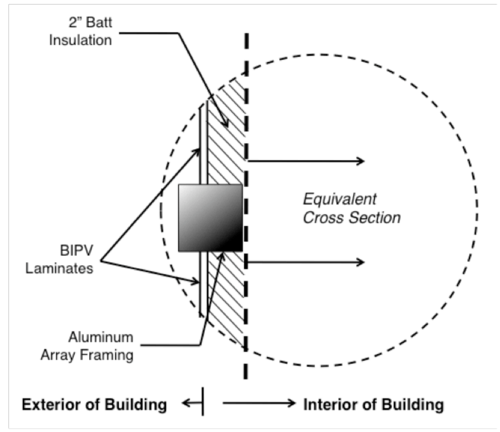

Fig 1. Cross-section through the BIPV curtain wall array

The Electrical BOS components comprise five primary elements: two types of steel Junction-boxes, four steel-enclosed AC and DC disconnect switches, four lightning arresters and four 2.5 kVA inverters from SMA. Ninety percent of the inverters' mass is iron, copper and aluminum while the remaining ten percent is comprised of minor plastic and printed circuit board and other elements. SMA, who graciously provided us with this material breakdown, also provided an estimate of the energy used to manufacture the unit as a whole—9.4 kWh—and thus a gross underestimation of the inverters' life cycle impact is unlikely. [5, 13] [14]

In addition, all conduit and cabling at the site is modeled – once again—from precise specification sheets provided from the architect and lead designer.

2.4 Alternative Cladding Systems:

The alternative cladding system, which the BIPV Curtainwall entirely replaces, blankets ~90% of the rest of the Solaire's façade apart from the window space. Two primary layers form this alternative cladding system, which is of a Concrete Masonry Unit (CMU) and brick construction: a 4" face brick and soldier brick external façade and a grouted 6" CMU-Block interior. The CMU blocks are reinforced with vertical steel rebar and the rows of soldier bricks with steel reinforcing dowels. Pre-cast concrete ledges connect the CMU inner wall to the face brick outer wall below the window openings. Cement mortar fills the gaps between bricks and blocks, while steel masonry ties attach the brick external façade to the CMU blocks. In addition, 16-gauge steel angles attach the outer brick façade to each concrete floor slab. [15]

From the façade's elevations and sections, the quantity of face bricks, soldier bricks, CMU block, concrete ledges, mortar, masonry ties, rebar and steel dowels per unit area of the façade was ascertained. [15]

Although the CMU system is the façade system which we can say that the Solaire BIPV actually replaced as a design choice, we have also modeled several typical 'alternative' facade systems to demonstrate their effect on environmental performance were *they* the systems being replaced: Aluminum Shadow Boxes, Steel Shadow Boxes, Aluminum Spandrel Panels, Natural Stone Panels, Opaque Spandrel Glass Panels. LCI for each of the above systems was calculated from widely available manufacturers' specification sheets or from the Solaire's architectural elevations.

3. METHODOLOGY

3.1 Life Cycle Assessment

Material inventories for the LCI were complied in the SimaPro (version 7.1) LCI and LCA tool by analyzing original structural and electrical construction diagrams and bill of materials lists using CAD software. Component and material specifications for the most common products used in the construction of the system were obtained from eight companies along the supply-chain as catalogued in bill-of-materials lists. [5-7, 9, 12-18]

Most important in calculating the system's life-cycle impact is the physical boundary drawn around the façade's cross-section. Establishing a logical line of demarcation is critical since we compare the BIPV array to what it replaces as a design choice. Using the structural cross-sections and elevations of both the BIPV and alternative cladding system schemas, we define a 'line of equivalency' (LoE) through both cross sections beyond which both systems are thermally identical as one penetrates further into the building. These LoE is denoted by the dotted line in figure 2. External to the LoE, we compile our LCI material balances for both the alternative façade system and the BIPV system.

Simapro is used to operate the 2007 IPCC GWP 100a model and calculate ingrained GWP (g CO_2-eq) impacts for the BIPV array 'as is' using reject wafers, in our 'realistic scenario' including wafer processing, and for each alternative cladding system. [19, 20] The values we report for the system's GWP account for the replacement of each alternative cladding systems by subtracting their impact and reflect global warming potential over a timeframe of 100 years per unit of electrical energy produced. We also note that in the LCA calculations, the inverters are counted twice to account for their replacement after 15 years (representing the standard industrial warranty for grid-tied PV inverters.)

Statistics for g CO_2-eq/kWh are generated from linearly forecasted AC-side power production for a cumulative 30-year lifetime. These GWP values per unit energy were then compared to GWP figures for other generation sources and other PV array archetypes in the literature. [10, 11, 21-23]

Net ingrained energy for the BIPV array 'as-is' and in the 'realistic' assessment was calculated using SimaPro and the Cumulative Energy Demand (CED) 1.05 metric, which converts the material balance of the systems and processes to ingrained primary energy. [24-26] Energy Payback Times for the array were then calculated from actual system performance recorded in-situ assuming a lifetime of 30 years. The EPBTs for both the array 'as-is' and in the 'realistic scenario' were then compared to reported EPBTs for other renewable technologies and other PV-arrays. [10, 11, 21-23]

3.1 Power Production, Radiation Modeling, and Performance Assessment

All historical production data from the system's inception in June 2004 through the end of July 2009 was collected on-site from an SMA SBC+ monitoring unit in 15-minute intervals and analyzed to extract performance statistics for the entire array. [5]

To model radiation on the tilted plane of the Solaire Array, we obtained site specific, hourly DNI and G_h radiation data from Clean Power Research's (CPR) Solar Anywhere® service. Solar Anywhere® data, consist of satellite-derived hourly DNI and G_h, for Manhattan that is temporally synchronized to the BIPV's power production. [27, 28]

The Perez et al. anisotropic radiation model and revised optical air mass tables on the basis of the ISO Standard Atmosphere (1972) were used for these calculations. [27-30]

The most important estimation for calculation of radiation incident on the array surface—aside from orientation—is that of the solar resource lost due to shading from surrounding obstructions. For the Solaire BIPV array, a 3-D mock-up of the building was created in Google Sketchup™; oriented and run through a proprietary global irradiance model using CPR data to estimate annual global losses of radiation due to ambient shading.

We used our modeled radiation data to calculate annual performance ratios (PRs), assessed by the method outlined by the International Energy Agency's (IEA's) PVPS Task 2. The average PR for the Solaire BIPV across all years of recorded data was then compared with the PRs of the 26 'façade' or 'façade-integrated' arrays in the IEA PVPS Task-2 database. [31-33]

4. RESULTS

4.1 Performance Assessment Results

Using the CPR dataset we calculated that the Solaire BIPV system on average receives 766 kWh/m^2/yr of radiation: a value that includes tilt, azimuth and shading losses. Were there no shading losses on the array surface, the incident radiation would be 822 kWh/ m^2/yr. Based on the same dataset, for the same location, the annual irradiation on a horizontal plane is 1430 kWh/m^2/yr, and on a south-facing latitude-tilt plane is 1615 kWh/m^2/yr. [21-23]

The array's average monthly production is shown to be at its peak in May, correlating strongly with the CPR-derived incident radiation statistics. Annual energy production from the 11.3 kW system over the four complete years of data averaged 5689 kWh/year.

Performance ratios calculated over the system's recorded lifetime demonstrate a slight decrease since the system's inception—confirming the effect of slight environmental degradation. PRs over the years of operation where complete datasets were available (2005-2008) come to an average of 64.4%.

This PR calculated for the Solaire falls directly on the median and within half a standard deviation of the mean of all BIPV Performance Ratios reported in the IEA PVPS Task 2 database. By examining the PRs in this context, the Solaire's PR can be said to fall within an expected range for façade PV systems. When calculating life cycle impacts as a function of incident radiation, the PR is held fixed at this value calculated for the Solaire. [31-33]

4.2 Results: Life Cycle Assessment

Fig. 2 demonstrates the EPBT in years for the Solaire array 'as-is' and the EPBT in the 'realistic scenario' that includes wafer processing. The effect of crediting for replaced materials—in this case for the CMU/brick wall—is readily apparent. Since the array was fully integrated into the façade from the building's inception, the two systems share the same thermal cross-section inside the LoE, and the alternative cladding system covers nearly all of the remainder of the façade, we consider that crediting the impact of the CMU system in this manner is a valid assumption. The measured EPBT for the Solaire array 'as is' is 0.81 years; while in the 'realistic' scenario the EPBT increases to 3.81 years. These correspond, respectively, to an Energy Return on Investment (EROI) of 34.6 and 7.2 assuming a 30-year system lifetime. EROI is used here to reflect the net energy generated by the system throughout its lifetime divided by its net embodied energy—referred to as a second-order EROI in the framework proposed by Mulder and Hagens.[34] Since the wafer processing steps included in the realistic scenario are tied to the wafers' thicknesses, it follows that as thicknesses continue to drop, so will the EPBT. [35]

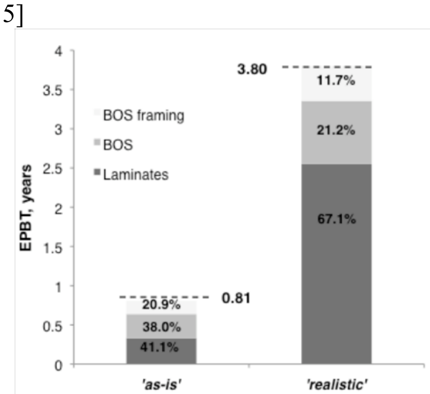

Fig. 2. EPBT Sensitivity analysis and Sub-component Contribution

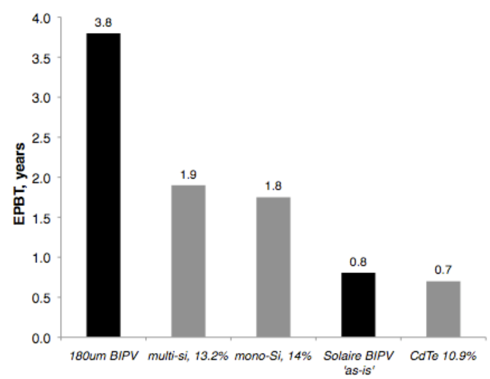

Fig 3. EPBT of the Solaire BIPV array compared to other renewable generation sources.

We contrast the Solaire's two calculated EPBTs to recent estimates of EPBTs of other renewable energy systems in Fig 3. [10, 11, 21-23] Interestingly, the system 'as-is', even with annual incident radiation at 765.76 kWh/m^2/yr and its PR of 64.4%, has a lower EPBT than most of the other systems (all of which assume an irradiance of 1700 kWh/m^2/yr and a PR of 80%). The reason for this dissimilarity is the energy credited back from the avoided CMU/brick façade system, a critical assumption. Even in the 'realistic' scenario, which includes wafer processing, the EPBT is within the same order-of-magnitude as the other PV systems shown. A starker contrast is highlighted in comparing the 'realistic scenario' EPBT to a traditional wall cladding system, which, aside from thermal considerations which are assumed to be equivalent, has an infinite EPBT. It is this contrast that defines BIPV as an excellent choice for wall cladding—both on environmental and energetic basis—especially if the decision is made early on in the stages of designing the building; where it can be considered as an option to entirely replace a wall that does not share the same multi-functionality.

Interesting results stem from applying the IPCC 100a GWP impact metric to the LCI. In the ‘realistic’ scenario, the system has an ingrained CO_2 burden of 9,329 kg CO_2-eq, while in the ‘as-is’ scenario, the CO_2 burden drops to -1,578 kg CO_2-eq. With this minimal a burden—negative as a result of the credited alternative CMU façade system—the Solaire ‘as-is’ has a GWP of -10.2 g CO_2-eq/kWh when assuming a 30-year system lifetime. As demonstrated in Fig 4, this impact is smaller than all other generation technologies in comparison. In the ‘realistic’ scenario, with its wafer-processing steps included, the GWP is 60.5 g CO_2-eq/kWh. This GWP, though larger than that of other PV systems, still falls within the same order-of-magnitude—a feat considering its relatively lower incident radiation.

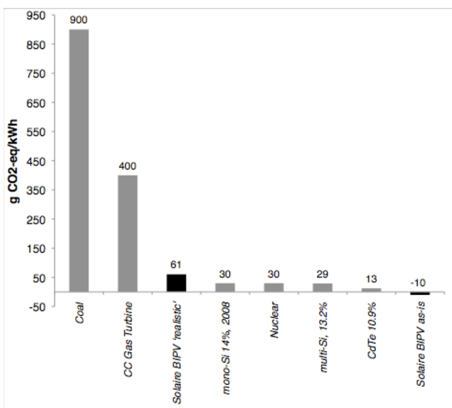

Fig 4. GWP of the Solaire BIPV array in comparison to other energy generation schemas

5.0 DISCUSSION:

We provide herein a thorough LCI for environmental impact-analyses of façade-integrated BIPV systems based on detailed bills of material and construction data directly from the designers, architects, and manufacturers in the supply chain of the Solaire’s BIPV array in New York City. Our primary findings indicate that when completely replacing an alternative cladding system a facade BIPV system has a competitive EPBT (3.8 years in the realistic scenario based on current Si production methods). This is interesting, given the Solaire’s less-than-optimal vertical/due-west orientation and average PR of only 64.4%. Consequently this PR falls within the expected range for façade systems as measured by examining PRs for façade systems in the IEA PVPS Task-2 database.

The PR is a measure of all losses the system experiences after radiation hits the surface—from DC/AC conversion efficiency, soiling, snow, system down-time, component failures, incomplete absorption, temperature, mismatch from partial shading, and wiring. As our array did not have any downtime, component failures, snow- or soiling-cover over the test period, the losses reflected in the PR likely derive from inverter inefficiency, mismatch, temperature and wiring. Temperature has a significant effect on the performance of crystalline silicon PV systems and the fact that the Solaire BIPV array abuts directly to a layer of insulation likely leads to higher back of module temperatures than more traditional system architectures and lower performance.

In comparison to other PV EPBT in the literature, the 3.8 years calculated in our realistic scenario is clearly longer, yet superior to the EPBT of the thermally-equivalent alternative façade system it replaces—which without generating any energy never pays back its embodied energy burden. This feat underlines BIPV’s greatest attribute—because these systems fully replace materials as a design and structural choice, the marginal material cost is much lower than if PV is added as a retrofit in a typical system. Thereby, a BIPV system’s environmental impact can be comparable to a ‘standard’ roof or ground mounted PV system even though its incident radiation is much lower and it may suffer greater performance losses from thermal effects.

A critical assumption is the expected lifetime of the system, which following IEA guidelines PV LCA is assumed to be 30 years. This lifetime assumption greatly affects the environmental performance of PV systems from a lifecycle perspective: assuming a lifetime of 40 years lowers the GWP GHG emissions by nearly 23% while the EROI increases by 29%, with capacity degradation included. The fully integrated BIPV laminates at the Solaire will likely remain in place for at least this amount of time, until the curtain-wall gets replaced. Barring an unforeseen extreme event, the only elements likely needing replacement before the laminates are the electrical BoS components—inverter, fuses, and cabling. A Longitudinal study of fully-integrated BIPV is recommended to define primary failure modes.

Under the ‘realistic’ scenario, we demonstrate that wafer processing comprises a very significant portion of the life-cycle impact metrics; since the environmental impacts are tied to the wafer’s mass, thinner wafers will lead to incrementally lower impacts in the future. The differences between EPBT, EROI, and GWP for the system "as is" and in our "realistic" scenario demonstrate the starting and present-day points of a trend that correlates not only with thinner wafers, but increased recycling of solar cells at the end of their operable lifetimes. Hence, it is expected that future façade-integrated BIPV systems, will follow a trend of diminishing environmental footprints as their embodied energy and CO_2 approach the embodied energy and CO_2 of the façade systems they replace.

Finally, and perhaps most interestingly, we use our modeled LCI and performance data for the Solaire to generate curves showing the environmental performance metrics (GWP, EPBT, EROI) as a function of incident radiation (kWh/m^2/yr) on a BIPV façade for each of the different alternative façade systems modeled. (Figs 5 – 7) The top most curve on the EPBT and GWP plots demonstrate the environmental metrics of a façade BIPV system if a material credit is not given—as in a retrofit. It is through these relationships where the effect of replacement materials is most apparent, and where BIPV differentiates itself from other PV system archetypes. The more energy and CO_2 intensive the material being replaced, the better the environmental performance metrics.

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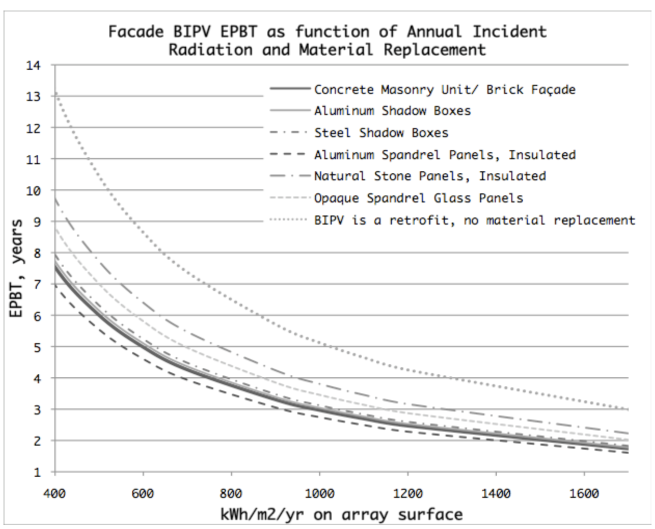

Fig 5. Facade Energy Payback Time as a Function of Annual Incident Radiation and replaced alternative cladding system

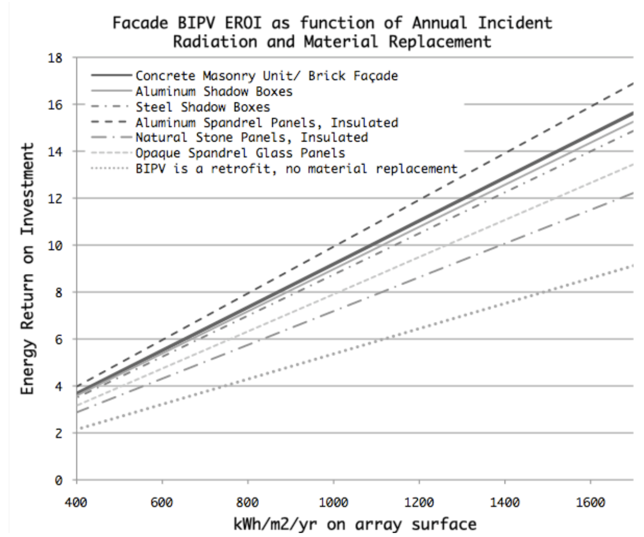

Fig 6. Facade Energy Return on Investment as a Function of Annual Incident Radiation and Material Replacement

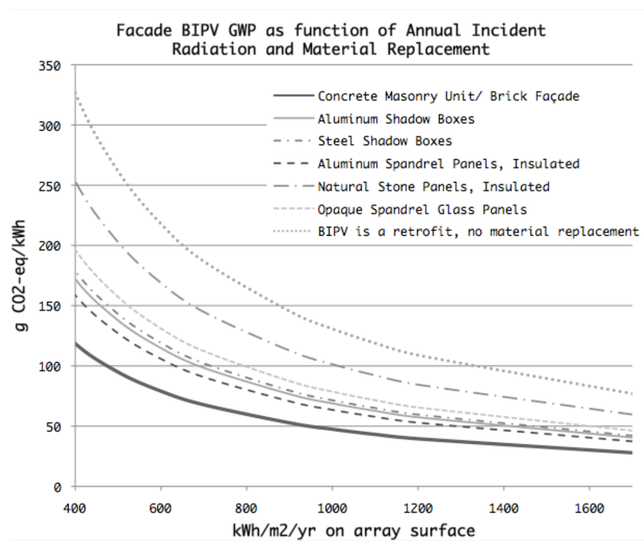

Fig 7. Facade Global Warming Potential as Function of Annual Incident Radiation and Replaced 'Alternative Cladding System'