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Net energy and cost benefit of transparent organic solar cells in building-integrated applications

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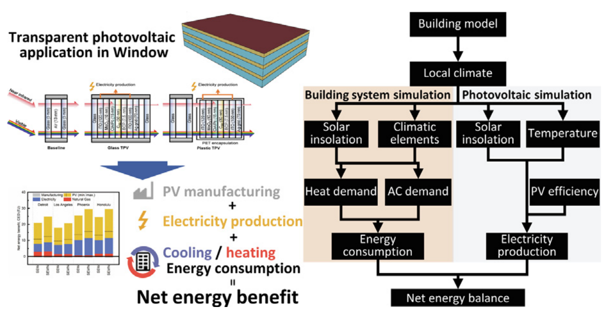
HIGHLIGHTS

- Evaluate organic transparent photovoltaics (TPV) for buildings in the US.
- Transparent photovoltaics produce electricity and reduce energy consumption.
- Life cycle assessment is used to calculate the net energy benefit.
- The energy payback time varies from 51 days to 1.1 years depending on the location.

GRAPHICAL ABSTRACT



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ABSTRACT

Transparent photovoltaics is a new technology that can be used in buildings applications to simultaneously save energy and produce electricity. This study evaluates the potential of transparent photovoltaic (TPV) in window and skylight applications for four cities in the United States: Detroit, Los Angeles, Phoenix and Honolulu. Building energy demand simulation, photovoltaic generation, and life cycle assessment (LCA) are combined to evaluate the net energy benefit (NEB). The use of TPV on windows is evaluated for both new windows, for which the solar cell is deposited in the interior surface of the glass pane, and for the refurbishment of existing windows, for which plastic encapsulated solar cells are placed on the interior surface of existing windows. The NEB was found to be positive for all scenarios considered, and the cradle to gate energy to manufacture a transparent organic photovoltaic module was found to be negligible. The NEB was used to calculate the energy return on investment (EROI) and the energy payback time (EPBT). Both were found to be either better or comparable to other photovoltaic technologies. For glass modules, the best EROI was 102 in Phoenix for window and 208 in Honolulu for skylights. The EPBT varied from 51 days to 1.1 years, depending on the location and type of module. The use of transparent photovoltaics in the US was found to have both environmental and cost benefits due to the combined reduction in building energy consumption and electricity production.

1. Introduction

In the United States, the residential and commercial building sectors account for 39% of the total U.S. energy consumption [1]. Since fossil fuels are used to produce around 50% of electricity production [2], buildings are responsible for a considerable amount of greenhouse gas emissions. One solution to reduce the energy consumption from the electricity grid is to use building-integrated photovoltaics (BIPV) that

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provide electricity during the day when demand is at its peak. Roof-mounted BIPV accounts for 80% of the market and includes shingles, slates, tiles, or cladding.

Organic semiconductors can be synthesized to selectively harvest a particular range of the solar spectrum, therefore allowing the fabrication of colored or transparent solar modules. Organic photovoltaics (OPV) are made by combining a donor and an acceptor material. The donor material can either be a polymer deposited using solution processing or small molecules deposited using evaporation. Common acceptor materials are fullerenes or fullerenes derivates such as C_{60}, C_{70}, and C_{60}-PCBM. Transparent solar modules can be added to the window area and increase the total available surface to produce electricity [3]. Previous work by our group has shown the potential for highly transparent photovoltaics (PV) for window applications due to their high average visible transmission [4].

Transparent photovoltaics (TPV) produce electricity by converting the near-infrared portion of the spectrum into electricity. Converting near-infrared, or heat into electricity, also changes the energy demand of the building. In the US, electricity consumption is higher during the summer due to cooling and ventilation, while natural gas is mostly used during the winter for heating [5]. During warmer months, the TPV reduces the amount of heat that reaches the inside of the building, therefore reducing the cooling energy demand. For colder months, the benefits of TPV could vary. TPV can help conserve the heat inside the building by reflecting the indoor radiant heat. However, since it also reduces the solar heat from the exterior, depending on the location and building design, it could either reduce or increase the heating demand. However, well-designed TPV is likely to reduce both the electricity and natural gas consumption since they have similar spectral properties as low emissivity coating technologies, which are deposited on the window to preserve heat loss [6]. The combined benefit of electricity production and change in energy demand for a building with TPV has not been evaluated.

Transparent photovoltaic modules are not possible with traditional semiconductor materials, but semi-transparent modules are. The energy saving and electricity production were evaluated for amorphous silicon [7], and organic [8] semi-transparent modules. Their use was found to reduce the cooling energy demand in warm climate but increase the heating demand in cold climate. However, for all studies except the organic solar module, the window properties in the building energy simulation were based on the UV–vis spectrometer measurement, which is incorrect since the energy absorbed for a PV module is transformed into electricity, not heat. Therefore, the spectrum needs to be corrected to account for this difference. The spectrum was corrected in one organic semi-transparent organic PV study [8]. However, the visible transmittance was only 23%, which is much lower than the 70% achieved for the technology considered in this work. Since the authors did not provide details about the solar cell material, device structure, and optical properties, it is impossible to compare the performance of semi-transparent photovoltaics with TPV.

The conventional approach to evaluate the benefit of PV in a building is to use building simulation such as EnergyPlus [9]. Only one study has used outdoor testing facility to validate the energy saving potential of semi-transparent silicon modules [10]. Previous studies have focussed on energy balance over one year, assuming that all properties would remain the same. The degradation of the PV module, the electricity production from the grid, and the price of electricity and natural gas over time were not considered. Most importantly, all previous studies focussed on semi-transparent rather than transparent technologies. This work is the first to estimate the potential energy saving and electricity production associated with the use of highly transparent photovoltaics that can be employed for window applications.

Lifecycle assessment (LCA) can be used to evaluate the benefit of PV and TPV over its full lifetime and is used extensively to compare the environmental impact of photovoltaic technologies using the IEA LCA guidelines for PV [11]. We compiled a comprehensive literature review of OPV LCA studies that have been published since 2009 to ensure the novelty of this work, and the results are available in the supplementary material (SM) in Table S1. Out of the 27 papers published since 2009, only one considers small molecules donor materials [12], which is the type of material required for transparent photovoltaics. In addition to the limited number of materials that have been considered, 25 focus on power generation, and the studies that include building applications are for façade integration [13] and window retrofit [14]. The window retrofit study is the same application as this work, but it is a company presentation with limited details on the modelling and assumptions, and the results have not been published in the scientific literature. The only LCA study of PV for window application we could find looks at adaptive shading made of CIGS module, which also reduces the cooling and heating energy demand [15]. The system was significantly different since it was made of multiple solar photovoltaic modules attached to a support structure placed on top of a window. Therefore, this work is the first life cycle assessment of transparent for OPV.

In LCA, the functional unit refers to the unit of comparison where products perform similarly. Using the power generation from ground-mounted or rooftop application in LCA simplifies the analysis but also makes it possible to compare OPV with other types of photovoltaics that use Watt peak (Wp) as a functional unit. For new applications where OPVs provide additional synergistic functions beyond just electricity production, there is a need to redefine an adequate functional unit and a method to assess the potential of OPV beyond the traditional cost, efficiency, and lifetime approach. In this work, we demonstrate that the use of the net energy and net cost saving method enables us to account for the solar heat management as well as the electricity production of TPV. The net environmental benefit approach is popular in environmental engineering since it considers the no-action scenario as the baseline process [16,17]. In this work, we used the term net energy benefits rather than net environmental benefits since we limited the analysis to energy. For buildings, the no-action scenario corresponds to the energy consumption for a building. The net energy considers the energy invested in manufacturing the solar cell, the electricity production, and the change in energy consumption compared to the baseline building. The same approach can be used to quantify the net cost-benefit or the cost-saving of the technology. A lifecycle approach was used to evaluate the net benefit of transparent photovoltaics in window and skylight applications for various locations in the United States for either new or retrofit applications.

2. Methodology

The overall approach to calculate the net energy balance, including the various modelling tools used for building energy consumption and electricity production, is summarized in Fig. 1(a). The system boundary for the cradle to gate LCA of organic TPV is shown in Fig. 1(b). A clear double pane window was used for the baseline scenario for both the window and the skylight structure. The double pane window was assumed to have a 13 mm air gap between two sheets of 3 mm clear glass. Two types of organic TPV modules for window were considered and are shown in Fig. 1(c). In the first instance, the TPV material is evaporated on the interior surface of a new window glass pane (Glass-TPV). The second scenario is for retrofit of existing windows. The TPV module is encapsulated and attached using adhesive on the interior surface of an existing window (Plastic-TPV).

The lifetime of the window and skylight was fixed at 20 years [18], and the Plastic-TPV was assumed to be replaced every 10 years. Two levels of technological maturity were considered. The best-case scenario corresponds to device expected performance in the near future with power conversion efficiency (PCE) of 10% and 25 years lifetime (T_{50}) [4,19,20]. The current case scenario corresponds to demonstrated lab-scale technology [21] with a PCE of 3% and a 7 year lifetime. The two limiting scenarios were used to evaluate the actual benefit of increasing

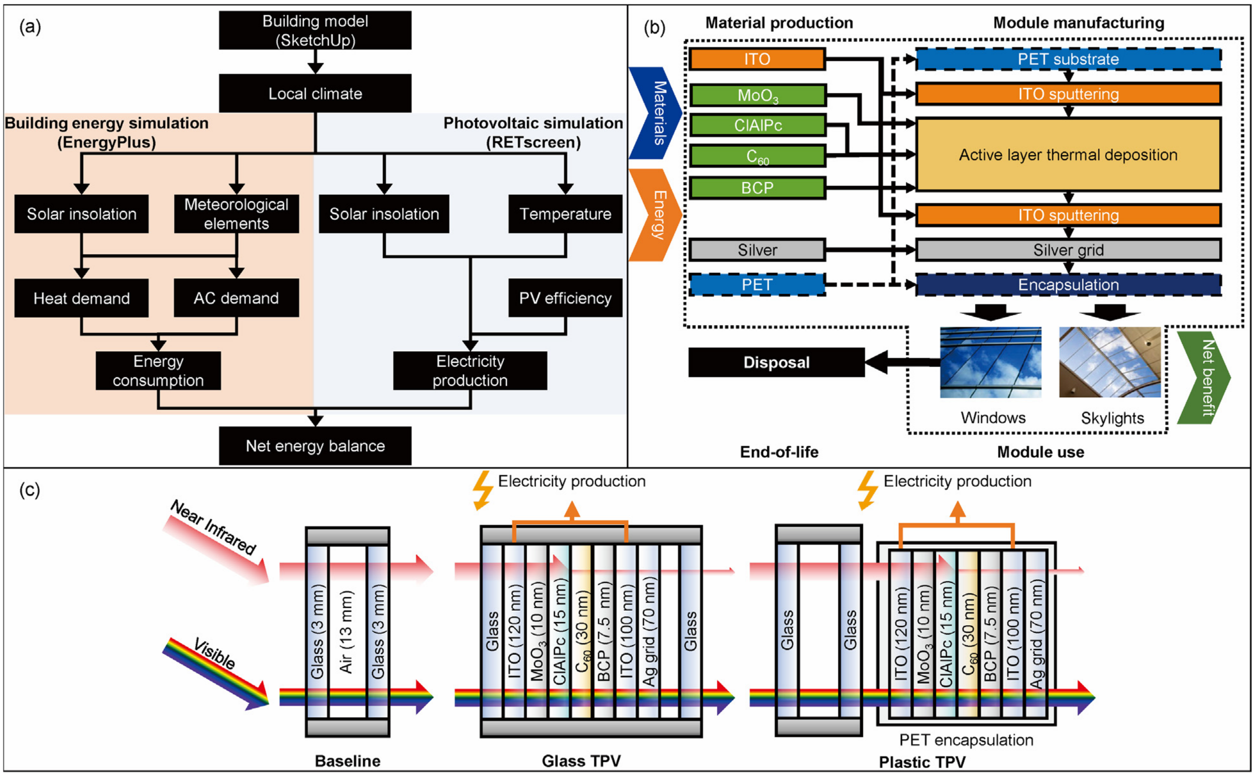


Fig. 1. (a) Overview of the modelling approach that combines the building and photovoltaic simulations to calculate the net energy balance, (b) LCA scope for transparent organic photovoltaic and (c) window architecture for the baseline double pane window and transparent photovoltaic either incorporated in the window structure (Glass-TPV) or externally using encapsulated TPV (Plastic-TPV).

efficiency and lifetime for transparent photovoltaics in building applications. The TPV materials, manufacturing process, and structure are illustrated in Fig. 1(b). The photovoltaic cell is made by successive deposition of chloroalumnium phthalocyanine (ClAlPc), a small molecule donor material, and C_{60} in between molybdenum oxide (MoO3) and bathocuproine (BCP) blocking layers. Indium tin oxide (ITO) is a transparent conductive oxide which is used on both sides of the device and silver grid is deposited for contact. We note that TPV with PCE > 10% has been certified at the laboratory scale, and pilot-scale modules are being produced with PCE around 3% [22].

The maximum window size was limited to 2.1 m by 3.7 m based on the largest existing tempering oven in the US, which is required for the heat treatment of glass to be resistant to impact, wind load, and thermal stress breakage [23]. The silver grid and the outer busbars required for individual glass panels covered 11% of the area [24]. For Plastic-TPV, the active photovoltaic area was smaller due to the encapsulation, which requires a 5 cm wide edge around the perimeter [25].

We selected Detroit, MI, Los Angeles, CA, Phoenix, AZ, and Honolulu, HI since they have a diverse range of solar insolation conditions, climate zones, energy cost and energy impact of electricity production that influence the benefit of both solar photovoltaic energy production and building energy balance. Fig. 2 illustrates the various grid regions in the US-based on the Emissions & Generation Resource Integrated Database (eGrid) sub-regions [26], climate zones, average annual solar insolation, and commercial energy prices. The climate zones were divided into subregions moist (A), dry (B), and marine (C) depending on the mean temperature and precipitation [27]. Table 1 provides details about the electricity regions, climate zones, average insolation, and energy prices for electricity and natural gas for each location.

2.1. Electricity and building model

The photovoltaic electricity production was calculated using RETScreen 4 on a daily basis [31], and the building energy demand was simulated using EnergyPlus 8.7 on an hourly basis [9]. RETScreen is a Clean Energy Management Software for renewable energy and project feasibility analysis from the Government of Canada. The solar insolation and climatic database was developed by NASA and RETScreen and provide global data based from 6700 ground-based stations and NASA's satellite data [32]. The net energy balance was calculated for the 20 years and included a reduction in electricity production over time due to solar module degradation. The degradation was assumed to be linear from to original efficiency value and degrade to half of its original value over a given time corresponding to the T_{50} value. For example, for the future technology, where to $\eta = 10\%$ and $T_{50} = 25$ yrs, the efficiency after 25 years would be 5%. We selected commercial buildings since they have large window areas that maximize the TPV module size. Also, commercial buildings have high occupancy and high energy demand during the day when electricity production and change in building energy demand occur for TPV.

The building energy demand simulation used the default values for the building internal loading [33] of the post-1980 construction DOE reference building [34]. The building geometry was modified using SkechUp Pro 2017 to increase the window to wall ratio or skylight to roof ratio (see Table 2). The thermal characteristics of the building envelop are available in Table S2. The medium office building model was used for the window application and the small office building for the skylight application. The reference for the mid-size office building was modified to increase the window to wall ratio from 33.0 to 67.8%. The small-size office for skylight application was also modified to incorporate a skylight onto the south roof, as shown in Table 2. All buildings were assumed to have a south azimuth orientation. The electricity production from TPV installation on the south, east, and east

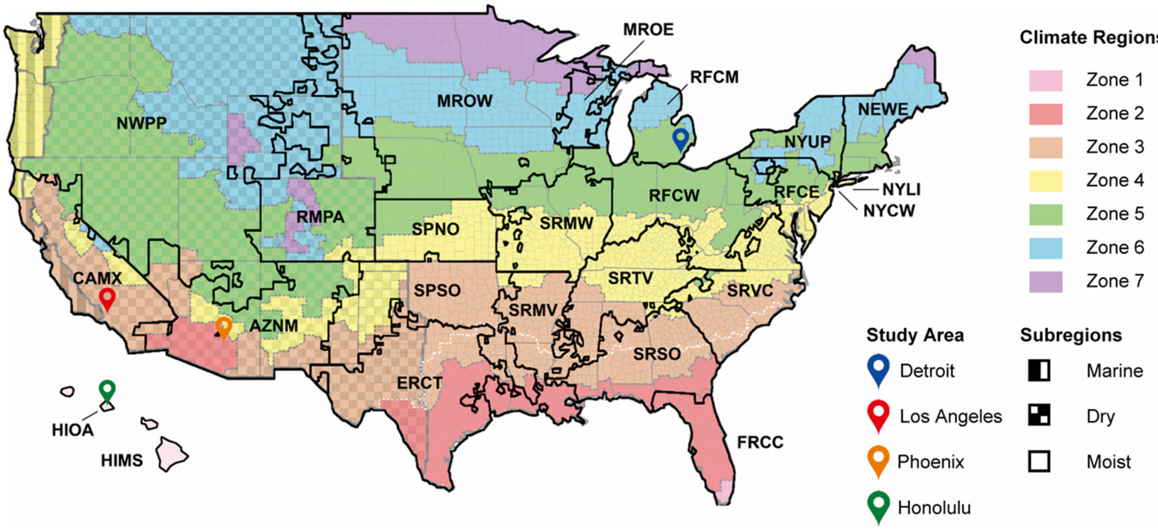


Fig. 2. Summary of the climate zones, electricity grid regions and locations considered in this study.

(SEW) sides of the building was compared to having modules on all sides, including the north side (SEWN). For the skylight, the tilt angle was fixed by the roof angle to 21°, and the azimuth was south. The default value for heating source in the reference DOE building was modified for each location based on the Commercial Buildings Energy Consumption Survey (CBECS) [5] and is summarized in Table S3 for all cities. The climate data and the building operation schedule were imported from the EnergyPlus database [35].

For the building energy simulation, the optical properties of the TPV module are required to calculate the solar heat gain of the building through the window. The UV–Vis absorption was measured from the front and back side using a Perkin Elmer Lambda 900 UV–Vis spectrometer. The resulting spectra are shown in Fig. 3(a) and (b)). Fig. 3 highlights the ultraviolet (< 435 nm), visible, and near-infrared (> 670 nm) regions of the solar spectrum compared to the organic TPV. Fig. 3(c) illustrates the solar spectrum reflectance, transmittance, and conversion, as well as the back reflectance from the radiant heat. The front and back side spectra (Fig. 3(a) and (b)) are not the same, and in particular, the absorbance is more important on the back side, which contributes to heat conservation. EnergyPlus does not account for electricity production from the TPV, and therefore the near-infrared radiations are considered absorbed by the building rather than converted to electricity, which causes an overestimation of the solar heat gain and cooling energy demand. The UV–Vis spectrum can be adjusted to consider the portion of the spectrum that is converted to electricity, as reflected rather than absorbed by the building [8]. The spectrum of converted electricity corresponds to the external quantum efficiency (EQE) spectra.

Fig. 3(a) shows the front illumination original spectra front transmittance (T_f), reflectance (R_f), and absorbance (A_f) of the ClAlPc:C_{60} TPV. The corrected absorption A_f* was calculated using Eq. (1) and the EQE of the TPV (Fig. 3(d)). Since the sum of the transmittance, absorbance, and reflectance is 1, and the transmittance remains constant, the corrected reflectance R_f* can be calculated using Eq. (2). The spectra correction was only applied for the front illumination spectra since the electricity production from indoor illumination was not considered in this work. The spectrum correction was performed on the current ClAlPc:C_{60} technology and therefore a more significant reduction in heat absorption can be expected for future technologies due to a higher external quantum efficiency in the same region of the spectrum. However, the EQE of future technology was not estimated. This is because the EQE, which corresponds to the amount of light that is absorbed and efficiently converted to electricity, is difficult to predict since it is a combination of materials, device structure and fabrication.

$$A_f * (\lambda) = Af(\lambda) - EQE(\lambda) \quad (1)$$

$$R_f * (\lambda) = 1 - Tf(\lambda) - A_f * (\lambda) \quad (2)$$

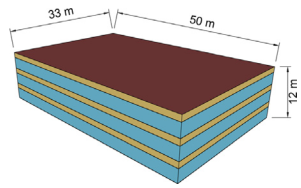
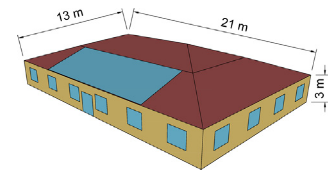
2.2. Life cycle assessment

The overall scope of the LCA is illustrated in Fig. 2(a) and excluded the end-of-life stage due to the lack of knowledge about potential end-of-life management options. The functional unit was the operation of one building for 20 years. The life cycle inventory used previously published data for material production, module fabrication [12,36], and direct measurement during device fabrication in the lab. TPVs were fabricated using previously reported device structure [37]. For large-scale applications, devices require busbar and silver grid, which cover approximately 11% of the total area [24]. Material consumption was calculated based on the measured material thickness and material density from the literature using a 30% material deposition efficiency [12]. The direct energy consumption during device fabrication was recorded using a Fluke 345 clamp meter. Module manufacturing was assumed to take place in the US. The impact categorie was cumulative

Table 1
Summary of electricity grid regions, climate zones, average insolation and energy prices for each location.

		Detroit, MI	Los Angeles, CA	Phoenix, AZ	Honolulu, HI
Latitude		42.33	33.90	33.44	21.31
Grid	eGrid region [26]	RFCM	CAMX	AZNM	HIOA
Climate zone	IECC 2015 [28]	5A	3C	2B	1A
Solar photovoltaics potential	Annual average insolation for south azimuth module at a tilt angle of 0°/90° (kWh/m^2/day)	3.8/2.9	4.9/3.5	5.7/4.0	5.4/2.9
Energy prices	Natural Gas ($/Thousand Cubic Feet) [29]	6.97	8.89	8.77	29.62
	Electricity (¢/kWh) [30]	10.64	10.41	15.07	24.64

Table 2
Building geometry and properties for photovoltaics electricity production and building energy demand.

	Medium office		Small office	
Building geometry				
PV application	Window		Skylight	
HVAC System type [34]	Variable Air Volume (VAV) with re-heat terminal		Packaged single-zone (PSZ)	
Heat/cooling coils [34]	Direct expansion cooling coil, gas heating coil and electric heating coil (Terminals)		Direct expansion cooling coil Gas heating coil	
Window to wall ratio or skylight to roof ratio (%)	67.8		14.9	
Window area (m^2)	938.2 (SEW)/1340.3 (SEWN)		81.0 (S)	
PV area (m^2)	Glass	Plastic	Glass	Plastic
	SEW: 835.1 SEWN: 1193.0 Sub-area S and N: 357.9 E and W: 238.6	SEW: 799.0 SEWN: 1141.4 Sub-area S and N: 342.4 E and W: 228.3	72.1 (S)	68.9 (S)

energy demand (CED) based on the Cumulative Energy Demand Method v1.09 in SimaPro8 [38]. The LCA included the change in electricity generation over time for each region. The carbon footprint for the electricity grid over time was calculated using the TRACI 2.1 method [39]. Additional information on the lifecycle inventory input for the OPV manufacturing and the energy production is available in Tables S12 to S13 of the SI.

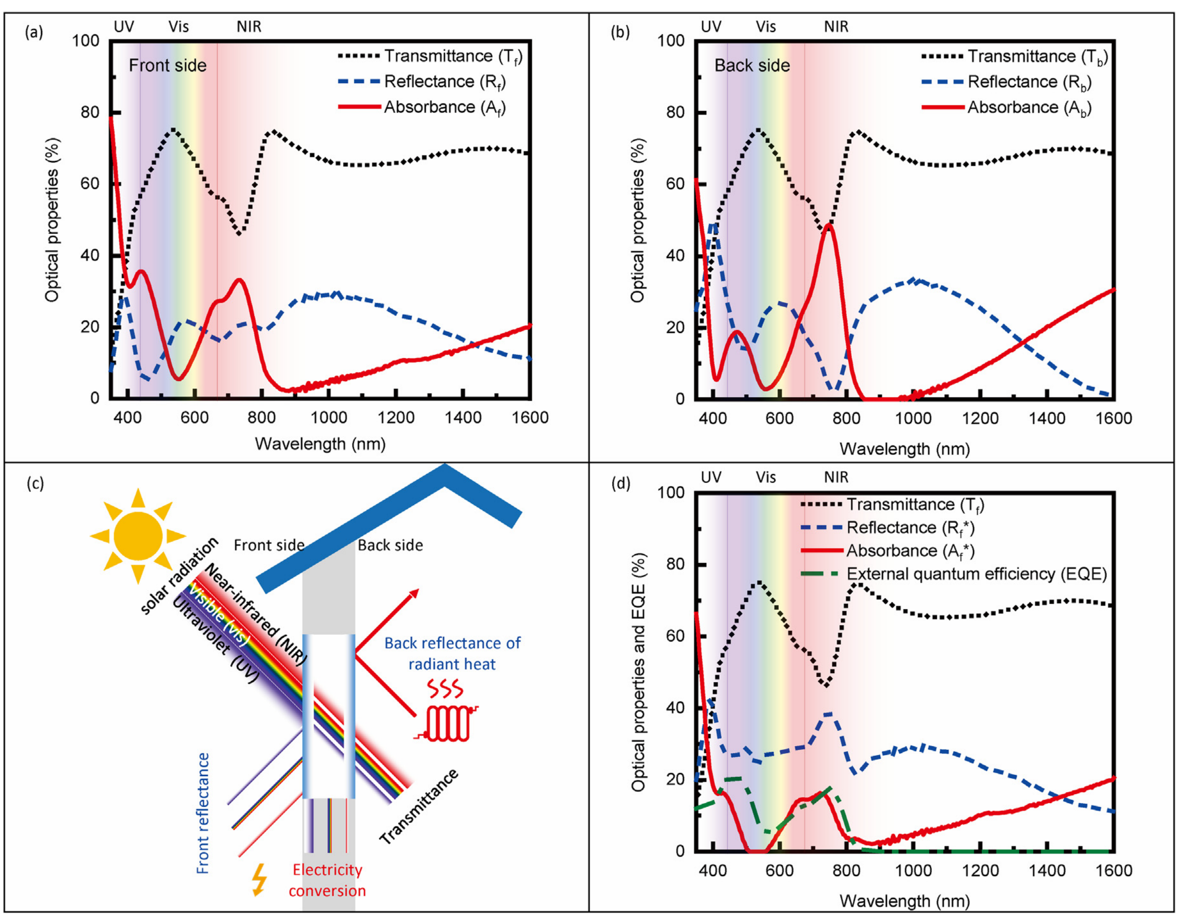


Fig. 3. Transparent photovoltaic UV–vis spectra for (a) front illumination and (b) back illumination. (c) The proportion of the solar radiation in range of ultraviolet, visible, and near-infrared for reflectance, transmittance, and electricity conversion and, (d) corrected front illumination absorbance and reflectance spectra used in the EnergyPlus simulation to account for the electricity generation.

2.3. Performance metrics

The net energy benefit (NEB) is the difference in energy balance between the building with and without TPV. It is calculated using Eq. (1). It includes the impact of electricity generation from the TPV (PV_{gen}), the cradle to gate life-cycle manufacturing of TPV (PV_{CED}), as well as the change in electricity or natural gas consumption from the building. Our NEB analysis was limited to cumulative energy demand (CED). This is because the greenhouse gas impact associated with TPV manufacturing cannot be adequately estimated when using of fullerene as the acceptor material and other fine chemicals with missing inventory information [36].

To convert the direct energy to primary energy, we used the conversion efficiency value for either natural gas (η_{NG}) or electricity (η_{Grid}). The average US grid efficiency was used for the life-cycle manufacturing of TPV while the regional data was employed for the energy building. The grid efficiency at each location changed over time ($\eta_{Grid\ X}$) due to the changing energy source in the US electricity grid (Table S14 and Fig. S3). The NEB was calculated using the annual PV generation (E_{aPVgen}), avoided electricity consumption (ΔE_{aElec}), and natural gas (ΔE_{aNG}) to account for degradation and changing grid efficiency over the 20 year lifetime of the study.

$$\mathrm{NEB(CED)} = -PV_{CED} + \sum \frac{E_{aPVgen}}{\eta_{\mathrm{GridX}}} \pm \sum \frac{\Delta E_{aElec}}{\eta_{\mathrm{GridX}}} \pm \sum \frac{\Delta E_{aNG}}{\eta_{NG}} \tag{3}$$

The most common metrics to compare energy technologies are the levelized cost of electricity (LCOE), the energy return on investment (EROI), and the energy payback time (EPBT). The LCOE takes into account the systems energy conversion efficiency, lifetime, and cost, including construction, operation, and maintenance over its lifetime to calculate an electricity price in ¢/kWh that is often used to evaluate grid parity for new renewable technologies [40]. The LCOE approach does not capture many of the advantages of organic photovoltaics such as flexibility, low weight, and selective spectrum absorption, which enables their adoption in new applications such as portable electronics, smart fabrics, and building-integrated photovoltaics (BIPV) [41–47]. Alternatives methods, such as the EROI or EPBT, use a life cycle assessment approach. The energy payback time (EPBT) corresponds to the amount of time the solar panel needs to produce electricity to payback for the energy required for its production. The EPBT calculation from the IEA guidelines for PV [48] assumes a constant grid efficiency and annual electricity production, which simplify the calculation to Eq. (4). However, this equation is inaccurate since it does not consider the change in building energy consumption, the decreasing electricity generation with degradation, and the electricity grid efficiency change over time.

$$EPBT\,(years) = \frac{PV_{CED}}{\frac{E_{aAveragePVgen}}{\eta_{\mathrm{GridAverage}}}} \tag{4}$$

For this project, the EPBT was calculated by considering the change in electricity ($\pm\ \Delta E_{aElec}$)and natural gas ($\pm\ \Delta E_{aNG}$), the TPV degradation impact on the annual electricity generation (E_{aPVgen})and the changing grid efficiency (η_{GridX}). The payback time was calculated using Eq. (5), where t corresponds to the payback time.

$$PV_{CED} = \sum_{1}^{t} \frac{E_{aPVgen}}{\eta_{\mathrm{GridX}}} \pm \sum_{1}^{t} \frac{\Delta E_{aElec}}{\eta_{\mathrm{GridX}}} \pm \sum_{1}^{t} \frac{\Delta E_{aNG}}{\eta_{NG}} \tag{5}$$

The methodology for EROI was recently reviewed by the IEA task 12 to provide guidelines specific to photovoltaic applications [49]. EROI is a standard method that provides information on the ratio of energy returned to society in the form of a useful energy carrier over the total energy required or "invested" in finding, extracting, processing, and delivering the energy [50,51]. Energy systems should have an EROI higher than one, implying that the energy delivered is higher than the amount of energy required to manufacture the system. Studies that use a life cycle approach to include all energy changes are referred as second-order EROI [52]. It is an accepted method by the IEA [49], and it was used to evaluate non transparent PV [7,53,54] for BIPV. However, it considered only electricity consumption change, not natural gas, which is commonly used in the United States for heating. Both EROI and EPBT methods are recommended by the IEA LCA methodology and are geographically dependent [11]. In theory the EPBT can be calculated directly using the EROI value by dividing the lifetime of the system by the EROI. However, using this calculation method overestimates the EPBT because the solar module electricity production decreases over time.

$$\mathrm{EROI} = \frac{\sum \frac{E_{aPVgen}}{\eta_{\mathrm{GridX}}} \pm \sum \frac{\Delta E_{aElec}}{\eta_{\mathrm{GridX}}} \pm \sum \frac{\Delta E_{NG}}{\eta_{NG}}}{PV_{CED}} \tag{6}$$

Because of the lack of information on the greenhouse gas generation during TPV manufacturing, the analysis considered the reduction in GHG due to photovoltaics generation (PV_{gen}) and the change in building energy demand ($\pm\ \Delta E_{aElectricity/NG}$). Similar to the NEB analysis, the analysis was performed on an annual basis to account for the degradation of TPV and changing carbon footprint of the grid. The annual increase in energy prices in the US for the next 20 years was calculated based on the EIA 2018 forecast [55] in 2017$ to account for inflation. It was calculated to be 0.22% per year for electricity and 1.01% per year for natural gas. The maximum module price was calculated based on the lifetime saving for each location and the net present value.

3. Results and discussion

3.1. Net energy balance

Fig. 4 combines the building energy demand and the electricity production from the TPV module with 10% power conversion efficiency for the four cities considered. For the window application, the two electricity generation curves correspond to whether all the windows are covered with TPV (SEWN) or only the south, east, and west-facing directions (SEW). The electricity production depends on the azimuth and tilt of the module. The tilt is fixed at 90° for TPV in windows, which is not the optimal angle for the PV module at any location. The south direction of the building has the largest solar insolation. However, the northern side can also produce electricity since the global horizontal irradiance (GHI) used in the electricity production from photovoltaics considers not only the direct solar radiations but also the reflected and diffuse insolation [56].

The PV production from the window application results in an almost constant electricity production throughout the year, in all cases except Detroit. Solar modules are generally installed at a tilt angle that corresponds to their latitude to maximize electricity production. The tilt angle from the skylight was 21°, which is similar to the Honolulu latitude. We assumed that the PV electricity production only reduced the consumption of electricity and not natural gas. Therefore, there is a relatively good match between electricity production from TPV and electricity demand for all cities.

3.2. LCA of organic TPV

The cumulative energy demand associated with the TPV manufacturing of a 1 m^2 module on glass or plastics is shown in Fig. 5. The area corresponds to the size of the module, not the active area of the solar module. This is because the window area is the same per building, but the active solar cell area change depending on the type of modules. Because of the additional substrate and encapsulation, the Plastic-TPV has a 6% higher CED than Glass-TPV. In single-junction small molecules solar cells, the ITO sputtering accounts for about 50% of the total CED, and the active layer deposition varies from 10 to 20% depending on the

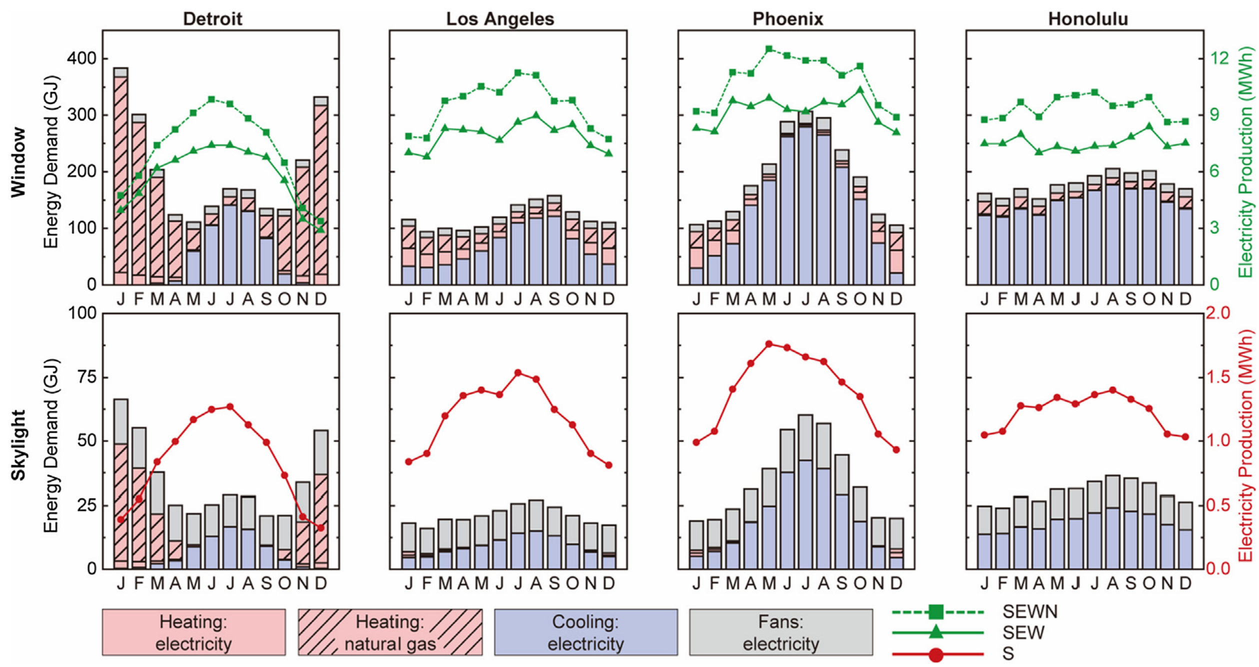


Fig. 4. Annual building energy demand and electricity production for a TPV (η = 10%) for the four cities considered with window replacement on the south east west-north (SEWN) or south-east-west (SEW) directions and for the skylight application.

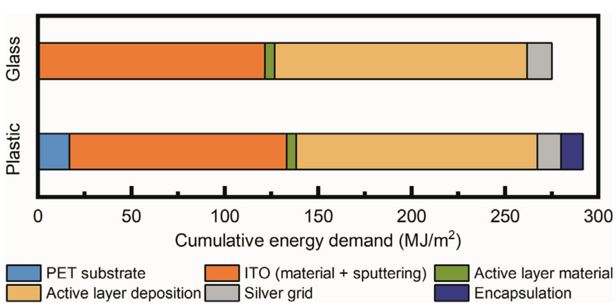


Fig. 5. Cradle to gate cumulative energy demand for the production of 1 m^2 Glass-TPV and Plastic-TPV modules.

material combination [12]. For TPV, the direct energy during the active layer deposition was measured to be 39.8 MJ/m^2, which is 73% higher than previously reported values [12] and can be explained by a different deposition system with pumps having higher energy consumption. Even with higher deposition energy than in previous studies, the CED varied from 3.1 to 10.3 MJ/Wp for Glass-TPV and 3.4–11.4 MJ/Wp for Plastic-TPV while considering current and future technology. Previous values for single-junction OPV ranged from 3.6 to 8.4 MJ/Wp [12,57], which is similar to the values calculated in this work. By comparison for inorganic modules, CdTe embodied energy varies from 5.9 to 7.8 MJ/Wp and monocrystalline Silicon from 18.5 to 29.4 MJ/Wp [58]. Additional comparisons are available in SM (Fig. S1).

3.3. Net energy benefit

The annual change in building energy demand with TPV is summarized in Tables S4-S11 in the SM. The net energy benefit of TPV for glass and plastic solar cells is shown in Fig. 6 and is positive for all scenarios considered. The photovoltaics electricity generation was based on the current (η = 3%, T_{50} = 7 yrs) and future (η = 10% T_{50} = 25 yrs) technologies. The manufacturing energy was found to be negligible compared to the energy saving over 20 years for all scenarios. In addition to electricity production, the TPV reduces the summer electricity consumption due to the reduction in the NIR radiations entering the building. At the same time, the TPV layer reduces the heat loss from the building, which is helpful during the colder periods and contributes to reducing the natural gas consumption in most scenarios except for the skylight application in Detroit.

The electricity production difference between Plastic-TPV and Glass-TPV is 73% in the current scenario but around 8% for the future scenario. This difference highlights the benefit of replaceable solar modules over integrated modules until high modules lifetimes are achieved. In the current scenario, energy saving had the most benefit, but as efficiency and lifetime of PV device increase, PV electricity production will become more important than energy saving. In Fig. 6 for current technology Glass-TPV, the PV electricity corresponds to 15–20% of the energy saving but it increases to 94–126% for future technology. Using plastic modules (Plastic-TPV) and replacement every 10 years, the PV electricity contribution double to 32–41% of the energy saving for current technology and it increases to 110–143% for future technology. The trend is similar for skylight. Covering the south direction of the building with TPV increased the PV production by 15–20% for Glass-TPV and 18–25% for Plastic-TPV, with the lowest increase in Phoenix and the largest in Honolulu.

The combination of various energy sources in buildings highlights the importance of the cumulative energy approach since 1 GJ of natural gas burned in a furnace is not equivalent to 1 GJ consumed in an electrical furnace. In 2016, the production of 1 GJ of solar electricity prevented the production of 2.2–3.5 GJ of primary energy from the grid, depending on the location. By comparison, reducing the natural gas consumption by 1 GJ only reduces the CED by 1.3 GJ. The change in electricity production from the grid was included in this work. The grid efficiency factors are available in Table S15.

3.4. Energy return on investment and energy payback time

Since the CED from manufacturing is negligible compared to the energy produced during the 20 years lifetime considered for this study, the energy return on investment (EROI) and the energy payback time (EPBT) (Fig. 7) were calculated for each scenario. An EROI greater than one implies that more energy is produced or saved due to the technology than used during its manufacturing. In Fig. 7, the range of values

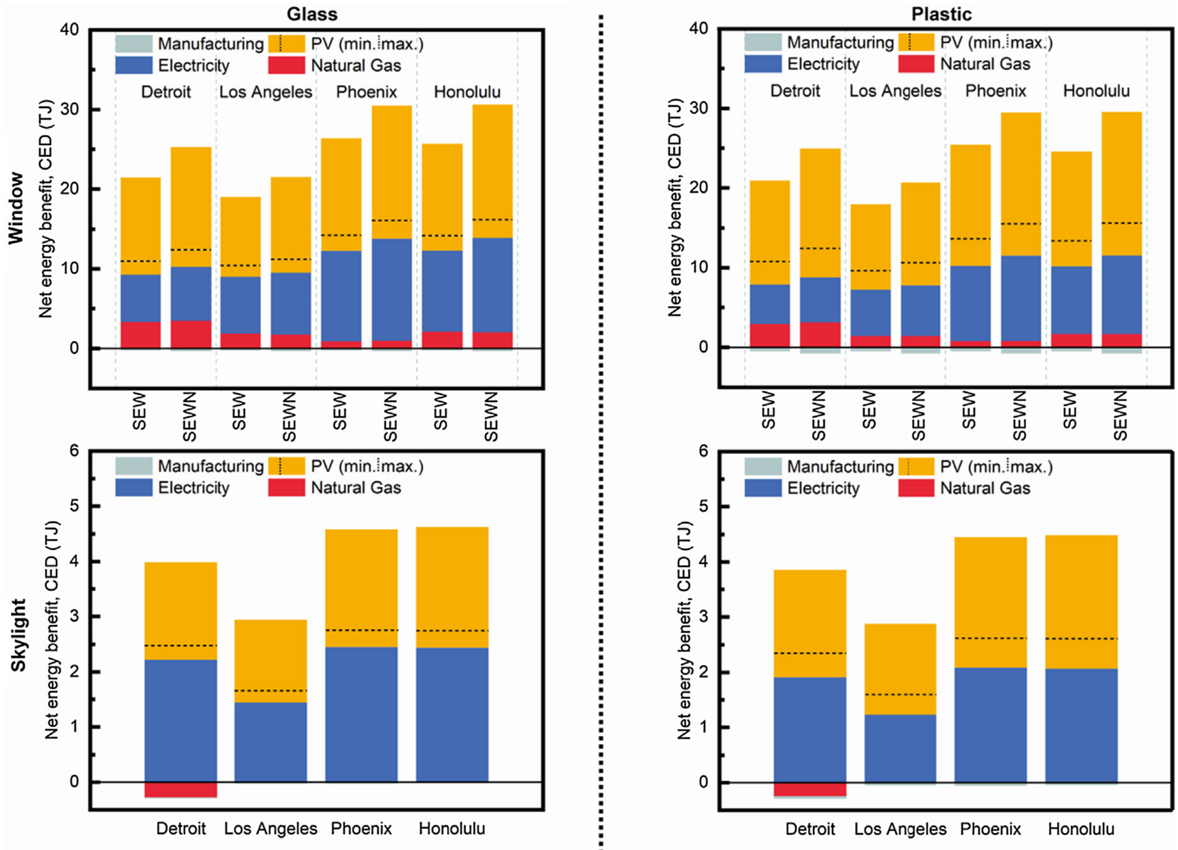


Fig. 6. Net cumulative energy benefit for glass and plastic TPV for window and skylight applications for all four locations. The photovoltaics electricity generation was based on the current (min: η = 3%, T_{50} = 7 yrs) and future (max: η = 10% T_{50} = 25 yrs) technologies.

corresponds to the current and future cases. All scenarios considered have an EROI greater than 1. The combined energy savings and electricity production can result in a higher EROI for TPV than a traditional opaque organic PV. In Fig. 7, to compare with other types of solar modules, we used the results from a comprehensive review that included various types of modules manufactured after 2009 and calculated their EROI and EPBT, assuming a 25 years lifetime and 1000 W/m^2 insolation [58]. We want to note that the best average normal insolation for the US is 970 W/m^2, for a two-axis system. Therefore, the reference results for EROI are higher and EPBT lower than what is achievable in the US.

The EROI allows the comparison of the same module in different applications, in our case, between the window and skylight application. The NEB in Fig. 6 was higher for the window than for the skylight application, but this was due to the specific building and module size considered. The EROI is higher for the skylight than for the window application since the orientation of the skylight at 21 degrees is more optimal than the vertical windows. The EROI for plastic TPV was lower than glass due to the module replacement after 10 years but would be similar to glass if plastic modules could last 20 years.

The EROI metric compared to the NEB results provides a better insight into the diminishing return of covering the north side of the building. For example, in Phoenix, the EROI decreases from 102 to 83 for the glass application and best-case scenario. For the window application, Phoenix had the highest EROI (102 for SEW), while for the skylight application, Honolulu (208) was slightly higher than Phoenix (205). Previous studies for BIPV reported EROI for semi-transparent silicon modules that varied from 11.7 to 34.5 in Singapore, which was lower than what is calculated for all TPV in most locations in the US. The lower EROI can be attributed to the lower module efficiency of semi-transparent silicon PV, the additional light required to maintain the building operation [7], as well as the high manufacturing energy for silicon modules compared to organic photovoltaics [12]. In other BIPV applications in New York City where the silicon module was used as cladding rather than in window, the EROI was 7.2 [53], The higher EROI from this work demonstrates the benefit of OPV for building applications.

The EPBT is a useful metric to quantify the time needed for the system to payback the energy that is required for manufacturing it. The EPBT needs to be lower than the lifetime of the energy system, which in this work was assumed to be 20 years. For all types of transparent photovoltaic modules and locations, the EPBT is less than 1.2 years. From the reference study, organic PV had the lowest EPBT reported to date at 113 days [58], but this works shows that the EPBT for transparent organic PV can be even shorter at 51 days for building-integrated application. In Fig. 7. (b), the EPBT is shown to vary from 51 days to 405 days (0.14–1.11 years) for all scenarios considered in this work.

3.5. Avoided cost and greenhouse gas emissions

In addition to energy saving, the benefit of TPV in four locations in the US was evaluated based on the avoided cost and greenhouse gases for all scenarios. The detailed results are available in Tables S16-S17. The cumulative avoided cost and greenhouse gas emissions, which included the change in electricity and natural gas prices for each location over time, and the changing electricity grid are shown in Fig. 7 for the best-case scenario of the window application. The highest value corresponds to SEWN. The NEB for glass SEWN in Honolulu was 22% higher than Detroit, but the energy saving was calculated to be 246% higher due to the highest cost of both electricity and natural gas. Due to its high electricity cost of more than 15¢/kWh, Los Angeles had the

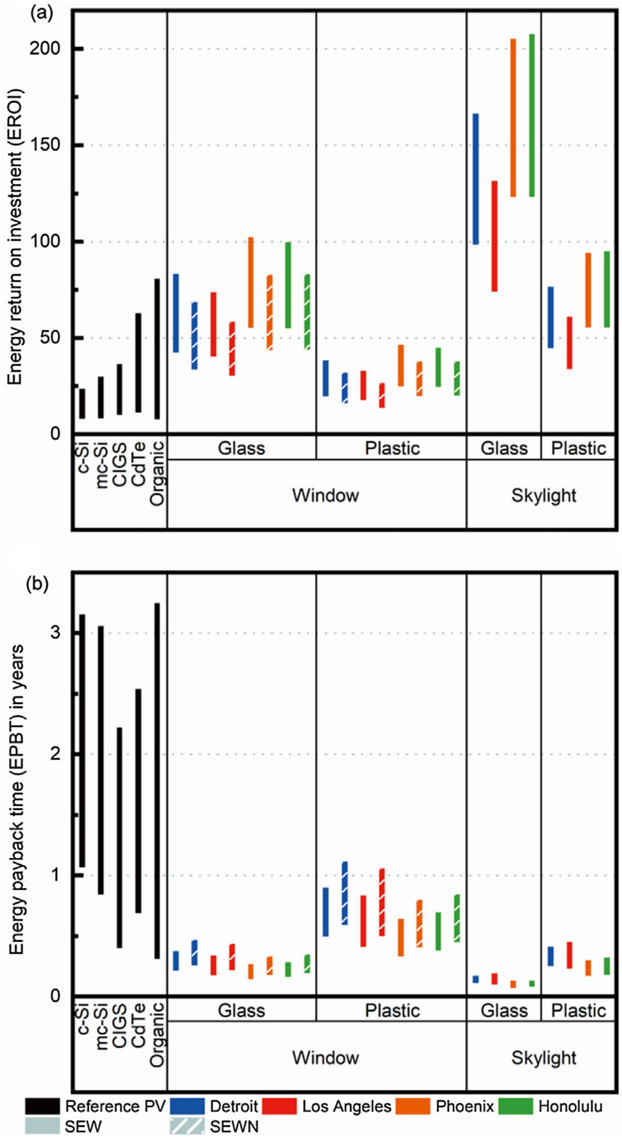


Fig. 7. (a) The energy return on investment (EROI) and (b) energy payback time (EPBT) for all types of transparent photovoltaics considered. For comparison purpose, the EROI and EPBT for various types of modules manufactured after 2009 were calculated under standard conditions (25 years lifetime and 1000 W/m^2 insolation) [58].

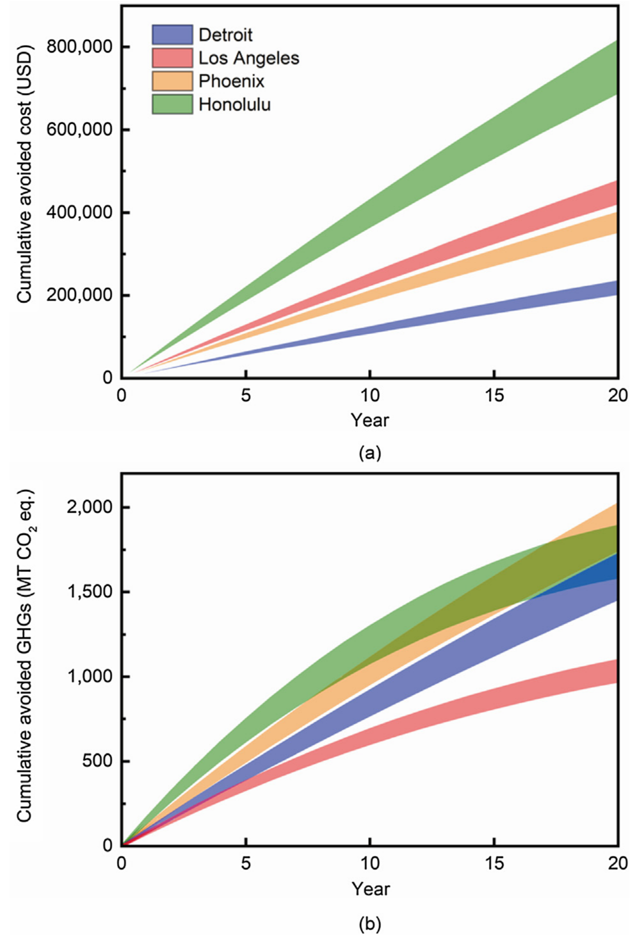


Fig. 8. Cumulative avoided (a) cost and (b) greenhouse gases over the 20 year lifetime of glass transparent PV window (η = 10% T_{50} = 25 yrs), where the lowest value corresponds to application on the South, East and West (SEW) direction of the building and the highest with the addition of the North face (SEWN).

second-largest energy saving even though it had the lowest net energy benefit. The second benefit of TPV is the reduction in greenhouse gases, which is illustrated in Fig. 8(b). Currently, Honolulu has the highest carbon footprint at 897 kgCO_2/MWh, but it has ambitious renewable energy goals and plans to replace its coal and oil electricity production with solar and wind. The forecasted carbon footprint in 2035 was calculated to be 189 kgCO_2/MWh, which suggest that the greenhouse gases reduction due to TPV over time will decrease in Honolulu. The change in slope for the avoided emissions in Honolulu and Los Angeles is due to the important decrease in carbon footprint over time. By comparison, the carbon footprint in Phoenix will only slightly decrease due to the replacement of coal by natural gas, and in Detroit, nuclear is replaced with natural gas, which could increase the carbon footprint. In Los Angeles, there is also plans to more than double renewable energy sources. The current electricity production has already a low carbon footprint of 443 kgCO_2/MWh, which is less than half the current impact of electricity production in Honolulu, the use of TPV results in the lowest GHG benefit.

3.6. Maximum price of TPV

The cumulative energy saving for each location was used to calculate the maximum price of TPV per unit of area (USD/m^2), which corresponds to a breakeven price for all the scenarios considered in each city. The range of values for each location corresponds to the current and future case scenario. Given that the current price of the module is unknown, the maximum price of the module is calculated. Rather than estimating the energy saving to the consumer, Fig. 9. provides manufacturing cost goals for manufacturers.

The highest prices per area were for Honolulu and the lowest for Detroit for all scenarios. The maximum price was lower for plastic modules due to their replacement every 10 years. It was calculated to be between 41 and 187$/m^2 for low-efficiency solar cells and 88–350 $/m^2 for the best TPV modules. For the skylight application, the price was higher and varied from 137 to 759 $/m^2. In the window application, the price range for each location was broader since the current case scenario assumed rapid degradation, and therefore the difference in electricity production was significant. The range for window applications was 80–730 $/m^2 while it was between 286 and 1565 $/m^2 for the skylight application. The potential of manufacturing plastic modules moderate efficiency for retrofit at a very low price might result in the early commercialization of the plastic product rather than integration into the glass window, which will be more expensive.

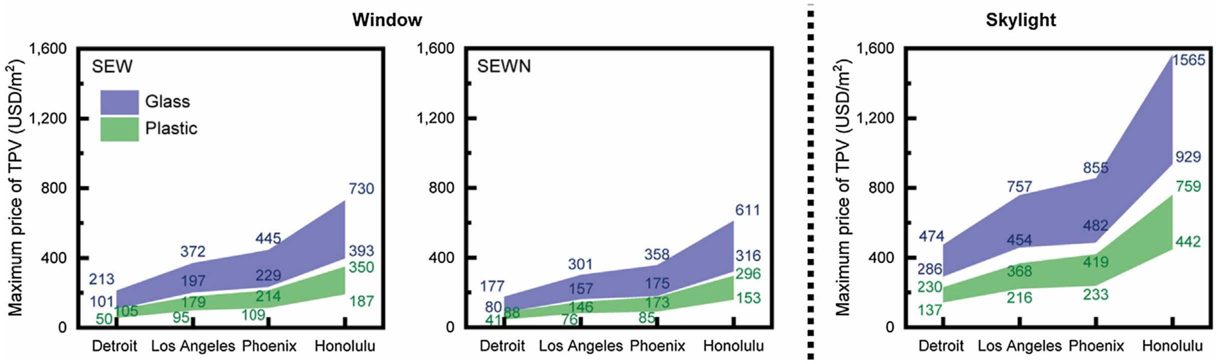


Fig. 9. Maximum price of TPV film per m^2 for the glass and plastic application for all the scenarios considered.

4. Conclusion

We demonstrate, for the first time, the net energy benefit of transparent photovoltaics in building applications across the United States using a life cycle approach that considered electricity production and change in building performance. We accounted for a range of module performance possible today and in the near future ($\eta = 3\%$ $T_{50} = 7$ yrs to: $\eta = 10\%$ $T_{50} = 25$ yrs) and evaluated the technology impact in terms of energy and cost benefit. All scenarios had positive NEB and led to a reduction of greenhouse gas emissions and energy costs due to the energy saving in addition to electricity production. The NEB was used to calculate the EROI and EPBT, which were found to be either better or comparable to other photovoltaics technologies even when considering lower efficiency and replacement after 10 years. To evaluate the impact of transparent photovoltaics over time in each location, the effect of changing electricity grid and energy price was included in the greenhouse gas emissions and energy cost. This work was limited to one type of organic photovoltaics module. Nonetheless, it provides key insights regarding the possibility of designing transparent photovoltaics that maximizes the electricity generation and energy saving based on the location.

CRediT authorship contribution statement

Annick Anctil: Conceptualization, Methodology, Investigation, Writing - original draft. **Eunsang Lee:** Investigation, Visualization. **Richard R. Lunt:** Writing - review & editing, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.114429.

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