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Guiding Urban Scale Building Integrated Photovoltaic Integration Decisions: Coupled Building Energy Simulation, Life Cycle Assessment and Radiation Simulation

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Abstract

This paper introduces a method and computational platform that combines urban building energy modeling (UBEM), life cycle assessment (LCA), and solar irradiance simulations to assess building integrated photovoltaics (BIPV) at an urban scale. Demonstrated through three BIPV scenarios applied to three case studies, the method enables computing key performance indicators (KPIs) to understand design and planning opportunities that can ultimately support decision making. The tool can predict a wide range of design approaches for BIPV deployment at urban scale. With the capacity to efficiently combine energy performance simulation with systematic KPI estimation, the tool offers stakeholders a powerful resource for creating optimized BIPV neighborhoods and fostering sustainable urban development.

Introduction

Building integrated photovoltaics (BIPV) are widely considered a crucial pathway toward achieving near zero energy building (nZEB) and communities (nZEC) in urban areas (Jelle and Breivik 2012). Previous studies have focused solely on the financial viability of BIPV installations (Shirazi, Zomorodian, and Tahsildoost 2019). Others have worked on urban building energy modeling (UBEM) considering BIPVs while excluding all processes and impacts that are captured through a full life cycle assessment (LCA) of BIPVs (Boccalatte, Fossa, and Ménézo 2020; Chen, Yang, and Peng 2019; Saretta, Caputo, and Frontini 2020). This limits arriving at a holistic understanding of the environmental impact of BIPV projects. While a few BIPV research efforts have adopted LCA (Gholami et al. 2020; Sierra et al. 2020; Hadi and Heidari 2021), their methodologies often lack the capability of properly modeling the intricate interaction between BIPVs and the surrounding environment. This oversight is paramount, as the urban context significantly influences the energy consumption and energy harvesting potential of BIPVs. Furthermore, prior studies lack adaptability as they are often tailored to a specific case study, requiring extensive adjustments and reanalysis if any parameters or design alternatives are altered. These shortcomings hamper their ability to provide comprehensive guidance on urban-scale BIPV, where varying architectural configurations and multiple design scenarios need to be considered.

This paper introduces a novel and comprehensive workflow for guiding urban-scale BIPV integration decisions. Addressing the limitations of existing works, the proposed method considers both UBEM and LCA, to provide decision-makers with the necessary tools to evaluate the environmental relevance of BIPV projects. By estimating key performance indicators (KPIs), such as the energy return on investment (EROI), energy and carbon payback times, net energy compensation (ratio of energy harvested to energy consumed), and greenhouse gas (GHG) emission intensity, this approach enables effective comparisons of different design alternatives and variations, which can assist stakeholders in making informed decisions. Finally, the workflow we introduce emphasizes automation and adaptability for simulating a wide range of scenarios, thereby enabling the sustainable and energy-efficient design and planning of urban communities. To demonstrate the applicability and relevance of the method, detailed case studies in Tel Aviv (Israel) are presented in this paper. They serve as a practical demonstration, showcasing the method's effectiveness in guiding decision-makers, architects, and urban planners. The research aims to empower stakeholders with the tools needed to navigate the complexities of urban-scale BIPV integration, to foster a future where sustainable, energy-efficient design is seamlessly woven into the fabric of our urban communities.

Method

To couple all processes that affect the net energy inputs in urban buildings equipped with PV panels, the UBEM,

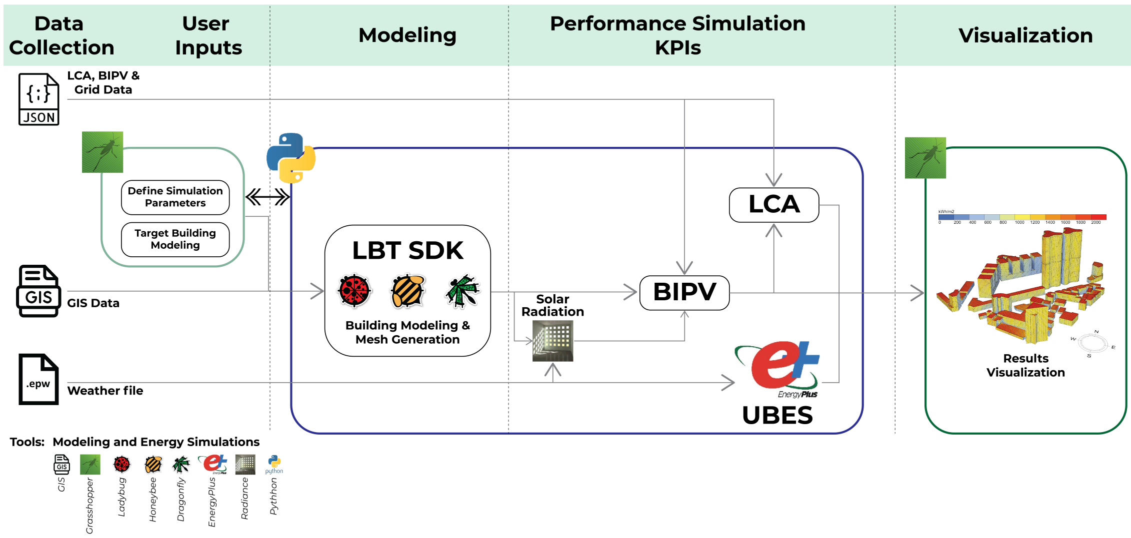


Figure 1: Modeling and simulation flow chart

LCA, solar radiation computation and the PV panels are modeled together on a single platform. This approach allows the simulation to manipulate the same data and objects, facilitating the automation and scaling of the simulation process. The platform is coded in Python using the Ladybug Tools (LBT) software development kit (SDK) libraries (Ladybug Tools SDK 2023) among others. The modeling and simulation steps required to perform the simulations can be called from components developed in Grasshopper (Grasshopper 2023), the visual programming interface for the 3D modeling program Rhinoceros (Rhinoceros3D 2023), used as a user interface. Context buildings are loaded in the platform from geographic information system (GIS) files and the target buildings are generated within Grasshopper using the LBT model format. The buildings in the platform are considered as one building collection and the simulations are performed at the urban scale. The modeling and simulation steps are detailed below and the overall flow is described in Figure 1.

Urban building energy modeling and simulation

Context and target buildings are stored in the platform in the LBT format preserving their metadata which include building geometries and various properties (thermal zone subdivision, construction materials, schedules, etc.) necessary to perform an energy simulation through EnergyPlus (EnergyPlus) for the target buildings. Relevant shading surfaces are selected from the surrounding buildings in the building collection for each target buildings. To perform the simulation through EnergyPlus, the models of the target buildings are converted to EnergyPlus format (idf files) and are then sent to the simulation engine along with the input weather file. The heating, cooling, lighting and equipment energy demands are collected and saved after the computation. The simulations are performed for one year and a coefficient of performance for heating and cooling loads is applied to determine the energy consumption of the buildings.

Mesh generation and solar irradiance simulation

The incident solar radiation on the BIPVs of target buildings must be computed to calculate the energy harvested by the panels. Prior to this irradiance simulation, a mesh with rectangle faces, subdividing the external surfaces of the buildings, is created to allocate dedicated space for each of the panels. The mesh can be generated on the roof(s) and/or on all facades of the buildings. Each face of the mesh represents a potential panel location. An energy efficiency criterion, explained in the Panel Modeling subsection below, determines if a panel is placed on mesh faces. The grid size is inputted in x and y directions according to the size of the panels.

The mesh generating algorithm ensures that no panel overlaps with a window. The grid ignores the artificial subdivisions between floors and apartments that building models usually contain. These subdivisions split the buildings into numerical computation nodes called thermal zones for EnergyPlus models. The software Radiance (Radiance 2023), driven by one of the LBT library, performs the computation using the inputted weather file of the simulated location and returns the hourly incident

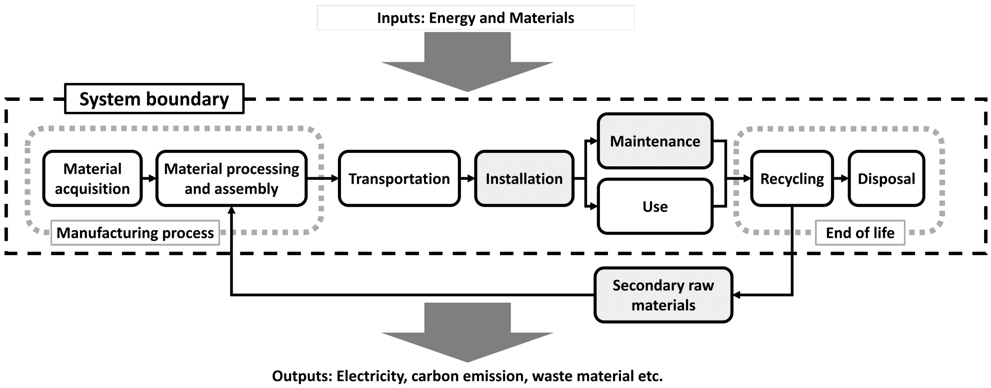


Figure 2: System boundary of the LCA of BIPV panel and BOS, the hatched stages are not considered in the study

solar irradiance on every face in the grid in W/m^2. This computation considers the same obstructions from the surrounding building used in the energy simulation. The meshing and irradiance simulation step are performed automatically using user parameters.

Life cycle assessment of panels

LCA is used to determine the embodied primary energy and carbon footprint of the BIPV panels. A cradle-to-grave system boundary, as presented in Figure 2, is used in this study. It includes the manufacturing process, transportation, the use phase and end-of-life (EOL) processes. The installation and maintenance of the panels are ignored and there. No credits were applied for recycling of panel materials at EOL due to the lack of data related to the process, and the fact that few recycling operations exist on the market. Excluding a credit results in a conservative estimate. Panel recycling is expected to be a growing market in the near future (Latunussa et al. 2016) and could be added to the recycling contribution.

The LCA is performed on the panels themselves, which includes the PV cells and the frame, and the balance of system (BOS), composed of the wiring, mounting system and inverter. The functional unit used is a m^2 of panel except for the transportation step, which uses kg of panels. The LCA values are converted to one panel unit to fit the other modeling and simulation steps of the method that deal with panels individually. A distinction is made between roof and facade panels as they can have different characteristics and life cycle aspects.

Panel modeling

Photovoltaic panels have complex behavior that is affected by their environment and their age. They are especially prone to efficiency degradation over their service life. In this study, this degradation is calculated following (Khalifa et al. 2022), assuming a degradation of 2% in the first year and 0.5% in the following (Equation 1).

$$degradation = \begin{cases} 0 & if\, age = 0 \\ 0.02 + 0.005 * (age - 1) & else \end{cases} \quad (1)$$

The electricity harvested by a panel in kWh is computed yearly using Equation 2. The performance ratio corresponds with the loss due to the BOS of the infrastructure, especially the inverter, which cannot convert the DC current of the panel to AC without energy loss.

$$\begin{aligned} electricity\, harvested(age) = {} & cumulative\, irradiance \\ & * panel\, area \\ & * performance\, ratio \\ & * efficiency \\ & * (1 - degradation(age)) \end{aligned} \quad (2)$$

BIPV panels do not have a fixed life time. They are likely to fail prematurely and consequently stop producing electricity until their replacement. The failure probability is modeled by a Weibull law, as suggested by (Weckend, Wade, and Heath 2016). Equation 3, derived from the cumulative Weibull probability distribution function, is used to randomly set the lifetime of a panel. λ and k correspond to the shape and the scale parameters of the Weibull law. The $\lceil\rceil$ symbol corresponds to the ceiling function and r is a random number in $[0:1]$.

$$lifetime = \left\lceil -\lambda (log(1-r))^{\frac{1}{k}} \right\rceil \quad (3)$$

This modeling does not consider mismatch losses of the PV panels caused mostly by non-uniform irradiance, temperature, efficiency or by failed panels. This

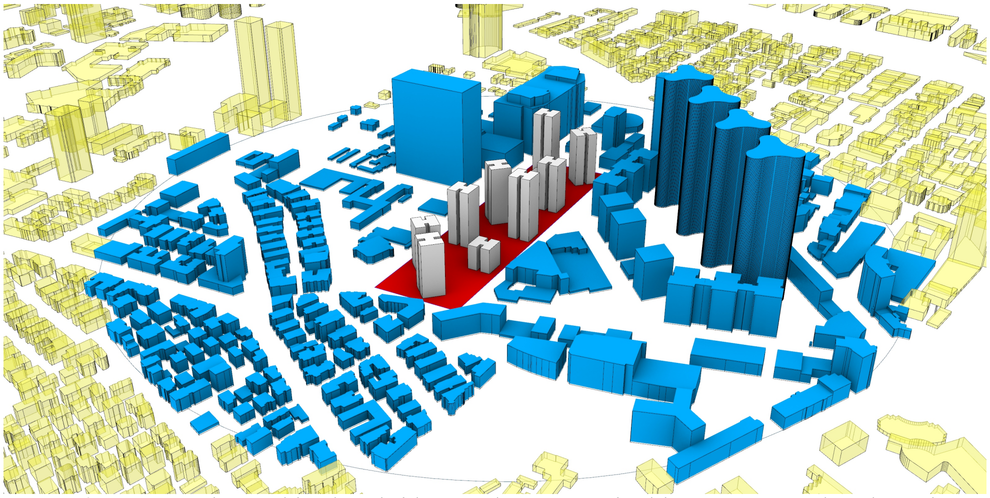


Figure 3: Case study neighborhood (blue) with its target buildings (grey) within the red area

phenomenon limits the electricity harvested by panels. The mismatch losses can be mitigated with optimized wiring among the panels (Sarquis Filho, Fernandes, and da Costa Branco 2021; Thanikanti et al. 2023) and require a dedicated simulation afterwards. Some new technologies, such as power optimizer from SolarEdge (SolarEdge, power optimizer 2024), aim to negate mismatch losses at the price of a slight efficiency loss. Uptake of such technology could grow in coming years, especially for BIPV. The energy harvested computed with the presented method is thus overestimated and reflects the full potential of the BIPV installation simulated.

BIPV installations can be made to last for longer than the average life expectancy of a panel, thus requiring replacement of the panels. Two replacement scenarios are used in the case study section: replacing failed panels and replacing all panels at a given frequency. Failed panel replacement is environmentally preferable as it makes the most out of panels' potential, but requires a short replacement frequency not to leave failed panels production-less for too long. An adequately timed replacement of all, according to the expected life time of the panels and the whole infrastructure, prevents suboptimal replacements of failed panels in the last years of existence of the infrastructure.

In order to determine if a panel should be installed on a face of a building mesh, the ratio between energy harvested and embodied energy of the panel during its lifetime is estimated. The energy harvested is calculated using Equation 2 assuming that the panel lasts for it's average lifetime. If the ratio is superior or equal to a threshold, the panel is installed. This threshold is an input parameter and is called the minimum panel EROI.

Key performance indicators

KPIs are defined and calculated to guide decision making. The objectives and focus of a given project determine which KPIs are relevant to use and how they should affect the decision process. For urban scale BIPV deployment, the EROI, the net energy compensation, the primary energy and carbon payback times and the GHG emission intensity are the most suitable KPIs to guide decision making. Economically oriented KPIs would also be relevant, but they are not included in the scope of this paper. The KPIs are computed over the whole life time of the projects.

The EROI is the ratio of the electricity harvested over the embedded primary energy of the BIPV installation. It gives an indication of the energy viability of an energy source. The net energy compensation is the ratio of the electricity harvested over the electricity consumed by the buildings during the use phase. This KPI is especially relevant for nearly zero energy community (NZEC) projects.

Contrary to the first two KPIs, the three last indicators depend on the electricity grid of a project location. The primary energy and carbon payback times correspond to the time required for the BIPV infrastructure to offset its embedded primary energy and carbon, respectively. The offset primary energy and carbon generated by the panels are the product of the electricity harvested by the primary energy demand (in MJ of primary energy per MJ of electricity produced) and the GHG emission intensity (in $gCO2_{eq}/kWh$ of electricity produced) of the grid, re-

Table 1: *BIPV panels specifications, LCA data and electricity grid characteristics*

Parameters	Value Roof	Value Facade	Data source
General PV parameters			
Weibull shape factor	2.49	–	(Weckend, Wade, and Heath 2016)
Lifetime (Weibull scale parameter) [*years*]	30	–	(Weckend, Wade, and Heath 2016)
BOS performance ratio [%]	80	–	(ISE 2022)
Module parameters			
Manufacturer	Mitrex	–	
Technology	Monocrystaline Silicon	–	(Mitrex 2023a; Mitrex 2023b)
Efficiency [%]	19.5	17.3	(Mitrex 2023a; Mitrex 2023b)
Weight per module [kg]	22	–	(Mitrex 2023a; Mitrex 2023b)
Area per module [m^2]	2.03	–	(Mitrex 2023a; Mitrex 2023b)
Environmental impacts per panel			
Primary energy manufacturing [kWh]	2.84E+03	–	(de Wild-Scholten 2013)
Climate change manufacturing [$kgCO2_{eq}$]	904	–	(de Wild-Scholten 2013)
Primary energy transport [kWh]	19.0	–	
Climate change transport [$kgCO2_{eq}$]	4.44	–	
Primary energy end of life [kWh]	17.0	–	(Latunussa et al. 2016)
Climate change end of life [$kgCO2_{eq}$]	8.14	–	(Latunussa et al. 2016)
Electricity grid parameters			
Primary energy demand [MJ/MJ]	2.84	–	
GHG emission intensity [$gCO2_{eq}/kWh$]	660	–	

spectively. These two metrics describe the time needed to recoup energy and capital carbon invested in the panels over their lifetime. Finally, the GHG emission intensity of the project is not a function of any characteristic of the local electricity grid, but needs to be compared to the GHG emission intensity of the grid to estimate the relevance of the project.

Case Study Description

Three alternatives of a case study neighborhood in Tel Aviv, a city in Israel with high solar harvesting potential, are presented in this paper. They are all located in the same red study zone shown in Figure 3, surrounded by their context environment. The alternatives have different densities: the ***low***, ***medium*** and ***high*** density alternatives have a floor to area ratio (FAR) of 1, 2 and 3, respectively within the study zone. All the alternatives contain 11 buildings sharing the same position and orientation, but with varying number of floors to match their associated FAR. The alternatives can be visualized in Figure 4. The *low* density alternative, with its low rise buildings, fits sub-urban areas while *medium* and *high* density variations are adequate for cities and central areas. Only the buildings in the study zone of the alternatives are considered as target buildings and are consequently simulated. The surrounding buildings are only used as context for mutual shading. The target buildings act as shading elements as well in each other's simulation.

The study zone has an area of 34100 m^2. The alternatives contain only H-shaped buildings with identical stories, composed of 4 apartments of 126 m^2 and an unconditioned core of 15 m^2 in the center. The glazing ratios, construction materials, loads, schedule, and heating and cooling setpoints are set according to the standards of the case study location. The energy consumption of the building is assumed to be electricity only and the COP of heating and cooling system is 3.

For this case study, the BIPV panels are assumed to be manufactured in China as it is the largest panel producer worldwide. The specifications of the panels for the roof and facades were chosen according to BIPV models from the manufacturer Mitrex to get representative panel properties on the market today. Colored panels are used for facades despite their lower efficiency

Table 2: Parameters of the efficiency, balanced and production BIPV scenarios of the case studies

Scenario	Minimum Panel EROI	Replacement Scenario	Replacement Frequency [*year*]
Efficiency	3	all panels	25
Balanced	2	all panels	25
Production	1.2	failed panels	5

as they merge better in the building external wall and improve aesthetics. The LCA values for manufacturing and recycling are obtained from the literature (de Wild-Scholten 2013; Latunussa et al. 2016) and are assumed identical for the roof and facade panels. Transportation distances for PV panels supplied by manufacturers in China were estimated following methods for bulk material transport (Nguyen et al. 2018), based on efficient routes determined from Google maps, and correspond with ocean barge (bulk cargo ship), freight train and commercial trucks modules from the ecoinvent database (Wernet et al. 2016). The estimated route is the following : 600 *km* of railroad transport from production site to Shanghai, followed by 15000 *km* of cargo shipment to the project country, then by a 50 *km* delivered to the construction site by lorry. The inverter is not included in the transportation and recycling stage. Its manufacturing embedded primary energy and climate change is estimated from the values in the literature (de Wild-Scholten 2013), no sizing depending on the peak power of the infrastructure is performed. The detailed specifications of the BIPVs and the electricity grids are summarized in Table 1.

To obtain the primary energy demand and the GHG emissions intensity of the electricity grid, a cradle-to-grave electricity supply that tracks power supplied to the grid and thence to urban electricity outlets was built. A customized energy mix was used, consisting of natural gas (76 %), coal (3 %) and renewable energy sources (6 %) using ecoinvent data (Wernet et al. 2016).

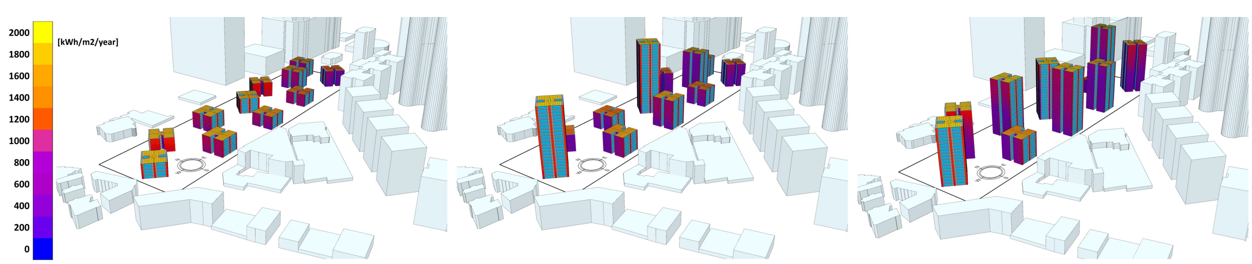
For each alternative, three BIPV scenarios prioritizing different aspects were simulated. They are not optimal for given requirements, they are just representative of the three main tendencies that were found relevant for urban scale BIPV integration. The **efficiency** scenario fits low environmental impact projects aiming to integrate a low carbon electricity production in its infrastructure, maximizing the energy efficiency of its BIPV panels. The **production** scenario corresponds to projects requiring substantial inner energy production, in order to lower the load on the grid or to compensate as far as possible its own electricity consumption. The **balanced** scenario is an in-between option of the efficiency and production scenario that fits projects requiring a decent electricity production with a reasonable environmental impact. The input parameters and the scenarios are detailed in Table 2. The study timeframe for all the alternatives and scenarios is **50 years**.

Results and Discussion

The results of the nine combinations of density alternatives and BIPV scenarios are presented at the urban scale.

Harvesting potential of roof and facade panels

The cumulative annual solar irradiance on the building (see Figure 4) shows the general harvesting potential gap between roof and facade panels. However, especially in dense urban areas, land space is very limited and while facade area increases with the height of buildings, the maximum roof area is easily reached. For solar electric-



Low density Medium density High density

Figure 4: Annual solar irradiance on the target buildings for the three case study alternatives

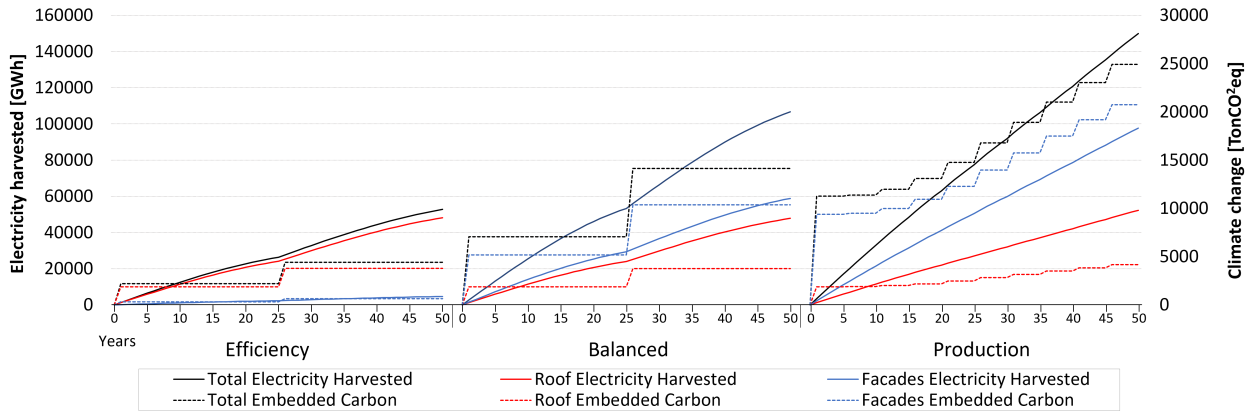


Figure 5: Contribution of roof and facade BIPV in the energy harvesting and embedded carbon for the high density alternative

ity harvesting, adding facade panels is the only solution to increase the energy production once all the roof area available is covered with PVs. It is verified in the computed electricity harvested as shown in Figure 5. The electricity harvested by the panels on the roof for the *high* density variation is identical for the *efficiency* and *balanced* scenarios while the electricity harvested from facades goes from almost null to superior in relation to the roof. It is due to the minimum panel EROI criterion that enabled all the roof to be fully covered with panels for both scenarios due their high solar irrandiance, but only a few panels matched the criterion on the facades for the *efficiency* scenario due to the high threshold. However, Figure 5 clearly shows that the cost of doubling BIPV-generated electricity from the *efficiency* to the *balanced* is a 3-fold increase in the embedded carbon footprint of the BIPV installation.

Impact of mutual shading

The effect of mutual shading on solar irradiance is visible in Figure 4, especially on facades. While in this specific case study mutual shading does not prevent facades from harvesting decent amount of energy as shown in Figure 5; denser environment with shorter distances separating buildings could impact facade harvesting significantly.

Influence of replacement scenarios

For the study duration and the BIPV scenarios parameters used, the replacement scenario does not significantly affect the electricity harvesting and the embedded carbon and primary energy. This could be verified for the roof only as the number of panels placed on the roof is the same for each BIPV scenario in these case studies, the roof panels all having an individual EROI higher than the maximum requirement. The electricity harvested for the

Table 3: Results of the case study simulation for the 50 years study period

Density	Scenario	Building Energy Consumption [GWh]	BIPV Electricity Harvested [GWh]	BIPV Embedded Primary Energy [GWh]	BIPV Embedded Carbon Footprint [$kgCO2_{eq}$]
Low	Efficiency	113	50.4	13.0	4.16E+06
	Balanced	–	73.3	25.9	8.25E+06
	Production	–	88.7	36.1	1.15E+07
Medium	Efficiency	227	53.9	14.9	4.75E+06
	Balanced	–	85.0	32.7	1.04E+07
	Production	–	120	59.8	1.90E+07
High	Efficiency	339	52.8	13.9	4.43E+06
	Balanced	–	107	44.4	1.41E+07
	Production	–	150	78.1	2.49E+07

roof panel increased by only 8.64%,8.65% and 8.55% for the *production* scenario compared to the *efficiency* and *balanced* scenarios for the *low*, *medium* and *high* density alternatives, respectively. The GHG emission intensity for the roof panel increased by only 1.89%, 2.10% and 1.55% for the *production* scenario compared to the *efficiency* and *balanced* scenarios for the the *low*, *medium* and *high* density alternative, respectively.

The main advantage of replacing the failed panels only is that they provide an almost constant production of electricity every year as shown by the nearly linear cumulative electricity harvested by the *production* scenario in Figure 5. Another advantage would be to guaranty a sturdier electricity supply if the lifetime of the project is eventually extended, even if the panel stopped being replaced, compared to the other scenarios. This last point requires deeper investigation. The technical feasibility of high frequency replacement should be investigated for BIPVs as well.

Interpretations of the KPIs

Table 3 shows the raw output results of the simulations and Table 4 the computed KPIs from these outputs. All the configurations tested have acceptable EROIs. In the literature (Gupta 2018), it is expected for the EROI of PV panels to be between 3 and 8, but these expectations are for PVs on roofs or on ground utility power plants only. Having alternatives with EROIs between 1.9 and 4 was expected. Panels manufactured in China are also considered in this study and their embedded primary energy and carbon are higher than those manufactured in other locations (de Wild-Scholten 2013). The GHG emission intensity of the simulated configurations are also expected for BIPV installation (de Wild-Scholten 2013). They are satisfactory as they all maintain a significantly lower GHG intensity as compared to the project location composite electricity grid mix. The payback times are satisfactory as well as they remain far below the the duration of the study.

The results also show that reaching nZEC is feasible, especially for low rise neighborhoods like the *low* density alternative. A net energy compensation of 78.4% is attained in the *production* scenario, and some optimization of building geometries, glazing distribution and construction material to lower the the energy consumption and maximize the electricity harvested could even improve this KPI. For medium and high rise neighborhoods like the *medium* and *high* density alternatives, optimization can improve the net energy compensation but it is less likely to get close to 100%, especially for cases with smaller distances between buildings that will lower the electricity harvesting potential.

Versatility of method

The case studies presented, while insightful, serve as one instance of the method's potential applications. This robust method and its dedicated platform can be seamlessly applied to any project, provided a model of the target building and surrounding structures is furnished as input data. It is designed to cater to a wide array of scenarios, from low-density residential neighborhoods to bustling high-density urban areas. Its ability to simulate then compare a large spectrum of BIPV incorporated neighborhood alternatives consecutively facilitates decision making. The computed KPIs play a pivotal role in guiding design decisions for BIPV projects. These metrics offer a quantitative lens through which stakeholders can evaluate and fine-tune design choices. Whether

Table 4: KPI values of the case study simulation for the 50 year study period

Density	Scenario	EROI	Primary Energy Payback Time [*years*]	Carbon Payback Time [*years*]	Net Energy Compensation [%]	GHG Emission Intensity [$gCO2_{eq}/kWh$]
Low	Efficiency	3.87	3.8	5.1	44.6	82.4
	Balanced	2.83	5.0	7.0	64.8	112
	Production	2.46	6.3	8.8	78.4	130
Medium	Efficiency	3.62	4.0	5.5	23.5	88.0
	Balanced	2.60	5.6	7.7	37.4	123
	Production	2.00	8.0	11.0	52.7	159
High	Efficiency	3.80	3.8	5.2	15.6	83.9
	Balanced	2.40	6.0	8.3	31.5	133
	Production	1.92	8.2	11.5	44.2	166

prioritizing energy efficiency, minimizing environmental impact, or finding a balanced approach, the KPIs serve as navigational tools, facilitating decisions aligned with the project's specific goals.

This adaptability finds further strength with the integration of optimization capabilities. Positioned as a top layer on the method, optimization opens new avenues for crafting sustainable solutions in the realm of Building Integrated Photovoltaics. It provides a reliable foundation for the addition of optimization, opening avenues for tailor-made solutions accommodating the intricacies and nuances of each unique project.

Conclusion

The developed method presents a significant leap forward in the field of urban-scale BIPV evaluation. By integrating UBEM, LCA, and solar irradiance simulations into a unified platform, our approach streamlines the complex task of evaluating BIPV installations at an urban scale. This approach provides a practical and scalable framework for sustainable urban design due to the automation achieved through the Python-based platform, utilizing LBT SDK libraries, making it flexible and user-friendly. With minimal inputs, such as target building geometries and BIPV user-parameters, the platform can compute KPIs that are critical for decision-making in BIPV projects.

Beyond theoretical contributions, the method directly addresses the challenges of sustainable urban development. It not only enhances efficiency in assessing energy performance combined with life cycle energy and GHG emissions for BIPV installations, it also opens avenues for rapid and comprehensive evaluations in various urban contexts and project specifications. Whether optimizing energy efficiency in low-density residential areas, striving for net-zero energy communities, or exploring the potential for renewable energy in high-density urban environments, this method offers a versatile and accessible solution for sustainable urban planning and decision-making.

Future Developments

The future developments of the proposed method for evaluating BIPV installations at an urban scale encompasses several key areas. First and foremost, the integration of economic analysis is imperative to provide a comprehensive assessment of BIPV projects, considering both environmental and economic sustainability. This integration will introduce relevant and complementary KPIs, including the economic payback time, electricity rate, and solar savings. An essential refinement involves implementing the sizing of the inverter, improving the evaluation of its life cycle. Furthermore, enhancing the LCA component by including installation and maintenance phases, along with incorporating advanced recycling methods, is crucial for a more accurate representation of the environmental impact throughout the entire life cycle. The introduction of dynamic panel efficiency models that account for external factors such as temperature and solar irradiance variations will contribute to more precise energy supply predictions. Including the mismatch loss phenomenon should be considered. It could be modeled as an overall reduction percentage of the total harvested energy. A range of the expected loss would be estimated, leading to a predicted range of KPIs. Reevaluating the study period to align it with the average lifetime of panels, typically around 30 years, will provide a more realistic representation of the BIPV system's long-term performance and environmental impact. Finally, adopting a progressive building addition approach, mirroring the construction timeline of a neighborhood, will enhance the method's applicability to real-world scenarios, contributing to its effectiveness in sustainable urban planning and decision-making.

Acknowledgments

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