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Do we need a saw? Carbon-based analysis of facade BIPV performance under partial shading from nearby trees

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Abstract.
Building integrated photovoltaics (BIPV) are becoming more common in urban spaces. The impact of shading from nearby trees on BIPV performance and the potential conflict between the carbon sequestration benefits of trees and the carbon mitigation benefits of BIPV is not well documented in research. Therefore, this paper investigates the cost-benefit relationship of the carbon storage potential of trees vs. their shading effects on a nearby BIPV facade from the perspective of a life cycle assessment (LCA) using a high-resolution BIPV model and temporally sensitive tree growth model. The study is based on a typical Swiss residential building with adjacent vegetation and includes various BIPV facade permutations with different cell types, module orientations, inverter types, facade azimuths, grid emissions profiles, and tree planting scenarios. The results indicate that the removal of trees does not necessarily influence the overall carbon balance when considering LCA to the same degree as other features of the model space such as the grid carbon intensity or the configuration of the BIPV array. Furthermore the parametric-based analysis enables reporting on which BIPV configurations operate with the highest system efficiency under partial shading.

1. Introduction

Building integrated photovoltaic (BIPV) devices are land, material, and energy intensive products, despite their utilisation of the free energy of the sun as a feedstock. BIPVs also tend to operate in conditions that are less than optimal for PV (i.e. low-light, high temperature, etc.). As more individuals deploy them a more in-depth analysis is necessary to understand the implications of their use from a life-cycle analysis (LCA) perspective. Additionally, it is key to assess the performance of any BIPV system with respect to its surrounding conditions - including other buildings and shadow casting trees, such as those shown in Figure 1. It is understood that the partial shading caused by nearby trees can have detrimental effects on the performance of a BIPV module.

The impact of partial shading or mismatch (when the irradiance levels across a PV module are uneven) has been studied in simulation and laboratory conditions for some time with the understanding that loss can be considerable for a module even if only a few cells are mismatched [1]. However, the influence of trees on BIPV facade performance is not well documented in the literature and recent research suggests that a proposed solution to the loss brought on by

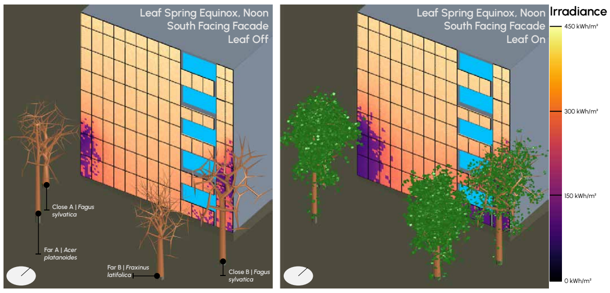

Figure 1: The building model used for the analysis shown with irradiance values simulated, for solar cells in a sample BIPV facade, at midday on the Spring Equinox for both the leaf off and leaf on conditions.

partial shading, the microinverter, only provides large benefits over string inverter systems in months with lower irradiance levels [2]. Urban trees are well researched with regard to their generally positive impact on building energy performance [3]. Additionally, urban trees are well understood in their capacity to store carbon in their biomass [4]. Urban trees are therefore important to consider for lifetime carbon assessments or buildings in urban spaces. Another important characteristic to consider in this realm is the emissions intensity of local electricity grid C_{grid} $[\frac{\mathrm{kgCO_{2e}}}{\mathrm{kWh}}]$. Happle et al. (2019) [5] showed that the local grid electricity mix can influence the performance and effectiveness of BIPV as a carbon mitigation tool more than urban form and climate. It has also been shown that despite low levels of irradiance, BIPV arrays placed on urban surfaces can be considered a part of an optimum urban energy system [6]. Therefore, one could expect BIPV modules to be placed in conditions where irradiance levels are generally low, given the right economic value and C_{grid}.

We consider all of the above aspects that relate to how PV performance can be quantified (i.e. partial shading, urban tree carbon sequestration, C_{grid}) at the fine scale required to assess PV modules under partial shading. Research to date has used simple methods to mask modules that do not reflect tree and leaf dynamics. Studies focused on PV and BIPV performance in different local grids have not used scenarios of the local tree context for LCA despite the influence nearby trees can have on power output. We therefore focus the attention of this paper on the relationship between tree shading and BIPV performance, but consider performance to be a life-cycle indicator related to Global Warming Potential of a site S_{GWP} [$\mathrm{tCO_2}$], including the trees themselves. It is expected that that cutting trees down to increase BIPV output will yield a negative effect with respect to S_{GWP} in regions like France (FRA) or Switzerland (CHF) with low C_{grid}, whereas it will be beneficial in regions like the United States of America (USA) or Germany (DEU) whose electricity C_{grid} is largely driven by fossil fuels. We evaluate the impact that the shading of nearby trees has on a variety of different BIPV systems that are simulated on a typical multi-family residential facade. We use this simulated information to conduct LCA and then re-simulate the BIPV performance without trees to quantify the impact that their shade has on the performance of the array. Using carbon storage quantification methods for the nearby trees we then calculate if removing the trees is beneficial to the site's greenhouse gas (GHG) emissions. We provide the results of this analysis with respect to several levels of C_{grid} (i.e. USA, DEU, FRA) to ensure that our results can be generalised across more regions in the hope that more designers are able to relate our findings to their own design. Our analysis of the proposed problem is motivated by the following questions:

(i) From a GHG emissions perspective is it justifiable to remove nearby trees to benefit BIPV productivity?
(ii) Does one BIPV configuration perform better under a situation in which the trees are not cut down?

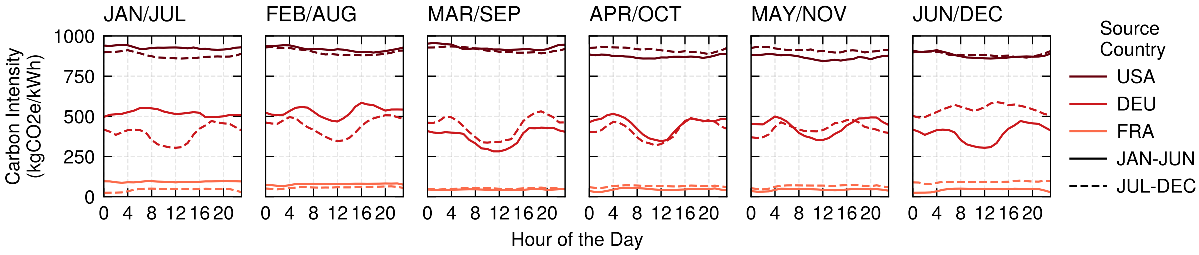

Figure 2: For each hour of the day in each month the median C_{grid} is shown for the considered electricity grids.

2. Methodology

We utilise a facade with adjacent vegetation from an existing building in Switzerland (Figure 1) to simulate 18 BIPV system configurations (cell type, module orientation, inverter type) and the implications of removing the trees on S_{GWP}. The site was modeled using a Level-of-Detail 2 model from the city of Zurich with window placement from photographs. The trees were reconstructed from Swiss LiDAR data to estimate their mass and then replaced with generic model trees to minimise mesh face count. Leaves were generated for each tree as individual mesh faces. The leaves were used for irradiance simulations from May through the end of September (leaf-one); otherwise they were assumed to have fallen (leaf-off).

The parameters of the BIPV system configurations include cell type (Monocrystalline [m-Si, 18.4%], Polycrystalline [p-Si, 16.3%], Copper indium gallium selenide [CIGS, 15.3%]), module orientation (portrait and landscape), and the type of inverter (central, string, micro), and three facade azimuths (East, South, West). We consider the module and inverter for the assessment of a BIPV array's embodied emissions.[1] The BIPV array was modeled using a parametric tool for BIPV modeling in McNeel's Rhino-Grasshopper that aims to minimise the number of unique modules present in a custom BIPV array. In total, the parameter combinations result in 36 scenarios for which we simulate four tree-planting scenarios: all trees, no nearby trees, no street trees, no trees. We look at multiple scenarios to see if distance plays a role in the shading impact. The results of the simulations are analysed under the three C_{grid}.

We use Radiance-based ray tracing [7] on a 5cm X 5cm sensor grid of the whole facade to create irradiance maps.[2] Four maps, for each tree scenario, are generated for each of the three azimuths. The irradiance map is interpolated to the layout of each BIPV system. From the interpolation, we simulate yield at the cell level within each BIPV module using a temperature-sensitive single-diode approach [8]. Each module in the facade array is then connected and the power output is evaluated for each of the three types of inverters (micro, string, central) following Walker et al. (2019) [9]. The yield data is evaluated alongside an hourly electricity demand profile for the building taken from a database of urban energy demand profiles [6].

Using the results of the simulation we calculate the GHG emissions avoided for the BIPV-host building based on self consumption of the generated electricity, using LCA to calculate module GWP measured in kgCO2-equivalent ($kgCO_{2e}$). The embodied carbon of the BIPV systems are calculated following Galimshina et al. (2023) [10] and we assume that they are manufactured in Europe.

This evaluation is conducted for the three C_{grid} profiles (8,760 hours) from 2019, summarised in Figure 2 [11].[3] For the trees we use the equations of McPherson et al. (2016) [4] to estimate

[1] carbon intensity of BIPV components: m-Si = 246 $\frac{\text{kgCO}_{2e}}{\text{sqm.}}$, p-Si = 202 $\frac{\text{kgCO}_{2e}}{\text{sqm.}}$, CIGS = 68.9 $\frac{\text{kgCO}_{2e}}{\text{sqm.}}$, central = 28.0 $\frac{\text{kgCO}_{2e}}{\text{kW}}$, string = 95.9 $\frac{\text{kgCO}_{2e}}{\text{kW}}$, micro = 96.8 $\frac{\text{kgCO}_{2e}}{\text{kW}}$.

[2] parameters: -ab 3 -ad 17500 -as 4096 -c 1 -dc 0.75 -dp 512 -dr 3 -ds 0.05 -dt 0.15 -lr 8 -lw 2e-07 -ss 1.0 -st 0.15

[3] The USA data comes from the Western Area Power Administration - Rocky Mountain Region

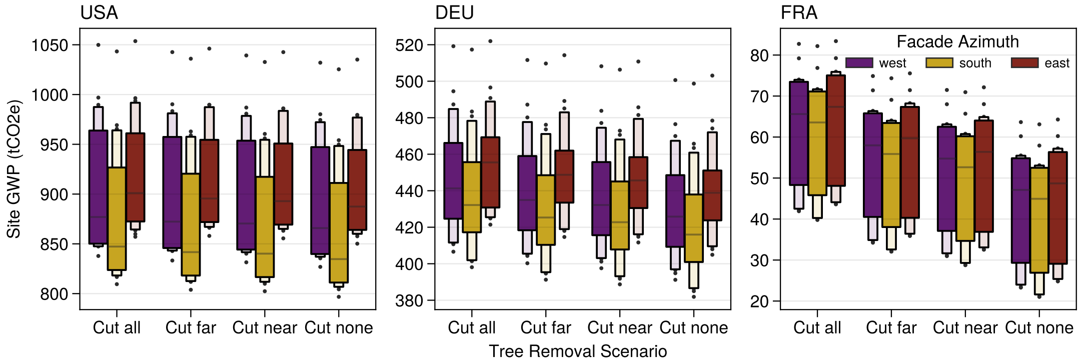

Figure 3: The distribution of the S_{GWP} for the various tree scenarios (clusters of boxes) calculated for each of the grids. Each box plot is made of a collection of the 18 BIPV configurations tested. Note that the y-axis scales differ.

above- and below-ground biomass carbon of the four trees in the study. These are allometric equations specific to tree species that are based on dry-mass volume content which is derived from height and diameter at breast-height (DBH). Nowak et al. (2008) [3] provides an estimate for DBH growth at 0.83 cm/year. Height is derived from DBH for each year, while the initial DBH is derived from the crown diameter of the modeled trees which is extracted from the initial LiDAR data. Tree initial ages were either assigned from the Zurich Tree Map or estimated from crown diameter. In the event of their removal we assume that their carbon can be considered sequestered in wood-based building materials. For trees that are not cut down, their total sequestered carbon is considered to be that of the biomass at the end of the lifetime of the PV panels. At this point they are considered to be treated the same as if they had been cut down.

3. Results & Discussion

Our hypothesis indicated that the removal of trees in the low C_{grid} would lead to a negative impact on S_{GWP} while having a positive impact in situations with a high C_{grid}. In Figure 3 we can see that the first element of this holds up. Removing the trees has the potential to influence S_{GWP}, shifting the median of the systems from around 45 $\mathrm{tCO_{2e}}$ to 64 $\mathrm{tCO_{2e}}$ under FRA C_{grid}. While the magnitude of shift is the same for the other two C_{grid}, it is much smaller, proportionally speaking, to the overall S_{GWP}. In plain terms and responding to our first research question, keeping or removing trees is not expected to be a driver of substantial change of S_{GWP} in regions with high C_{grid}, but keeping trees in regions of low C_{grid} can be expected to improve S_{GWP}.

Relative to the magnitude of shift between the tree scenarios, the analysis of different BIPV system configurations is more relevant. In Figure 4 we provide a more detailed view of how different configurations perform under the various circumstances and find that central inverter systems perform far worse than string and micro inverter systems in all but the low C_{grid}. However, in this case we observe that configurations in which the modules are oriented in the landscape format the S_{GWP} is lower for both m-Si and p-Si.

Regarding the second research question of system performance under shading we find that the systems with CIGS modules perform better across all scenarios. By looking at the S_{GWP} of each system configuration, when no trees are cut down, the CIGS system designs yield lower S_{GWP} than m-Si and p-Si; around 7% and 4% lower respectively. This is interesting as the module selected for the monocrystalline, a Half-Cut module design, is designed to be resistant to partial shading. However, our findings do have footing in the literature as thin-film modules, like CIGS, do operate better in low-light intensity situations [12]. Additionally, the capacity of a PV module to perform under partial shading is in some degree due to the existence of bypass diodes. The CIGS module, and most thin films, have more bypass didoes by design and have been shown to perform better under partial shading - particularly those positioned in the landscape format [1]. Furthermore the embodied carbon of the CIGS system is much lower than that of the monocrystalline and polycrystalline, which drives the S_{GWP} down despite the lower performance level, as shown in Figure 5.

4. Conclusion

In this paper we employed parametric analysis of BIPV system configurations and boundary conditions to assess the influence of trees near to a residential building facade on the S_{GWP}

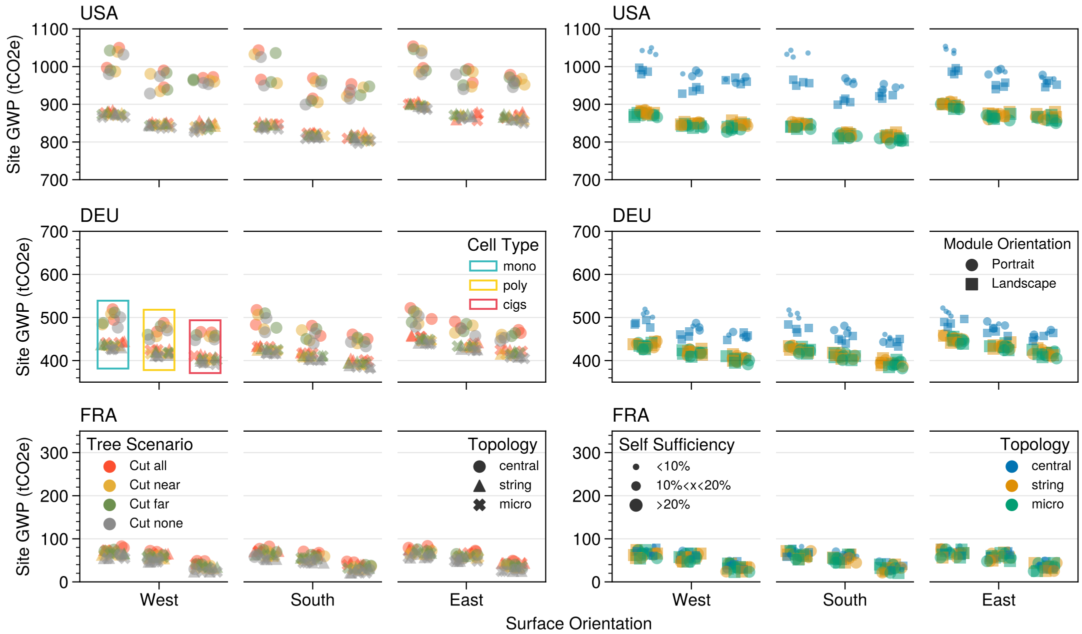

Figure 4: The results of the simulations shown for each of the three C_{grid} levels (USA, DEU, FRA). Each marker on the scatter plots indicates a simulation result of a BIPV system configuration. Note that the left and right sets of plots present the same results but in a different form. In each plot, for each surface orientation, the data points are organized such that the leftmost column are monocrystalline systems, the middle are polycrystalline, and the right-most CIGS.

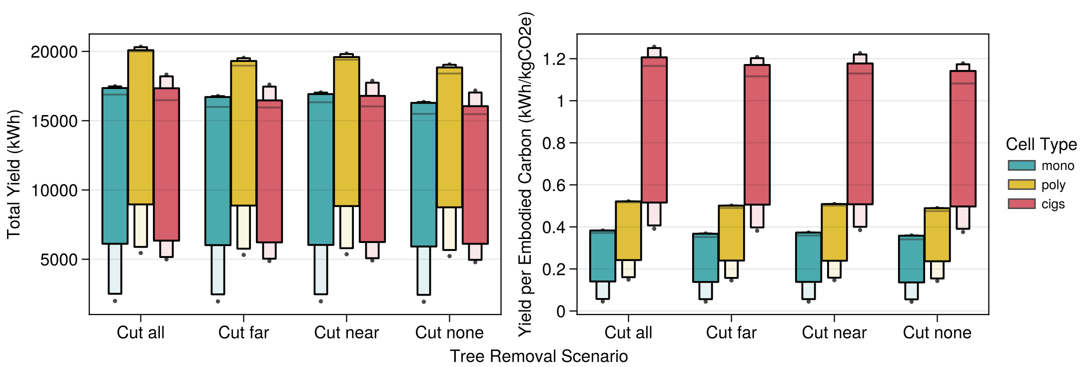

Figure 5: A comparison of total yield to the total yield per kg of embodied carbon in the system for each system organized by cell type under each of the tree scenarios for the south facing facade.

over the lifetime of the BIPV system. We found that the trees are not as influential on S_{GWP} as other boundary conditions such as regional C_{grid} or input conditions such as the embodied carbon of a module. We find that in no situation is it sensible from a S_{GWP} standpoint to remove trees. However, some observations may be due to the building type (i.e. residential), which is associated with low self-sufficiency and the need to match consumption to production on an hourly basis. This can be connected with the selected method of allocating the carbon savings of the BIPV electricity production. Lastly, we witnessed that the metric by which you evaluate the performance of a BIPV system can change which system you may select as embodied carbon can have a mitigating effect for a system's performance despite lower base conversion efficiency values.

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