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A Critical Review of Carbon Footprint and Life Cycle Assessment of Building Integrated Photovoltaic (BIPV) Panels and Systems

MASTER'S DEGREE THESIS IN BUILDING AND ARCHITECTURAL ENGINEERING

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1. Executive Summary

This thesis critically reviews the carbon footprint and life-cycle assessment (LCA) of Building-Integrated Photovoltaic (BIPV) panels and systems, with a specific focus on embodied carbon and the methodological challenges that affect comparison between studies. BIPV systems are important for low-carbon building design because they combine two functions: they generate renewable electricity and replace conventional building-envelope materials such as façade cladding, glazing, curtain walls, or roofing elements. However, this multifunctional role also makes their environmental assessment more complex than conventional photovoltaic systems or ordinary construction materials.

The research is motivated by the increasing need to reduce both operational and embodied emissions in the building sector. As electricity grids become cleaner and buildings become more energy efficient, embodied carbon becomes a larger part of total environmental impact. For this reason, assessing BIPV only through operational electricity generation is not sufficient. A complete evaluation must include raw material extraction, manufacturing, transport, installation, maintenance, replacement, end-of-life treatment, recycling, and possible avoided impacts from substituted building materials.

The thesis adopts a literature-based comparative LCA approach. Recent peer-reviewed studies, case studies, and Environmental Product Declaration-based data were collected and organized into a structured database. The reviewed studies include different BIPV and PV technologies, building applications, geographical contexts, system boundaries, and component scopes. Particular attention is given to studies published after 2021, because PV technology, manufacturing processes, LCA databases, and electricity mixes are changing rapidly.

A key methodological contribution of the thesis is the harmonization of different carbon footprint results into a common functional unit: kg CO_2-eq/kWp. This allows systems of different sizes and capacities to be compared more consistently. Since the reviewed studies used different units. According to EN 15804 and EN 15978, life-cycle stages: A1–A3 for production, A4 for transport, A5 for installation, B for use and replacement, C for end-of-life, and D for benefits beyond the system boundary, such as recycling credits. Module D is reported separately to avoid mixing direct life-cycle impacts with external benefits.

The results show that the product stage A1–A3 is the dominant contributor to the carbon footprint of BIPV and PV systems. In many cases, manufacturing represents more than 90% of embodied emissions. This is mainly due to energy-intensive processes such as polysilicon production, wafer manufacturing, cell production, module assembly, glass production, and aluminum processing.

Transport, installation, use-stage impacts, and end-of-life burdens are usually smaller, although they become more relevant when full-system components, inverter replacement, or heavy mounting structures are included.

The harmonized carbon footprint values generally range from about 0.8 to 1.7 tCO_2-eq/kWp, depending on system scope, balance-of-system inclusion, manufacturing location, electricity mix, and end-of-life assumptions. Module-only systems tend to show lower and more consistent values, while full-system assessments show wider variability because they include inverters, cables, mounting structures, substructures, and other supporting elements. The analysis shows that balance-of-system components can significantly increase total impacts, especially in BIPV systems where structural integration is more complex than in conventional rooftop PV.

The thesis also highlights the importance of Module D recycling credits. When recycling or material recovery is included, net carbon footprint values can be reduced by several hundred kg CO_2-eq/kWp. However, the size of this reduction depends on assumptions about recovery rates, recycling technologies, allocation methods, and material composition. Façade BIPV systems may have higher end-of-life burdens due to complex integration, but they can also receive larger recycling credits because of recoverable materials such as glass and aluminum. For this reason, the thesis recommends reporting both gross values excluding Module D and net values including Module D.

Another important finding is the effect of manufacturing geography and electricity mix. Since PV manufacturing is energy intensive, the carbon intensity of the electricity used during production strongly affects embodied emissions. Scenario comparisons show that shifting production from carbon-intensive supply chains, such as coal-based manufacturing, to lower-carbon European or Norwegian contexts can reduce embodied emissions by approximately 19–37%. This confirms that cleaner manufacturing of electricity and transparent reporting of production location are essential for reducing BIPV carbon footprints.

The comparison between rooftop and façade applications shows that integration type strongly influences performance. Rooftop systems usually have better solar exposure and higher electricity yield, while façade systems may generate less electricity due to vertical orientation, shading, or architectural constraints. However, façade BIPV can still be environmentally beneficial when it replaces carbon-intensive façade materials. Therefore, BIPV should be assessed using multiple indicators, including kg CO_2-eq/m^2, kg CO_2-eq/kWp, g CO_2-eq/kWh, and payback indicators such as Energy Payback Time.

The thesis concludes that BIPV systems can contribute significantly to low-carbon building strategies, but their benefits are highly context-specific. The main drivers of carbon footprint are manufacturing stage, electricity mix, component scope, BOS design, integration type, lifetime assumptions, and end-of-life treatment. The study recommends more transparent and standardized reporting in future BIPV LCAs, including clear functional units, system boundaries, component inclusion, lifetime, degradation, electricity yield, manufacturing location, and Module D assumptions. Overall, the thesis provides a harmonized framework that improves comparability across studies and supports better design and policy decisions for low-carbon BIPV systems.