Wood Waste Management in Europe and the Łódzkie Region: LCA, LCC and S-LCA analysis

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Europe has been facing a significant wood waste challenge. In 2020, the EU-27 generated approximately 48.3 million tonnes (Mt) of wood waste, of which only ~3.9% was classified as hazardous. The Łódzkie region of Poland is a representative case of these challenges and opportunities. As a hub for forestry and wood-processing (furniture factories, sawmills, paper mills), Łódzkie generates a substantial volume of wood waste. A significant portion comes from wood packaging (pallets, crates, etc.), much of which is often discarded after single use or due to minor damage. Studies estimate that if wood packaging waste were systematically collected and refurbished, up to 4,500 tonnes per year of wood materials could be given a second life in the Łódzkie region. Such recovery would create new economic opportunities (e.g. low-cost furniture production and jobs in repair/refurbishment) and reduce demand for virgin timber.

This study presents a comprehensive analysis of the environmental, economic, and social impact assessment of a circular solution for wood waste management in the Łódzkie region. In particular, this work has been developed in the context of the FRONTSH1P project (Horizon 2020, GA No. 101037031), which aims to implement circular, holistic, and inclusive territorial economy solutions for waste valorisation via four different Circular Systemic Solutions. As part of this effort, Circular Systemic Solution 1 (CSS1) addresses wood packaging waste. CSS1 approach seeks to move away from landfilling or one-time use, and instead maximize reuse, recycling, and energy recovery from wood waste. CSS1 integrates multiple innovative processes to valorise wood waste – from mechanical refurbishment of wood products to advanced thermal conversion and carbon capture. This integrated solution contributes to the circular economy by closing material loops (giving materials like wood a second life) and by linking with other systemic solutions (for instance, captured CO_2 can be utilized in other industrial processes, creating symbiotic value chains).

The primary objective of this study is to evaluate the Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) methodologies applied to CSS1 and estimate the potential reduction in carbon footprint for each CSS1 scenario pinpointing "hotspots" for improvement.

An LCA was performed to quantify the environmental impacts of each CSS1 scenario across its entire life cycle – from wood waste collection and processing, through production of outputs (furniture, energy, CO_2, char), up to end-of-life or final disposal of any residues. The LCA follows ISO 14040/14044 principles, encompassing goal and scope definition, inventory data collection, impact assessment, and interpretation. Sphera LCA software and databases (e.g. ELCD) were used to model processes and baseline (linear) alternatives. The functional unit is defined as the treatment of 1 tonne of wood packaging waste, providing a common basis to compare scenarios. Impact categories evaluated include global warming, acidification, eutrophication, various ecotoxicity metrics, resource depletion, water use, and others, using CML 2001 and EN 15804+A2 indicators. A LCC analysis was undertaken to assess the economic performance of CSS1 from a cradle-to-grave perspective. This approach tallies all relevant costs incurred over the life cycle of each scenario, including initial capital investments (CAPEX), operating and maintenance costs (OPEX), and end-of-life or disposal costs, as well as any revenues or savings (e.g. from energy sold or products created). The analysis follows the EU's definition of LCC (Directive 2014/24/EU, Article 68) and relevant standards, accounting not only for direct costs of acquisition and operation, but also externalities where monetizable (such as the cost of greenhouse gas emissions). The LCC was carried out over a 20-year time horizon, reflecting a typical project lifetime for such installations, and using discounted cash flow to compute net present costs. To complement the environmental and economic analysis, a Social LCA was conducted, evaluating the social and socio-economic impacts across the stakeholder groups influenced by the system. The S-LCA methodology adheres to the UNEP/SETAC Guidelines for Social Life Cycle Assessment of Products (2009), extending the ISO 14040/44 framework to include social aspects. It considers the life cycle stages of wood packaging waste management and assesses impacts on five main stakeholder categories: Workers, Consumers, Local Community, Society, and Value Chain (Supply Chain) Actors. For each stakeholder group, relevant impact sub-categories were examined (e.g. occupational health and fair wages for workers, community well-being and local employment for communities, etc.), using a combination of quantitative and qualitative indicators gathered via questionnaires and case studies.

To evaluate CSS1's performance, three scenarios are defined that reflect different waste-valorisation pathways:

- Scenario 1 – "Furniture and Wooden Goods" (Reuse): This scenario prioritizes material reuse. Wood packaging waste (pallets, etc.) is collected and repaired or repurposed into new object or furniture pieces, extending the product life cycle.

- Scenario 2 – “Electrical and Thermal Energy Production and CO_2 Capture” (CHP & CCS): In this scenario, wood waste is used for energy recovery. Waste wood is processed into pellets and gasified, and the syngas is used in a Combined Heat and Power (CHP) plant to generate electricity and thermal energy. Importantly, it incorporates Carbon Capture and Storage (CCS) to trap CO_2 from the process, preventing emissions from entering the atmosphere.
- Scenario 3 – “Thermal Energy Production and CO_2 Capture” (Syngas combustion & CCS): This scenario is another energy-focused pathway, similar in intent to 1.2 but using a different technology mix. Wood waste is pelletized, gasified and then combusted to produce thermal energy. As in Scenario 1.2, a CCS system is employed to capture the CO_2 from flue gases.

The analysis of all three provides a comprehensive view of how different approaches trade off environmental benefits, economic costs, and social impacts, thereby informing the optimal strategies for wood waste management in a circular economy. All analyses were conducted in accordance with relevant international standards and guidelines to ensure consistency and credibility.

Regarding the results, CSS1 demonstrates significant sustainability benefits across environmental, economic, and social dimensions. The LCA reveals that Scenario 2 and 3 achieved net-negative Global Warming Potential (GWP) values, acting as carbon sinks by displacing fossil fuel use and capturing CO_2, while Scenario 1reduced GWP but remained slightly positive due to processing emissions. Scenario 2 also showed the lowest Acidification Potential (AP) at –0.95 kg SO_2 eq., significantly reducing acidifying emissions, whereas Scenario 3 had a slightly higher AP due to combustion byproducts. Eutrophication (EP) was minimized in Scenario 2 (–0.099 kg PO_4 eq.), outperforming the baseline (1.72×10^{-1} kg PO_4 eq.), while Scenario 1 and 3 reduced but did not invert eutrophication impacts. Regarding resource use, 2 and 3 achieved net-negative Abiotic Depletion values, meaning they saved more non-renewable resources than they consumed, while Scenario 1 showed the highest fossil fuel depletion (~12,700 MJ per fu) due to energy-intensive refurbishment.

According to the LCC analysis, the baseline scenario remains the lowest-cost option (~€373 million over 20 years), whereas CSS1 scenarios implementation increases costs due to infrastructure and operational expenditures. Among the alternatives, Scenario 1 had the lowest cost (2.93 billion), while Scenarios 2 and 3 required higher investments (~€4.34 billion and €4.27 billion, respectively) due to the need for palletisation, CHP plants, and CCS equipment. However, Scenarios 2 and 3 generated energy revenue, demonstrating potential long-term financial viability.

The S-LCA highlights positive social outcomes, workers and local communities. CSS1 implementation increased worker satisfaction scores from ~4.25 to 4.59 (out of 5) and consumer satisfaction from 2.68 to 3.66 due to improved recycling rates and end-of-life safety. Local employment and community engagement improved, as more spending was directed toward locally. Minor gaps were identified, such as the absence of a formal environmental management system. The supply chain impact remained neutral, meaning CSS1 did not negatively affect existing supplier relationships, CSS1 provides strong environmental benefits, moderate economic trade-offs, and positive social impacts, with emerging as the most balanced option due to its superior environmental performance and energy recovery potential. Policy incentives, cost optimizations, and technological improvements could further enhance the feasibility and scalability of these circular economy solutions.

CSS1 demonstrates a viable pathway for transforming wood waste from a disposal problem into a resource opportunity. The extended analysis shows that through a combination of reuse, energy recovery, and carbon capture, it is possible to drastically reduce the carbon footprint and environmental impacts of wood packaging, create economic value (especially when supported by the right market conditions), and enhance social well-being in the process. These outcomes strongly support the principles of the circular economy – keeping materials in use, regenerating natural systems, and doing so in an inclusive way. For policy makers and industry stakeholders, the findings underscore that investing in circular systemic solutions can deliver multidimensional benefits, but strategic support is needed to overcome initial cost hurdles and technical challenges. The recommendations provided aim to align policy and research efforts with the needs identified in the study: boosting recovery technologies, facilitating waste supply chains, and incentivizing circular products. By implementing such measures, regions like Łódzkie, and indeed the EU as a whole, can accelerate towards their sustainability targets, turning front-runner demonstrators like FRONTSH1P CSS1 into mainstream practices. While upfront costs are high, the long-term advantages in emissions reduction, energy recovery, and circular material flows justify the investment. Further research is recommended to enhance scalability and regional adaptability.