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Integration of Circular Systemic Solutions for Wood and Plastic Waste Valorisation in the Production of Insulation Materials: An Environmental/Sustainability Assessment

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Abstract

This study presents an environmental and circularity assessment of an integrated insulation-production system that valorises plastic waste and wood packaging waste as secondary material and energy resources. The analysis evaluates the recovery of incoming waste streams and their reintegration into a new production cycle, while the downstream end-of-life of the resulting insulation product remains outside the assessed system boundary. The process chain includes mechanical pre-treatment of wood (grinding, metal separation, and pelletising); thermochemical conversion via wood gasification and gas combustion; and post-combustion CO_2 capture. The captured CO_2 is used in the subsequent polymer processing stages, which comprise mixing, extrusion, thermal treatment, and cooling. Environmental impacts are evaluated through Life Cycle Assessment (LCA), while circularity indicators are assessed within the framework of EN 15804+A2. The results demonstrate the environmental and circularity potential of valorising wood packaging and plastic waste in the context of carbon capture and utilisation (CCU) and sustainable material development.

Keywords: wood packaging waste; plastic waste valorisation; insulation materials; circular economy; life cycle assessment; carbon capture and utilisation; gasification; environmental assessment

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1. Introduction

The global production of plastics has increased steadily over the past decades, raising growing concerns due to the intensive use of fossil resources and the associated environmental impacts [1]. Conventional plastics are predominantly produced from primary raw materials derived from fossil resources, following a largely linear production model characterised by high energy consumption, significant greenhouse gas (GHG) emissions, and substantial waste generation [2]. In 2022, global plastic production reached approximately 400.3 million tonnes, with Europe accounting for about 14% of this total (58.7 million tonnes). The majority of this production remains fossil-based (47.2 million tonnes), while only a limited share originates from post-consumer recycled plastics (7.7 million tonnes) and bio-based plastics (0.4 million tonnes) [3].

The environmental implications of plastic production are considerable. Within the European Union (EU), plastics production accounts for approximately 9% of fossil gas consumption and represents a significant share of emissions within the chemicals sector [4]. Annual emissions related to plastics production in the EU amount to around 13.4 million tonnes of CO_2, corresponding to nearly 20% of the chemicals industry's emissions [5]. When considering the entire plastics value chain, total GHG emissions in the EU were estimated at approximately 193 million tonnes of CO_2 equivalent in 2022 [4]. Most of these emissions originate from the production phase itself (63%), followed by polymer conversion into products (22%) and end-of-life treatment of plastic waste (15%), mainly due to incineration.

Plastic production is also characterised by high energy requirements. For instance, the production of polyethylene terephthalate (PET) requires significant primary energy inputs, with European plants consuming on average 37.1 MJ/kg as fuel energy and 34.1 MJ/kg as raw material energy. Overall, the total primary energy demand associated with the production of virgin PET and its conversion into packaging products ranges between 109.2 and 115.2 MJ/kg, highlighting the energy-intensive nature of conventional polymer production processes [6].

Despite these impacts, plastics continue to experience a growing demand due to their favourable functional characteristics, including their lightweight properties, versatility, durability, and resistance to corrosion and chemicals [7]. These properties make plastics essential materials across a wide range of sectors. In 2022, packaging represented the largest share of plastic demand (39%), followed by the building and construction sector, which accounted for approximately 23% of total plastic use [3]. The construction sector, therefore, represents one of the most important application areas for plastic materials and a key domain in which improvements in material sustainability could lead to significant environmental benefits.

The building sector widely uses plastics in applications such as pipes, membranes, window frames, coatings, and insulation materials. Among these, thermal insulation plays a particularly important role in improving building energy efficiency. Insulation materials reduce heat losses in the winter and heat gains in the summer, thereby lowering the energy demand associated with heating and cooling during the operational phase of buildings. As a result, they represent a crucial component in strategies aimed at reducing the environmental footprint of the built environment.

The importance of insulation materials has increased significantly recently due to stricter energy efficiency regulations and climate targets for buildings [8]. Consequently, demand for insulation materials is expected to grow steadily. In Europe, the insulation market is projected to increase by approximately 3.1% annually, reaching €22.04 billion by 2028, while demand in volume terms is expected to grow to approximately 6.6 million metric tonnes [9]. Although insulation materials contribute substantially to reducing operational energy consumption in buildings, their environmental impacts during the production phase are becoming increasingly relevant as building energy efficiency improves [10].

With the rising need for sustainability and growing energy efficiency, the impact of insulation requires attention on both material choice and process/system integration throughout the entire life cycle. A wide range of insulation materials is currently available, including inorganic materials, fossil-based polymeric materials, and renewable-based alternatives. Commonly used materials include expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (PUR), glass wool, and stone wool. Comparative studies indicate that these materials exhibit varying environmental performances [8]. EPS, glass wool, and stone wool generally present similar environmental impacts and tend to perform better than materials such as XPS and PUR. Renewable-based alternatives such as cellulose and hemp are often associated with lower environmental burdens, although this is not always the case, as demonstrated by materials such as cork.

Another widely used category of insulation materials consists of flexible elastomeric foams (FEFs), which are typically based on synthetic rubber blends such as nitrile butadiene rubber (NBR) combined with polyvinyl chloride (PVC) [11]. These materials are commonly used for insulation of refrigeration and chilled water pipe systems due to their closed-cell structure and excellent condensation control properties. However, their production remains heavily dependent on fossil-derived raw materials and energy-intensive processes. Manufacturing processes significantly influence the environmental performance of insulation systems, beyond just material selection. Industrial production often generates waste streams, chemical by-products, and emissions that contribute to environmental degradation if not properly managed. Consequently, reducing the environmental footprint of plastic-based insulation materials requires improvements not only in material selection but also in resource efficiency and production technologies. Therefore, implementing integrated solutions for the systemic valorisation of waste across the entire life cycle is essential to developing low-impact materials.

In 2022, the EU generated an estimated 186.5 kg of packaging waste per capita, with plastics and wood packaging comprising substantial shares [12]. These waste streams can be strategically redirected into the production of insulation materials. In particular, conventional plastic manufacturing from virgin polymers and filler feedstocks can be replaced by processes that valorise both plastic waste (as a material) and wood packaging waste (as a source of materials and energy), offering a more resource-efficient and sustainable alternative. In this context, circular economy strategies are increasingly recognised as key approaches to reducing the environmental impact of plastic production. The circular economy promotes resource efficiency through waste reduction, recycling, and the continuous valorisation of materials within production cycles [13]. Although recycling rates have increased steadily over the past decades—from 25.2% in 2005 to 40.7% in 2022—large quantities of plastic waste remain underutilised as potential secondary resources [14]. Simultaneously, other waste streams, like wood packaging waste, also serve as valuable resources that could integrate into industrial production systems. Redirecting these waste streams into industrial processes could contribute to reducing reliance on virgin raw materials and fossil-based energy sources.

In this context, technical innovations are already being implemented. For instance, in Europe, high-GWP blowing agents for insulation materials are now prohibited and have been replaced by low-GWP alternatives to minimise emissions and mitigate climate change [15]. Apart from the positive impact on the environment, it must be noted that lower chemical consumption leads to lower production costs as well as higher safety due to reduced concentration of flammable gases during the degassing/storing phase [16]. The sustainable development trend, which is still increasing nowadays, should motivate engineers to thoroughly consider the adopted solutions. In line with these objectives, the Horizon 2020 FRONTSH1P project has developed several circular systemic solutions (CSS) aimed at promoting waste valorisation and resource circularity in industrial systems [17]. The present study investigates the integration of two of these solutions, namely CSS1 and CSS4, in the production of FEF insulation materials. While CSS4 focuses on the valorisation of plastic waste as a material input, CSS1 targets wood packaging waste as a source of both thermal energy and secondary materials [18]. In particular, the research explores the potential of CO_2 mitigation through post-combustion gas treatment and CO_2 utilisation within polymer processing through improved process integration and energy efficiency. In this integrated circular approach, wood packaging waste is gasified to produce thermal energy for the manufacturing process, the resulting char is used as a filler to replace conventional carbon black, and the CO_2 generated during combustion is used as a foaming agent in the insulation production.

This study aims to compare the proposed alternative production approach with the conventional method by evaluating both environmental and technical performance indicators utilising data collected throughout the FRONTSH1P project and during the implementation of the CSSs. For this purpose, two cradle-to-factory-gate (CtFG) scenarios (baseline and proposed solution) are assessed via Life Cycle Assessment (LCA). Several midpoint environmental indicators are used, including Global Warming Potential (GWP), Ozone Layer Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), and abiotic resource depletion. In addition, resource use and waste-flow indicators reported under EN 15804+A2 [19] are applied to evaluate the circularity-related performance of the assessed material and energy flows [20]. The results of this work reveal insights into the environmental and circularity benefits associated with the integration of plastic and wood packaging waste valorisation within carbon capture and utilisation (CCU) frameworks, contributing to the development of more sustainable insulation materials and circular production systems for the industrial sector.

2. Materials and Methods

2.1. LCA Methodology

To assess the environmental impacts of the integrated process that valorises wood packaging and plastic waste for the production of insulation material and compare it with common practices, a LCA was performed. The study followed the standardised procedures described in ISO 14040:2006 and ISO 14044:2006/A1:2018, as well as the guidelines of the International Life Cycle Data (ILCD) Handbook [21–23]. The LCA framework comprises four main stages: (1) the goal and scope definition, (2) the Life Cycle Inventory (LCI), (3) the Life Cycle Inventory Assessment (LCIA) and (4) the interpretation of the results. The analysis of the investigated scenarios was conducted using the commercial software package Sphera LCA for Experts [24].

2.2. Goal, Scope, and Functional Unit

The goal of the LCA for this study is to evaluate the environmental performance of the insulation material produced through the valorisation of both wood and plastic waste and compare it with commercial products. The proposed scenarios were developed using data on raw materials, energy and water consumption, and emissions collected during the implementation of CSS1 and CSS4 in the FRONTSH1P project. All process steps were considered, from the mechanical pre-treatment of wood and thermochemical conversion via gasification and combustion to CO_2 capture and its subsequent utilisation in polymer mixing and extrusion. The dataset was supplemented with relevant literature and information from the Sphera LCA for Experts database. The functional unit (FU) that represents the reference quantity of the product for the assessment was defined as 1 m^3 of the produced insulation material.

2.3. Scenario Descriptions and System Boundaries

For this study, two main production scenarios were developed. Scenario 1 represents conventional fossil-based FEF insulation production and is used as the baseline for comparison. A conventional FEF is considered a representative baseline reference case referred to as Scenario 1—conventional FEF baseline, based on K-FLEX® ST/K-FLEX® ST PLUS [25]. The baseline case follows the general production route of compounding, extrusion, foaming, cooling, finishing, and packaging. Scenario 2 represents the proposed circular integrated system, in which wood packaging waste and plastic waste are valorised through gasification, energy recovery, CO_2 capture and utilisation, and substitution of selected virgin inputs.

The system boundaries define the processes included in the assessment. Both scenarios follow a cradle-to-factory-gate (CtFG) perspective covering raw material extraction and supply (A1), transportation of materials to the production facility (A2), and manufacturing processes (A3). Product transport to the construction site, installation, use, and downstream end-of-life treatment are outside the assessed system boundary.

Scenario 1 represents the conventional production of FEF insulation based primarily on virgin fossil-derived polymeric inputs. The system includes raw material supply, transportation and the principal manufacturing stages, including compounding, extrusion, furnace foaming, cooling, finishing and packaging. The formulation and process inventory are based on the K-FLEX® ST/K-FLEX® ST PLUS reference product provided by K-FLEX Polska Sp. z o.o. from Uniejów, Poland. The system boundary for Scenario 1 is presented in Figure 1.

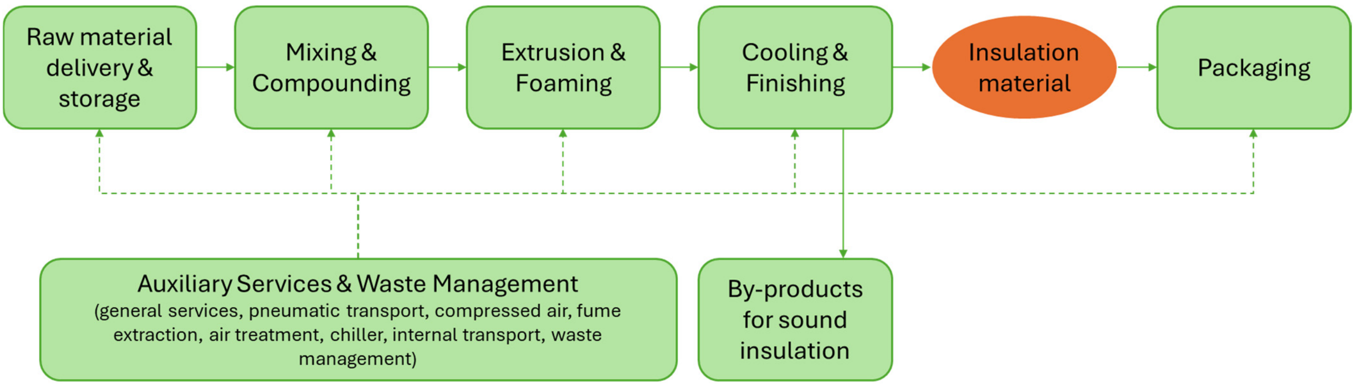

Figure 1. Scenario 1 workflow—conventional FEF baseline.

Regarding the Scenario 2 system boundaries, this study adopts a CtFG perspective. Stages related to product use (B), end-of-life treatment of the insulation material (C1–C4), and any potential benefits or burdens beyond the system boundary (Module D) are not considered in the present assessment. Wood packaging waste (disused pallets in this case) is first pre-treated through grinding and metal separation and then pelletised to feed a commercial rising co-current stationary fluidised-bed gasifier (mass flow rate of 40 kg/h), provided by Burkhardt GmbH operating with pellets and air as the gasifying agent. The scheme of gasification plant is provided by Benedetti et al. [18]. The produced gas with a stable composition, 1.90% CH_4, 18.50% H_2, 8.85% CO_2, 22.20% CO, 7.40% H_2O, and 41.15% N_2 is combusted, and the resulting heat is used in other process steps. The coupling of the gasifier with the combustion rig is presented by Qureshi et al. [26]. The flue gases are subsequently directed to a post-combustion CO_2 capture system based on monoethanolamine, and the captured CO_2 is used as a foaming agent [27]. The captured CO_2 has a purity of 99.9% and is used directly as a foaming agent without additional purification.

Plastic waste is used in place of virgin material, while char collected from the gasification of wood packaging waste serves as a secondary filler material, replacing conventional fossil-based materials such as carbon black that are widely used in elastomeric insulation products. The blended mix is then conveyed to an extruder for melting and shaping, after which thermal foaming occurs in the combustion/oven [28].

Plastic waste and discarded wood packaging are treated as inputs to the production system. The thermal energy, char, and captured CO_2 generated from wood waste processing are used internally in insulation production, replacing conventional heat, filler/pigment materials, and foaming agents. Environmental benefits are accounted for through avoided-input credits. As these recovered flows remain within the system and are not sold as co-products, no allocation is applied. The system boundaries for Scenario 2 are shown in Figure 2.

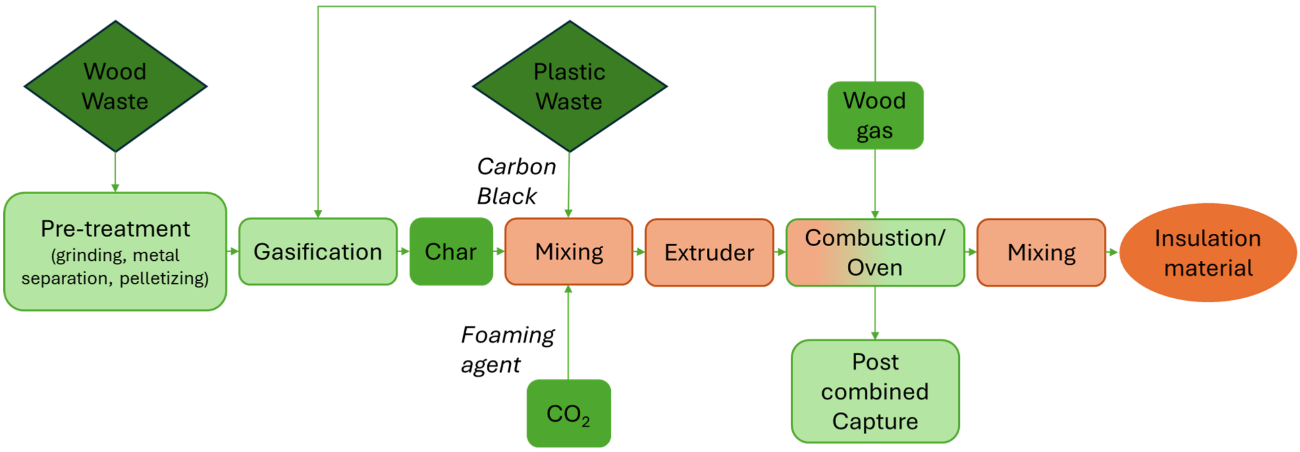

Figure 2. Scenario 2 workflow—circular integrated system.

2.4. Life Cycle Impact Assessment

The LCIA quantifies the environmental impacts of the inventory data by applying relevant impact category factors and following the guidelines of ISO 14040 [21] and ISO 14044 [22]. In this study, seven impact categories were selected to evaluate the environmental performance of the proposed system. These include the GWP reduction potential of each scenario and the overall environmental impacts related to air emissions and other impact categories that are summarised in Table 1. Higher values within specific impact categories highlight the environmental "hot spots" of the integrated process.

Table 1. Evaluated LCIA impact categories.

Impact Category	Indicator	Unit
Climate Change	Global Warming Potential (GWP) EN15804+A2 (EF 3.1)	kg CO_2 eq.
Ozone Layer Depletion	Ozone Depletion Potential (ODP) EN15804+A2 (EF 3.1)	Kg CFC-11 eq.
Acidification	Acidification Potential (AP) EN15804+A2 (EF 3.1)	Mole of H+ eq.
Eutrophication	Eutrophication Potential (EP) EN15804+A2 (EF 3.1)	kg P eq.
Photochemical Ozone Creation	Photochemical Ozone Creation Potential (POCP) EN15804+A2 (EF 3.1)	kg NMVOC eq.
Abiotic resources	Depletion of abiotic resources (elements)	kg Sb eq.
Abiotic resources	Depletion of abiotic resources (fossil)	MJ
Circularity Indicator	Resource use	MJ
Circularity Indicator	Output and waste	kg

It is noted that human-toxicity and freshwater-ecotoxicity indicators were outside the defined scope of the present assessment, which focused on waste-stream valorisation, industrial decarbonisation, resource efficiency and waste optimisation; consequently, no conclusions are drawn regarding the comparative toxicity performance of the investigated insulation formulations.

Resource use and waste-flow indicators were assessed within the EN 15804+A2 reporting framework using characterisation factors aligned with the Environmental Footprint 3.1 methodology. The assessment is restricted to the A1–A3 system boundary. The recovered internal flows directly replace equivalent conventional inputs within the A1–A3 product system; therefore, the inventory includes the reduced quantities of conventional heat, filler and foaming-agent inputs [20]. Specifically, the LCIA considered a set of resource use and output flow-waste indicators. Resource use indicators included renewable and non-renewable primary energy (PERE, PERM, PERT, PENRE, PENRM, PENRT), secondary materials and fuels (SM, RSF, NRSF), and fresh water (FS), capturing the total demand on natural resources throughout the building material system. Output flow and waste indicators considered in this study include hazardous waste disposed (HWD), non-hazardous waste disposed (NHWD), and radioactive waste disposed (RWD). In addition, indicators related to circularity were included, such as components prepared for reuse (CRU). All these indicators are summarised in Table 2.

Table 2. Standardised resource use indicators and output flows and waste indicators.

Impact Category	Indicator	Unit
Resource use	Use of renewable primary energy excluding renewable primary energy resources used as raw materials (PERE)	MJ
Resource use	Use of renewable primary energy resources used as raw materials (PERM)	MJ
Resource use	Total use of renewable primary energy resources (PERT)	MJ
Resource use	Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials (PENRE)	MJ
Resource use	Use of non-renewable primary energy resources used as raw materials (PENRM)	MJ
Resource use	Total use of non-renewable primary energy resources (PENRT)	MJ
Resource use	Use of secondary material (SM)	kg
Resource use	Use of renewable secondary fuels (RSFs)	MJ
Resource use	Use of non-renewable secondary fuels (NRSFs)	MJ
Resource use	Use of net fresh water (FW)	m^3
Output flows and waste	Hazardous waste disposed (HWD)	kg
Output flows and waste	Non-hazardous waste disposed (NHWD)	kg
Output flows and waste	Radioactive waste disposed (RWD)	kg
Output flows and waste	Components for reuse (CRU)	kg

To identify the main environmental and resource use contributors, a contribution-based hotspot analysis was performed, examining the effects of key assumptions such as material composition, water use, process, natural gas, electricity and components prepared for reuse. This analysis allowed the identification of the most influential parameters on resource efficiency and circularity performance, highlighting the improvements in material selection, waste valorisation, or energy use that could have the greatest impact.

3. Life Cycle Inventory

The LCI identifies and includes the input and output data of the system, including the mass, energy and emissions. Data for the analysis mostly derive from industrial measurements from an East European region found in the Sphera LCA for Experts. When database data for specific processes is unavailable, literature sources are consulted.

3.1. Inventory Data for Baseline Conventional FEF Insulation Scenario

In Scenario 1, the insulation material is suitable for all applications both civil and industrial that require the use of insulation material, without neglecting the price/quality relationship: refrigeration, air-conditioning, heating and plumbing, tanks, pipe fittings and water ducts. The product consists of several components as shown in Table 3.

Table 3. Materials involved in Scenario 1: conventional FEF baseline.

Product Materials	%*w*/*w*	kg
Polymers	21.60	10.00
Fillers	37.80	17.60
Plasticiser	20.10	9.30
Chemical additive (vulcanisation agents)	11.30	5.30
Others	9.20	4.30
Packaging paperboard	16.80	7.80
Pallet	9.90	4.60

The weighted gross density is considered 46.5 kg/m^3. As regards the flows and energy, a declared unit is defined as 1 m^3 of thermal insulation product, including packaging. Raw materials are first weighed in the warehouse according to the specific production recipe. The measured ingredients are then mixed in a mixer and processed in a roll mill to complete the formation of the masterbatch. All components are combined with the masterbatch in the mixer and again passed through the roll mill. Small samples are taken at this stage for quality control. Once cooled, the final batch is transferred to the extrusion area, where the material is extruded into the required shape and dimensions. The extruded rubber moves directly into the oven for vulcanization and foaming. Then, it is cooled in a water bath and dried in a dedicated tunnel. Before packaging, the material undergoes ink printing and is cut to the specified lengths. Throughout the entire production process, small samples of the finished product are regularly collected for continuous quality checks.

3.2. Life Cycle Inventory of the Integrated Circular FEF Insulation Production Scenario

In Scenario 2, the insulation material consists of several components, summarised in Table 4. The plastic waste used in this study was sourced from the Łódzkie region of Poland and entered the insulation manufacturing process through the local collection and recovery network. According to the industrial data available for the assessment, the material consisted of a processed plastic waste fraction considered suitable for use in the production of flexible elastomeric foam. More detailed information regarding the distribution of polymer types and the degree of contamination was not provided in the dataset.

Table 4. Materials involved in Scenario 2—circular integrated system.

Product Materials	%*w*/*w*	kg
Polymers	25.39	11.81
Fillers	36.81	17.12
Plasticizer	1.48	0.69
Chemical additive (vulcanisation agents)	2.94	1.37
Others	33.38	15.52

All these components add up to a total of 46.5 kg/m^3 weighted gross density. During stages A1–A3, the process requires 38.95 kWh of electricity, 36.49 kWh of natural gas and 95.3 kg of tap water for the manufacturing of 1 m^3 insulation material. More specifically, plastic waste and char from the process of CSS1 were incorporated at a proportion of 3.7% (18.4 kg) while the foaming agent CO_2 was used at 11.5% (44 kg). In addition, wood waste amounting to 8.31 kg was utilised in the process. The internally recovered thermal energy substituted 34.3 kWh of conventionally supplied thermal energy from natural gas, and the corresponding avoided input was represented as an environmental credit in the model. The Sphera model developed is presented in Figure A1. The detailed system assembly, unit allocations, and interconnected material/energy flow loops within the software environment are visually presented in the Sphera models in Appendix A.

Within Table 4, the recycled plastic fraction is included under "Polymers", the gasification char is included under "Fillers", and the captured CO_2 used during foaming is represented within the process inventory rather than as a retained component of the final product mass.

4. Results

The LCIA outcomes for the two scenarios described are presented in Tables 5 and 6. For Scenario 1 representing the conventional FEF reference product, the total life cycle GWP was 190 kg CO_2 eq. per functional unit of 1 m^3 while the following environmental impacts were obtained. Scenario 1 showed higher impacts in selected categories, particularly climate change, photochemical ozone creation potential, and abiotic depletion of elements, suggesting that improvements in climate-related indicators may be accompanied by trade-offs in other impact categories. In Scenario 2, the air emissions across all life cycle stages, calculated per functional unit of 1 m^3, led to the following environmental impact as shown in Table 5.

Table 5. LCIA results for Scenario 1 and Scenario 2 per FU 1 m^3.

	Scenario 1	Scenario 2
GWP [kg CO_2 eq.]	190.00	89.09
ODP [kg CFC-11 eq.]	2.30×10^{-6}	3.09×10^{-6}
AP [Mole of H+ eq.]	1.12	2.26×10^{-1}
EP [kg P eq.]	0.05	6.43×10^{-1}
POCP [kg NMVOC eq.]	0.77	1.89×10^{-1}
ADPE [kg Sb eq.]	1.18	8.73×10^{-4}
ADPF [MJ]	2990.00	2299.32

Table 6. Comparative resource use indicators and waste categories of the two scenarios in accordance with EN 15804+A2.

	Scenario 1	Scenario 2
PERE [MJ]	57.00	867.83
PERM [MJ]	78.10	86.22
PERT [MJ]	135.10	954.05
PENRE [MJ]	2720.00	2226.89
PENRM [MJ]	266.00	72.43
PENRT [MJ]	2986.00	2299.32
SM [kg]	0.00	7.08
RSF [MJ]	0.00	0.00
NRSF [MJ]	0.00	84.24
FW [m^3]	3.95	4.84
HWD [kg]	0.00	7.53×10^{-7}
NHWD [kg]	13.40	5.75
RWD [kg]	0.00	2.50×10^{-2}
CRU [kg]	0.00	1.71

Overall, Scenario 2 shows a more favourable environmental profile in most of the assessed impact categories, while presenting trade-offs in ozone depletion and eutrophication, based on the results per FU of 1 m^3. Considering air emissions, Scenario 2 provides substantial environmental improvements in several impact categories, although trade-offs remain. The results show that Scenario 2 achieves a notable reduction in global warming potential, decreasing from 190.00 to 89.09 kg CO_2 eq. per functional unit, which represents a reduction of about 53%. This decrease can be linked to the replacement of certain virgin materials, the use of thermal energy recovered from wood waste gasification, and the reuse of by-products such as gasification char and captured CO_2 within the system. Similar improvements are observed for acidification potential and photochemical ozone creation potential, which decline by roughly 80% and 75%, respectively. A particularly significant improvement is seen in abiotic depletion of mineral resources, where ADPE falls by more than 99%, highlighting the reduced reliance on primary raw materials. Fossil resource depletion also decreases, although to a lesser extent, with ADPF showing a reduction of approximately 23%.

Despite these benefits, Scenario 2 does not outperform Scenario 1 across all environmental indicators. ODP rises from 2.30×10^{-6} to 3.09×10^{-6} kg CFC-11 eq., an increase of around 34%. This suggests that some of the additional materials, chemicals, or energy inputs required in the integrated process contribute more strongly to ozone-depleting emissions than those used in the conventional system. Overall, the findings indicate that the circular production approach can substantially reduce impacts related to GWP, AP, POCP, and resource depletion. At the same time, it introduces higher burdens in ODP and especially EP. Figure 3 summarises the results of the LCIA for the scenarios.

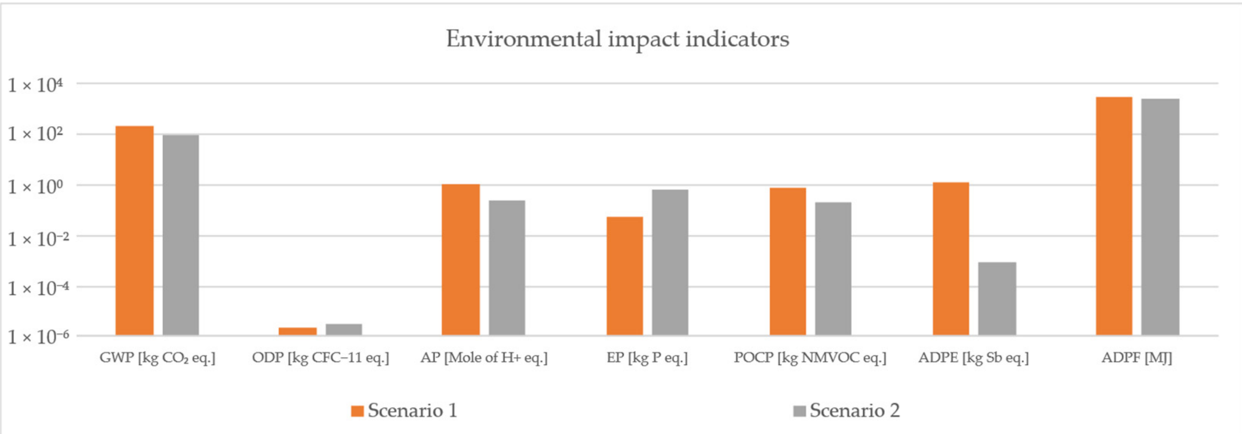

Figure 3. Comparative life cycle environmental impact indicators of the two scenarios in accordance with EN 15804+A2.

Table 6 and Figure 4 present the resource use indicators of all scenarios in accordance with EN 15804+A2, enabling a comparative assessment of resource efficiency and circularity performance. The resource use results indicate that Scenario 2 substantially changes the energy and material profile of insulation production. PERE increases from 57.0 to 867.83 MJ, while PERM increases moderately from 78.10 to 86.22 MJ, resulting in a total renewable primary energy use of 954.05 MJ. Consequently, total non-renewable primary energy use falls from 2986.0 to 2299.32 MJ, corresponding to a reduction of approximately 23%. These results indicate a clear shift toward renewable and secondary resource inputs and a reduced overall dependence on non-renewable primary energy. These results support the conclusion that the circular configuration lowers overall dependence on non-renewable energy sources. However, PENRM increases from 266.0 to 572.43 MJ, suggesting that non-renewable material inputs remain significant within Scenario 2.

The clearest circularity improvement is observed in the use of secondary materials. Scenario 1 contains no secondary material input, whereas Scenario 2 incorporates 7.08 kg per FU. Scenario 2 also uses 84.24 MJ of non-renewable secondary fuels, while no such input is reported for Scenario 1. These results confirm that the proposed system improves resource circularity by incorporating recovered material and energy streams into the production process. Renewable secondary fuels remain absent in both scenarios.

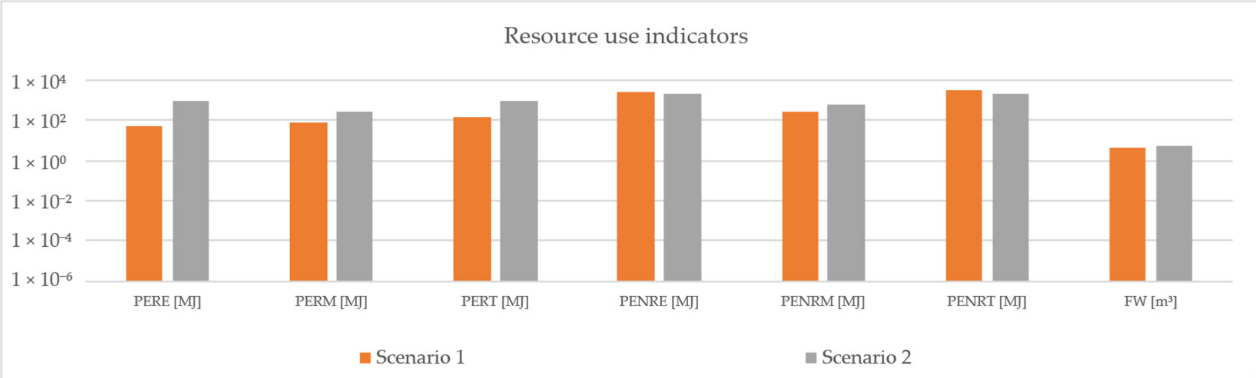

Figure 4. Comparative resource use indicators of the two Scenarios in accordance with EN 15804+A2.

Freshwater use increases moderately from 3.95 to 4.84 m^3, corresponding to an increase of approximately 23%. This indicates that the improvements in renewable energy use, secondary material integration and reduced non-renewable energy demand are accompanied by a higher water requirement.

As shown in Table 7 and Figure 5, output flow and waste indicators show that Scenario 2 improves performance in relation to non-hazardous waste and material recovery, while introducing small additional burdens in other waste categories. Non-hazardous waste disposed decreases from 13.40 kg in Scenario 1 to 5.75 kg in Scenario 2, corresponding to a reduction of approximately 57%. This reduction is consistent with the greater recovery and internal utilisation of material streams within the circular production system.

Table 7. Hotspot analysis distribution for Scenario 2—environmental impact indicators.

Categories	Material	Water Use	Process	NG	Electricity	CRU
Climate Change−total [kg CO_2 eq.]	65.27	0.46	0.28	9.21	3.39	10.47
Climate Change, fossil [kg CO_2 eq.]	65.31	0.41	0.28	9.20	3.40	10.43
Climate Change, biogenic [kg CO_2 eq.]	−0.16	0.05	9.77×10^{-15}	0.02	−0.01	0.04
Climate Change, land use and change [kg CO_2 eq.]	0.13	3.70×10^{-4}	0.00	0.00021	3.00×10^{-3}	0.001
ODP [kg CFC−11 eq.]	3.08×10^{-6}	1.74×10^{-12}	0.00	2.39×10^{-13}	5.01×10^{-9}	1.37×10^{-11}
AP [Mole of H+ eq.]	0.20	6.80×10^{-4}	0.0051	0.0054	8.60×10^{-3}	0.01
EP, freshwater [kg P eq.]	0.001	5.12×10^{-5}	0.00	5.63×10^{-7}	3.52×10^{-6}	9.28×10^{-6}
EP, marine [kg N eq.]	0.05	3.80×10^{-4}	0.00016	0.0025	0.0019	0.0023
EP, terrestrial [Mole of N eq.]	0.49	0.002	0.022	0.028	0.021	0.026
POCP [kg NMVOC eq.]	0.16	0.0006	0.00	0.0077	0.0055	0.01
Resource use, mineral and metals [kg Sb eq.]	0.0008	2.08×10^{-8}	0.00	2.53×10^{-7}	2.69×10^{-5}	8.71×10^{-7}
Resource use, fossils [MJ]	1801.75	5.57	0.00	145.63	35.97	310.40
Water use [m^3 world equiv.]	10.38	8.74	0.00	0.01	0.29	0.10

Scenario 2 also reports 1.71 kg of components prepared for reuse, whereas no such output is recorded for Scenario 1. This result indicates that the proposed system creates a measurable recovery pathway and retains part of the material value that would otherwise be lost through disposal.

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Circularity indicators are further assessed through a hotspot analysis on Scenario 2, aligned with EN 15804+A2 (based on EF 3.1) in Table 7. Specifically, the hotspot analysis shows that material production clearly dominates the environmental, resource and waste indicators. For the environmental hotspot analysis, the total impact of climate change amounts to 89.1 kg CO_2 eq., mainly driven by materials (65.27 kg CO_2 eq.), followed by electricity (3.39 kg CO_2 eq.), natural gas (9.21 kg CO_2 eq.), and CRU (10.47 kg CO_2 eq.), while water use and process contributions remain below 0.5 kg CO_2 eq. Similar patterns are observed for fossil climate change (65.31 kg CO_2 eq. from materials), whereas biogenic climate change is slightly negative for materials (−0.16 kg CO_2 eq.).

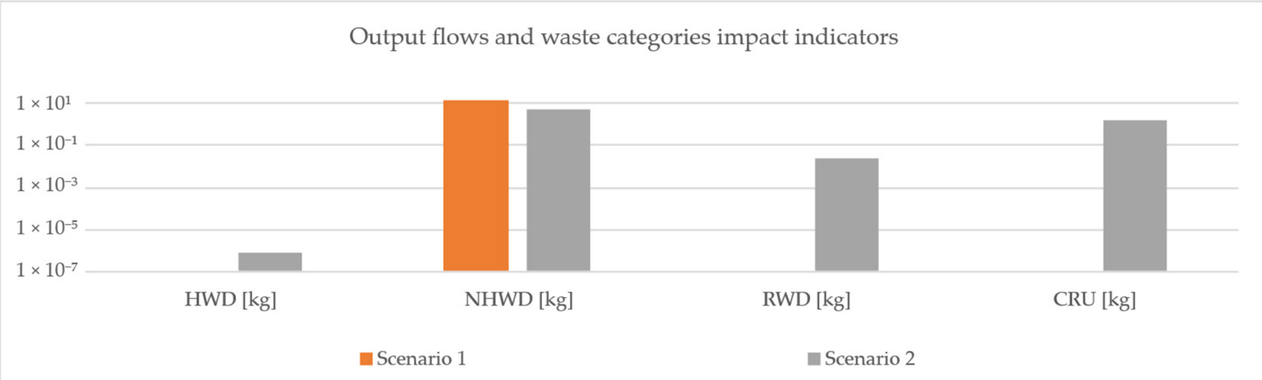

Figure 5. Comparative output flow and waste category impact indicators of the two scenarios in accordance with EN 15804+A2.

Other environmental indicators are likewise material-based, including acidification (0.196 mol H^+ eq.), freshwater eutrophication (0.00109 kg P eq.), marine eutrophication (0.0453 kg N eq.), terrestrial eutrophication (0.4896 mol N eq.), and photochemical ozone formation (0.162 kg NMVOC eq.), with secondary contributions from electricity and natural gas.

Moreover, the materials contribution to fossil resource use is 1801.75 MJ, while total PENRT across all hotspot contributors is 2299.32 MJ. Materials remain the dominant contributor, followed by CRU, natural gas and electricity. Electricity and natural gas together account for approximately 182 MJ. The materials contribution to renewable primary energy use is 195.04 MJ, while the total PERT across all hotspot contributors is 954.05 MJ. Water-scarcity impacts show a different contribution pattern, with materials representing the largest contribution at 10.38 m^3 world eq., followed by direct water use at 8.74 m^3 world eq., while electricity, natural gas and other processes contribute less. Table 8 summarises the detailed results of this analysis.

Table 8. Hotspot analysis distribution for Scenario 2—resource use indicators.

Categories	Material	Water Use	Process	NG	Electricity	CRU
PERT [MJ]	195.04	0.85	0	0.18	751.70	6.28
PENRT [MJ]	1801.75	5.57	0	145.63	35.97	310.40
FW [m^3]	0.34	4.44	0	4×10^{-4}	0.01	0.05

Finally, waste outputs are overwhelmingly linked to materials, with non-hazardous waste at 3.94 kg, hazardous waste at 3.5×10^{-7} kg, and radioactive waste at 0.0235 kg, while electricity and other contributors remain minimal. The results are presented in Table 9.

Table 9. Hotspot analysis distribution for Scenario 2—output flows and waste categories.

Categories	Material	Water Use	Process	NG	Electricity	CRU
HWD [kg]	3.50×10^{-7}	1.90×10^{-9}	0	3.30×10^{-9}	3.75×10^{-7}	2.27×10^{-8}
NHWD [kg]	3.94	1.27	0	0.04	0.45	0.06
RWD [kg]	0.02	8.68×10^{-5}	0	2.35×10^{-5}	6×10^{-4}	7.00×10^{-4}

5. Discussion

This study evaluates the environmental performance of two insulation material production pathways, one conventional baseline scenario and one circular integrated scenario integrating wood and plastic waste valorisation with carbon capture and utilisation (Scenario 2). The results highlight the importance of raw material sourcing and energy consumption in insulation material production, which generates relatively high life cycle environmental impacts. In this context, the primary contribution of this study is the evaluation of the potential of the solution to reduce industry emissions.

Across all scenarios, the raw material supply chain stage (A1) was identified as the dominant contributor to most impact categories, particularly GWP and ADPF. This observation aligns with the existing literature on insulation materials where polymer production and its energy requirements serve as key environmental hotspots. The dominance of the A1 stage is primarily associated with the production of virgin polymeric materials and other fossil-based inputs used in the insulation formulation, particularly NBR, PVC, and vinyl acetate-based polymers which are characterised by substantial energy and resource requirements. Although mineral fillers such as calcium carbonate and aluminium hydroxide constitute a substantial fraction of the formulation by mass, their specific environmental burdens are generally lower than those of the polymeric components. Therefore, approaches that minimise the use of virgin fossil-based materials or replace them with recycled or recovered alternatives can significantly enhance environmental performance. In the present study, this is reflected in Scenario 2 through the incorporation of secondary resources, including plastic waste, gasification char and captured CO_2, which reduce the environmental impact associated with the A1 stage by decreasing the demand for virgin raw materials. Consequently, material sourcing and resource circularity represent the primary observed environmental improvements.

Scenario 2 achieves better performance than the baseline option in most environmental impact categories. The significant reduction in GWP results from reducing the use of virgin polymer feedstocks through recycled-plastic substitution, recovering energy through wood gasification and utilising captured CO_2 as a foaming agent, thereby reducing both direct and indirect greenhouse gas emissions. However, the higher ODP value suggests that certain upstream materials, chemical inputs, or energy requirements associated with the circular system are linked to greater ozone-depleting emissions than those involved in the conventional production route. Moreover, reductions in AP and ADPF in the circular scenario reflect the benefits of substituting fossil fuels with energy recovery processes. Although these processes offer many benefits, there may also be some drawbacks. For instance, in this scenario, the EP is higher than that of Scenario 1, which indicates that emissions from energy production or waste treatment stages remain relevant.

The environmental improvements observed for Scenario 2 are broadly consistent with findings from previous LCA studies addressing insulation products, recycled polymers and CO_2-utilisation pathways. Reviews of thermal insulation materials have generally identified raw material production as a principal source of embodied impacts, particularly for fossil-based polymeric products such as polyurethane, extruded polystyrene and other petrochemical foams, whereas materials incorporating renewable or secondary feedstocks frequently show lower climate change and fossil resource burdens [8]. Nevertheless, these studies also demonstrate that the relative ranking of insulation products is sensitive to density, thermal performance, service life, manufacturing energy and the selected functional unit. Within this context, the GWP obtained for Scenario 2 indicates that the substitution of virgin inputs, rather than insulation production alone, is responsible for a substantial part of the improvement over the conventional FEF baselines.

This interpretation is also supported by LCAs of recycled polymers, which commonly report lower energy demand and greenhouse gas emissions when mechanically recovered polymers displace virgin resin [29,30]. However, the magnitude of the benefit depends on collection, sorting, reprocessing yields, material quality and the allocation of recycling credits [29,30]. The present results further show that these benefits can extend beyond polymer substitution when recycled plastic is combined with gasification char, recovered process heat and captured CO_2.

The circularity benefits observed in Scenario 2 could be interpreted with reference to the waste streams entering the system rather than the final insulation product itself. In this scenario, plastic waste and discarded wood packaging are recovered after reaching the end of their original service lives and are used as inputs for a new manufacturing process. The plastic fraction replaces a portion of virgin polymer materials, while the wood waste is converted through gasification to supply thermal energy and produce char that can be utilised within the process. As a result, materials and energy that would otherwise be discarded are retained in productive use, reducing the demand for primary resources. In addition, the assessment does not include the end-of-life stage of the flexible elastomeric foam produced in Scenario 2. Therefore, the findings demonstrate the environmental advantages associated with recovering and reusing plastic and wood waste within the production system, but they do not provide a complete evaluation of the insulation product across its entire life cycle. A broader assessment that includes end-of-life stages would be needed to determine the overall circular performance of the final product.

Furthermore, the resource use indicators confirm that Scenario 2 delivers enhanced circularity through increased renewable energy use, reduced dependence on non-renewable feedstocks and improved material recovery, while the reduction in waste and improvement in resource efficiency are primarily achieved through integrated recycling, substitution and internal energy use, demonstrating that circularity is a result of an integrated system design rather than downstream waste treatment. It is worth mentioning that, in Scenario 2, plastic waste and wood packaging waste are recovered and used as secondary resources, providing an alternative pathway to conventional waste management. The plastic waste is incorporated back into polymer production, while the wood packaging waste is processed through gasification to generate thermal energy and char that can be utilised within the insulation system. As a result, materials that would otherwise be discarded are returned to productive use, reducing the demand for virgin raw materials, fossil-based energy sources and conventional filler materials. At the same time, the study does not extend to the end-of-life stage of the newly produced flexible elastomeric foam insulation. Processes that may occur after the product's service life, such as collection, recycling, energy recovery through incineration or final disposal, are outside the scope of the current assessment and were not included in the calculations. For this reason, the circularity findings presented in this work relate to the recovery and utilisation of incoming waste streams and the associated resource efficiency within the production system. They should not be interpreted as an evaluation of the complete life cycle circularity of the insulation product itself. Regarding the hotspot analysis, the results quantitatively demonstrate that material-related choices represent the main point for reducing impacts across all EN 15804+A2 (EF 3.1) indicators.

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The assessment framework is modular and may be extended to other manufactured products by modifying the relevant material, energy, emission and waste-flow inputs. Indicators can be added or removed, and indicators, inventory parameters and characterisation methods can be modified without rebuilding the model. However, the numerical results and parameter settings used in the present study are specific to flexible elastomeric foam production, the selected waste streams and the defined system boundaries. Application to other products would therefore require recalibration of the functional unit, process inventory, substitution ratios, technological assumptions and any inventory parameters and characterisation methods. The framework is thus transferable in structure, but not directly universal in its present parameterisation.

Overall, the results underline that technological improvements as a system are essential for achieving important environmental benefits. Scenario 2 demonstrates how the combination of waste valorisation and efficient energy recovery and utilisation can generate reductions across multiple environmental impact categories.

6. Conclusions

This study assessed the environmental and circularity performance of insulation material production through a cradle-to-gate life cycle assessment, comparing one conventional baseline scenario and one circular integrated scenario integrating wood and plastic waste valorisation and carbon capture and utilisation. Actual data, relevant literature and information from the Sphera LCA for Experts database were used. Based on the results, the conventional insulation materials are primarily impacted by emissions and resource consumption associated with virgin raw material and fossil energy use. In contrast, within the assessed cradle-to-factory-gate boundary, Scenario 2 shows lower impacts than Scenario 1 in GWP, AP, POCP, ADPE and ADPF, with reductions of approximately 53%, 80%, 75%, more than 99% and 23%, respectively. In contrast, ODP increases by approximately 34%, while EP rises substantially from 0.05 to 0.643 kg P eq. per functional unit. The proposed circular system therefore provides significant benefits in climate change, acidification, photochemical ozone formation and resource depletion, but introduces trade-offs in ozone depletion and eutrophication. From a circular economy perspective, this scenario enhances the circularity of incoming material and energy flows. Scenario 2 reduces non-hazardous waste disposal from 13.40 to 5.75 kg per functional unit, corresponding to a decrease of approximately 57%, and generates 1.71 kg of components prepared for reuse compared with none in Scenario 1. In summary, the results demonstrate that the incorporation of secondary resources, including plastic waste, gasification char and captured CO_2, into elastomeric insulation production can reduce dependence on virgin raw materials and improve environmental performance across most impact categories. The proposed framework can be adapted to other manufacturing systems by revising the inventory data, functional unit, system boundaries and evaluation parameters. Its modular structure allows inventory parameters and characterisation methods to be modified without rebuilding the model. However, the present results are specific to the investigated insulation product and waste valorisation scenario. These findings provide practical evidence for implementing circular resource strategies within insulation manufacturing and highlight material substitution as a key pathway for reducing the environmental burden associated with raw material production. As circular technologies mature, their integration into industrial production could become a key pathway toward more sustainable material systems.

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funding acquisition, M.B. and A.P. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request. Public access to the data is restricted because the data were provided by industry partners and are protected under confidentiality agreements.

Conflicts of Interest: Authors Kamil Maszczyk and Mateusz Imiela were employed by the company K-FLEX POLSKA Sp. z o.o. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

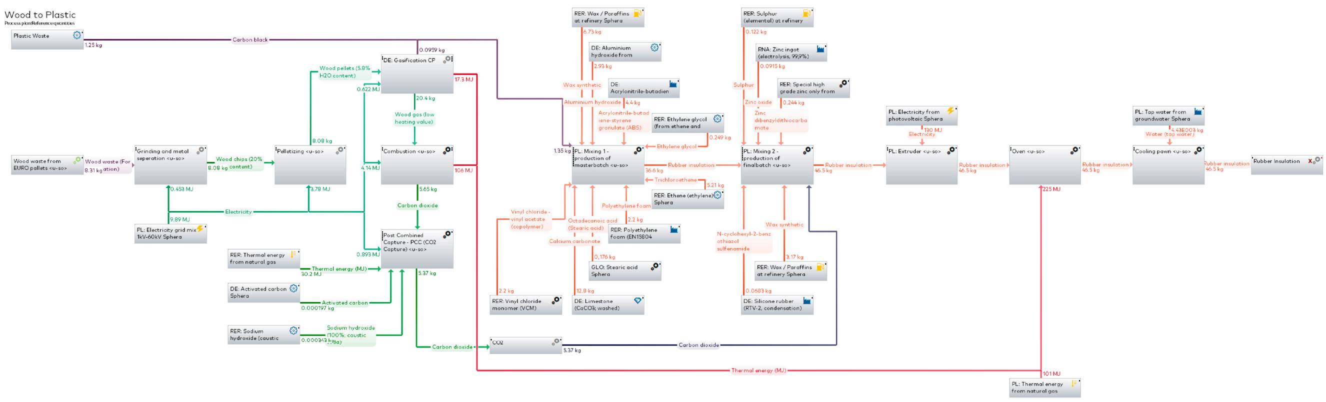

Figure A1. Material Flowsheet of the Sphera about the insulation material production of FRONTSH1P.

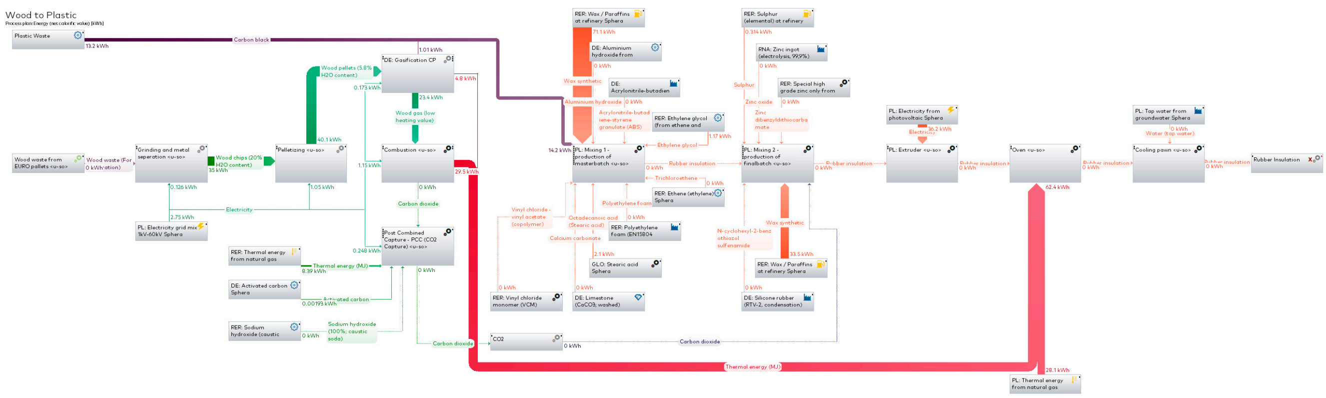

Figure A2. Energy Flowsheet of the Sphera about the insulation material production of FRONTSH1P.

Table A1. Sphera processes used for modelling Scenario 2.

	Process Name—Information	Source
1.	Plastic Waste ∣ DE ∣ Carbon black (furnace black; deep black pigment) ∣ agg	Sphera
2.	Wood waste from EURO pallets ∣ u-so	Custom
3.	IT ∣ Grinding and metal separation ∣ agg	Custom
4.	PL ∣ Electricity grid mix 1kV–60kV ∣ agg	Sphera
5.	Pelletizing ∣ agg	Custom
6.	Post Combined Capture—PCC (CO2 Capture) ∣ agg	Custom
7.	RER ∣ Thermal energy from natural gas ∣ agg	Sphera
8.	DE ∣ Activated carbon ∣ agg	Sphera
9.	RER ∣ Sodium hydroxide (caustic soda) mix (100%) ∣ agg	Sphera
10.	Combustion ∣ agg	Custom
11.	DE ∣ Gasification ∣ agg	Custom
12.	PL ∣ Mixing 1—production of masterbatch ∣ u-so	Custom
13.	RER ∣ Vinyl chloride monomer (VCM) ∣ agg	IFEU/ PlasticsEurope
14.	DE ∣ Limestone (CaCO3; washed) ∣ agg	Sphera
15.	GLO ∣ Stearic acid ∣ agg	Sphera
16.	RER ∣ Polyethylene foam (EN15804 A1–A3) ∣ agg	Sphera
17.	RER ∣ Ethene (ethylene) ∣ agg	Sphera
18.	RER ∣ Wax/Paraffins at refinery ∣ agg	Sphera
19.	DE ∣ Aluminium hydroxide from aluminium sulphate ∣ agg	Sphera
20.	DE ∣ Acrylonitrile-butadiene-styrene granulate (ABS) mix ∣ agg	Sphera
21.	RER ∣ Ethylene glycol (from ethene and oxygen via EO) ∣ agg	Sphera
22.	CO2 ∣ GLO ∣ Product—auxiliary dataset ∣ u-so	Sphera
23.	PL ∣ Mixing 2—production of final batch V2 ∣ u-so	Custom
24.	RER ∣ Sulphur (elemental) at refinery ∣ agg	Sphera
25.	RNA ∣ Zinc ingot (electrolysis, 99.9%) ∣ agg	Sphera
26.	RER ∣ Special high-grade zinc only from Zn concentrate ∣ agg	IZA
27.	DE ∣ Silicone rubber (RTV-2, condensation) ∣ agg	Sphera
28.	RER ∣ Wax/Paraffins at refinery ∣ agg	Sphera
29.	PL ∣ Extruder ∣ u-so	Custom
30.	PL ∣ Electricity from photovoltaic ∣ agg	Sphera
31.	Oven ∣ u-so	Custom
32.	PL ∣ Thermal energy from natural gas ∣ agg	Sphera
33.	Cooling pawn ∣ u-so	Custom
34.	PL ∣ Tap water from groundwater ∣ agg	Sphera
35.	Rubber Insulation ∣ GLO ∣ Product—auxiliary dataset ∣ u-so	Sphera

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