INTEGRATION PROJECT

Protective Layer in Solar Panel Modules with Sustainable Building Materials: The Potential of the Solar-Assisted Chemical Brushing Technique for Transparent Wood Production

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Chapter 1 Abstract

In the current situation of depletion of non-renewable resources, the development and utilization of renewable biomass materials offer a promising solution to alleviate environmental pollution and energy scarcity. The nanoscale organization of wood, the most widely used bio-based structural material, provides opportunity for tailored design of advanced wood-based multifunctional materials while preserving mechanical integrity. This Integration Project delves into the potential replacement of Ultra-white rolled glass (UWRG) in solar panels with Transparent wood (TW) derived from Balsa species.

Solar panels are assembled with a protective layer on top usually made of tempered glass, which slightly improves its efficiency. Nevertheless, its production is very energy intensive and is associated with significant environmental emissions. TW is investigated as a more sustainable alternative produced by two different methods. The current technique used by the Boltz company, based on hydrogen peroxide (H_2O_2) submersion and Polymethyl methacrylate (PMMA) infiltration, and the Solar-assisted chemical brushing (SACB) technique, involving H_2O_2 brushing, ultraviolet (UV) irradiation and Epoxy resin infiltration (Polylactic Acid (PLA) and PMMA are also considered polymers for this method).

The research evaluates and compares the production of TW with that of UWRG from three different perspectives: sustainability, economics and technology. Sustainability is assessed through cradle to grave Life cycle analysis (LCA), assessing environmental indicators such as CO_{2-eq} emissions, acidification or energy consumption. Economically, raw materials and production costs are derived from several commercial sources. Technological performance examines their optical, mechanical and thermal properties, compared among several reports and articles. Moreover, TW is fabricated in the laboratory via the SACB method with PMMA infiltration.

The collective insights gained from these multidisciplinary analyses reveal that, although wood is naturally renewable, TW production using Boltz's methods still entail higher environmental impacts than glass (primarily due to the high quantity of solvents used). Using the SACB method with Epoxy resin, as well as PLA as bio-based polymer and PMMA, reduces emissions, being even less harmful than UWRG for the production of one solar panel. Economically, TW currently requires higher investment costs than UWRG. However, its superior optical, mechanical and thermal properties highlight its potential as a future material for solar panel applications. Between the three polymers, SACB with PMMA used in a ratio of 50/50 v% excels as the best alternative for TW production. Therefore, further developments focused on this technique is crucial for the viable implementation of TW in solar panels.

Contents

Chapter 2 List of Abbreviations

- Fe_2O_3 - Iron.
- H_2O_2 - Hydrogen peroxide.
- ISO - International Organization for Standardization.
- LCA - Life Cycle Analysis.
- LPG - Liquefied Petroleum Gas.
- MEFA - Material and Energy Flow Analysis.
- PCE - Power Conversion Efficiency.
- PLA- Polylactic Acid.
- PMMA - Polymethyl Methacrylate.
- PSCs - Perovskite Solar Cells.
- SACB - Solar-Assisted Chemical Brushing.
- TW - Transparent Wood.
- UV - Ultraviolet.
- UWRG - Ultra-White Rolled Glass.

Chapter 3 Introduction

The significant increase of the risks and impacts of climate change has led to the adoption of the Paris Agreement in December 2015, entering into force in November 2016. This legally binding international treaty aims to limit the global average temperature to 1.5°C by the end of this century. According to the United Nations Intergovernmental Panel on Climate Change, crossing this threshold could trigger more frequent and serious droughts, heatwaves and rainfall. To reach this target, greenhouse gas emissions must peak before 2025 and decline 43% by 2030 [Nations,]. This research primarily targets the study of the possibility to decrease environmental impacts in the production of the top protective layer of solar panels in the Netherlands, typically made of glass.

Glass production includes significant energy inputs and emissions of about 60 million tons of CO_{2-eq} per year in the solar panel industry [Belançon et al., 2023], with European glass factories emitting around 0.74 tonnes of CO_{2-eq} per ton of glass. Due to high melting temperatures (1500 to 1600°C) needed to melt raw materials, like silica or sodium carbonate [Simelane et al., 2024], and the reliance on fossil fuels like natural gas and coal, producing 1 ton of glass requires 3-4 MWh of energy [Chowdhury et al., 2025]. These severe impacts have prompted the need for cleaner alternatives that significantly can reduce energy consumption and harmful emissions.

The Groningen-based start-up company Boltz is exploring Transparent wood (TW) as an alternative material, first prepared with preserved structure by Fink in 1992 for the purpose of morphology studies. Since then, the use of techniques such as the acidic sodium chlorite ($NaClO_2$) treatment for delignification (to remove the light absorption in wood and reduce the refractive index mismatch between the air gap and the cell wall) and the utilization of synthetic PMMA for polymerization [Li, 2019] have been used. However, it still relies on large quantities of petroleum-based chemicals, raising concerns about its sustainability. To address this, a new technique, the Solar-assisted chemical brushing (SACB), is analysed. It uses hydrogen peroxide (H_2O_2) and UV radiation for lignin modification, followed by infiltration usually with Epoxy resin.

The research provides a thorough sustainable, economical and technical comparison between Ultra-white rolled glass (UWRG), Boltz's and SACB production techniques for TW. These offer insights to assess whether the SACB method can outperform UWRG and Boltz's TW. The ultimate aim is to provide an advisory report for Boltz evaluating the trade-offs of the different options for solar panel applications and a final recommendation. Therefore, this study aims to answer the following main question:

How does the Transparent wood production via Solar-assisted chemical brushing compare to the Boltz's current method for Transparent wood and the Ultra-white

rolled glass in terms of sustainability, economics and technology, as the top protective layer of solar panels in the Netherlands?

The analyses conducted help answer the main question by addressing the following ones:

- What are the desired optical, mechanical and thermal properties Transparent wood needs to possess to be a viable candidate for glass replacement as the top protective layer of solar panels?
- How do chemical consumption levels affect the sustainability of Transparent wood production and what modifications in delignification and/or polymerisation can be implemented to reduce emissions?
- Which material exhibits the most favorable balance between durability and deployment emissions?
- What are the most critical trade-offs between sustainability, economic cost and technical performance among the three materials studied?

The Integration Project begins with a literature review exploring application, material selection and production techniques. This is followed by a detailed Methods and tools section explaining the analytical tools used, including LCAs, cost analysis and property testing comparison. The results are then presented and discussed to assess the impacts of each material. Additionally, a laboratory testing is performed to produce TW via the SACB technique with PMMA. The thesis concludes with the key findings and a final recommendation for Boltz.

Chapter 4 Literature Study

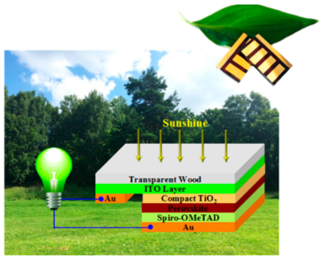
4.1 *Application: protective top layer in solar panels.*

Each year, almost 5×10^{24} J of solar energy reaches the Earth's surface, which surpasses global annual energy consumption by nearly 10000 times. Solar energy, being abundant and sustainable, has become one of the most important renewable energy sources [Soklič et al., 2018]. Commercial solar technologies are primarily dominated by crystalline silicon and thin-film solar cells, which require high-purity, single-crystalline semiconductors and energy-intensive manufacturing processes. The choice of substrate is crucial in determining solar cell performance, sustainability and cost-effectiveness. While glass remains the standard, its brittleness and high thermal conductivity pose challenges for long-term durability and energy efficiency. Additionally, performance is also affected by the loss of solar energy due to reflection at the air/glass interface. This has driven research towards materials with superior optical properties, including high transmittance (amount of light that passes through a material) and haze (dispersing light), which help to diffuse light more effectively and enhance its absorption in active photovoltaic layers [Wachter et al., 2023].

Transparent wood (TW) has emerged as a promising candidate for various advanced applications due to its good optical properties, high strength-to-weight ratio and distinctive hierarchical structure (lightweight). Among its potential uses, it has shown great promise as a protective layer for solar panels, offering a high-performance alternative to conventional glass [Wu et al., 2023]. Its combination of high optical transmittance ($\succ$ 85%) and haze ($\approx$ 95%) allows for effective light diffusion, reducing reflection losses and increasing the path length of light within solar cells. This enhances photon absorption and overall power conversion efficiency [Li et al., 2019].

Recently, Perovskite solar cells (PSCs) have gained significant attention due to their high power conversion efficiency (PCE), low processing costs and scalability. PSCs demonstrate high electron mobility, long carrier lifetimes, strong absorption coefficients and high structural defect tolerance, making them highly competitive with traditional silicon-based solar cells [Li et al., 2019]. PSCs fabricated on TW substrates have achieved PCEs of up to 16.8%, demonstrating effective light transmittance (86% at 550 nm for 1 mm thickness) and high haze levels (70%) that significantly boost light absorption. Notably, when TW was employed as a top protective layer for solar cells, the energy conversion efficiency improved to 18%, highlighting its practical benefits in photovoltaic applications (*Figure 4.1*). Furthermore, its lifespan is comparable to that of the Ultra-white rolled glass (UWRG), 20-30 years [Renewables,], depending on the polymer used.

Figure 4.1: The solar cell structure is TW substrate/ITO layer/compact TiO_2/perovskite/spiro-OMeTAD/Au. The yellow arrows represent light [Li et al., 2019].



Future research focuses on further optimizing the delignification and polymer infiltration processes to enhance the transparency and mechanical strength of TW while minimizing environmental impact.

4.2 *Ultra-white rolled glass production.*

Ultra-white rolled glass (UWRG) is a crucial, and the current, component in solar panels due to its exceptional light transmittance and mechanical strength. Compared to ultra-clear float glass, it undergoes specialized surface treatments that enhance its optical properties. The front surface receives a suede treatment to reduce light reflection, while the back surface is patterned to improve sunlight transmittance at various incident angles. This increases the total light transmittance by approximately 3–4% [Xingyao, 2023].

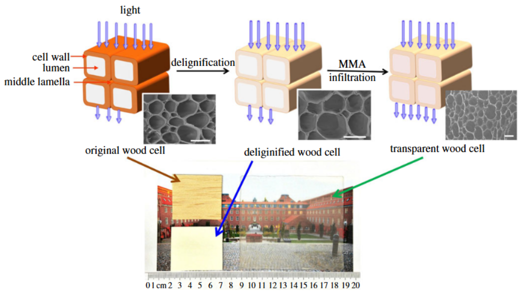
The manufacturing process begins with heating the raw materials in a furnace at high temperatures to form molten glass. This step is energy-intensive, where carbonates decompose during melting [Ramírez et al., 2010]. Then, the molten glass undergoes homogenization in a forehearth to eliminate air bubbles before it is passed through rollers for calendering, annealed to relieve internal stresses and cut to size. Depending on the application, lamination, coating and tempering are applied. Tempered UWRG is particularly valued for its long-term stability and resistance to environmental stresses [Adekomaya and Majozi, 2021].

The calendering process optimizes light capture and minimizes reflection. It involves passing molten glass through rollers to achieve the desired thickness and surface texture, followed by annealing, cutting and tempering. This process also strengthens the structural integrity of the glass, granting a lifespan of 30 years [Renewables,]. The primary raw materials include silica (SiO_2), which forms the main structure, sodium carbonate (Na_2CO_3), that lowers the melting point to save energy, limestone ($CaCO_3$), which reduces the viscosity of molten glass, dolomite ($CaMg(CO_3)_2$), that controls crystallization and enhances melting performance, and mirabilite [Chowdhury et al., 2025]. A critical aspect is the stringent control of iron (Fe_2O_3) content in the raw materials. Its impurities can cause discoloration and increase heat absorption, reducing light transmittance. To prevent this, the Fe_2O_3 content should be maintained below 150 ppm through purification processes such as acid leaching [Gold, 2017].

4.3 *Transparent wood general production technique.*

Currently, Transparent wood (TW) is being studied as a replacement for glass in different applications. It is produced by modifying natural wood to achieve high optical transmittance and mechanical strength (*Figure 4.2*). The key lies in the removal or alteration of lignin, as it accounts for most of the light absorption in wood, giving the brown colour. It presents a density of 1200 kg/m^3 [Windle, 2017].

Figure 4.2: Sketch showing an example of TW preparation: delignification followed by polymer infiltration. Scale bars are 40 µm [Windle, 2017].



The primary step is the delignification, which aims to remove the light-absorbing components and reduce the refractive index mismatch between the air gaps and the cellulose matrix of the cell walls. This process enhances light transmission through the wood structure [Zhu et al., 2023]. An alternative is lignin modification, which targets only the chromophores within the lignin structure and retains higher lignin content, while its color-inducing chromophores are deactivated. This method preserves the mechanical integrity of the wood to a greater extent compared to full delignification, providing stronger structural performance along with improved transparency [Li, 2019].

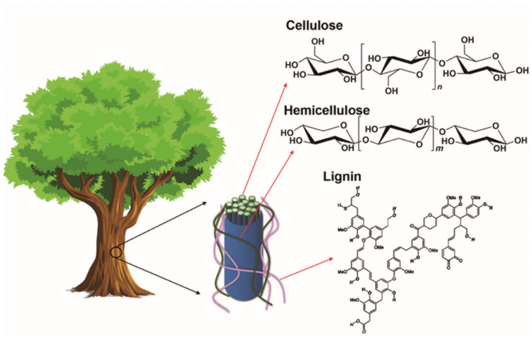
The second step is the polymer infiltration, which involves filling the porous wood structure with a transparent polymer to reduce the contrast in refractive indices between the cell wall and the void spaces. The polymers commonly used and their refractive indices include PMMA (1.49), Epoxy resin (1.50) and Polyvinyl pyrrolidone (1.53). They reinforce the mechanical properties of the wood template, allowing it to achieve both transparency and durability in different degrees.

In this Integration Project, the focus is on the current method used by the company Boltz (*Section 4.6*) and the Solar-assisted chemical brushing (SACB - *Section 4.7*) with Epoxy resin. To gain a more comprehensive insight into the influence of polymer type on the outcomes, PLA (refractive index of 1.49 [Hutchinson et al.,]) and PMMA are also included in the analysis for SACB.

4.4 *Natural wood.*

Wood is a sophisticated and hierarchically structured natural nanocomposite, composed of cellulose, hemicellulose and lignin (*Figure 4.3*). These are organized in a nanostructure that provides wood its distinctive optical, mechanical and thermal characteristics [Windle, 2017].

Figure 4.3: Diagram showing how the cellulose strands are surrounded by hemicellulose and lignin in the wood cell wall, and the corresponding structures of cellulose, hemicellulose and lignin [Simelane et al., 2024].



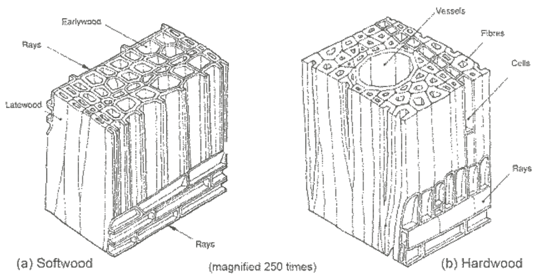
Cellulose consists of nanofibrils arranged in a highly ordered crystalline structure, which makes it the main contributor to its mechanical strength, and accounts for 40–50 wt% of wood. These nanofibrils form a porous, fibril-based network within the cell wall, creating opportunities for multifunctional material design when processed into Transparent wood (TW). Hemicellulose represents 20–40 wt% of wood, is amorphous and serves as a hydrated matrix that binds cellulose fibrils together and prevents cellulose agglomeration, enhancing the structural integrity [Li, 2019]. These two are polysaccharides, both being transparent, contributing positively to the potential for light transmittance in TW applications. Finally, lignin constitutes 20–30 wt% of wood, an aromatic polyphenolic macromolecule that provides stiffness, even in the absence of turgor pressure [Wang and Zhu, 2021]. Its brownish color is attributed to light-absorbing tannins and chlorophyll, responsible for 80–95% of the total light absorption in wood, significantly hindering its natural transparency [Pandit et al., 2025].

Additionally, the cell wall is organized into hollow fibers usually aligned along the longitudinal axis of the tree stem, contributing to the wood's anisotropic behavior, influencing its mechanical strength, water transportation, thermal conductivity and optical properties. Its porosity varies from 20% to 90% by volume, depending on the density. These pores, distributed across micro, meso and macroscales, also facilitate these features [Li, 2019]. Nevertheless, the micro-capillary system, formed by pores of less than 10 nm in diameter within the cell walls, and the large-capillary system, which allow fluid movement, are interconnected. Thus, their solid-gas interfaces scatter light due to mismatches in the refractive index. Many of these pores have diameters larger than the wavelength of visible light (380–780 nm), causing severe light diffusion [Wang and Zhu, 2021]. This scattering effect is a critical limitation for TW applications unless properly mitigated through polymer infiltration. By filling the interconnected pore channels with a polymer possessing a refractive index close to that of cellulose (1.53 [Windle, 2017]), it is possible to match light paths and improve transparency.

4.5 *Balsa wood.*

Wood templates influence the optical, mechanical and thermal properties of the final Transparent wood (TW). They can be categorized into two main types (*Figure 4.4*): hardwood (stronger, leading to enhanced structural properties) and softwood (lower lignin content, being easier to delignify, typically resulting in TW with higher transparency) [Simelane et al., 2024].

Figure 4.4: Cellular structure of a softwood compared to that of a hardwood [Timber, 2021].



TW research predominantly focuses on hardwood species due to their structural benefits. These are typically balsa, poplar, basswood and birch. Furthermore, low density hardwood exhibits good optical properties due to its high porosity and easy lignin removal, promoting uniform resin impregnation [Li, 2019]. Among them, balsa wood stands out as the most frequently used. Its exceptionally low density (121 kg/m^3) and minimal lignin content ($\approx$ 18.3%) facilitate easy delignification and high optical transmittance [Li et al., 2017]. Furthermore, it is known for its rapid growth rate; a 10-year-old balsa tree can reach up to 16 meters in height and 0.5–0.6 meters in diameter [Pandit et al., 2025].

Chemically, balsa wood comprises 54% cellulose, 22% hemicelluloses, and 24% lignin [Céline Montanari et al., 2020]. Its xylem structure is primarily composed of three cell types: fibers, rays and vessels. Fibers account for approximately 80–90% of the xylem, providing structural support and rigidity. Rays contribute 8–15%, aiding in radial transport, while vessels, making up 2–5%, are responsible for water transport [Rai et al., 2022]. It has a refractive index of 1.52 [Chen et al., 2020] and its high porosity allows for effective resin infiltration.

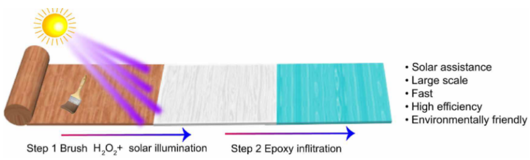
4.6 *Boltz's current production technique for Transparent wood.*

Boltz's method utilizes balsa wood sawdust as a feedstock for Transparent wood (TW) fabrication, presenting an innovative approach that valorizes wood waste. By exploiting its high surface area and porous structure it enhances chemical reactivity and polymer infiltration efficiency. The process begins with mechanical homogenization to standardize particle size, ensuring uniform treatment during subsequent steps. Delignification is conducted using H_2O_2, which removes light-absorbing lignin. Compared to conventional bulk wood substrates, sawdust facilitates faster and more thorough chemical penetration, resulting in a more efficient bleaching process. After delignification, the sawdust is rinsed and stored in ethanol to maintain porosity and prevent structural collapse due to dehydration. Then, it is immersed in a pre-polymerized PMMA solution, where cyclic deep vacuum is applied to extract residual solvents and air, enabling an easier polymer infiltration. Once saturated, the composite is molded and compressed between glass plates to produce a TW panel. Final polymer curing is performed either at room temperature or via dark ultraviolet (UV) light exposure, depending on the specific PMMA formulation.

4.7 *Solar-assisted chemical brushing production technique for Transparent wood.*

The Solar-assisted chemical brushing (SACB) method represents an innovative approach for the fabrication of Transparent wood (TW) (*Figure 4.5*). Unlike conventional delignification techniques that rely on high chemical consumption and energy-intensive immersion processes, this method selectively modifies lignin chromophores while retaining most of the lignin structure. This reduces light absorption and enhances optical transmittance without compromising the mechanical integrity of the wood template [Li, 2019].

Figure 4.5: Potential large-scale fabrication of transparent wood based on the SACB process [Xia et al., 2019].



Traditionally, alkaline H_2O_2 bleaching has been employed for lignin modification due to its environmentally friendly nature, producing only water as a by-product [Pandit et al., 2025]. Before this, a trace amount of NaOH is coated on the wood surface to improve the oxidation efficiency of H_2O_2. To further enhance efficiency and sustainability, SACB incorporates UV light to activate photocatalytic reactions. These specifically target chromophore groups in lignin, breaking down their light-absorbing structures and notably increasing its transparency, while preserving its natural strength and porosity [Jiang et al., 2022].

It overcomes two critical limitations of conventional lignin modification. First, it eliminates the need for large chemical baths by applying H_2O_2 directly onto the wood surface through brushing, significantly reducing chemical waste. The hierarchical porous structure of the wood template enhances the penetration and diffusion of the H_2O_2 solution. Second, UV light, which can be naturally sourced from sunlight, promotes chromophore degradation without external energy requirements. These improvements also prevent the release of toxic gases, which are typically generated in standard immersion-based methods [Pandit et al., 2025].

Then, the wood is immersed in ethanol to remove any remaining chemicals. To prepare the wood for Epoxy infiltration (the polymer mostly used in this technique), ethanol is then replaced with toluene, as it is chemically compatible with the Epoxy resin. It also evaporates cleanly, leaving fewer residues, which helps achieve better clarity and stronger bonding in TW applications. Using only ethanol, polar and incompatible with Epoxy, can lead to curing issues, poor bonding and cloudiness. Lastly, the Epoxy resin is infiltrated, which matches the refractive index of the cellulose matrix, greatly improving optical clarity.

Chapter 5 Methods and tools

This chapter outlines the Methods and Tools used to determine the environmental impact, cost-effectiveness and material properties of three distinct materials proposed as top protective layers for solar panels: Ultra-white rolled glass (UWRG), Transparent wood (TW) via Boltz's technique and TW via Solar-assisted chemical brushing (SACB) method. This provides a comprehensive comparison that supports the identification of the most viable solution for sustainable solar panel design. Additional calculations are provided in the *Appendix (9)* to justify the values presented. Furthermore, it is important to highlight that all values have as functional unit the production of 1 kg of TW or 1 kg of UWRG, unless stated otherwise.

The sustainability assessment is performed through a cradle-to-grave LCA for each material, following the guidelines of International Organization for Standardization (ISO) 14040 and ISO 14044. The analysis is conducted using SimaPro 9.4, with data sourced from the Ecoinvent 3 database, complemented by literature values and calculations. The environmental impacts of each technique are evaluated across multiple impact categories, including global warming potential or energy consumption. Additionally, two scenarios are considered for each TW production technique; 50/50 v% and 69/31 wt% ratio (polymer/wood). The first ratio is the one the company Boltz uses and the second one is applied in [Wu et al., 2024], in which it is said that the highest mass polymer content in existing studies is as high as approximately 69%. This comparison aims to identify which method and ratio contributes least to environmental degradation. Moreover, Material and Energy Flow Analysis (MEFA) are also created for visual aid.

For the economic evaluation, cost assessments are performed based on the price of raw materials, production processes and logistical considerations for importation to the Netherlands. Literature values are used to estimate raw material costs, taking into account import tariffs and market fluctuations.

The technical study compares their optical, mechanical and thermal metrics, based on data derived from literature. These are gathered from different sources related to the same method and an average value is presented. The goal is to highlight and compare material strengths and identify potential areas for improvement in terms of overall performance in solar panel applications. It is crucial to highlight that for the Boltz' technique the data from literature gathered corresponds to TW that use PMMA, but no to the actual method as there are no studies specifically related to it. Likewise, the SACB values represent the use of Epoxy resin, as it is the original polymer used in this technique.

These combined analyses provide a robust framework for determining the optimal top protective layer material production for solar panels in the Netherlands. The following sections detail the methodological approach per method for each of these analyses.

5.1 *Ultra-white rolled glass production.*

The manufacturing process consists of:

- Batch mixing:
  - The raw materials (silica, sodium carbonate, limestone, dolomite and mirabilite) are mixed to ensure homogeneity before processing. This is crucial to avoid impurities and uneven melting during the subsequent heating phase.
- Melting process:
  - This is transferred into a furnace and heated to 1450-1600°C, taking approximately 24 to 36 hours. A deep pool and stepped-bottom furnace are utilized to maintain uniform temperature and composition. Then it is homogenized to eliminate air bubbles [Chowdhury et al., 2025].
- Calendering and forming:
  - The molten glass is passed through rollers to achieve the desired thickness and surface textures, performed at around 1050°C for 15 to 20 minutes [Chowdhury et al., 2025].
- Annealing:
  - Then it is transferred to a lehr for annealing, where it is gradually cooled to relieve internal stresses. It is carried out over 4 to 8 hours, with temperatures gradually reduced from 600°C to room temperature [Chowdhury et al., 2025].
- Cutting:
  - The glass is cut into the required dimensions.
- Coating:
  - An anti-reflective coating is applied, typically using the sol–gel method. This layer boosts light transmittance and reduces surface reflection.
- Tempering:
  - The glass is heated to around 700°C and rapidly cooled, introducing compressive stress that enhances its mechanical strength, making it 4 to 6 times stronger than conventional glass. It generally takes about 30 to 45 minutes [Park et al., 2018].

All the pertinent calculations are in the *Appendix 9.1.5*.

5.1.1 *Data for the sustainability analysis.*

In order to conduct the LCA, the assumptions described in *Appendix 9.1.1* and the modelling inputs shown in *Appendix 9.1.2* (based on *Table 5.1*) have been applied. Additionally, *Figure 9.1* shows the numerical inputs used for each stage.

Table 5.1: Quantity of materials and energy needed for the production of 1 kg of UWRG.

Material	Quantity per kg of UWRG
White silica sand low iron dry quartz sand	0.745 kg
Soda ash	0.254 kg
Dolomite	0.12 kg
Limestone	0.117 kg
Mirabilite (sodium sulfate)	0.014 kg
Electricity	1.36 kWh
Natural gas	13.98 MJ
Water	1.51 L

5.1.2 *Data for the economic analysis.*

For the economic analysis, the products and the sites where they were bought from are displayed in *Table 5.2*. In *Appendix 9.1.4* these are visually presented.

Table 5.2: Sources of materials and energy prices for the production of 1 kg of UWRG.

Material	Sources
Silica	Alibaba.com [Alibaba, e]
Soda ash	Lerochem [LEROCHEM,]
Dolomite	Alibaba.com [Alibaba, b]
Limestone	Alibaba.com [Alibaba, c]
Mirabilite	Alibaba.com [Alibaba, d]
Electricity	0.19 €/kg kWh [Overstappen, 2025]
Natural gas	0.072 €/kWh [Eurostat, 2025]

5.2 *Boltz' technique for Transparent wood production.*

Although Boltz uses sawdust for Transparent wood (TW) preparation, this study adopts a more conventional technique using thin slices of natural wood. This choice facilitates a more direct comparison with established TW benchmarks found in earlier studies. Thus, the manufacturing process consists of the following steps (full LCA depicted in *Figure 5.1*):

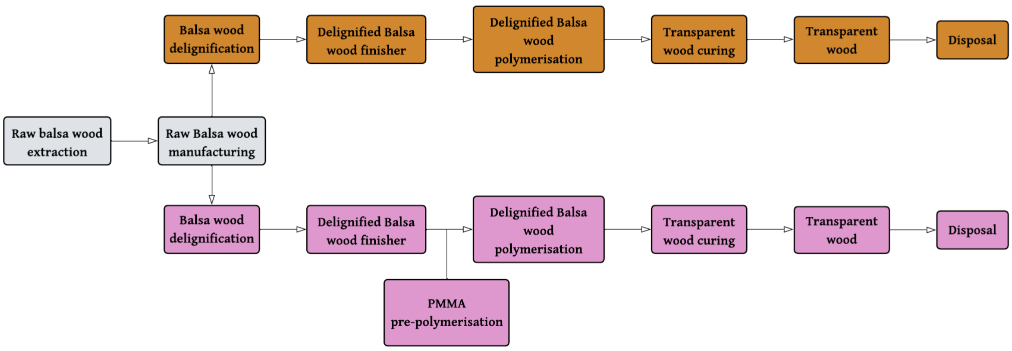
- Delignification treatment:
  - The wood sample is placed in a round-bottomed flask/beaker with 30 wt% H_2O_2.
  - The mixture is heated and maintained at approximately 65°C for 1 hour to remove lignin, enhancing optical properties and permeability.

- Ethanol rinsing and preservation:
  - After bleaching, it is rinsed with ethanol to remove residual H_2O_2 and lignin by-products.

- Then it is stored in ethanol to prevent dehydration, which could collapse the porous structure and reduce transparency potential.

- Polymer infiltration of pre-polymerized PMMA:
  - It is transferred into a beaker filled with sufficient pre-polymerized PMMA, ensuring complete submersion.
- Vacuum treatment:
  - Three vacuum cycles, each lasting 10 minutes, are performed to promote full infiltration by removing residual ethanol and air.
- Curing process:
  - The PMMA is polymerized to solidify the composite under UV black light overnight.

Figure 5.1: Overview of the Boltz and SACB technique for TW production (grey common; brown SACB; pink Boltz).



All the pertinent calculations are in the *Appendix 9.2.4* and *9.3.4*.

5.2.1 *Data for the sustainability analysis.*

In order to conduct the LCA, the assumptions described in *Appendix 9.2.1* and *9.3.1* and the modelling inputs shown in *Appendix 9.2.2* and *9.3.2* (based on *Table 5.3*) have been applied. Additionally, *Figure 9.9* shows the numerical inputs used for each stage.

Table 5.3: Quantity of materials and energy needed for the production of 1 kg of TW via the Boltz technique.

Material	Quantity per kg of TW (50/50 v%)	Quantity per kg of TW (69/31 wt%)
H_2O_2	600 ml	2.07 L
Ethanol	1.49 L	5.12 L
PMMA	0.91 kg	0.69 kg
Balsa wood	0.09 kg	0.31 kg
Electricity	3.23 kWh	4.46 kWh
Diesel	1.12 MJ	3.87 MJ
Biomass	1.26 MJ	4.33 MJ
LPG	0.39 MJ	1.345 MJ
Water	1.5 L	5.15 L

5.2.2 *Data for the economic analysis.*

The products and the sites where they were bought from are displayed in *Table 5.4*. In *Appendix 9.2.3* the products are visually presented.

Table 5.4: Sources of materials and energy prices for the production of 1 kg of TW via the Boltz technique.

Material	Sources
H_2O_2	Indiamarkt.com [Indiamarkt, a]
Ethanol	Hadron Group [Group, 2025]
PMMA	Businessanalytiq [Mike, 2023]
Balsa wood	Alibaba.com [Alibaba, a]
Electricity	0.076 €/kWh [CEIC,]
Diesel	0.93 USD/L [LLC,]
Biomass	0.75 CNY/kWh [Guo et al., 2022]
LPG	110 Yuan/mt [Echemi,]

5.3 *Solar-assisted chemical brushing technique for Transparent wood production.*

While Solar-assisted chemical brushing (SACB) has primarily been studied using Epoxy resin, two additional polymer options are also examined. PLA serves as a bio-based alternative, whereas PMMA is considered to assess the potential effects of switching the Boltz fabrication method while maintaining the same polymer material. The manufacturing process consists of the following steps (full LCA depicted in *Figure 5.1*):

- Material preparation:
  - A balsa wood slice with dimensions of approximately 400 mm × 110 mm × 1 mm is selected [Xia et al., 2019].

- A trace amount of NaOH (10 wt%) is applied to the wood surface to enhance the oxidation efficiency of the H_2O_2 solution.

- H_2O_2 brushing:
  - The wood sample is brushed with a 30 wt% H_2O_2 solution, ensuring full surface coverage.
  - It is done uniformly to allow even penetration of the H_2O_2, crucial to initiate the breakdown of chromophore groups in lignin, promoting bleaching.

- UV-assisted photo-catalytic reaction:
  - Then it is exposed to UV light with a wavelength range of 380–395 nm to simulate solar radiation for 1 hour, or until the wood turns completely white [Xia et al., 2019].

- Ethanol immersion and rinsing:
  - The wood sample is immersed in ethanol for 5 hours to remove any residual chemicals [Xia et al., 2019].

- Toluene exchange:
  - The wood is transferred into toluene to replace the ethanol in the wood matrix for 3 hours and make the polymerisation step easier for Epoxy resin [Xia et al., 2019].

- Epoxy infiltration:
  - After this, it is vacuum-infiltrated with Epoxy resin for 1.5 hours at a pressure between 0.2-0.25 bars [Chincinska, 2021].
  - It reduces the refractive index mismatch between the cell wall and the impregnated polymer, improving transparency.

- Curing process:
  - Finally, it is left to cure at room temperature for 12 to 24 hours, so the Epoxy resin solidifies and fully bonds with the cellulose matrix [Xia et al., 2019].

All the pertinent calculations are in the *Appendix 9.2.4* and *9.4.4*.

5.3.1 *Data for the sustainable analysis.*

In order to conduct the LCA, the assumptions described in *Appendix 9.2.1* and *9.4.1* and the inputs shown in *Appendix 9.2.2* and *9.4.2* (based on *Table 5.5*) have been applied. Additionally, *Appendix 9.4.3* shows the inputs used for each stage with Epoxy resin (*9.12*), PLA (*9.13*) and PMMA (*9.14*).

Table 5.5: Quantity of materials and energy needed for the production of 1 kg of TW via the SACB technique.

Material	Quantity per kg of TW (50/50 v%)	Quantity per kg of TW (69/31 wt%)
H_2O_2	140.25 ml	486.75 ml
NaOH	46.75 ml	162.25 ml
Ethanol	1.49 L	5.12 L
Toluene	1.49 L	5.12 L
Epoxy resin **PLA** **PMMA**	0.91 kg	0.69 kg
Balsa wood	0.09 kg	0.31 kg
Electricity	1.7 kWh	3.15 kWh
Diesel	1.12 MJ	3.87 MJ
Biomass	1.26 MJ	4.33 MJ
LPG	0.39 MJ	1.345 MJ
Water	7.17 ml	28 ml

5.3.2 *Data for the economic analysis.*

For the economic analysis, the products and the sites where they were bought from are displayed in *Table 5.6*. In *Appendix 9.2.3* the products are visually presented.

Table 5.6: Sources of materials and energy prices for the production of 1 kg of TW via the SACB technique.

Material	Sources
H_2O_2	Indiamarkt.com [Indiamarkt, a]
NaOH	G3Chem [G3Chem,]
Ethanol	Hadron Group [Group, 2025]
Toluene	Indiamarkt.com [Indiamarkt, b]
Epoxy resin	Aeromarineproducts.com [Products, 2023]
PLA	Made-in-China [in China,]
PMMA	Businessanalytiq [Mike, 2023]
Balsa wood	Alibaba.com [Alibaba, a]
Electricity	0.076 €/kWh [CEIC,]
Diesel	0.93 USD/L [LLC,]
Biomass	0.75 CNY/kWh [Guo et al., 2022]
LPG	110 Yuan/mt [Echemi,]

Chapter 6 Results

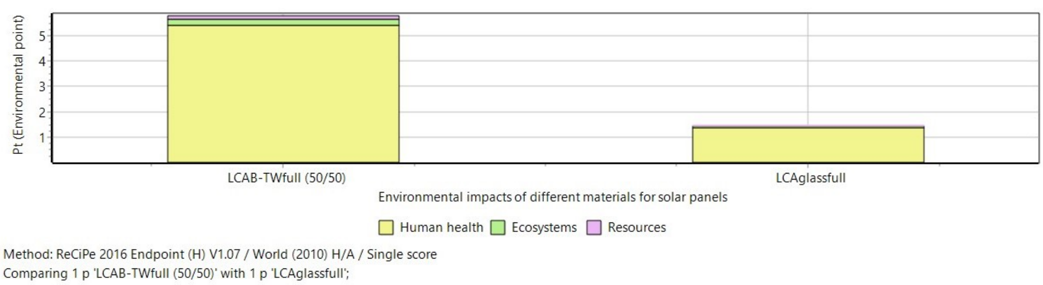
The results presented are based on the functional unit of 1 kg of Transparent wood (TW) and of Ultra-white rolled glass (UWRG), allowing for a standardized comparison across materials and fabrication methods. However, as these differ in density, the actual mass required to produce the top protective layer of a single solar panel varies. Therefore, the 1 kg results are subsequently extrapolated in the sustainable (*Table 6.1*) and economic (*Table 6.2*) analyses. This reflects the specific material quantities and investments needed for one panel, ensuring a realistic and application-relevant comparison. With the calculations provided in the *Appendix 9.5.4* the results were obtained.

6.1 *Sustainable analysis.*

Based on the LCAs conducted using SimaPro and the input parameters detailed in the *Mehtods and tools (5)* the key sustainability results for 1 kg of material are presented below. Supplementary figures and tables are provided in the *Appendix 9.5.1*.

Starting with the Total environmental impact (endpoints) of the TW (50/50 v%) produced by Boltz and the UWRG, *Figure 6.1* shows that the company's impacts are significantly higher. The highest impact contributes to the Human health area of protection.

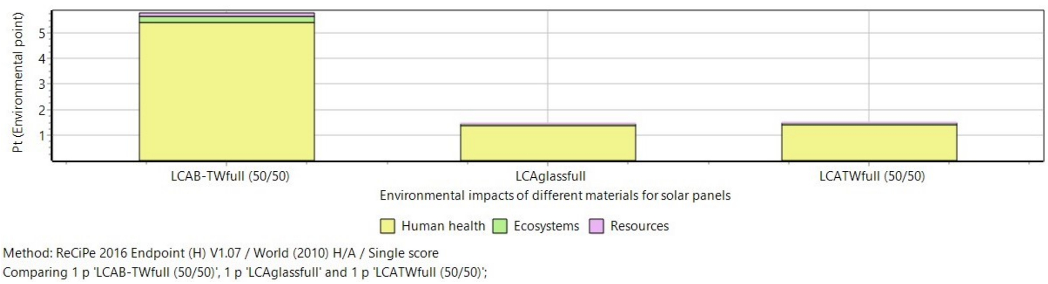
Figure 6.1: Comparison of the Total environmental impacts in each area of protection between Boltz's TW (50/50 v%) and UWRG production.



Both productions influence primarily the Human carcinogenic, the Freshwater eco-toxicity and the Marine eco-toxicity impact categories midpoints (*Figure 9.17*). Similarly, their most impactful stage is the Disposal. The different stages and their effects for UWRG are presented in *Figure 9.18* and for Boltz TW (50/50 v%) in *Figure 9.19*. For the company, the Disposal is followed by Stage 6-Delignified balsa wood polymerisation and Stage 7-Post polymerisation.

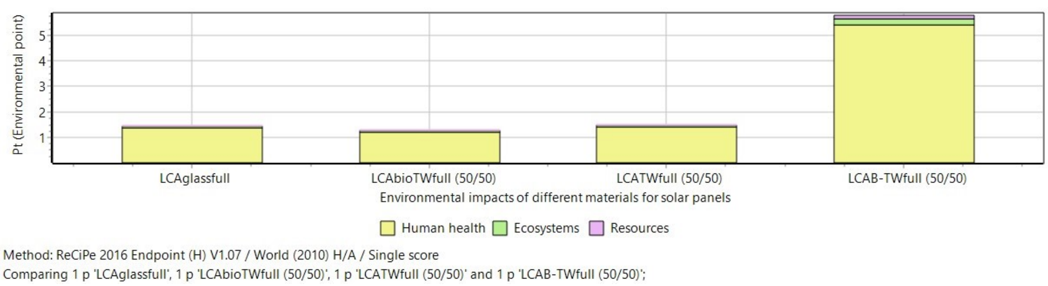
Due to the high difference between their impacts, the Solar-assisted chemical brushing (SACB) technique with Epoxy resin (50/50 v%) is proposed and studied as a potential alternative for a more sustainable TW production. The impacts are clearly lowered, but still slightly higher than the UWRG production (*Figure 6.2*).

Figure 6.2: Comparison of the Total environmental impacts in each area of protection between Boltz's TW (50/50 v%), UWRG and SACB-Epoxy (50/50 v%) production.



Again, the highest impacts are related to the same three impact categories (*Figure 9.20*) and the Disposal conforms to the highest environmental impact, followed by Stage 5.1-Delignified wood Polymerisation (*Figure 9.21*). As the Polymerisation and Disposal highly contribute to the environmental impacts, one option to decrease it can be via the use of a bio-polymer, such as Polylactic acid (PLA), instead of the current synthetic Epoxy resin. Accordingly, this reduces its environmental impact in these stages (*Figure 9.22*). Thus, it slightly improves the total environmental impact compared to UWRG and SACB with Epoxy resin (50/50 v%) as seen in *Figure 6.3*.

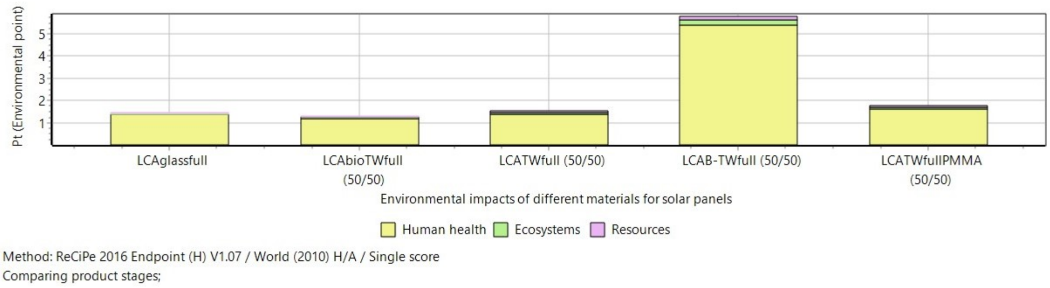
Figure 6.3: Comparison of the Total environmental impacts in each area of protection between Boltz's TW (50/50 v%), UWRG, SACB-Epoxy's TW (50/50 v%) and SACB-PLA's TW (50/50 v%) production.



However, one of the drawbacks of using Epoxy resin and PLA is that they both show low UV resistance [Li et al., 2022], hence they would need to be coated for solar panel applications [Nikafshar et al., 2017]. As the SACB technique is proved to be less environmentally polluting than the current Boltz one and PMMA itself presents good resistance to long UV exposure times, this method combined with PMMA is also considered (*Figure 9.23*). The only difference is the type of polymer infiltrated, the rest of the data remain the same.

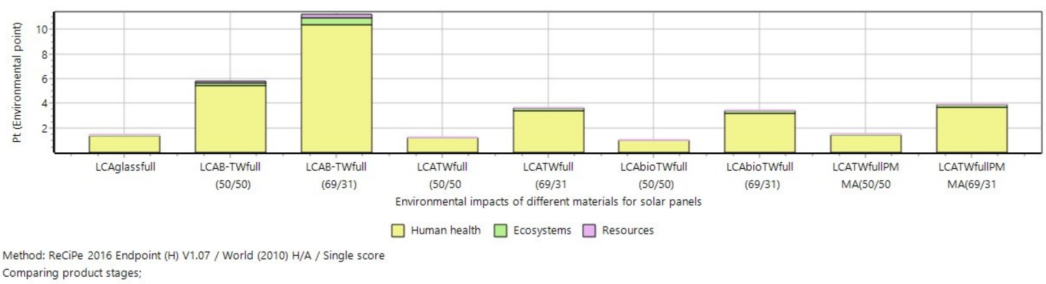
Figure 6.4 shows that SACB with PMMA infiltration has a lower impact than the current technique used by Boltz, in which they also use PMMA. Nevertheless, as PMMA is a more hazardous polymer than Epoxy resin and PLA, its impact is slightly greater than for these other SACB techniques and UWRG. For a clearer comparison between the SACB techniques, *Table 9.1* expresses the numerical results of their total environmental impacts.

Figure 6.4: Comparison of the Total environmental impacts in each area of protection between Boltz TW (50/50 v%), Ultra-white rolled glass, SACB-Epoxy (50/50 v%), SACB-PLA (50/50 v%) and SACB-PMMA (50/50 v%) production.



According to literature, the highest reported polymer-to-wood mass ratio in TW composites is 69/31. However, the company Boltz has achieved a significantly higher ratio of 91/9 (mass-based), corresponding to a 50/50 volume ratio. When this ratio is applied, a trend emerges, in which increased polymer content correlates with enhanced material properties and, counter-intuitively, a reduction in overall environmental impact. This outcome is favourable, as it suggests that performance improvements may be achieved alongside sustainability benefits. *Figure 6.5* depicts the decrease of the sustainability of all the alternatives when the 69/31 wt% ratio is implemented.

Figure 6.5: Comparison of the Total environmental impacts of UWRG and the different scenarios for TW production.



Tables 9.2, 9.3, 9.4 and 9.5 demonstrate that the environmental impacts of TW increase with a higher content of wood. Nevertheless, the effects of using more polymer does not show a higher impact in the polymer-related stages, but a lower one. Lastly, *Table 6.1*

summarizes the main findings of the sustainable analysis for 1 kg of material and the solar panel-extrapolated results.

Table 6.1: Summary of the sustainable analyses and their solar panel extrapolation.

	Unit	UWRG	Boltz TW (50/50 v%)	Boltz TW (69/31 wt%)	SACB-Epoxy resin TW (50/50 v%)	SACB-Epoxy resin TW (69/31 wt%)	SACB-PLA TW (50/50 v%)	SACB-PLA TW (69/31 wt%)	SACB-PMMA TW (50/50 v%)	SACB-PMMA TW (69/31 wt%)
Environmental impact per kg of material	Pt	1.47	5.79	11.2	1.52	3.7	1.3	3.46	1.76	3.98
Environmental impact per solar panel	Pt	6.62	12.52	21.19	3.28	7.99	2.81	7.47	3.8	8.6

The analysis considers the use of the SACB-PLA's TW (50/50 v%) as the best sustainable technique (2.81 Pt) for a single panel production and the Boltz's TW (69/31 wt%) as the most damaging for the environment (21.19 Pt), based on the boundaries set by the SimaPro software. Moreover, implementing the three different polymers studied with the SACB render lower total harmful emissions than UWRG (6.62 Pt), which supports its further study and implementation in solar panels.

6.2 *Economic analysis.*

Based on an analysis conducted through the review of various suppliers and relevant literature, the primary economic results are presented in this section. Supplementary tables are provided in the *Appendix 9.5.2*.

Table 6.2 gathers the total economic investments needed per kg of material and the solar panel-extrapolated results.

Table 6.2: Summary of the economic analyses and their solar panel-extrapolation.

	Unit	UWRG	Boltz TW (50/50 v%)	Boltz TW (69/31 wt%)	SACB-Epoxy resin TW (50/50 v%)	SACB-Epoxy resin TW (69/31 wt%)	SACB-PLA TW (50/50 v%)	SACB-PLA TW (69/31 wt%)	SACB-PMMA TW (50/50 v%)	SACB-PMMA TW (69/31 wt%)
Price per kg of material	€	1.2	8.53	21.8	51.67	68.82	13.18	39.61	13.73	40.03
Price per solar panel	€	5.4	18.42	47.09	111.61	147.57	28.47	85.86	29.66	86.46

The analyses indicate that UWRG represents the most cost-effective technique (5.4 €) for one solar panel, while the SACB-Epoxy resin (69/31 wt%) constitutes the most expensive option (147.57 €). The technique currently employed by Boltz (18.42 €) is the closest in cost to UWRG. Nonetheless, it still requires an investment of approximately three times greater.

6.3 *Technical analysis.*

Based on data gathered and compared from literature review, the main properties are presented in *Table 6.3*. Supplementary tables can be found in *Appendix 9.5.3*.

Table 6.3: Summary of the technical analyses.

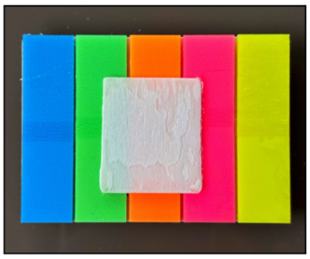
	Optical transmittance	**Haze**	**Tensile strength**	**Lignin content**	**Toughness**	**Thermal conductivity**
UWRG	85%	52%	33 MPa	-	0.1 MJ/m^3	1.03 W/m × K
Boltz	84.5%	63.25%	62.5 MPa	2.8%	3.33 MJ/m^3	0.118 W/m × K
SACB	85.5%	76.25%	46 MPa	80.67%	3.33 MJ/m^3	0.295 W/m × K

In terms of optical properties, all three techniques exhibit high transmittance values; however, SACB demonstrates a notably higher haze. Regarding mechanical and thermal performance, TW outperforms UWRG, with the Boltz method showing particularly strong results. As expected, in terms of lignin content, the SACB method retains a significantly higher proportion due to its selective lignin modification approach.

6.4 *Laboratory testing.*

A series of SACB-PMMA tests were conducted using varying material thicknesses, quantities and processing times. The two samples that yielded the most favourable results are presented in *Figure 6.6*. Detailed descriptions of the procedures followed and other samples can be found in the *Appendix* in *Table 9.14* and *Figure 9.27*, respectively.

Figure 6.6: Transparent wood samples from laboratory work.

Original	**Sample 1**	**Sample 2**
Natural Balsa wood	Transparent wood	
		

Chapter 7 Discussion

7.1 *Sustainable analysis results.*

The analysis highlights a critical trade-off between material composition and environmental performance in Transparent wood (TW) production. While it may be intuitively assumed that increasing the proportion of polymers (particularly the fossil-based Epoxy resin and PMMA) would result in a higher environmental burden, the findings reveal a counterintuitive trend. TW fabricated with a 50/50 v% ratio (which presents a 91/9 wt% one) consistently demonstrates a lower overall environmental impact compared to its 69/31 wt% ratio counterpart, despite containing a higher mass of polymer.

This observation is primarily explained by the intensive chemical treatments associated with wood processing. The delignification and post-treatment stages include chemicals that are significant contributors to several environmental impact categories, most notably to the Human carcinogenic eco-toxicity. Hence, increasing the wood content proportionally amplifies the environmental burden associated with these processing stages.

To illustrate this dynamic the focus is on the previously mentioned midpoint, which registered the highest impact values among all categories. Taking as an example the SACB-PMMA (the other polymers show the same trend), in the 69/31 wt% scenario (*Figure 9.25*) the delignified wood and its associated processing steps contribute approximately to 48.7% of the total impact, while PMMA accounts for only 8.05%. In contrast, the 50/50 v% configuration (*Figure 9.24*) reduces the wood contribution to 45.3% and increases the PMMA share to 21%. Despite the greater polymer mass, wood stages remain the dominant contributor to environmental impacts in both scenarios, even when used in smaller quantities.

Moreover, the studies of SACB techniques with different polymers demonstrate that polymer type has less influence on environmental impact than the proportion of wood. Nonetheless, among the 50/50 v% options, PLA exhibited the lowest environmental footprint (2.81 Pt) per solar panel, reinforcing its potential as a bio-based alternative. However, its known limitations in UV resistance may restrict its use in solar applications, similarly to what happens with the Epoxy resin (3.28 Pt). PMMA, while slightly more impactful than PLA or Epoxy resin in SACB scenarios (3.8 Pt), provides superior long-term optical performance. Additionally, it still presents a lower impact than UWRG (6.62 Pt), contributing to its future solar panel application.

These findings underline the potential advantages of the SACB technique, its selective retention reduces chemical usage and enhances structural integrity. Nevertheless, in this study, for the sake of consistency and comparability, the same ratios of polymer were applied across both techniques (Boltz's and SACB), without accounting for the reduced infiltration potential in SACB-treated samples. As a result, the environmental impact associated with them may be overestimated. Future research could investigate the actual polymer uptake in lignin-retaining structures to determine whether lower polymer volumes are sufficient, potentially leading to further reductions in environmental impact.

7.2 *Economic analysis results.*

The economic analysis shows that UWRG remains the most cost-effective option for the top layer of a single solar panel by a substantial margin (5.4 €). Its widespread industrial adoption process contributes to its low per-kilogram and per-panel production cost. Importantly, its manufacturing does not require any solvents, which are typically costly. Instead, it relies primarily on the bulk procurement of inorganic raw materials, which are generally more affordable and easier to scale economically than the chemicals used in TW production.

In contrast, TW fabrication, particularly via the SACB technique using Epoxy resin (69/31 wt%), represents the most expensive option per solar panel (147.57 €). This is primarily due to the high cost of the polymer itself (30.74 - 40.54 €/kg of TW), which is significantly more expensive than all the polymer alternatives (1.55 - 2.6 €/kg of TW). Moreover, the SACB process requires ethanol and toluene solvents which are quite costly as well (4.9 - 17.89 €/kg of TW). Additionally, the vacuum infiltration and curing steps demand energy and equipment that add to the running costs. The ratio of polymer to wood also plays a significant role in the cost structure. A higher proportion of polymer increases the expenditure on resin, while a higher wood content raises costs related to delignification and chemical treatment.

Boltz's current method with PMMA (50/50 v%) is the second cheapest method (18.42 €). Although it avoids some solvents such as toluene it still requires a considerable volume of PMMA and higher amounts of H_2O_2 than the SACB. As a result, the per-panel production cost is approximately three times that of UWRG, limiting its competitiveness at scale.

7.3 *Technical analysis results.*

The technical analysis indicates that all three materials satisfy the fundamental optical requirements for top-layer solar panel applications, achieving transmittance values exceeding 84%. SACB demonstrates superior haze performance (76.25%), promoting greater light scattering and diffuse transmission, enhancing overall panel efficiency.

In terms of mechanical performance, TW produced via Boltz's method offers the highest tensile strength (62.5 MPa) and toughness (3.33 MJ/m^3). This strengthen mechanical behaviour is likely due to the use of PMMA, which provides excellent structural reinforcement. This robustness is particularly advantageous for solar modules installed in outdoor environments, where durability against weathering, impact and mechanical stress is essential. The SACB method still delivers adequate strength (46 MPa).

Thermal conductivity is another important consideration for materials used in solar panels, especially in regions with high solar irradiance. Lower thermal conductivity helps minimize heat transfer to underlying photovoltaic cells, thus preserving their efficiency. TW via Boltz's method exhibits the lowest thermal conductivity (0.118 W/m × K), followed closely by SACB (0.295 W/m × K). Both TW options offer better insulating properties than UWRG (1.3 W/m × K). This highlights the added value of TW not only as a protective layer but also as a passive thermal regulator in solar panel assemblies.

However, it is important to note that the use of Epoxy resin and PLA may affect the material's long-term stability, as it is known to be more susceptible to UV degradation over time, potentially reducing the mechanical and optical performance of the TW under prolonged exposure. This underlines the need for additional research into long-term durability Epoxy resins. For instance, applying a coating will increase its life-span, but it will negatively impact its environmental and economic characteristics. Another option is to further research the use of SACB with PMMA due to its improved mechanical properties.

7.4 *Score table.*

This multidisciplinary analysis demonstrates that none of the evaluated techniques emerges as the optimal solution across all criteria. UWRG excels in economic viability and durability, benefiting from mature industrial processes and inexpensive raw materials, but it underperforms in environmental sustainability. Boltz's TW method achieves the highest technical scores, owing to complete delignification and high-strength PMMA reinforcement, yet it is both economically and environmentally harmful. In contrast, the SACB method, particularly when combined with PLA or PMMA at a 50/50 v%, offers the most balanced performance, significantly lowering environmental impact while maintaining acceptable mechanical and optical properties and offering cost reductions.

To synthesize the findings across sustainability, economic feasibility and technical potential, a weighted score table has been developed to study the performance of each method in the production of the top protective layer for one solar panel (*Table 7.1*). Each category is assigned a weight that reflects its relative importance for this Integration Project and the decision-making context of Boltz as a startup, prioritizing sustainability, followed by economic and then technical feasibility. The scale ranges from 1 (best performer) to 9 (worst performer) in each criterion.

Table 7.1: Final score comparison.

Analysis	Score	UWRG	Boltz TW (50/50 v%)	Boltz TW (69/31 wt%)	SACB-Epoxy resin TW (50/50 v%)	SACB-Epoxy resin TW (69/31 wt%)	SACB-PLA TW (50/50 v%)	SACB-PLA TW (69/31 wt%)	SACB-PMMA TW (50/50 v%)	SACB-PMMA TW (69/31 wt%)
Sustainable	0.5	4	8	9	2	6	1	5	3	7
Economic	0.3	1	2	5	8	9	3	6	4	7
Technical	0.2	5	1	2	7	6	9	8	3	4
Total		3.3	4.8	6.4	2.9	6.9	2.7	5.9	3.3	6.4

SACB with PLA at 50/50 v% achieves the lowest overall score (2.7), apparently making it the most balanced and promising option under the current evaluation framework. This is primarily due to its excellent sustainability and economic performance, despite moderate technical constraints. Nonetheless, as UWRG and SACB with PMMA at 50/50 v% perform competitively (3.3) and PMMA shows better properties than PLA, SACB with PMMA (50/50 v%) is considered to be the best alternative for solar panel applications. On the other hand, Boltz's current method, although technically strong, ranks lower (4.8) due to its significantly higher environmental impact.

These results underline the importance of trade-offs in material selection and reinforce the role of SACB as a scalable and sustainable alternative. Future research should focus on adapting SACB for large-scale applications by reducing polymer demand through lignin-retentive structures, further investigating PMMA implementation and including solvent recovery techniques. Long-term performance testing under real environmental conditions will also be essential to confirm the material's reliability and competitiveness in photovoltaic systems. Collectively, these steps will strengthen SACB-PMMA (50/50 v%) TW's position as a viable, eco-efficient and multifunctional alternative to traditional solar panels with UWRG.

7.5 *Laboratory testing results.*

Additionally, laboratory results reflect the influence of process parameters on the optical quality of TW samples impregnated with PMMA. Initially, a thickness of 0.33 mm was tested, but it proved too fragile and fractured during handling. In contrast, a maximum thickness of 1.68 mm was found to be incompatible with the chosen process conditions, as the quantities and durations applied were insufficient for effective polymer infiltration and curing. The two most successful samples, both with a thickness of 0.76 mm, are shown in *Figure 6.6*. Although these are not fully transparent, background colours are visibly distinguishable.

Sample 2 exhibited slightly greater transparency than Sample 1. This outcome is primarily attributed to a longer vacuum infiltration period applied during the impregnation of the delignified wood with MMA and the AIBN initiator (five cycles of 10 minutes each, compared to three cycles for Sample 1). In addition, Sample 2 was inmersed in a greater volume of the MMA-AIBN mixture (22 ml against 15 ml for Sample 1), enhancing saturation and polymer distribution. Likewise, smaller white shadows are present in Sample 2, due to a longer exposure time to H_20_2, NaOH and Ethanol.

Another critical factor was the pre-polymerisation of PMMA. In the samples shown in the *Appendix* in *Figure 9.28*, the polymerisation was not successful due to improper thermal activation. Although the procedure considered required stirring the MMA-AIBN solution for 15 minutes at 75°C, time constraints and slow heating led to premature placement of the mixture in the machine, where the temperature gradually increased over 40 minutes. As a result, the mixture was only exposed to the target temperature for approximately two minutes, leading to incomplete polymerisation. In contrast, Samples 1 and 2 followed the intended protocol: the heating system was preheated to 75°C before introducing the solution, which was then stirred for 15 minutes. This ensured proper activation of the initiator and yielded more consistent polymerisation, improving transparency. The poorly polymerised samples

(*Figure 9.28*) also discoloured during oven curing, developing a yellow-brown-white colour, likely due to incomplete reaction.

It is also worth noting that although Samples 1 and 2 were polymerised in the drying oven for four hours, they did not appear fully transparent immediately afterward. After being left curing wrapped in foil overnight, transparency improved noticeably the next day. As of the submission date of this Integration Project, both samples have maintained their transparency, with Sample 1 produced on June 2nd and Sample 2 on June 4th.

Chapter 8 Conclusion

This research helps to determine whether Transparent wood (TW) produced via the Solar-assisted chemical brushing (SACB) technique could serve as a more sustainable, economically viable and technically effective alternative to Ultra-white rolled glass (UWRG) and Boltz's current method as the protective top layer in solar panels in the Netherlands. A comprehensive comparative analysis was conducted across three main categories; sustainability, economic feasibility and technical performance, using LCAs modeled in SimaPro, literature-based cost evaluations and a benchmarking of relevant material properties.

The sustainability analysis highlighted that environmental impact in TW production is highly sensitive to the wood-to-polymer ratio. Counterintuitively, configurations with higher polymer content (50/50 v%) resulted in lower overall environmental burdens (i.e. 3.28 vs 7.99 Pt for SACB-Epoxy), largely due to the reduced need for chemically intensive wood treatments. SACB further improves this performance by retaining a portion of the lignin, thereby minimizing wood treatment-related impacts. Among the polymers assessed, replacing Epoxy resin (3.28 Pt) with bio-based PLA (2.81 Pt) enhances environmental performance. However, both suffer from low UV resistance, limiting their durability in outdoor photovoltaic applications. In contrast, PMMA, while slightly more impactful environmentally (3.8 Pt), offers superior long-term stability under sunlight, aligning more closely with the durability of UWRG (6.63 Pt). This makes PMMA a practical compromise, slightly less sustainable but with a far greater lifespan and functional reliability.

All materials studied meet the minimum optical requirement of over 84% transmittance, but SACB-TW distinguished itself through high haze (76.25%), which enhances light scattering and can improve solar cell efficiency. Technically, Boltz's method achieved the highest mechanical and thermal performance, largely due to deep polymer infiltration using PMMA. However, this is a resource and cost-intensive method. SACB, by contrast, offers a better balance, its selective lignin modification yields satisfactory strength and high optical haze while significantly lowering environmental impact.

Trade-offs between the three alternatives also exist. UWRG remains the most affordable (5.4 €) and industrially robust option for one solar panel, but its energy-intensive production makes it the least sustainable. Boltz's current method excels technically but demands high financial (18.42 €) and environmental investment (12.52 Pt). SACBs, particularly in their 50/50 v% configuration provide the best compromise across all metrics. They are more sustainable than both UWRG and Boltz's approach, economically competitive with further optimization and technically sufficient for integration into solar panel applications.

Based on the overall findings, the SACB configuration using PLA at 50/50 v% theoretically achieves the most favorable total score (2.7). However, its limited resistance to prolonged

UV exposure, similar to that of Epoxy resin, raises concerns about its long-term durability in outdoor solar applications. In contrast, SACB with PMMA at 50/50 v% emerges as the most practical option for Boltz to pursue. It offers strong optical and mechanical performance, significantly reduces environmental impact compared to Boltz's current method and performs similarly to UWRG in the weighted evaluation (3.3), while surpassing it in sustainability (3.8 vs 6.62 Pt) and mechanical and thermal properties. PMMA's superior UV stability makes it more suitable for extended outdoor use, ensuring a lifespan comparable to that of UWRG. Moreover, process optimizations (solvent recovery or improved polymer utilization) could further improve its feasibility. As such, SACB with PMMA at 50/50 v% presents a compelling, scalable and sustainable alternative for future product development within the solar panel industry, which aligns with Boltz's goals.

Lastly, concerning the laboratory experiments, they highlight the critical influence of process parameters, such as vacuum infiltration time, polymer volume or accurate pre-polymerisation conditions, on the final transparency of the samples. Proper thermal initiation and extended infiltration cycles significantly improved optical performance as seen in Sample 2, while deviations led to reduced clarity (Sample 1) and discolouration (other samples). Further laboratory work could focus on an increase in the time the sample is brushed with NaOH and H_2O_2 and submerged in ethanol, which could remove more thoroughly the white shadows currently present in Sample 1 and 2.

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Note: The Integration Project's structure has benefited from the application of ChatGPT. Nonetheless, it is important to highlight that no data was produced by it and all outputs were analysed and rephrased to ensure that no incorrect concepts were incorporated.

Chapter 9 Appendix

9.1 *Ultra-white rolled glass production technique.*

9.1.1 *Assumptions.*

- In SimaPro 9.4 the Allocation, cut-off by classification, system [support,], the Ecoinvent 3 database and the Endpoint (H) and Midpoint (H) for the Impacts in areas of protection and the Impact categories, respectively, are used.

- Only consider the raw materials mentioned in the *Literature study 4.2*, the others are in so little quantity that can be considered as negligible.

- European and glass factories primarily rely on natural gas for 75–85% of their energy needs [Yao et al., 2008]. Electricity (increasingly from renewable but still primarily from fossil sources) accounts for 10–15% [Chowdhury et al., 2025]. The rest, 5–10%, comes directly from other fossil fuels [Nugent et al., 2021].

- Sourcing and refining the raw materials needed to produce 1 t of molten glass require an estimated total energy of 3800–4800 MJ [Chowdhury et al., 2025]. Hence an average of 4300 MJ is chosen.

- 12000 MJ/ton glass is only for the industry process: from melting onwards [Chowdhury et al., 2025]. The melting of raw materials consumes around 75% of total energy requirement [Padilla et al., 2021]. The forming process consumes up to 12%, with the furnace being the primary energy consumer. The annealing process consumes 2–5% of total energy (gas is mostly used, but there is a growing trend towards using electricity to reduce CO_2 emissions). Thus an average value of 3.5% is used [Chowdhury et al., 2025]. The remains (9.5%) are included in the finishing process, consisting of drying and surface treatments such as cutting, tempering, coating, polishing, decorating and sizing [Miserocchi et al., 2024].

- Due to lack of specific data, float glass Life cycle inventory was used as a proxy for UWRG, with an adjustment factor of +5% energy demand to account for raw material purification and surface texturing, based on industry estimates [Usbeck et al.,].

- For the disposal, 6.9873×10^{-5} kWh was used for the electricity consumption, from the Ecoinvent 3 database.

9.1.2 *SimaPro modelling inputs.*

- Glass raw materials' extraction and mixing:

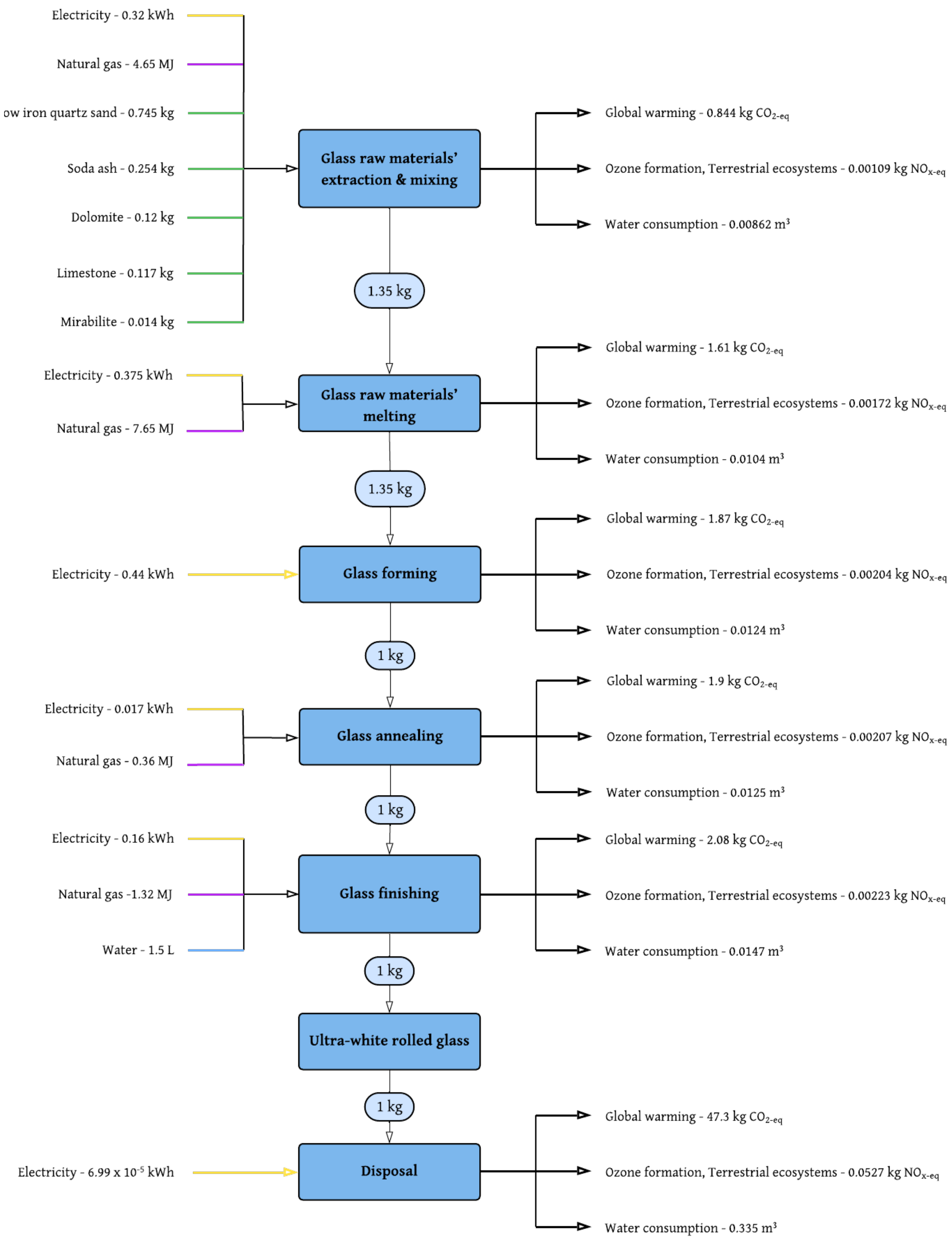
  - Electricity: Electricity, medium voltage NL— electricity voltage transformation from high to medium voltage — Cut-off, U.
  - Heat, district or industrial, natural gas Europe without Switzerland— heat production,

natural gas, at boiler condensing modulating $\succ$ 100kW — Cut-off, U.
- Silica sand: Silica sand DE— production — Cut-off, U.
- Soda ash: Soda ash, dense GLO— modified Solvay process, Hou's process — Cut-off, U.
- Dolomite: Dolomite RER— market for dolomite — Cut-off, U.
- Limestone: Limestone, crushed, for mill RoW— market for limestone, crushed, for mill — Cut-off, U.
- Mirabilite: Sodium sulfate, anhydrite RER— market for — Cut-off, U.

- Glass raw materials' melting:
  - Glass raw materials' extraction and mixing.
  - Electricity: Electricity, medium voltage NL— electricity voltage transformation from high to medium voltage — Cut-off, U.
  - Natural gas: Heat, district or industrial, natural gas Europe without Switzerland— heat production, natural gas, at industrial furnace $\succ$ 100kW — Cut-off, U.
- Glass forming:
  - Glass raw materials' melting.
  - Electricity: Electricity, medium voltage NL— electricity voltage transformation from high to medium voltage — Cut-off, U.
- Glass annealing:
  - Glass forming.
  - Electricity: Electricity, medium voltage NL— electricity voltage transformation from high to medium voltage — Cut-off, U.
  - Natural gas: Heat, district or industrial, natural gas Europe without Switzerland— heat production, natural gas, at boiler condensing modulating $\succ$ 100kW — Cut-off, U.
- Glass finishing:
  - Glass annealing.
  - Water: Tap water RER— market group for — Cut-off, U.
  - Electricity: Electricity, medium voltage NL— electricity voltage transformation from high to medium voltage — Cut-off, U.
  - Natural gas: Heat, district or industrial, natural gas Europe without Switzerland— heat production, natural gas, at boiler condensing modulating $\succ$ 100kW — Cut-off, U.

9.1.3 *MEFA.*

Figure 9.1: MEFA of the production chain of the UWRG.



9.1.4 *Products purchased.*

Figure 9.2: Products used for UWRG production.

White Silica Sand Low Iron Dry Quartz Sand	Soda ash 99%	Dolomite	Limestone	Mirabilite (sodium sulfate)
				

9.1.5 *Calculations.*

Figure 9.3: Extrapolate raw materials for 1 kg of UWRG from [Anhui, 2023] and prices.

Step	Description	Formula	Calculation	Result	Price data	Price
1	Silica	$\mathrm{Si} = \frac{S_{1\,ton\,UWRG} \times UWRG_{DESIRED}}{1000}$	$\frac{745 \times 1}{1000}$	**Si = 0.745 kg**	141.49 €/ton	**0.14 €**
2	Soda ash	$\mathrm{So} = \frac{So_{1\,ton\,UWRG} \times UWRG_{DESIRED}}{1000}$	$\frac{254 \times 1}{1000}$	**So = 0.254 kg**	2 €/kg	**0.51 €**
3	Dolomite	$\mathrm{D} = \frac{D_{1\,ton\,UWRG} \times UWRG_{DESIRED}}{1000}$	$\frac{120 \times 1}{1000}$	**D = 0.12 kg**	0.19 €/kg	**0.02 €**
4	Limestone	$\mathrm{L} = \frac{L_{1\,ton\,UWRG} \times UWRG_{DESIRED}}{1000}$	$\frac{117 \times 1}{1000}$	**L = 0.117 kg**	0.267 €/kg	**0.031 €**
5	Mirabilite	$\mathrm{M} = \frac{M_{1\,ton\,UWRG} \times UWRG_{DESIRED}}{1000}$	$\frac{14 \times 1}{1000}$	**M = 0.014 kg**	133.48 €/ton	**0.002 €**

Figure 9.4: Energy, water and prices for 1 kg of UWRG..

Step	Description	Formula	Calculation	Result	Price data	Price
1	Mining, processing, batching and mixing energy	$E_{PRE\text{-}NG} = \frac{Total\ raw\ materials \times Energy_{1\ ton\ UWRG}}{1000} \times 0.8$	$\frac{1.35 \times 4300}{1000} \times 0.8$	**$E_{PRE\text{-}NG}$ = 4.65 MJ**	0.072 €/kWh	**NG = 0.28 €** **EL = 0.26 €**
		$E_{PRE\text{-}EL} = \frac{Total\ raw\ materials \times Energy_{1\ ton\ UWRG}}{1000} \times 0.2$	$\frac{1.35 \times 4300}{1000} \times 0.2$	**$E_{PRE\text{-}EL}$ = 0.32 kWh**	0.19 €/kWh	
2	Total energy from melting to finishing	$E_{M\text{-}F} = \frac{Total\ Energy_{1\ ton\ UWRG} \times UWRG_{DESIRED}}{1000}$	$\frac{1200 \times 1}{1000}$	**$E_{M\text{-}F}$ = 12 MJ**	-	
3	Melting energy	$E_{M\text{-}NG} = E_{M\text{-}F} \times Contribution \times 0.85$	$12 \times 0.75 \times 0.85$	**$E_{M\text{-}NG}$ = 7.65 MJ**	0.072 €/kWh	
		$E_{M\text{-}EL} = E_{M\text{-}F} \times Contribution \times 0.15$	$12 \times 0.75 \times 0.15$	**$E_{M\text{-}EL}$ = 0.375 kWh**	0.19 €/kWh	
4	Forming energy	$E_{F\text{-}EL} = E_{M\text{-}F} \times Contribution \times 1$	$12 \times 0.12 \times 1$	**$E_{F\text{-}EL}$ = 0.44 kWh**	0.19 €/kWh	
5	Annealing energy	$E_{A\text{-}NG} = E_{M\text{-}F} \times Contribution \times 0.85$	$12 \times 0.035 \times 0.85$	**$E_{A\text{-}NG}$ = 0.36 MJ**	0.072 €/kWh	
		$E_{A\text{-}EL} = E_{M\text{-}F} \times Contribution \times 0.15$	$12 \times 0.035 \times 0.15$	**$E_{A\text{-}EL}$ = 0.017 kWh**	0.19 €/kWh	
6	Finishing energy	$Contribution = E_{M\text{-}F} \times (C_{MELTING} + C_{FORMING} + C_{ANNEALING})$	$12 \times (0.75 + 0.12 + 0.035)$	**$E_{F\text{-}NG}$ = 1.32 MJ**	0.072 €/kWh	
				$E_{F\text{-}EL}$ = 0.16 kWh	0.19 €/kWh	
7	Finishing water (cleaning and cutting)	$W_F = W_{F\text{-}DATA} \times Estimation_{UWRG}$	1.44×1.05	**W_F = 1.51 L**	-	-

9.2 *General Transparent wood production technique.*

9.2.1 *Assumptions.*

- In SimaPro 9.4 the Allocation, cut-off by classification [support,], the Ecoinvent 3 database and the Endpoint (H) and Midpoint (H) for the Impacts in areas of protection and the Impact categories, respectively, are used.

- Two scenarios are analysed: 50/50 v% (91/9 wt%; current ratio used by Boltz) and 69/31 wt% (Highest polymer content from literature [Wu et al., 2024]).

- The loss of wood material in wood slices during the delignification and infiltration processes and the solvent evaporation are considered negligible.

- The size of the balsa wood used = the final TW size.

- The energy source comes from diesel, biomass, LPG and electricity [Rai et al., 2022].

- In SimaPro the data for Liquefied Petroleum Gas (LPG) is not available, so it is replaced by propane, because LPG is a mix between this and butane [Synák et al., 2019].

- The Raw balsa wood extraction considers that the balsa wood is mainly composed of wood (Adhesive: 1%; Fiberglass: 1%; Others: $\prec$ 1% of the total composition) and the manufacturing covers kiln drying, cutting and trimming and sanding [Materials, 2023].

- In SimaPro the process of kiln drying is obsolete, hence a comparable method has been chosen.

- In SimPro the raw wood is not balsa but birch, as it is not present in the database. It is chosen as birch and basswood are the most similar to balsa wood [Fowler, 2022].

- In the Raw balsa wood manufacturing the Renewable energy is divided into 90% Biomass and 10% Electricity, whereas the Non-renewable is divided as 50% Electricity and 50% LPG. Furthermore, the electricity grid used is the one from China, as the wood is exported from there, the rest of the processes are represented by the Netherlands' grid.

- In SimaPro, although the description says without water and can be misinterpreted, H_2O_2 and NaOH solution do have water, it is referring to the percentage shown, which indicates the purity of only the chemical compounds.

- In SimaPro H_2O_2 (30% wt) and NaOH (30% wt) are calculated for a concentration percentage of 50% wt.

- The application of H_2O_2 and/or NaOH involves minimal energy, primarily manual labor. Consider negligible.

- Partial coverage and dilution adjustment are applied only to the SACB technique, as brushing requires less solvent than full immersion and the UV light used during lignin modification enhances the process. In contrast, the Boltz method involves full submersion in chemicals and applies dark UV light only during polymerisation, offering no reduction in solvent use during earlier stages.

- Depending on the purity, the amount of solvent (ethanol and/or toluene) required for the exchange process typically ranges from two to three times the volume of wood [Hai et al., 2025] to ensure full immersion, effective lignin modification and uniform UV exposure. Balsa's high porosity requires significant fluid uptake, and an excess of reactive chemicals maintains consistent reaction conditions. In this case double the volume of the wood.

- For ethanol and/or toluene no vacuum pumps or active filtration during immersion are needed, hence a smaller machine is used, the C-MAG MS 7. It has a stirring quantity of maximum 10 L and a power of 30 W [Sysmatec,].

- For the vacuum infiltration the Vacuum Welch CRVpro 4 is used. It has a power of 0.37-0.4 kW [welch,].

- For the Disposal, 1478 MJ of non-renewable energy consumption is associated with 1 ton of wood waste at landfills (in which 81% is associated with transport, and 19% with processing [Hossain and Poon, 2018]).

- Only chemical recycling and incineration are suitable routes for chemically hardening polymers [Schelte et al., 2023].

- Specific energy of 0.51 GJ/ton for Municipality solid waste [Nabavi-Pelesaraei et al., 2017].

9.2.2 *SimaPro modelling inputs.*

- Raw balsa wood extraction:
  - Wood: Sawlog and veneer log, hardwood, measured as solid wood under bark RoW— hardwood forestry, birch, sustainable forest management — Cut-off, U.
  - Electricity: Electricity, medium voltage CN— market group for — Cut-off, U.
  - Diesel: Diesel, burned in agricultural machinery GLO— diesel, burned in agricultural machinery — Cut-off, U.
  - Water: Tap water GLO— market group for — Cut-off, U.

- Raw balsa wood manufacturing:
  - Raw balsa wood extraction.
  - Wood: Sawnwood, board, hardwood, raw, dried (u=10%) RoW— board, hardwood, raw, kiln drying to u=10% — Cut-off, U.
  - Electricity: Electricity, medium voltage CN— market group for — Cut-off, U.
  - Biomass: Heat, central or small-scale, other than natural gas RoW— heat production, wood pellet, at furnace 300kW — Cut-off, U.
  - LPG: Heat, district or industrial, other than natural gas RoW— heat production, propane, at industrial furnace $\succ$ 100kW — Cut-off, U.
  - Water: Tap water GLO— market group for — Cut-off, U.

- Balsa wood delignification:
  - Raw balsa wood manufacturing.
  - H_2O_2: Hydrogen peroxide, without water, in 50% solution state RER— hydrogen peroxide production, product in 50% solution state — Cut-off, U.

- Delignified Balsa wood finisher: - Balsa wood delignification.
  - Ethanol: Ethanol, without water, in 99.7% solution state, from ethylene RER— ethylene hydration — Cut-off, U.
  - Electricity: Electricity, low voltage NL— electricity voltage transformation from medium to low voltage — Cut-off, U.

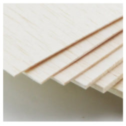
- Delignified Balsa wood polymerisation:

- Vacuum electricity: Electricity, low voltage NL— electricity voltage transformation from medium to low voltage — Cut-off, U.

- Disposal:
  - All previous stages.
  - Electricity, medium voltage NL— electricity voltage transformation from high to medium voltage — Cut-off, U.
  - Balsa wood: Waste wood, untreated RoW— treatment of, sanitary landfill — Cut-off, U.

9.2.3 *Products purchased.*

Figure 9.5: Products used for TW production.

Balsa wood	H_2O_2 30%	NaOH Solution 10% (Unstandardised)	Ethanol 99%
			
99% Toluene Industrial Solvent, Liquid	**Epoxy resin**	**PLA**	**PMMA**
			

9.2.4 *Calculations.*

Figure 9.6: TW content for 50/50 v% and 69/31 wt% ratio with prices.

Step	Description	Formula	Calculation	Result	Price data	Price
1	Volume of the TW sample	$V_{TWS} = L \times W \times H$	$V_{TWS} = 0.4 \times 0.11 \times 0.001$	**$V_{TWS} = 4.4 \times 10^{-5}$ m^3**	-	-
2	Balsa wood volume content (50/50 v%) for small sample	$V_{BWS(50)} = V_{TWS} \times 0.5$	$(4.4 \times 10^{-5}) \times 0.5$	**$V_{BWS(50)} = 2.2 \times 10^{-5}$ m^3**	-	-
	Balsa wood mass content (69/31 wt%) for 1 kg TW	$M_{BW(31)} =$ TW kg $\times 0.31$	1×0.31	**$M_{BW(31)} = 0.31$ kg**	0.53 €/piece 0.17 kg/piece 0.31kg	**0.97 €**
3	Balsa wood mass content (50/50 v%) for small sample	$M_{BWS(50)} = V_{BWS(50)} \times \text{Density}_{BW}$	$(2.2 \times 10^{-5}) = 121$	**$M_{BWS(50)} = 2.66 \times 10^{-3}$ kg**	-	-
4	Epoxy resin/PLA/PMMA mass content (50/50 v%) for small sample	$M_{POLYMERS(50)} = (V_{TWS} - V_{BWS(50)}) \times \text{Density}_{PMMA}$	$(4.4 \times 10^{-5} - 2.2 \times 10^{-5}) \times 1180$	**$M_{POLYMERS(50)} = 0.026$ kg**	-	-
	Epoxy resin/PLA/PMMA mass content (69/31 wt%) for 1 kg TW	$M_{POLYMER(69)} = (1 - M_{BW(31)})$	$1 - 0.31$	**$M_{POLYMER(69)} = 0.69$ kg**	253.06 €/ 5.68 kg Epoxy resin	**1.55 €**
					45 €/ 20 kg PLA	**30.74 €**
					3.2 $/kg PMMA	**1.97 €**
5	Multiplying factor for 1 kg of TW (50/50 v%)	Factor $= \frac{1}{M_{BWS\,(50)} + M_{POLYMERS\,(50)}}$	$\frac{1}{2.66 \times 10^{-3} + 0.026}$	**Factor = 31.98**	-	-
6	Balsa wood mass content (50/50 v%) for 1 kg TW	$M_{BW(50)} = M_{BWS(50)} \times$ Factor	$(2.66 \times 10^{-3}) \times 31.98$	**$M_{BW(50)} = 0.09$ kg**	0.53 €/piece 0.17 kg/piece 0.09kg	**0.28 €**
	Epoxy resin/PLA/PMMA mass content (50/50 v%) for 1 kg TW	$M_{POLYMER(50)} = M_{POLYMERS(50)} \times$ Factor	0.026×31.98	**$M_{POLYMER(50)} = 0.91$ kg**	253.06 €/ 5.68 kg Epoxy resin	**40.54 €**
					45 €/ 20 kg PLA	**2.05 €**
					3.2 $/kg PMMA	**2.6 €**

Figure 9.7: Balsa wood extraction, manufacturing and disposal energy and prices.

Step	Description	Formula	Calculation	Result	Price data	Price
1	Balsa wood extraction renewable electricity	$E_{RAW\text{-}R\ (50)} = \frac{2360 \times M_{BW\ (50)}}{Density_{BW}}$	$\frac{2360 \times 0.09}{121}$	**$E_{RAW\text{-}R\ (50)}$ = 0.49 kWh**	0.076 €/kWh	**0.04 €**
		$E_{RAW\text{-}R\ (31)} = \frac{2360 \times M_{BW\ (31)}}{Density_{BW}}$	$\frac{2360 \times 0.31}{121}$	**$E_{RAW\text{-}R\ (31)}$ = 1.68 kWh**		**0.13 €**
2	Balsa wood extraction diesel	$E_{RAW\text{-}D\ (50)} = \frac{1510 \times M_{BW\ (50)}}{Density_{BW}}$	$\frac{1510 \times 0.09}{121}$	**$E_{RAW\text{-}D\ (50)}$ = 1.12 MJ**	0.82 €/kWh	**0.02 €**
		$E_{RAW\text{-}D\ (31)} = \frac{2360 \times M_{BW\ (31)}}{Density_{BW}}$	$\frac{1510 \times 0.31}{121}$	**$E_{RAW\text{-}D\ (31)}$ = 3.87 MJ**		**0.08 €**
3	Balsa wood extraction water	$W_{RAW\ (50)} = \frac{6.4 \times M_{BW\ (50)}}{Density_{BW}}$	$\frac{6.4 \times 0.09}{121}$	**$W_{RAW\ (50)}$ = 4.76×10^{-3} L**	-	-
		$W_{RAW\ (31)} = \frac{6.4 \times M_{BW\ (31)}}{Density_{BW}}$	$\frac{6.4 \times 0.31}{121}$	**$W_{RAW\ (31)}$ = 0.02 L**		
4	Balsa wood manufacturing biomass	$E_{MAN\text{-}B\ (50)} = \frac{1880 \times M_{BW\ (50)}}{Density_{BW}}$	$\frac{1880 \times 0.09}{121} \times 0.9$	**$E_{MAN\text{-}B\ (50)}$ = 1.26 MJ**	0.091 €/kWh	**0.35 €**
		$E_{RAW\text{-}B\ (31)} = \frac{1880 \times M_{BW\ (31)}}{Density_{BW}}$	$\frac{1880 \times 0.31}{121} \times 0.9$	**$E_{RAW\text{-}B\ (31)}$ = 4.33 MJ**		**0.11 €**
5	Balsa wood manufacturing renewable electricity	$E_{MAN\text{-}R\ (50)} = \frac{1880 \times M_{BW\ (50)}}{Density_{BW}}$	$\frac{1880 \times 0.09}{121} \times 0.1$	**$E_{MAN\text{-}R\ (50)}$ = 0.04 kWh**	0.076 €/kWh	**3.04×10^{-3} €**
		$E_{MAN\text{-}R\ (31)} = \frac{1880 \times M_{BW\ (31)}}{Density_{BW}}$	$\frac{1880 \times 0.31}{121} \times 0.1$	**$E_{MAN\text{-}R\ (31)}$ = 0.13 kWh**		**0.01 €**
6	Balsa wood manufacturing LPG	$E_{MAN\text{-}L\ (50)} = \frac{1880 \times M_{BW\ (50)}}{Density_{BW}}$	$\frac{1050 \times 0.09}{121} \times 0.5$	**$E_{MAN\text{-}L\ (50)}$ = 0.39 MJ**	48.5 kg/MJ 0.01 €/kg	**8.04×10^{-5} €**
		$E_{MAN\text{-}L\ (31)} = \frac{1880 \times M_{BW\ (31)}}{Density_{BW}}$	$\frac{1050 \times 0.31}{121} \times 0.5$	**$E_{MAN\text{-}L\ (31)}$ = 1.345 MJ**		**3×10^{-4} €**
7	Balsa wood manufacturing non-renewable electricity	$E_{MAN\text{-}NR\ (50)} = \frac{1880 \times M_{BW\ (50)}}{Density_{BW}}$	$\frac{1050 \times 0.09}{121} \times 0.5$	**$E_{MAN\text{-}NR\ (50)}$ = 0.11 kWh**	0.076 €/kWh	**8.36×10^{-3} €**
		$E_{MAN\text{-}NR\ (31)} = \frac{1880 \times M_{BW\ (31)}}{Density_{BW}}$	$\frac{1050 \times 0.31}{121} \times 0.5$	**$E_{MAN\text{-}NR\ (31)}$ = 0.37 kWh**		**0.03 €**
8	Balsa wood manufacturing water	$W_{MAN\ (50)} = \frac{3.24 \times M_{BW\ (50)}}{Density_{BW}}$	$\frac{3.24 \times 0.09}{121}$	**$W_{MAN\ (50)}$ = 2.41×10^{-3} L**	-	-
		$W_{MAN\ (31)} = \frac{3.24 \times M_{BW\ (31)}}{Density_{BW}}$	$\frac{3.24 \times 0.31}{121}$	**$W_{MAN\ (31)}$ = 0.008 L**		
9	Disposal of wood	$E_{D\text{-}W\ (50)} = 1478 \times 0.19 \times \frac{M_{BW\ (50)}}{1000}$	$1478 \times 0.19 \times \frac{0.09}{1000}$	**$E_{D\text{-}W\ (50)}$ = 0.03 kWh**	0.076 €/kWh	**2.28×10^{-3} €**
		$E_{D\text{-}W\ (31)} = 1478 \times 0.19 \times \frac{M_{BW\ (31)}}{1000}$	$1478 \times 0.19 \times \frac{0.31}{1000}$	**$E_{D\text{-}W\ (31)}$ = 0.087 kWh**		**6.61×10^{-3} €**
10	Disposal of polymer	$E_{D\text{-}P\ (50)} = \frac{510 \times M_{BW\ (50)}}{1000}$	$\frac{510 \times 0.09}{1000}$	**$E_{D\text{-}P\ (50)}$ = 0.46 kWh**	0.076 €/kWh	**0.03 €**
		$E_{D\text{-}P\ (31)} = \frac{510 \times M_{BW\ (31)}}{1000}$	$\frac{510 \times 0.31}{1000}$	**$E_{D\text{-}P\ (31)}$ = 0.35 kWh**		**0.04 €**

Figure 9.8: Extrapolate for SimaPro software.

Step	Description	Formula	Calculation	Result
1	Balsa wood volume (50/50 v%)	$V_{\text{SIMAPRO (50)}} = \frac{M_{BW\,(50)}}{Density_{BW}}$	$\frac{0.09}{121}$	7.44×10^{-4} **m³**
	Balsa wood volume (69/31 wt%)	$V_{\text{SIMAPRO (31)}} = \frac{M_{BW\,(31)}}{Density_{BW}}$	$\frac{0.31}{121}$	2.5×10^{-3} **m³**
2	H_2O_2 for 0.09 kg of Balsa wood for Boltz	$H_2O_{2\,\text{SIMAPRO-B(50)}} = H_2O_{2\,(50)} \times$ Purity $\times$ $\text{Density}_{H2O2} \times 2$	$600 \times 0.3 \times (1.11 \times 10^{-3}) \times 2$	**$H_2O_{2\,\text{SIMAPRO-B (50)}}$ = 0.4 kg**
	H_2O_2 for 0.31 kg of Balsa wood for Boltz	$H_2O_{2\,\text{SIMAPRO-B (31)}} = H_2O_{2\,(31)} \times$ Purity $\times$ $\text{Density}_{H2O2} \times 2$	$2066.67 \times 0.3 \times (1.11 \times 10^{-3}) \times 2$	**$H_2O_{2\,\text{SIMAPRO-B (31)}}$ = 1.34 kg**
	H_2O_2 for 0.09 kg of Balsa wood	$H_2O_{2\,\text{SIMAPRO-S (50)}} = H_2O_{2\,(50)} \times$ Purity $\times$ $\text{Density}_{H2O2} \times 2$	$140.25 \times 0.3 \times (1.11 \times 10^{-3}) \times 2$	**$H_2O_{2\,\text{SIMAPRO-S (50)}}$ = 0.1 kg**
	H_2O_2 for 0.31 kg of Balsa wood for SACB	$H_2O_{2\,\text{SIMAPRO-S (31)}} = H_2O_{2\,(31)} \times$ Purity $\times$ $\text{Density}_{H2O2} \times 2$	$486.75 \times 0.3 \times (1.11 \times 10^{-3}) \times 2$	**$H_2O_{2\,\text{SIMAPRO-S (31)}}$ = 0.32 kg**
3	NaOH for 0.09 kg of Balsa wood	$\text{NaOH}_{\text{SIMAPRO (50)}} = \frac{NaOH_{(50)} \times Purity \times Density_{NaOH}}{0.5}$	$\frac{486.75 \times 0.3 \times (1.11 \times 10^{-3})}{0.5}$	$\text{NaOH}_{\text{SIMAPRO (50)}}$ = **0.04 kg**
	NaOH for 0.31 kg of Balsa wood	$\text{NaOH}_{\text{SIMAPRO (31)}} = \frac{NaOH_{(31)} \times Purity \times Density_{NaOH}}{0.5}$	$\frac{486.75 \times 0.3 \times (1.11 \times 10^{-3})}{0.5}$	$\text{NaOH}_{\text{SIMAPRO (31)}}$ = **0.01 kg**
4	Ethanol for 0.09 kg of Balsa wood	$\text{Ethanol}_{\text{SIMAPRO (50)}} = \text{Ethanol}_{(50)} \times \text{Density}_{\text{ETHANOL}}$	1.49×0.79	**$\text{Ethanol}_{\text{SIMAPRO (50)}}$ = 1.18 kg**
	Ethanol for 0.31 kg of Balsa wood	$\text{Ethanol}_{\text{SIMAPRO (31)}} = \text{Ethanol}_{(31)} \times \text{Density}_{\text{ETHANOL}}$	5.12×0.79	**$\text{Ethanol}_{\text{SIMAPRO (31)}}$ = 4.04 kg**
5	Toluene for 0.09 kg of Balsa wood	$\text{Toluene}_{\text{SIMAPRO (50)}} = \text{Toluene}_{(50)} \times \text{Density}_{\text{TOLUENE}}$	1.49×0.87	**$\text{Toluene}_{(50)}$ = 1.3 L**
	Toluene for 0.31 kg of Balsa wood	$\text{Toluene}_{\text{SIMAPRO (31)}} = \text{Toluene}_{(31)} \times \text{Density}_{\text{TOLUENE}}$	5.12×0.87	**$\text{Toluene}_{(50)}$ = 4.45 L**

9.3 *Boltz's technique for Transparent wood production.*

9.3.1 *Additional assumptions.*

- Although Boltz's method is based on sawdust, this study uses wood slices. For the sustainability model, material input estimates were adapted from Boltz's data under the assumption of comparable lignin content and porosity. Sawdust yield is estimated at 15% [TranVan et al., 2014]. This approach could be explored further in future research.
- Heating is performed with a 500 W hot plate [Laboandco, 2013].
- Pre-polymerisation of PMMA is assumed to last 2 hours using a hot plate [Abu Hassan Shaari et al., 2022].
- Rinsed in water for 3 times and then in ethanol for 3 times. The last time it is placed

in ethanol, leave it there to avoid dehydration.

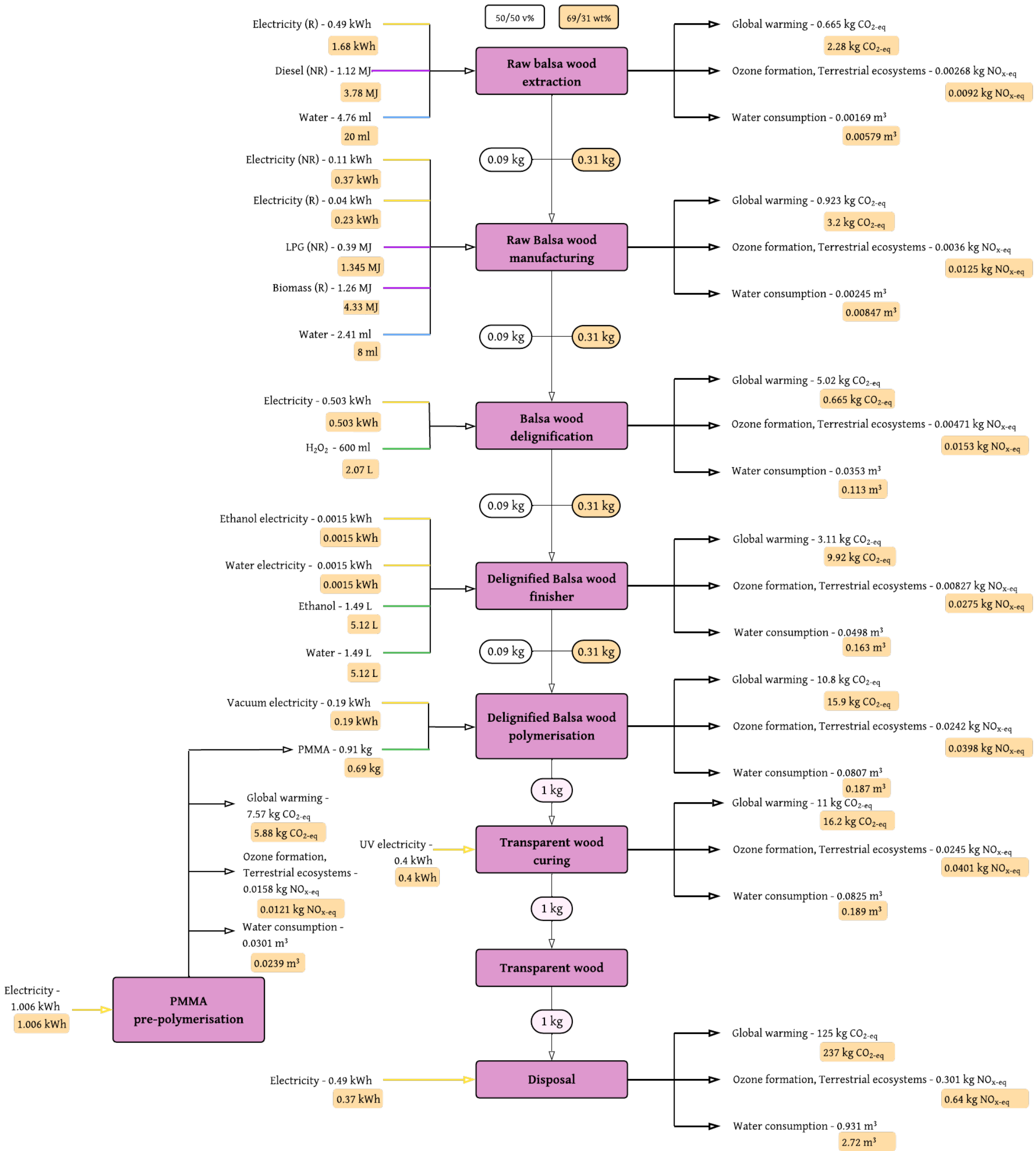
- The pressing between two plates is done manually, no need for energy.
- Curing under black UV light its consumption is 40 W for 10 hours (overnight) [Staff, 2024].
- Delignification uses 200 mL of 30 wt% H_2O_2 per batch to ensure saturation. Although not fully consumed, the entire volume is modeled as disposed.

9.3.2 *Additional SimaPro modelling inputs.*

- Balsa wood delignification:
  - Electricity: Electricity, low voltage NL— electricity voltage transformation from medium to low voltage — Cut-off, U.
- Delignified Balsa wood finisher:
  - Water: Tap water GLO— market group for — Cut-off, U.
- Pre-polymerisation:
  - PMMA: Polymethyl methacrylate, beads RER— production — Cut-off, U.
  - Electricity, low voltage NL— electricity voltage transformation from medium to low voltage — Cut-off, U.
- Delignified Balsa wood polymerisation:
  - Pre-polymerisation.
- Disposal:
  - PMMA: Waste plastic, mixture GLO— treatment of waste plastic, mixture, open burning — Cut-off, U.

9.3.3 *MEFA.*

Figure 9.9: MEFA of the production chain of the Transparent wood using Boltz's technique.



9.3.4 *Additional calculations.*

Figure 9.10: Boltz's Balsa wood treatment materials and prices.

Step	Description	Formula	Calculation	Result	Price data	Price
1	Balsa wood kg from Boltz's sawdust information	$M_{BWSAW} = \frac{Sawdust}{Yield} \times 10^{-3}$	$\frac{3.82}{0.15} \times 10^{-3}$	**$M_{BWSAW} = 0.03$ kg**	-	-
2	H_2O_2 for 0.09 kg of Balsa wood	$H_2O_{2\,(50)} = \frac{H_2O_{2\,(Saw)} \times M_{BW\,(50)}}{M_{BWSAW}}$	$\frac{200 \times 0.09}{0.03}$	**$H_2O_{2\,(50)} = 600$ ml**	0.72 €/L	**0.45 €**
	H_2O_2 for 0.31 kg of Balsa wood	$H_2O_{2\,(31)} = \frac{H_2O_{2\,(Saw)} \times M_{BW\,(31)}}{M_{BWSAW}} \times 10^{-3}$	$\frac{200 \times 0.31}{0.03} \times 10^{-3}$	**$H_2O_{2\,(31)} = 2.07$ L**		**1.49 €**
3	Ethanol for 0.09 kg of Balsa wood	$Ethanol_{(50)} = \frac{M_{BW\,(50)}}{Density_{PMMA}} \times 2 \times 10^3$	$\frac{0.09}{121} \times 2 \times 10^3$	**$Ethanol_{(50)} = 1.49$ L**	3.29 €/L	**4.9 €**
	Ethanol for 0.31 kg of Balsa wood	$Ethanol_{(31)} = \frac{M_{BW\,(31)}}{Density_{PMMA}} \times 2 \times 10^3$	$\frac{0.31}{121} \times 2 \times 10^3$	**$Ethanol_{(31)} = 5.12$ L**		**16.84 €**

Figure 9.11: Boltz's TW manufacturing electricity and prices.

Step	Description	Formula	Calculation	Result	Price data	Price
1	Plate electricity	$E_{PLATE} = E_{DELIGNIFICATION} \times 1 + E_{PRE\text{-}PMMA} \times 2$	$0.5 \times 1 + 0.5 \times 2$	**$E_{PLATE} = 1.5$ kWh**	0.076 €/kWh	**0.16 €**
2	Stirring electricity	$E_{STIRRING} = (E_{ETHANOL} + E_{WATER}) \times 0.5 + E_{PRE\text{-}PMMA} \times 2 + E_{WATER} \times 1$	$(0.003 + 0.003) \times 0.5 + 0.003 \times 2 + 0.003 \times 1$	**$E_{STIRRING} = 0.012$ kWh**		
3	PMMA polymerisation electricity	$E_{POLYMERISATION} = Power \times 0.5$	0.385×0.5	**$E_{POLYMERISATION} = 0.19$ kWh**		
4	Black UV light electricity	$E_{UV} = Power \times 10$	0.04×10	**$E_{UV} = 0.4$ kWh**		

9.4 *Solar-assisted chemical brushing technique for Transparent wood production.*

9.4.1 *Additional assumptions.*

- Data from [Xia et al., 2019] is extrapolated for 1 kg of TW.
- The different ratio scenarios are modelled for three different polyemers: Epoxy resin (1300 kg/m^3 [suppliers, 2025], PLA 1250 kg/m^3) and PMMA (1180 kg/m^3 [Omnexus, 2021]). The difference is not too much, hence the same kg are needed for all of them.
- LED diodes are an energy-efficient alternative to traditional mercury lamps for UV curing in transparent wood production. They consume 50–75% less energy, operate instantly without warm-up time, and eliminate harmful mercury and ozone emissions [Henke et al., 2023]. Their narrow spectral output (typically 365nm, 385nm, 395nm, or 405nm [Technology, 2021]) is well-suited for the photocatalytic reactions required in the SACB process.

9.4.2 *Additional SimaPro modelling inputs.*

- Balsa wood delignification:
  - NaOH: Sodium hydroxide, without water, in 50% solution state RER— chlor-alkali electrolysis, membrane cell — Cut-off, U.
  - UV light: Electricity, low voltage NL— electricity voltage transformation from medium to low voltage — Cut-off, U.
- Delignified Balsa wood finisher:
  - Toluene: Toluene, liquid RER— production — Cut-off, U.
- Delignified Balsa wood polymerisation (each polymer for different analysis):
  - Delignified Balsa wood finisher.
  - Epoxy resin: Epoxy resin, liquid RER— production — Cut-off, U.
  - PLA: Polylactide, granulate GLO— production — Cut-off, U.
  - PMMA: Polymethyl methacrylate, beads RER— production — Cut-off, U.
- Disposal (each polymer for different analysis):
  - Epoxy resin: Hazardous waste, for incineration Europe without Switzerland— treatment of hazardous waste, hazardous waste incineration — Cut-off, U.
  - PLA: Biowaste GLO— treatment of biowaste, municipal incineration — Cut-off, U.
  - PMMA: Waste plastic, mixture GLO— treatment of waste plastic, mixture, open burning — Cut-off, U.

9.4.3 *MEFA.*

Figure 9.12: MEFA of the production chain of the Transparent wood using the Solar-assisted chemical brushing method with Epoxy resin.

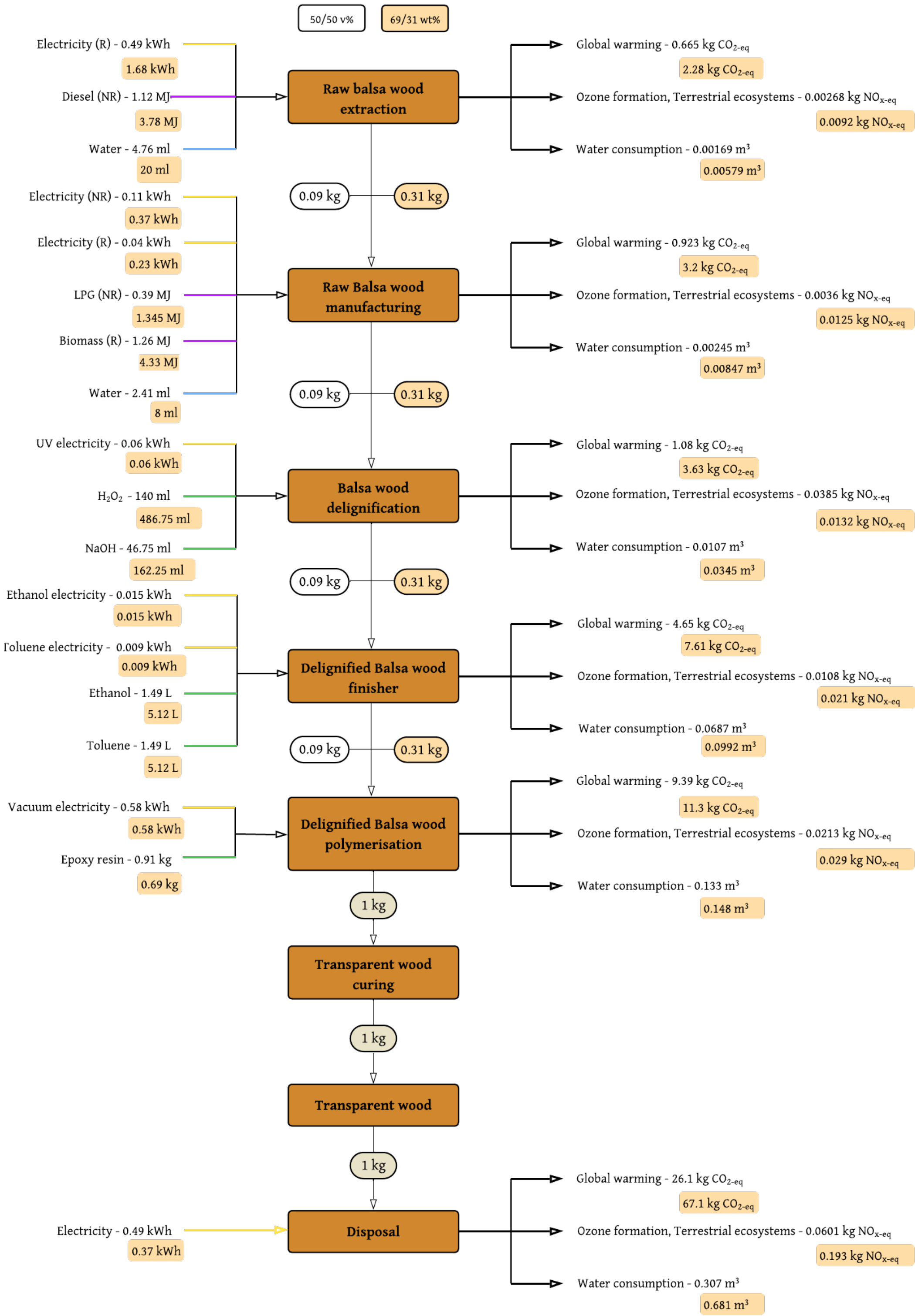


Figure 9.13: MEFA of the production chain of the Transparent wood using the Solar-assisted chemical brushing method with PLA.

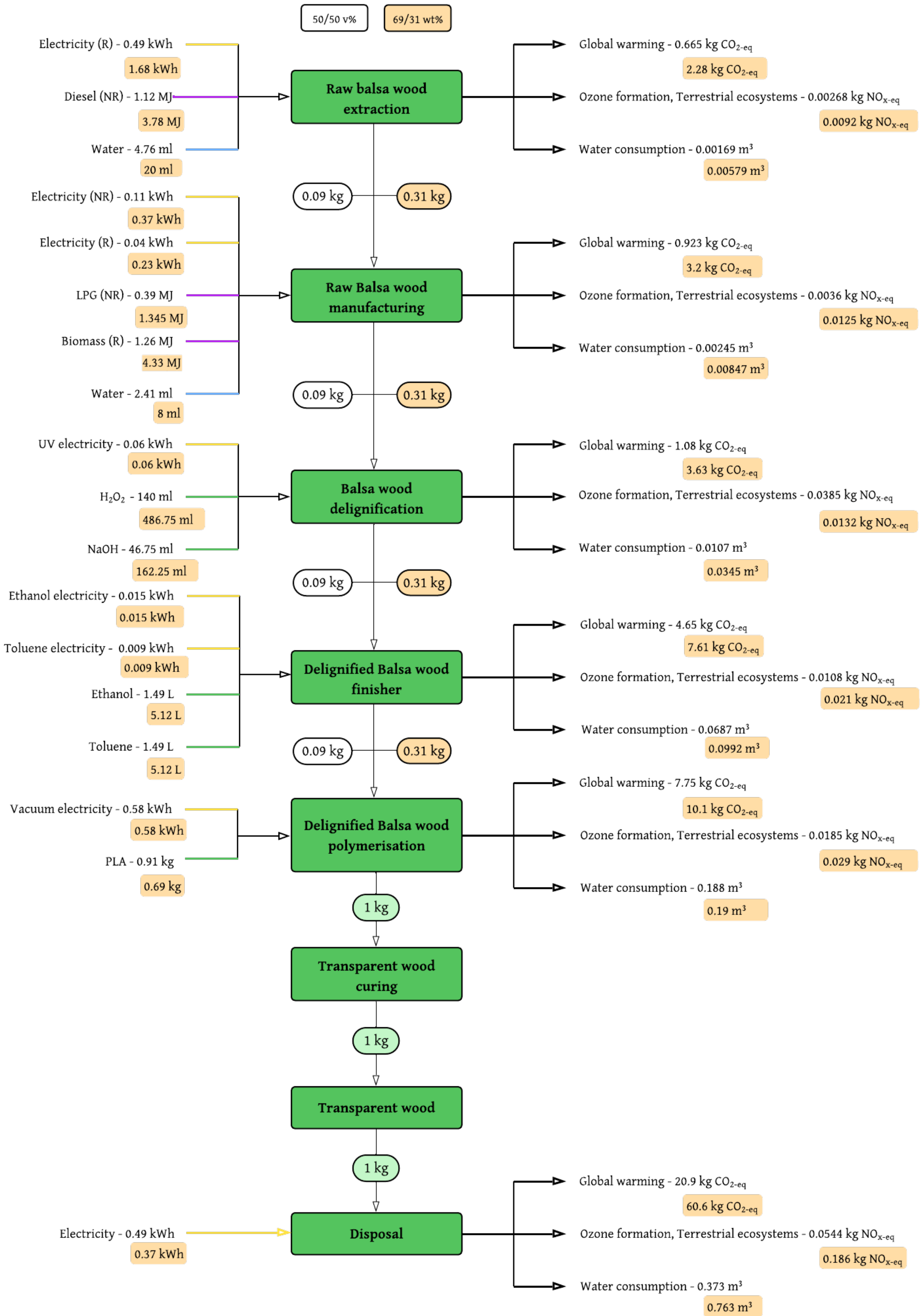
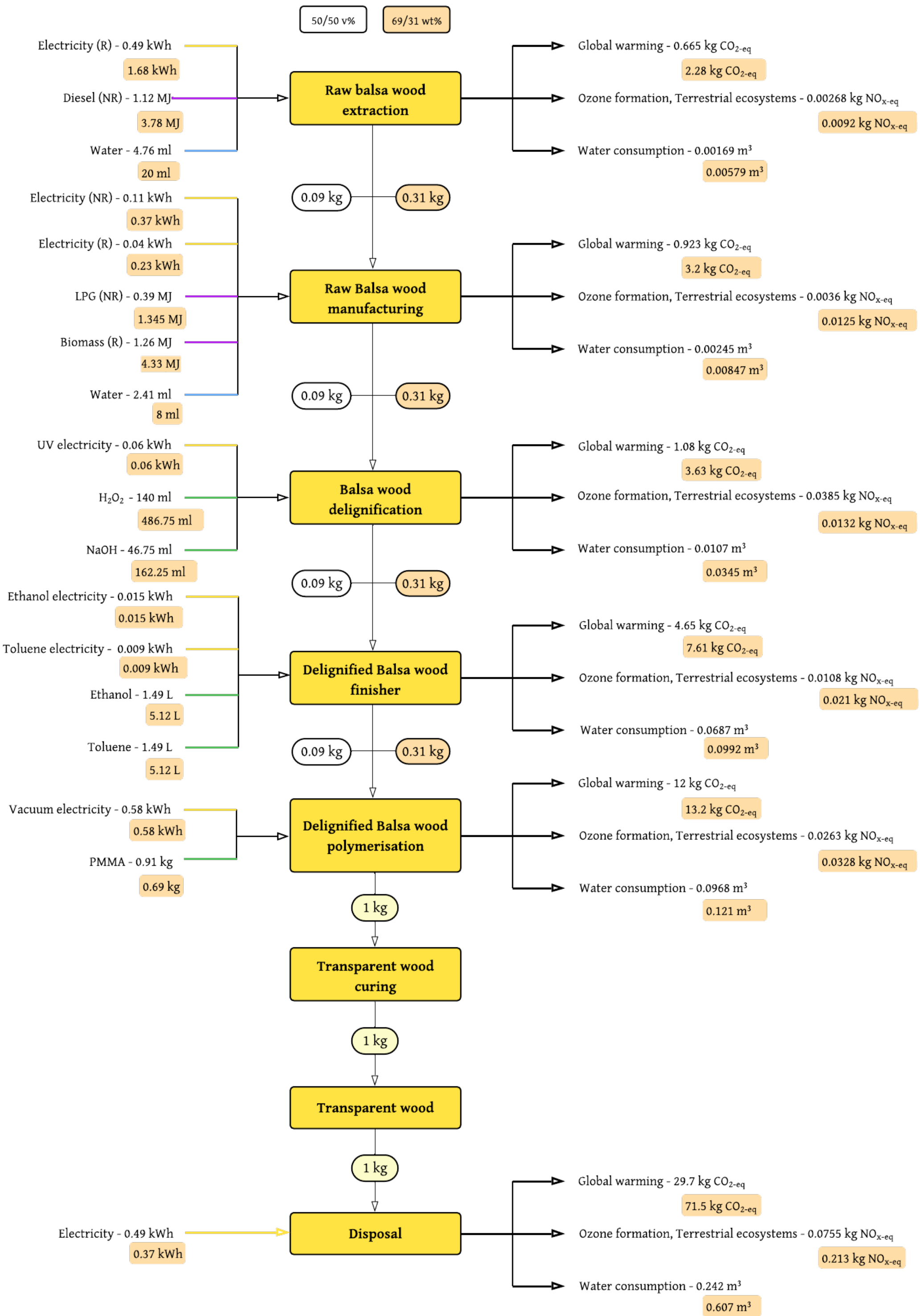


Figure 9.14: MEFA of the production chain of the Transparent wood using the Solar-assisted chemical brushing method with PMMA.



9.4.4 *Additional calculations.*

Figure 9.15: SACB's Balsa wood treatment materials and prices.

Step	Description	Formula	Calculation	Result	Price data	Price
1	Mass of the TW sample	$M_{TWS} = (L \times W \times H) \times Density_{BW}$	$M_{TWS} = (0.4 \times 0.11 \times 0.001) \times 121$	**$M_{TWS} = 5.32 \times 10^{-3}$ kg**	-	-
2	Nº of plates (50/50 v%) for 1 kg TW	$Plates_{(50)} = \frac{M_{BW\,(50)}}{M_{TWS}}$	$\frac{0.09}{5.32 \times 10^{-3}}$	**$Plates_{(50)} = 17$**	-	-
	Nº of plates (69/31 wt%) for 1 kg TW	$Plates_{(31)} = \frac{M_{BW\,(31)}}{M_{TWS}}$	$\frac{0.31}{5.32 \times 10^{-3}}$	**$Plates_{(31)} = 59$**		
3	H_2O_2 for 0.09 kg of Balsa wood	$H_2O_{2\,(50)} = (H_2O_{2\,(33ml/piece)} \times Plates_{(50)}) \times$ Partial coverage $\times$ Dilution adjustment	$(33 \times 17) \times 0.5 \times 0.5$	**$H_2O_{2\,(50)} =$ 140.25 ml**	0.72 €/L	**0.1 €**
	H_2O_2 for 0.31 kg of Balsa wood	$H_2O_{2\,(31)} = (H_2O_{2\,(33ml/piece)}) \times Plates_{(31)} \times$ Partial coverage $\times$ Dilution adjustment	$(33 \times 59) \times 0.5 \times 0.5$	**$H_2O_{2\,(31)} =$ 486.75 ml**		**0.35 €**
4	NaOH for 0.09 kg of Balsa wood	$NaOH_{(50)} = (NaOH_{(11ml/piece)} \times Plates_{(50)}) \times$ Partial coverage $\times$ Dilution adjustment	$(11 \times 17) \times 0.5 \times 0.5$	**$NaOH_{(50)} =$ 46.75 ml**	24.97 €/2.5L	**0.46 €**
	NaOH for 0.31 kg of Balsa wood	$NaOH_{(31)} = (NaOH_{(11ml/piece)}) \times Plates_{(31)} \times$ Partial coverage $\times$ Dilution adjustment	$(11 \times 59) \times 0.5 \times 0.5$	**$NaOH_{(31)} =$ 162.25**		**1.62 €**
5	Ethanol for 0.09 kg of Balsa wood	$Ethanol_{(50)} = \frac{M_{BW\,(50)}}{Density_{PMMA}} \times 2 \times 10^3$	$\frac{0.09}{121} \times 2 \times 10^3$	**$Ethanol_{(50)} =$ 1.49 L**	3.29 €/L	**4.9 €**
	Ethanol for 0.31 kg of Balsa wood	$Ethanol_{(31)} = \frac{M_{BW\,(31)}}{Density_{PMMA}} \times 2 \times 10^3$	$\frac{0.31}{121} \times 2 \times 10^3$	**$Ethanol_{(31)} =$ 5.12 L**		**16.84 €**
6	Toluene for 0.09 kg of Balsa wood	$Toluene_{(50)} = \frac{M_{BW\,(50)}}{Density_{PMMA}} \times 2 \times 10^3$	$\frac{0.09}{121} \times 2 \times 10^3$	**$Toluene_{(50)} =$ 1.49 L**	3.49 €/L	**5.2 €**
	Toluene for 0.31 kg of Balsa wood	$Toluene_{(31)} = \frac{M_{BW\,(31)}}{Density_{PMMA}} \times 2 \times 10^3$	$\frac{0.31}{121} \times 2 \times 10^3$	**$Toluene_{(31)} =$ 5.12 L**		**17.87 €**

Figure 9.16: SACB's manufacturing electricity and prices.

Step	Description	Formula	Calculation	Result	Price data	Price
1	Stirring electricity	$E_{STIRRING} = E_{ETHANOL} \times 5 + E_{TOLUENE} \times 3$	$0.003 \times 5 + 0.003 \times 3$	**$E_{STIRRING}$ = 0.024 kWh**	0.076 €/kWh	**0.05 €**
2	Polymer polymerisation electricity	$E_{POLYMERISATION} = Power \times 0.5$	0.385×1.5	**$E_{POLYMERISATION}$ = 0.54 kWh**		
3	UV light electricity	$E_{UV} = Power \times 2$	0.003×2	**E_{UV} = 0.06 kWh**		

9.5 *Supplementary results.*

9.5.1 *Sustainable analysis.*

Figure 9.17: Comparison of the Environmental impact categories between Boltz's TW (50/50 v%) and UWRG production.

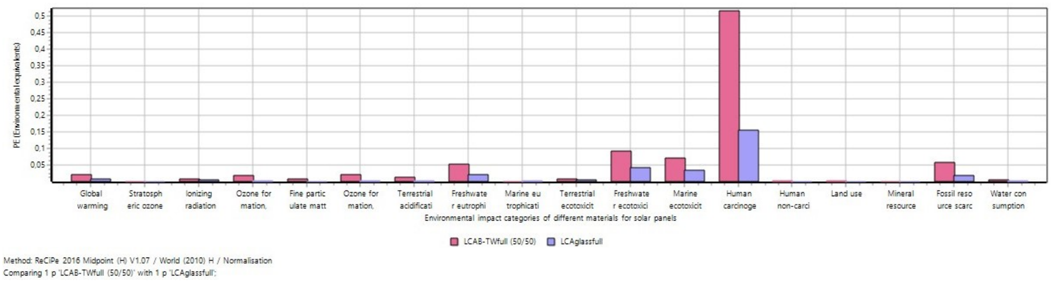


Figure 9.18: Environmental impact of each stage of the UWRG production.

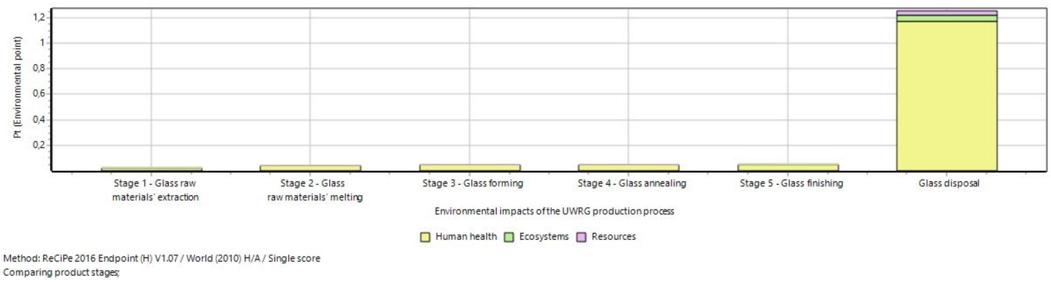


Figure 9.19: Environmental impact of each stage of the Boltz's TW (50/50 v%) production.

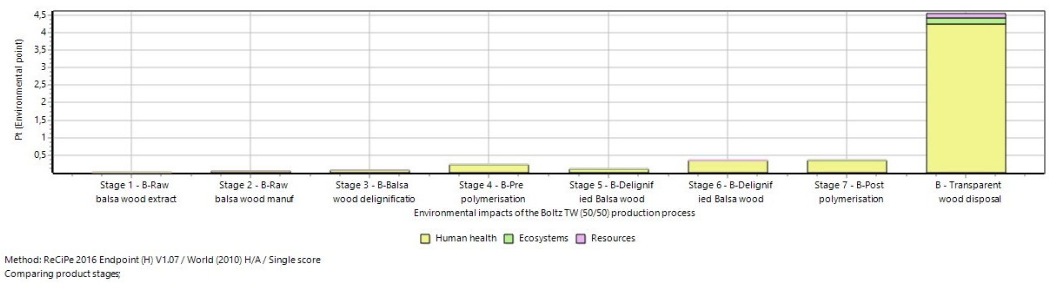


Figure 9.20: Comparison of the Environmental impact categories between Boltz's TW (50/50 v%), UWRG production and SACB-Epoxy's TW (50/50 v%).

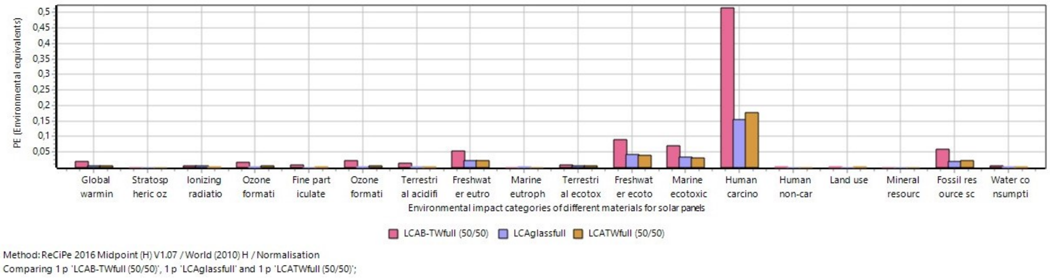


Figure 9.21: Environmental impact of each stage of the SACB-Epoxy resin's TW (50/50 v%) production.

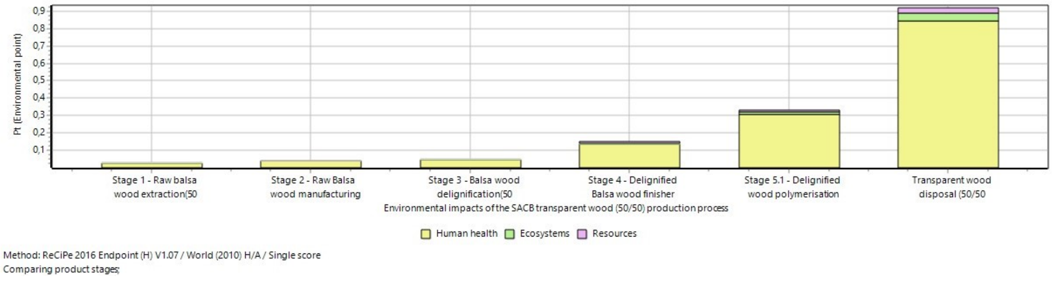


Figure 9.22: Environmental impact of each stage of the SACB-PLA's TW (50/50 v%) production.

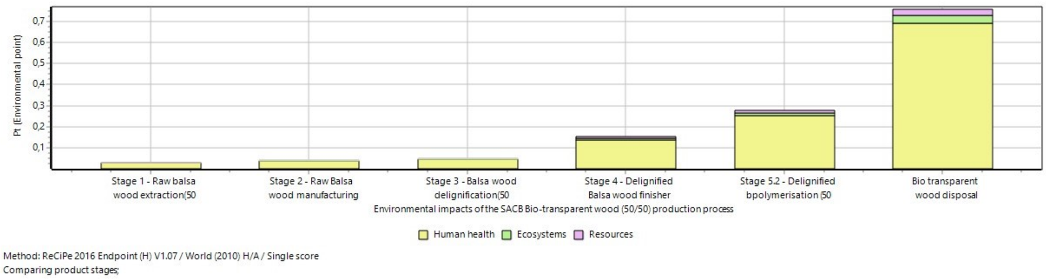


Figure 9.23: Environmental impact of each stage of the SACB-PMMA's TW (50/50 v%) production.

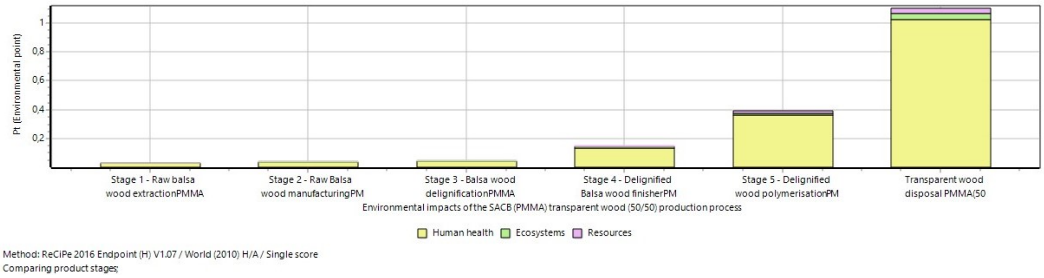


Figure 9.24: Human carcinogenic eco-toxicity of the SACB-PMMA's TW (50/50 v%) production.

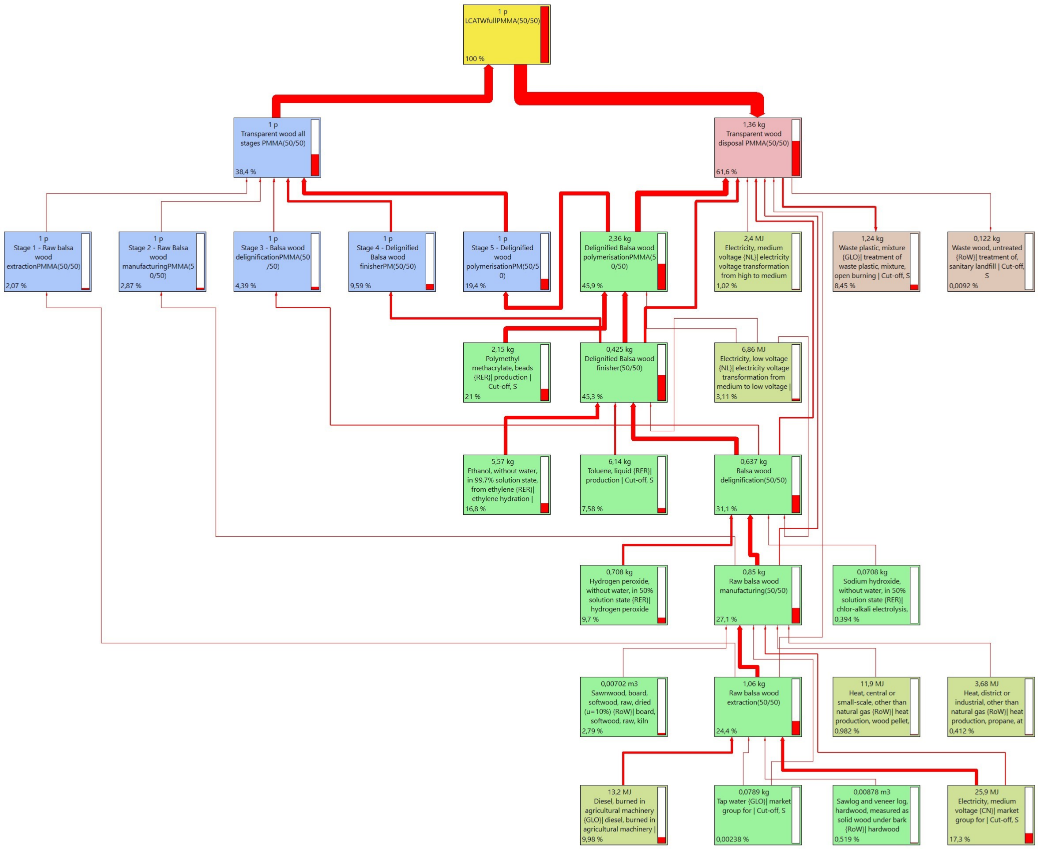


Figure 9.25: Human carcinogenic eco-toxicity of the SACB-PMMA's TW (69/31 wt%) production.

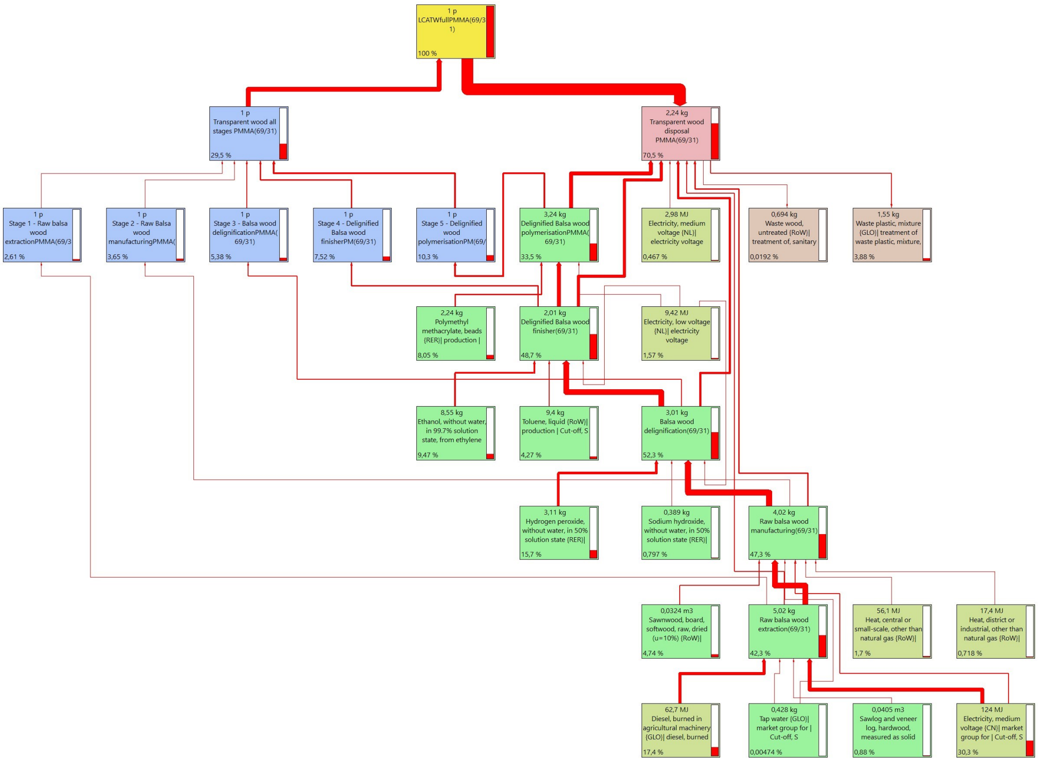


Table 9.1: Total environmental impact of the different SACB TW's (50/50 v%) alternatives.

	Unit	Wood extraction	Wood manufacturing	Delignification	Post-delignification	Polymerisation	Disposal
Epoxy resin	Pt	0.0289	0.0417	0.0482	0.152	0.333	0.919
PLA	Pt	0.0289	0.0417	0.0482	0.152	0.276	0.757
PMMA	Pt	0.0289	0.0417	0.0482	0.152	0.39	1.1

Table 9.2: Influence of the different ratios on the total environmental impact of the Boltz production.

Boltz	Unit	Wood extraction	Wood manufacturing	Delignification	Pre-polymerisation of PMMA	Post-delignification	Polymerisation	Post-polymerisation	Disposal
50/50 (v%)	Pt	0.0289	0.0417	0.0702	0.246	0.117	0.365	0.372	4.55
69/31 (wt%)	Pt	0.0933	0.144	0.221	0.19	0.38	0.573	0.58	8.38

Table 9.3: Influence of the different ratios on the total environmental impact of the SACB-Epoxy resin production.

Epoxy resin	Unit	Wood extraction	Wood manufacturing	Delignification	Post-delignification	Polymerisation	Disposal
50/50 (v%)	Pt	0.0289	0.0417	0.0482	0.152	0.333	0.919
69/31 (wt%)	Pt	0.0933	0.144	0.163	0.279	0.419	2.6

Table 9.4: Influence of the different ratios on the total environmental impact of the SACB-PLA production.

PLA	Unit	Wood extraction	Wood manufacturing	Delignification	Post-delignification	Polymerisation	Disposal
50/50 (v%)	Pt	0.0289	0.0417	0.0482	0.152	0.276	0.757
69/31 (wt%)	Pt	0.0093	0.144	0.163	0.279	0.375	2.4

Table 9.5: Influence of the different ratios on the total environmental impact of the SACB-PMMA production.

PMMA	Unit	Wood extraction	Wood manufacturing	Delignification	Post-delignification	Polymerisation	Disposal
50/50 (v%)	Pt	0.0289	0.0417	0.0482	0.152	0.39	1.1
69/31 (wt%)	Pt	0.0933	0.144	0.163	0.279	0.462	2.83

9.5.2 *Economic analysis.*

Table 9.6: Total price for the production of 1 kg of UWRG.

Material	Costs per kg of UWRG
White Silica Sand Low Iron Dry Quartz Sand	0.1 €
Soda ash	0.51 €
Dolomite	0.02 €
Limestone	0.031 €
Mirabilite (sodium sulfate)	0.002 €
Electricity	0.26 €
Natural gas	0.28 €
Water	-
Total	**1.2 €**

Table 9.7: *Total price for the production of 1 kg of TW via the Boltz's technique.*

Material	**Costs per kg of TW (50/50 v%)**	**Costs per kg of TW (69/31 wt%)**
H_2O_2	0.45 €	1.49 €
Ethanol	4.9 €	16.84 €
PMMA	2.6 €	1.97 €
Balsa wood	0.28 €	0.97 €
Electricity	0.25 €	0.34 €
Diesel	0.02 €	0.08 €
Biomass	0.03 €	0.11 €
LPG	8.04×10^{-5} €	3×10^{-4} €
Water	-	-
Total	**8.53 €**	**21.8 €**

Table 9.8: *Total price for the production of 1 kg of TW via the SACB with Epoxy resin.*

Material	**Costs per kg of TW (50/50 v%)**	**Costs per kg of TW (69/31 wt%)**
H_2O_2	0.1 €	0.35 €
NaOH	0.46 €	1.62 €
Ethanol	4.9 €	16.84 €
Toluene	5.2 €	17.87 €
Epoxy resin	40.54 €	30.74 €
Balsa wood	0.28 €	0.97 €
Electricity	0.14 €	0.24 €
Diesel	0.02 €	0.08 €
Biomass	0.03 €	0.11 €
LPG	8.04×10^{-5} €	3×10^{-4} €
Water	**-**	**-**
Total	**51.67 €**	**68.82 €**

Table 9.9: *Total price for the production of 1 kg of TW via the SACB with PLA.*

Material	Costs per kg of TW (50/50 v%)	Costs per kg of TW (69/31 wt%)
H_2O_2	0.1 €	0.35 €
NaOH	0.46 €	1.62 €
Ethanol	4.9 €	16.84 €
Toluene	5.2 €	17.87 €
PLA	2.05 €	1.55 €
Balsa wood	0.28 €	0.97 €
Electricity	0.14 €	0.24 €
Diesel	0.02 €	0.08 €
Biomass	0.03 €	0.11 €
LPG	8.04×10^{-5} €	3×10^{-4} €
Water	-	-
Total	**13.18 €**	**39.61 €**

Table 9.10: *Total price for the production of 1 kg of TW via the SACB with PMMA.*

Material	Costs per kg of TW (50/50 v%)	Costs per kg of TW (69/31 wt%)
H_2O_2	0.1 €	0.35 €
NaOH	0.46 €	1.62 €
Ethanol	4.9 €	16.84 €
Toluene	5.2 €	17.87 €
PMMA	2.6 €	1.97 €
Balsa wood	0.28 €	0.97 €
Electricity	0.14 €	0.24 €
Diesel	0.02 €	0.08 €
Biomass	0.03 €	0.11 €
LPG	8.04×10^{-5} €	3×10^{-4} €
Water	-	-
Total	**13.73 €**	**40.03 €**

9.5.3 *Technical analysis.*

Table 9.11: UWRG's optical, mechanical and thermal properties from different sources and average values.

Sources	Optical transmittance	Haze	Tensile strength	Toughness	Thermal conductivity
[Wang and Zhu, 2021]	-	-	-	-	1.03 W/m × K
[Zhu et al., 2023]	-	-	-	0.1 MJ/m^3	-
[Foster et al., 2019]	90%	-	31–35 MPa	-	-
[Park and Kim, 2021]	-	52%	-	-	-
[Majid et al., 2021]	80%	-	-	-	-
Average	**85%**	**52%**	**33 MPa**	**0.1 MJ/m^3**	**1.03 W/m × K**

Table 9.12: Boltz's optical, mechanical and thermal properties from different sources and average values.

Source	Optical transmittance	Haze	Tensile strength	Lignin content	Toughness	Thermal conductivity
[Wu et al., 2020]	<85%	71%	-	-	-	-
[Jungstedt et al., 2020]	-	-	62.5 MPa	2.8%	-	-
[Zou et al., 2022]	84%	38 ~73 %	-	-	-	0.110 ~ 0.126 W/m × K
[Zhu et al., 2023]	-	-	-	-	0.56 ~6.1 MJ/m^3	-
Average	**84.5%**	**63.25%**	**62.5 MPa**	**2.8%**	**3.33 MJ/m^3**	**0.118 W/m × K**

Table 9.13: SACB's optical, mechanical and thermal properties from different sources and average values.

Source	Optical transmittance	Haze	Tensile strength	Lignin content	Toughness	Thermal conductivity
[Xia et al., 2019]	<90%	80%	46 MPa	-	-	-
[Chen et al., 2022]	<82%	>75%	-	81%	-	-
[Li, 2019]	>80%	<70%	-	-	-	-
[Zhu et al., 2023]	-	-	-	-	0.56 ~ 6.1 MJ/m^3	0.19 ~ 0.4 W/m × K
[Li et al., 2019]	-	-	-	<80%	-	-
[Pandit et al., 2025]	<90%	80%	-	81%	-	-
Average	**85.5%**	**76.25%**	**46 MPa**	**80.67%**	**3.33 MJ/m^3**	**0.295 W/m × K**

9.5.4 *Extrapolation for one solar panel.*

Figure 9.26: Sustainable and economic results extrapolated to one solar panel.

Step	Description	Formula	Calculation	Result
1	Densities	-	-	**D_{UWRG} = 2510 kg/m³**
				D_{TW} = 1200 kg/m³
2	Solar panel volume	V_{SP} = Area × Thickness	1.8 × 0.001	**$V_{SP} = 1.8 \times 10^{-3}$ m³**
3	Mass of materials for one solar panel	$M_{UWRG} = D_{UWRG} \times V_{SP}$	$2510 \times (1.8 \times 10^{-3})$	**M_{UWRG} = 4.5 kg**
		$M_{TW} = D_{TW} \times V_{SP}$	$1200 \times (1.8 \times 10^{-3})$	**M_{TW} = 2.16 kg**
4	Environmental results extrapolation	$Pt_{SP\text{-}UWRG} = Pt_{1\ kg\ UWRG} \times M_{UWRG}$	1.47 × 4.5	**$Pt_{SP\text{-}UWRG}$ = 6.62 Pt**
		$Pt_{SP\text{-}TW} = Pt_{1\ kg\ TW} \times M_{TW}$	$B_{(50/50)}$ = 5.79 × 2.16	**$Pt_{SP\text{-}TW}$ = 12.51 Pt**
			$B_{(69/31)}$ = 11.2 × 2.16	**$Pt_{SP\text{-}TW}$ = 21.19 Pt**
			$SACB_{Epoxy\text{-}(50/50)}$ = 1.52 × 2.16	**$Pt_{SP\text{-}TW}$ = 3.28 Pt**
			$SACB_{Epoxy\text{-}(69/31)}$ = 3.7 × 2.16	**$Pt_{SP\text{-}TW}$ = 7.99 Pt**
			$SACB_{PLA\text{-}(50/50)}$ = 1.3 × 2.16	**$Pt_{SP\text{-}TW}$ = 2.81 Pt**
			$SACB_{PLA\text{-}(69/31)}$ = 3.46 × 2.16	**$Pt_{SP\text{-}TW}$ = 7.47 Pt**
			$SACB_{PMMA\text{-}(50/50)}$ = 1.76 × 2.16	**$Pt_{SP\text{-}TW}$ = 3.8 Pt**
			$SACB_{PMMA\text{-}(69/31)}$ = 3.98 × 2.16	**$Pt_{SP\text{-}TW}$ = 8.6 Pt**
5	Economic results extrapolation	$€_{SP\text{-}UWRG} = €_{1\ kg\ UWRG} \times M_{UWRG}$	1.2 × 4.5	**$€_{SP\text{-}UWRG}$ = 5.4 €**
		$€_{SP\text{-}TW} = €_{1\ kg\ TW} \times M_{TW}$	$B_{(50/50)}$ = 8.53 × 2.16	**$€_{SP\text{-}TW}$ = 18.42 €**
			$B_{(69/31)}$ = 21.8 × 2.16	**$€_{SP\text{-}TW}$ = 47.09 €**
			$SACB_{Epoxy\text{-}(50/50)}$ = 51.67 × 2.16	**$€_{SP\text{-}TW}$ = 111.61 €**
			$SACB_{Epoxy\text{-}(69/31)}$ = 68.32 × 2.16	**$€_{SP\text{-}TW}$ = 147.57 €**
			$SACB_{PLA\text{-}(50/50)}$ = 13.18 × 2.16	**$€_{SP\text{-}TW}$ = 28.47 €**
			$SACB_{PLA\text{-}(69/31)}$ = 39.61 × 2.16	**$€_{SP\text{-}TW}$ = 85.56 €**
			$SACB_{PMMA\text{-}(50/50)}$ = 13.73 × 2.16	**$€_{SP\text{-}TW}$ = 29.66 €**
			$SACB_{PMMA\text{-}(69/31)}$ = 40.03 × 2.16	**$€_{SP\text{-}TW}$ = 86.46 €**

9.5.5 *Laboratory testing.*

Table 9.14: Procedure followed for TW production via the SACB technique with PMMA.

	Dimensions	**NaOH**	H_2O_2	**UV light - 395 nm**	**Ethanol**	**Oven to dry ethanol**	**Pre-polymerisation (for four samples 56.16 g of MMA and 0.16848 g of AIBN)**	**Deep vacuum**	**Oven to polymerise (place sample between two glasses and cover in foil)**	**Cure overnight**
Sample 1	29 x 19 x 0.76 mm	0.4 ml	1.1 ml	1 hour	12 ml	Overnight at 60ºC	75ºC for 15 min; 15 ml	3 cycles of 10 minutes	4 hours at 70ºC	Room temperature
Sample 2	27 x 23 x 0.76 mm	0.6 ml	1.5 ml	1 hour	17 ml	Overnight at 60ºC	75ºC for 15 min; 22 ml	5 cycles of 10 minutes	4 hours at 70ºC	Room temperature

Figure 9.27: Visual representation of the procedure followed for TW production via the SACB technique with PMMA (after the oven the samples were left to cure at room temperature, rendering the final TW shown in Figure 6.6).

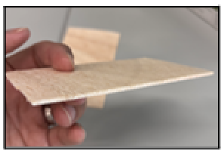
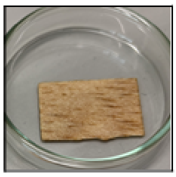
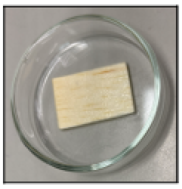
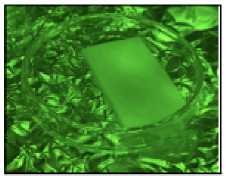
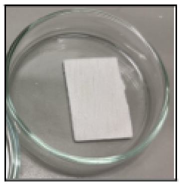
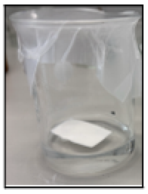
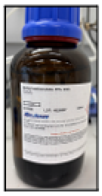
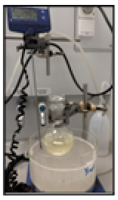
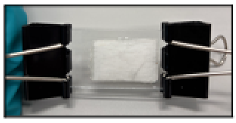
1. Balsa wood slice	2. Balsa wood thickness	3. NaOH	4. After NaOH
			
5. H_2O_2	**6. After H_2O_2**	**7. UV light**	**8. In UV light**
			
9. After UV light	**10 . Ethanol**	**11. MMA**	**12. AIBN**
			
13. Pre-polymerisation	**14. Deep vacuum**	**15. Between glasses**	**16. After oven**
			

Figure 9.28: Other samples produced unsuccessfully, different parameters were changed based on these results, which rendered Samples 1 and 2 (Figure 6.6).