Ref. Ares(2024)3464 - 02/01/2024

GREEN-LOOP

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

GREEN-LOOP

Sustainable manufacture systems towards novel bio-based materials

WP1 – Set-up of GREEN-LOOP Bio-based products, green and smart solutions.

D1.6 – KPI's to evaluate the integration of bio-based materials in manufacture and value chains.

Final Version

Document information:

Contractual Due date: 30.04.2023	**Delivery Date**: 02.01.2024
Author(s): AIMEN	
Lead Beneficiary of Deliverable: AIMEN	
Dissemination level: Public	
Nature of the Deliverable: Report	
Internal Reviewers: IDE, IRIS, FHF, NCC, NSB	

GA Nº **101057765**
D1.6 “KPI’s to evaluate the integration of bio-based materials in manufacture and value chains.”

GREEN LOOP Key Facts

Project title	Sustainable manufacture systems towards novel bio-based materials
Starting date	01/09/2022
Duration in months	36
Call (part) identifier	TWIN GREEN AND DIGITAL TRANSITION 2021 (HORIZON-CL4-2021-TWIN-TRANSITION-01)
Topic	HORIZON-CL4-2021-TWIN-TRANSITION-01-05 Manufacturing technologies for bio-based materials (Made in Europe Partnership) (RIA)
Consortium	17 organizations. 15 EU Member States + 2 non-EU state

GREEN LOOP Consortium Partners

	Partner	Acronym	Country
1	IDENER RESEARCH & DEVELOPMENT	IDE	ES
2	NATIONAL INSTITUTE OF CHEMISTRY	NIC	SI
3	SLOVENIAN NATIONAL BUILDING AND CIVIL E. I.	ZAG	SI
4	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	FHF	DE
5	LABRENTA SRL	LBRT	IT
6	MIXCYCLING SRL	MYX	IT
7	NERO SU BIANCO	NSB	IT
8	GERACE MARIA CRISTINA - TERRE DI ZOE’	TDZ	IT
9	IRIS TECHNOLOGY SOLUTIONS, SOCIEDAD LIMITADA	IRIS	ES
10	GLOWNY INSTYTUT GORNICTWA	GIG	PL
11	AACHEN UNIVERISTY: PROCESS CONTROL ENGINEERING / AACHEN UNIVERISTY: INSTITUTE OF SOCIOLOGY	AAU	DE
12	AUSTRIAN STANDARDS INTERNATIONAL	ASI	AT
13	INSTITUTO DE SOLDADURA E QUALIDADE	ISQ	PT
14	AXIA INNOVATION UG	AXIA	DE
15	ASOCIACIÓN DE INVESTIGACIÓN METALÚRGICA DEL NOROESTE	AIMEN	ES
16	NATIONAL COMPOSITE CENTER	NCC	UK
17	UNIVERSITY OF BRISTOL	UBRIS	UK

Funded by the European Union

GA Nº **101057765**
D1.6 "KPI's to evaluate the integration of bio-based materials in manufacture and value chains."

GREEN LOOP is a project funded by the European Commission under the Horizon Europe - HORIZON-CL4-2021-TWIN-TRANSITION-01-05- Manufacturing technologies for bio-based materials (Made in Europe Partnership) (RIA) under Grand Agreement Number 101057765.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

Executive Summary

Deliverable 1.6: ‘KPI’s to evaluate the integration of bio-based materials in manufacture and value chain’ is a document inside Green-Loop Project, as the output of Task 1.3: ‘Validation KPI’s definition’.

The context of this Deliverable is Work Package 1 (WP1): ‘Set-up of GREEN-LOOP Bio-based products, green and smart solutions’, and the goal of this WP1 is to develop technical, organizational, efficient and completed management of the project, setting the basis of the work to be done in the Green-Loop Project. Finally, the main point is to set the KPI’s to determine the innovation potential of bio-based materials. methodology (Material Circularity Indicator and European Commission) used in this deliverable will consider the main pillars of circular economy, connected to three principles: designing out waste and pollution; keeping products and materials in use; and regenerating natural systems[1]. The entire WP1 is divided in some tasks, which will expect the contributions related to the objectives mentioned before:

- Task 1.1: Scientific & Technical Coordination
- Task 1.2: Working framework, requirements definition and team alignment
- Task 1.3: Validation KPI’s definition
- Task 1.4: Inline monitoring and quality controls

With all the information before, Task 1.3 deals with the definition of the KPIs related with different procedures, based in circular economy. The objective of this Task is to establish reference calculation methodologies and define their main KPIs. To ensure replicability, a set of common core indicators is needed to make environmental, social and economic improvements that will be used in decision making throughout the life cycle assessments of bio-based products manufacturing.

Apart from WP1, this task will also be connected to other WPs. In the case of ‘WP2: Sustainability and Circularity by Design’, these Key Performance Indicators (KPIs) will be calculated at the end of the project mainly with data obtained from the different life cycle analyses that will be carried out in this package, mainly tasks ‘T2.2: Energy and Exergy analysis of the systems’ and ‘T2.3: Tools and methodology for LCA, LCC and Social LCA assessments’. Regarding technical WPs (WP3, WP4, WP5), the rest of these indicators are going to be calculated and they will set values that establish upper and lower limits for the transition from the current linear system to a new circular, Green-Loop process. For example, for each technical WP the amount of material to be reused/recycled, the refurbish rate of products to avoid landfill, or the amount of energy from renewable resources to be used in the process is to be established in this Deliverable.

[1] Material Circularity Indicator | Ellen Macarthur Foundation

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

These KPIs will be evaluated during the project, and special attention will be paid at the end of the Green-Loop Project, when overall performance of the new developed technologies will be evaluated.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

Table of Contents

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

List of Figures

List of Tables

Funded by
the European Union

Abbreviations

- **CDW:** Construction and Demolition Waste
- **CE:** Circular Economy
- **CO_2:** Carbon dioxide
- **EC:** European Commission
- **EU:** European Union
- **EoL:** End-of-Life
- **GDP:** Gross Domestic Product
- **GHG:** Greenhouse Gases
- **GPa:** Gigapascal
- **HaDEA:** Health and Digital Executive Agency
- **KPI:** Key Performance Indicator
- **LCA:** Life Cycle Assessment
- **LCC:** Life Cycle Cost
- **m/s:** Metre per second
- **m^2/s:** Square metre per second
- **MCI:** Material Circularity Indicator
- **mm^3/Nm:** Cubic millimetre per Newton and metre
- **MPa:** Megapascal
- **N:** Newton
- **REACH Regulation:** Registration, Evaluation, Authorisation and Restriction of Chemicals
- **RoHS Directive:** Restriction of the Use of Certain Hazardous Substances
- **S-LCA:** Social Life Cycle Assessment
- **W/m·K:** Watts per metre and Kelvin
- **WC:** Wood Composite
- **WEEE:** Waste from Electrical and Electronic Equipment
- **WP:** Work Package

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

1. Introduction

1.1. Purpose of the report

The main goal of the Green-Loop Project is to develop and demonstrate a set of novels, cost-effective and sustainable and green bio-based products, to substitute traditional materials generated by lineal processes. There will be three different case studies:

The first is the manufacture of multifunctional bio-rubber composite panels (with additives made with lignin residue generated in the kraft process to produce cellulose). This final product is for the reduction of the vibro-acoustics transmission loss, with fire-retardant properties too. In the current market, there is only available elastomeric materials, not any hybrid eco-elastomeric and natural fibre damping tile. This new bio-based material has more advantage with regard to its carbon footprint than with its technical characteristics. The formulation of materials must be carefully considered, with a focus on the production process. This process must take into account the calculation of the environmental footprint, verifying that a clean process is carried out from an environmental point of view, so that the products are of clean origin. The tests to be carried out on the bio-rubber to check its suitability are as follows the compressive strength, smoke production, thermal conductivity, and shear bond strength. In relation to end-of-life, there is currently no recycling of existing materials on the market, so the processing of waste is going to be very energy-intensive.[2]

Then, the bio-plastic bottle closures created from residues of the agricultural industry (these closures are oriented to packaging, food, and beverage sectors). These closures are manufactured with natural fibres (as filler), thermoplastic carriers mainly, and finally with some additives regulated by a Mixcycling's Patent. The current way of manufacturing these bottle closures is with aluminium and plastic, and they have a higher environmental impact. The performance of the new products made by Green-Loop Project has to be equal to the current one. At the beginning, the first validation will be at laboratory scale with the different fibres collected from agro industry. The tests for find the suitable blend will be Tensile Strength, Tensile Modulus, Flexural Modulus, Elongations, Flexural Deformations, Notched and Unnotched Impact. The materials used in these closures are 100% biodegradable, according to standard UNI EN 13432. The closures are totally safe for human use in food and beverage sector, while all the properties are maintained. As they are biodegradable products, their manufacture will have a much more sustainable carbon footprint and EoL. With the help of this organic recycling, the biodegradable caps will be composted at the end of their useful life.

Last use case, is the manufacturing of wood composites, bearing for appliance and tool industry in particular. The bearings have as compounds wood fibres, biopolymers, and natural graphite as filler. As the components are natural, the recyclability is 50% at least. Steel, and polymers are used nowadays for the current bearing industry, so a high amount of CO_2 is produced by the use of heavy metals as Pb, Cd, Sb, Cu, or Sn. The WC process will be demonstrated in a bio-plastic manufacturing system (injection system). The different prototypes are rings, cylinders, and half-shells in small production series. The new optimized chemical

[2] S. und B. Bundesministerium fuer Wohen, "Search | Database | ÖKOBAUDAT".

Funded by the European Union

structure of the bearings will be able to reduce the maintenance cost (taking into account the refurbishing the damaged bearings), reuse wood waste from nature or another industrial processes, and as result, as result, decrease the carbon footprint. The tests involved in this process are, the rate of retained lubricant in the material due to de microporosity, the wear coefficient, or the friction coefficient. The natural components of the structure allow to increase the recyclability at End-of-Life (EoL). The Green-Loop process, in comparison with the conventional, is entire derived from regeneration resources, eco-friendly, cost efficient, and lubricated with natural products.

1.2. Objectives

Green-Loop Project has as ambition to enhance the bioeconomy at the European Level, with a robust product design and new circular and sustainable schemes. It will reduce manufacturing costs and grow up at high speed the introduction of new bio-based products to the market. This project will develop some different and sustainable models for raw materials and recycling, so economy factors will be involved too. It is important to remark that industry personnel have to be qualified to apply these new technologies. Standardisation activities about bio-based materials, with methods, and quality controls will be addressed. ‘Sustainability and circularity by design in all stages of the value chains’, ‘Transformation to green and smart factories’, ‘Electrification of manufacture with microwaves and ultrasounds enhancement’, and ‘3 final users with replicability activities to ensure the results after the final of the project’ are the criteria will be followed for the three different use cases.

This Deliverable contains a proposal list of Key Performance Indicators regarding sustainable development and circular economy (CE), which is gaining importance as a suitable process to transform the current economy to a more sustainable and efficient one. It is a system based in the change of ‘EoL’ concept with reducing, reusing, recycling, and recovering materials in the processes. Use of renewable energies, eliminating the use of toxic chemicals and the waste removal are the pillars to achieve environmental quality, economic prosperity, and social equity, to benefit the future generations.

Funded by the European Union

2. Methodology

To maintain the value of the products, materials, or resources as long as possible is the main goal of the circular economy; that is, how effective is to make the transition from linear to circular economy. This objective is achieved based by returning them to the product cycle after the use phase to minimise the waste. It is better for the environment to extract less materials and to discard few products. The smart design of the product is the first step to start the circular economy process; the second stage is to define a smart production process, both are important to save resources, avoid unnecessary waste and create new business opportunities. In this section of methodology, both are explained, although the main one will come from the European Commission. This methodology stablishes how to measure the circularity, and a series of indicators which can quantify specific parameters, with concrete objectives. Then, the methodology used for estimating the circular economy in the Green-Loop Project are compiled.

2.1. Ellen MacArthur Foundation – Material Circularity Indicator

The circular economy is a global economic model that seeks to separate economic growth and development from the consumption of finite resources. Businesses see great opportunities in the circular economy, as it allows them to capture added value from their products and mitigate risks related to material prices and material supply. Then, it is described a methodology to calculate MCI for products, that measures how much the linear flow has been reduced and how much the restorative flow has been increased for each of its constituent materials. Use life and the intensity of use itself compared to a similar product in today's industry will also be taken into account. This MCI will be based on three fundamental pillars characteristic of each product: the amount of virgin raw material introduced into the manufacturing system (V), the mass of non-recoverable waste attributed to the product itself (W), and finally, the utility factor that establishes the duration and intensity of the product's life of use (X). In the Figure 1 it is possible to recognise how the flows can be, i.e., when only there are virgin feedstock and all the pieces go to landfill (only red arrows) at the end of its use life, the product flow could be considered fully linear. In the case that all the product is manufactured by recycling or component reuse and the recycling yield is 100%, the process follows a circular way (taking into account green arrows). In the industry today, the different products will follow somewhere between two extremes, measuring the circularity in the range 0-1. When the recycled material is included at the beginning of the process, this does not to be from the same product manufacturing but can come from other types of processes which use the same material.

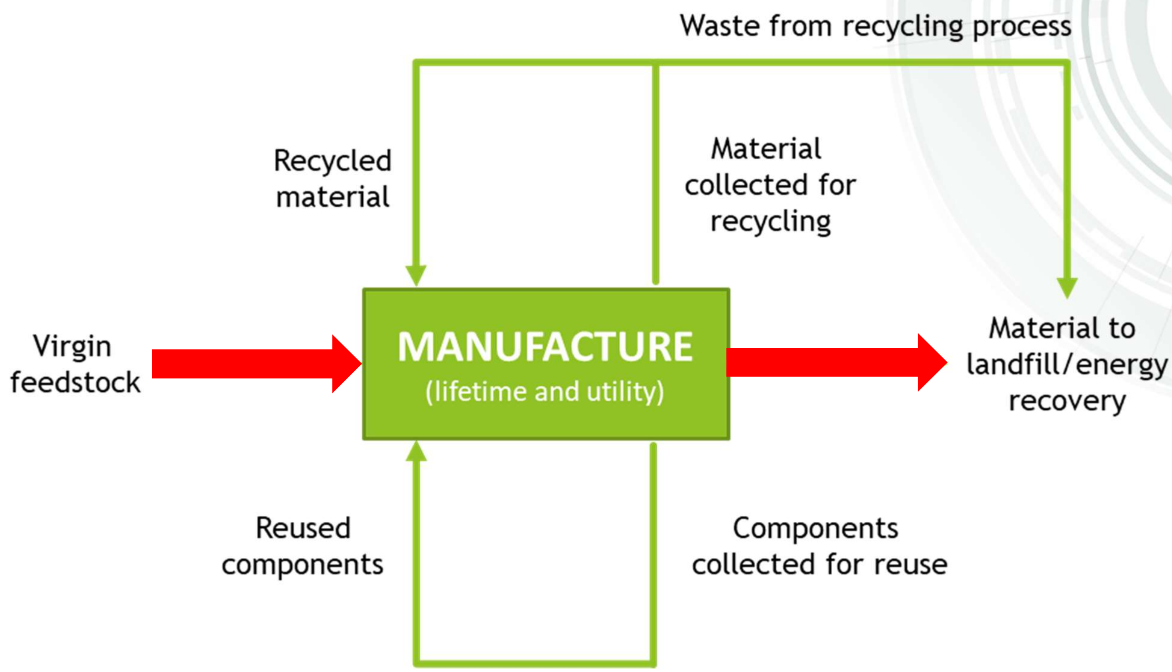

Figure 1 Diagram of different flows in a manufacturing process

The Ellen MacArthur Foundation (based on MCI) is one of the sources of methodology used in this document. Wherever possible, input data should be specific to the product under assessment, although where product data are not available, generic data may be used. The MCI for a product is developed based in the restoration of material flows at product level and is based on 4 principles:

- To use feedstock from reused/recycled sources
- To reuse components/to recycle materials after the use phase of the product
- To keep products in use longer (reuse, redistribution)
- To make more intensive use of products (service/performance models)

The following guidance may be used whenever the methodology is applied.

- *Recycled Feedstock* are materials or substances that are produced by the recycling of waste, which can be converted into raw materials for new materials. These new materials can be produced by mechanical recycling or by dissolving, and on the other hand they can be produced by chemical recycling. In the latter case, further treatment is required[3]. If the amount of Recycled Feedstock at

[3] Recycled feedstocks • Plastics Europe

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

the start of the process is not known, a regional or state average can be approximated by obtaining these figures from different commercial life cycle analysis databases. This flow of recycled material does not have to be from the manufacturing of the same product, and any product is collected for recycling, recycled raw material but none of that product is collected for recycling, no waste will be created when the product is recycled.

- When data for *Recycling Collection Rates* by specific product is not available, the Sector Collection Rate can be used. This rate is easier to obtain because there is specific legislation regulating recycling. The European Union, for example, sets targets for the collection of WEEE, vehicles or packaging. The collection rate for recycling will depend on the current market price of the virgin raw material. These rates are gradually increasing on the European continent, which means that the linear economy is being abandoned and the results of the circular economy are beginning to be seen. To control these three waste streams, the EU has set targets for their management, based on three directives: the Waste Electrical and Electronic Equipment (WEEE) Directive on separate collection and recycling, the Waste Framework Directive for the recycling and reuse of municipal waste, and the Packaging and Packaging Waste Directive, which defines the recycling target for packaging waste.
- The *Recycling Process Efficiency* provides the information about the efficiency for a specific recycled material and concrete recycling process. This value will depend on many different factors, as the material, the quantity of material or materials involved, and the recycling preparation process. The first factor, each material has a different efficiency, for example, metals are easier to recycle, so the efficiency will be higher than others. In the second one, the quantity of every material is important to take into account, because when a whole product is recycled, the products in larger quantities will have a higher recycling efficiency than those in smaller concentrations. Efficiency will also change if contaminants are present in the scrap or if coatings are present in the product. Finally, when preparing material for recycling, it is expected that there will be greater efficiency when the product is disassembled prior to the recovery of individual materials.
- *Downcycling* is used to describe a recycling process which reduces the quality and the economic value of a material or product. When a material is collected for recycling, next guides should be followed. As a general requirement, it must be possible to separate the product into its constituent materials by a proven and economical process. If downcycled material is introduced in the process feed, this material would be considered as recycled material - it should be noted that it cannot be taken as material for recycling if it does not meet certain requirements - as a practical example, a product containing aluminium and plastic is considered, where no economically viable separation is possible after the use phase of the product. Theoretically, it could be used in applications where plastic alone would be used, but it is assumed that there is currently no market or recycling stream to the product, so it will not be considered as a feedstock for recycling.
- Companies have an approximate knowledge of the *Utility* of their products. It is to be expected that in most cases lifetimes or functional units are used. If both lifetimes and functional units are used, it is important to ensure that a given effect is only considered once, either as an impact on lifetimes or on intensity of use, but not both.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

- In relation with *Shared Consumption Business Model,* the usage figure of a product increases if it is spread over many consumers throughout its use phase. In other words, when a product is rented by a large number of people in a relatively short period of time, the circularity of the product will be higher.
- *Consumables Related to a Product* will have different factors when compared to the product to which they relate, so it is not possible to introduce them directly into the evaluation of that product. This ratio is mainly related to materials consumed during the use stage of the product. It is advisable to calculate ICFs for consumables separately from those for products.
- The current methodology for *Material Losses in the Supply Chain* only considers the material in the product. To complete this, the extraction and conditioning of raw materials, all stages of manufacturing, and up to the shaping of the final part, could be taken into account. Indeed, it is complicated for practical reasons and lack of data. When this methodology evolves in the future, companies will be able to apply this methodology to the entire supply chain, as they will need to acquire knowledge about material flows.
- The methodology does not include *Material Losses During Product Use*, although is easy to take them into account as irrecoverable material. For example, when the rubber from a wheel has worn out through regular use and has been dumped in the environment, it can be compared to material that has been incinerated or sent to landfill, because it cannot be recovered. These kinds of losses should be included in the circularity of products.

While the indicators provide information on the degree of circularity of the product, they do not take into account the materials used in the development of the product, nor do they provide information on other impacts that the product may generate. In addition to circularity indicators, there are also *complementary risk indicators* and *complementary impact indicators*.

2.1.1. Complementary Risk Indicators

The Complementary Risk Indicators measure the urgency to implement the circular practices. These practices are the basis for the shift towards a circular economy from the current linear model. Practices are mainly based on measures of material scarcity and measures of toxicity. Then, these risk indicators will be listed one by one.

- The Material Price Variation Indicator has been developed in conjunction with this MCI methodology. It can provide an indication of the change in the price of materials for a given product, on an annual basis and over a given time horizon, e.g. the last five years. It also provides statistical analysis to indicate the trend over the same period. It represents a new indicator added by this methodology, unlike the other existing indicators.
- The Material Supply Chain Risks for the manufacture of a product are based on the availability of that material from the product manufacturer. At present, there is a complex relationship between availability, competing markets, supply and demand in each market, regulatory constraints, political stability in the states where the raw material exists, and the ability of purchasing companies to absorb these costs.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

- To evaluate the Material Scarcity and the supply of certain raw materials which may be affected in the future, there are several ways to look at the scarcity approach, such as the abundance in the earth's crust, the relationship between reserves and production, and the EU Ad-hoc Working Group about Defining critical raw materials[4].
- About Toxicity, in raw materials or products which contain toxic substances may be subject to certain restrictions in the future due to applicable regulations. Their use may also be affected over time, reducing utilisation and decreasing their economic value. Examples include the EU REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) Regulation - Regulation (EC) No 1907/2006 used to improve human health and the environment by promoting alternative methods for hazardous substances - and the EU RoHS (Restriction of the Use of Certain Hazardous Substances) Directive - Directive 2011/65/EU on the Restriction of Certain Hazardous Substances in Electrical and Electronic Equipment (EEE).

2.1.2. Complementary Impact Indicators

Finally, modifying the MCI of a product can generate impacts with important consequences that affect companies. Complementary Impact Indicators give an approximation of the benefits that circular models can provide. Within this category are the energy and water impact of a given configuration. The impacts of these optional risks are listed below.

- In most cases, increased circularity is expected to decrease the Energy Usage and CO_2 emissions to produce raw materials and product manufacturing, and CO2 emissions. To make this assessment, the energy intensity, the carbon footprint of materials, and the energies used in the manufacture and disposal of the product must be known. Two methodologies are stablished nowadays: Life Cycle Assessment (LCA) and an Environmental Product Declaration (EPD).
- Changes in the circularity of a product will change the amount of Water to be used in the production of raw materials and in the manufacture of the product. The ISO 14046:201439 standard on water footprint allows calculating the water footprint for products. It should be borne in mind that the greatest impact on water use will depend on where the water is extracted from and the level of water stress in the area.
- Talking about Toxicity, flame retardants, plasticisers or pigments are chemicals that are toxic to humans or the environment, and may be contained in materials to provide certain characteristics. Coatings and preservatives should also be included. These substances can accumulate in the food chain, reaching much higher levels at the top of the pyramid. This can happen in both virgin and recycled raw materials, so appropriate recovery or minimisation of these agents must be carried out.

---

[4] European Commission, Report of the Ad-hoc Working Group on defining critical raw materials, 2014

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

2.2. European Commission

The framework on the CE by the European Commission (EC) is based in ten indicators, although some of them are divided in sub indicators. These indicators are useful to highlight the main pillars of the circular economy. New indicators about green public procurement and food waste are being developed by different organisms and offices. In the Figure 2, it can see the 4 different areas into which the 10 indicators fall can be seen: Production and consumption, Waste management, Secondary raw materials and Competitiveness and innovation.[5]

Figure 2 Circular economy monitoring framework by EC

2.2.1. Production and consumption

To control the production and consumption step is the base to understand the progress to Circular Economy (CE). Economic and domestic sector should decrease the amount of waste generated. In the future, this behaviour could help to increase the self-sufficiency of certain raw materials for the production in the EU. The four indicators inside this area considered with this methodology are:

- The self-sufficiency of raw materials for production in the European Union (EU) aims to share a selection of key materials (including raw materials) used and produced in the EU.
- The green public procurement (as an indicator for financing aspects) has to include environmental requirements of major public procurement along the EU.

[5] Indicators - Circular economy - Eurostat (europa.eu)

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

- About waste generation (as an indicator for consumption), there are three sub indicators which belong to this general indicator, as the generation of municipal waste per capita; total waste generation (excluding major mineral waste) per Gross Domestic Product (GDP) unit and in relation to domestic material consumption.
- Finally, this methodology highlights food waste generation and management as a separate waste stream.

2.2.2. Waste management

The key to the transition to a CE is to increase the recycling. This area is focused on to share which waste is recycled and which is returned into the economic cycle to create more value. This area contains two indicators:

- The overall recycling rates, with two sub indicators inside, these are the recycling rate of municipal waste and of all waste but excluding major mineral waste.
- The recycling rates for specific waste streams has involved six more sub indicators, as the recycling rate of overall packaging waste, the plastic packaging, the wood packaging, the waste electrical and electronic equipment (WEEE), the biowaste recycled per capita, and finally, the recovery rate of construction and demolition waste (CDW).

2.2.3. Secondary raw materials

To re-introduce material and products into the economy is needed to close de loop of the CE. This re-introducing could be as new material or product. The materials extracted from natural resources are being replaced by recycled material; this is helping to reduce the environmental footprint, production, and consumption both included, to secure the future supply of raw materials. Two indicators are comprised in this area:

- The contribution of recycled materials to raw materials demand when it is stablished the rate of secondary raw materials overall materials demand (specific materials and the whole economy).
- The trade in recyclable raw materials, taking into account imports and exports of selected recyclable raw materials.

2.2.4. Competitiveness and innovation

The CE helps to the creation of jobs and economic growth, and with the development of new technologies improves the product designs for a facility in the re-use and promote this innovative industrial processes. To this are belongs two different indicators:

- Private investments, number of people employed, and gross value added are all inside the circular economy sectors.
- The number of patents related to waste management and recycling.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

3. Green-Loop Project Value Chains

The goal of this section is to put in context the value chain performance for each use case. A more extended explanation of each value chain considered in Green-Loop Project could be consulted in Deliverable *D2.1: Circular economy, and evaluation of circular value chains to boost Green-Loop results*.

3.1. Bio-rubber composites

The first value chain considered in Green-Loop Project is part of the Construction Sector. The product selected is a multifunctional bio-based rubber composite panels for the reduction of vibro-acoustics transmission loss and fire-retardant properties. The product will be made of recyclable elastomers. The materials used will be bio-based lignin and recycled rubber waste. The panels could be recycled for use in the same process through additional processing steps. The value chain for this first use case is showed in the Figure 3.

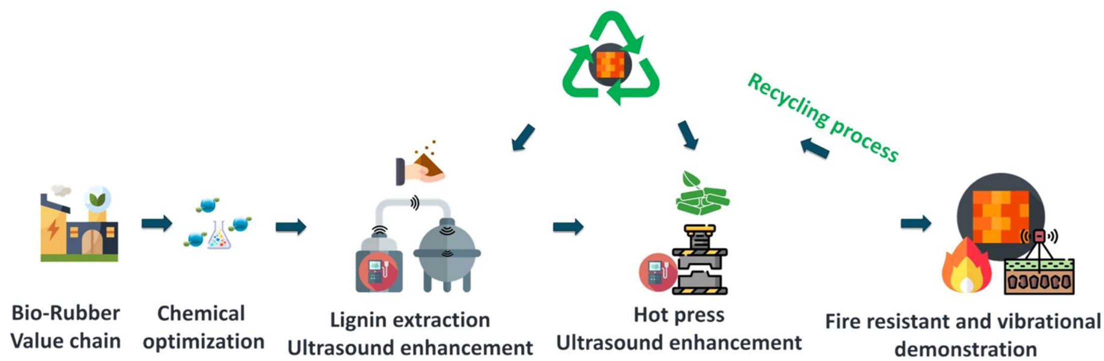

Figure 3 Bio-Rubber Composite Value Chain Representation

3.2. Bioplastic

The second value chain considered in the project is about Packaging in Food and beverage Sector. The product considered is a bottle closure for juice, spirits and olive oil. These bottle closures will be made of 100% biodegradable materials. Bio-based raw materials will be natural fibres, which will function as biodegradable thermoplastic carriers. These bottle closures could also be recycled in the same manufacturing process. Figure 4 summarises this use case value chain.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

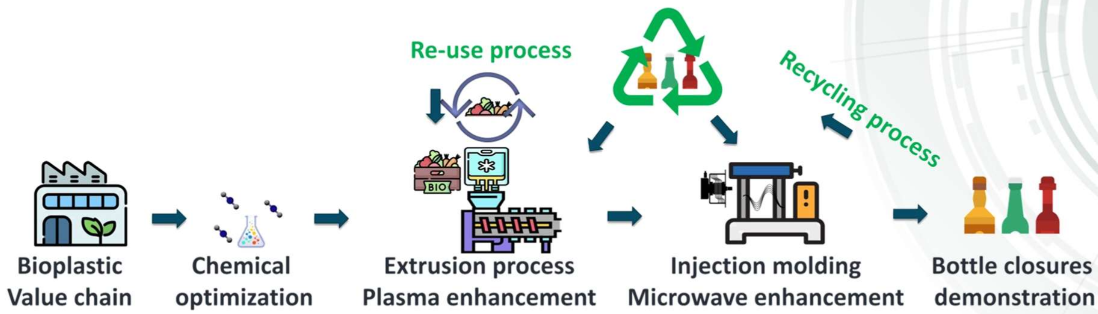

Figure 4 Bioplastic Value Chain Representation

3.3. Wood composite

The third and last value chain considered in the Green-Loop Project belongs to Appliance & Tool Industry. The selected demonstrator is bearing. Wood Composite (WC) bearings will be demonstrated in a bio-plastic manufacturing system (Injection System). These new bearings could be recycled or refurbished in order to extend their lifetime in the same process. In Figure 5, this last value chain is summarised.

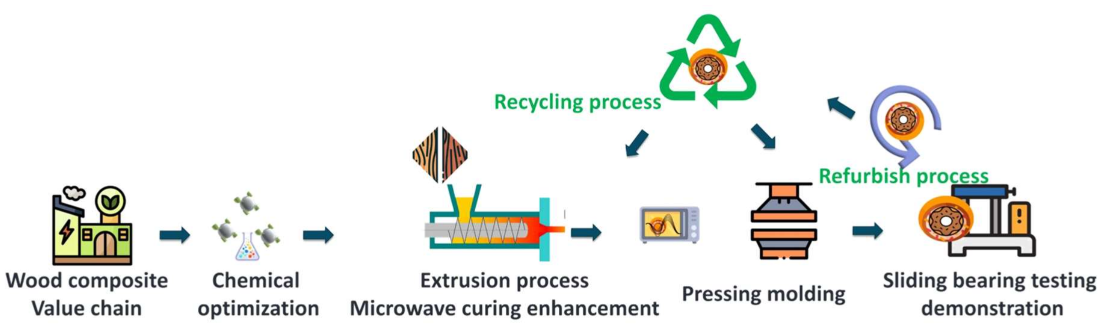

Figure 5 Wood Composite Value Chain Representation

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

4. Key Performance Indicators

Key performance indicators are a tool that helps to establish a periodic monitoring and evaluation of a product, system, company or organisation, until the achievement of specific objectives. In this case, they will be used to relate the performance of different categories for each of the products generated in three different systems included in the Green-Loop project and compare it with current manufacturing products.

The Tables added in the Annex shows the different Key Performance Indicators (KPIs) for the different use cases included in the Green-Loop processes. It is expected to obtain this set of KPIs at the end of the project, although some of them could be useful to calculate during the project (i.e., Sustainability KPIs). For each KPI it was defined:

- ***KPI Name:*** Designation name for each KPI.
- ***Percentage or Units:*** Value a priori defined as project objective, based in literature review or previous experience of Green-Loop experts.
- ***Description:*** Brief description of the KPI.
- ***Formula:*** Proposed formula for KPI calculation.
- ***Variables:*** Variables used for calculation.
- ***(WP)i:*** Work Package where is expected to obtain data and calculate each KPI.

In addition to the indicators collected by the consortium, a proposal list is also attached (Annex, Table 1), which includes different factors described above.

The first category is ***Sustainability***, where it is possible to find some indicators related to the reduction of waste generation, the rate of recyclable material used in the processes, how much reused material is included as feedstock at the beginning of the system, if it is possible to separate the different physical parts of the final product, or what is the fraction of wastewater/water reused in the Green-Loop processes.

The next category of proposed KPIs is ***Energy impacts***, focusing on the reduction of different consumptions (electricity and gas), in increasing the efficiency of the equipment involved in each of the stages of the different use cases, or establish how much renewable energy will be used in each of the Green-Loop processes compared to the current ones.

In relation with the ***Environmental burden of harmful substances***, the main indicator in this category it is going to be the reduction of Greenhouse Gases (GHG) emissions. This KPI is intended to demonstrate the reduction of emissions through each of Green-Loop’s processes compared to current manufacturing processes.

Regarding ***Occupational Health and Safety***, the reduction of occupational accidents is the first indicator identified. In addition, a second indicator that establishes the reduction in the use of substances that can cause health problems for the people involved in each process was given in the Table 1 on the Annex. These indicators will help to develop the Social Life Cycle Assessment (s-LCA).

Funded by
the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

And finally, as ***Economic factors***, it has been selected three indicators to help in the development of the Life Cycle Cost (LCC) and business models and exploitation activities. These indicators are the revenues invested rate, the return on innovation investment, and the reduction of final products costs during the whole life cycle.

4.1. Bio-rubber composites

For the first use case based on the production of bio-rubber composite panels that help reduce vibro-acoustic transmissions and have flame retardant properties, the different categories are Smart manufacturing, Environmental impacts, and Material properties. The indicators that are involved in this manufacturing are collected in Annex, Table 2.

As ***Smart manufacturing***, the principal KPIs to measure will be the Monitorization of the production, the Enhancement of the ultrasound during lignin and rubber production, and the measurement of the Circularity and Sustainable Ratio.

Inside the ***Environmental impacts***, the reduction of wastes and emissions of CO_2, the valorisation yield, the recyclability or the rate of final product refurbish are the indicators highlighted.

Finally, the KPIs about ***Material properties*** establishes a maximum or minimum value in different tests, as the Compressive Strength, the Smoke production, the Thermal conductivity or the Shear Bond Strength.

4.2. Bioplastic

During the production of the bioplastic closures for Spirits and Olive oil, the categories of indicators to be studied throughout the life of the project belong to the same categories mentioned above in the 'bio-rubber' section: Smart manufacturing, Environmental impacts and Material properties. In the Annex, is

Table **3** which include all these indicators.

For the ***Smart manufacturing*** in this value chain, the repeated indicators are the Monitorization of the production and the measurement of the Circularity and Sustainable Ratio, while the KPI on Microwave manufacturing improvement is added.

In the case of the indicators about ***Environmental impacts***, reduction of wastes and emissions of CO_2 are repeated, and it is necessary to add the reuse of biomaterial and the recyclability of organic material.

The ***Material properties*** category has more indicators in this value chain: Compressive Strength, Compressive Elastic Modulus, Flexural Modulus, Flexural Strength, Tensile Elastic, and Tensile Strength.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

4.3. Wood composite

Finally, for third value chain to manufacture wood composite bearings for Appliance & Tool Industry there are the same categories than the previous use cases; Smart manufacturing, Environmental impacts, and Material properties. All these indicators are summarised in the

Table **4** at the end of the Annex.

In the ***Smart manufacturing*** category, the indicators will also be repeated: Monitorization of production, Manufacture enhancement with microwaves, and the measurement of circularity and sustainable ratio.

For the ***Environmental impacts*** category, these will be the same indicators as in the bio-rubber value chain, but without the Valorisation yield.

The last category, ***Material properties***, collects the indicators which establish the retention of bio-lubricant due to the open microporosity, the wear coefficient, and the friction coefficient.

Funded by
the European Union

5. Conclusions

- In this Deliverable, the KPIs about the different Green-Loop technologies are defined in order to considered them during the project lifetime. A first approach will be made in proposal stage, but a review and extension of the number was already considered.

- This deliverable describes the methodology to be adopted to identify and define the KPIs of the Green-Loop Project. These KPIs will measure the impact of the new bio-based solutions considered in the project. The most appropriate KPIs for the different Green-Loop processes have been proposed according to the area that applies (Environmental, Energy, Economic, Technical...).

- In the KPIs Table is fulfilled with definition, parameters considered in the calculation, WP where will be calculated, and expected value at the end of the project. The value of the KPI proposed by Consortium were considered in proposal stage, defined by partners experts or considered from literature review.

- Furthermore, in the Annex tables is suggested in which work package is expected to obtain each of the KPIs based in the parameters needed to the calculation. It is considered to obtain them at least at the end of the project, although some of them could be useful to calculate during the project.

- This list of KPIs will be useful to help the consortium track the technological development of the different value chains throughout the life of the project. At the end of the project, these indicators will be calculated to demonstrate and compare the benefits of each of the existing value chains in the Green-Loop Project. Each indicator is to be calculated in the corresponding WP indicated in the Tables in the Annex.

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

References and Resources

[1] Hristov, I., Chirico, A. (2019). The Role of Sustainability Key Performance Indicators (KPIs) in Implementing Sustainable Strategies. Department of Management and Law, University of Rome Tor Vergata, 00133 Rome, Italy

[2] Amrina, E., & Yusof, S. M. (2011). Key performance indicators for sustainable manufacturing evaluation in automotive companies. 2011 IEEE International Conference on Industrial Engineering and Engineering Management.

[3] Yedlarajaiah, Pradeep Kumar, "Metrics for estimating the product disassembly effort" (1998). Theses. 814.

[4] Ellen MacArthur Foundation. http://www.ellenmacarthurfoundation.org/circularity-indicators/

[5] European Commission Eurostat. Indicators - Circular economy - Eurostat (europa.eu)

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

Annex

Table 1. Proposed KPIs based on literature review.

Sector	KPI name	Percentage [Units]	KPI Description	Formula	Variables	(WP)i
Sustainability	Waste reduction rate	16-64%[1]	This KPI relates the different rate between the current waste production and the Green-Loop waste production.	$WRR = \frac{[WRM]_{Current} - [WRM]_{GL}}{[WRM]_{Current}} x100$	WRR: Waste Reduction Rate WRM: Wasted Raw Material	WP2
	Recycled materials used rate	16-64%[1]	This indicator relates how much recycled material is used in the process in comparison with the total.	$RMUR = \frac{[ARM]}{[ATM]} x100$	RMUR: Recycled materials used rate ARM: Amount of recycled material ATM: Amount of total material	WP2
	Fraction of reused material in process	10-15%[6]	This KPI measures the amount of material which is reused in the process.	$FRM = \frac{[URM]}{[TRM]} x100$	FRM: Fraction of Reused Material URM: Unused Raw Material TRM: Total Raw Material	WP2
	Reusable/recycled material rate	>95%	This indicator measures the ratio of the amount of	$RMR = \frac{[ARM]}{[ATM]} x100$	RMR: Reusable material rate	WP2

[6] EU’s circular material use rate increased in 2020. EU’s circular material use rate increased in 2020 - Products Eurostat News - Eurostat (europa.eu)

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

Sector	KPI name	Percentage [Units]	KPI Description	Formula	Variables	(WP)ᵢ
			reusable material to the amount of total material used in the process.		ARM: Amount of reusable material ATM: Amount of total material	
	Final product disassembly rate[3]	>95%	This KPI establishes the relationship of the physical separation of the final product into its subassembly pieces, with the aim of reusing, recycling, incinerating, or disposing.[3]	$R_d = \left(\left[\frac{V-W}{C_s+C_d}\right]-1\right)x100$	R_d: Disassembly return on investment V: Expected value for recovered parts W: Value if the product is directly disposed C_s: Cost to sort into disassembly families plus the logical cost of moving the inventory C_d: Disassembly cost	WP2
	Fraction of wastewater reused	10%	This indicator establishes the amount of wastewater treated in relation to the total water to be used in each of the processes.	$FWwR = \left[\frac{AWWT}{TWU}\right]x100$	FWwR: Fraction of Wastewater Reused AWWT: Amount of water from wastewater treatment TWU: total water used	WP2
	Fraction of water reused	60%	This KPI measures the proportion of the total water to be reused in the process itself.	$FWR = \left[\frac{AWR}{TWU}\right]x100$	FWR: Fraction of Water Reused AWR: Amount of water reused TWU: total water used	WP2
Energy impacts	Electricity consumption reduction	15%	This KPI measures how much less electricity is consumed in	$ECR = \frac{[EC]_{Current}-[EC]_{GL}}{[EC]_{Current}}x100$	ECR: Electricity consumption reduction	WP2

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

Sector	KPI name	Percentage [Units]	KPI Description	Formula	Variables	(WP)i
			the Green-Loop process in comparison with the current one.		EC: Electricity consumption	
	Gas consumption reduction	10%	This KPI measures how much less gas is consumed in the Green-Loop process in comparison with the current one.	$GCR = \frac{[GC]_{Current} - [GC]_{GL}}{[GC]_{Current}} x100$	GCR: Gas consumption reduction GC: Gas consumption	WP2
	Efficiency of equipment	15%	This indicator sets the increase in efficiency of the different equipment used in the process.	$EoE = \sum_{1}^{i} \frac{[Eef_i]_{GL} - [Eef_i]_{Current}}{[Eef_i]_{GL}} x100$	EoE: Efficiency of equipment Eef: Efficiency of every equipment i: specific equipment considered	WP2
	Renewable sources rate	25-95%	In this KPI is set the amount of energy from renewable sources from the total energy used in the process.	$RER = \frac{RE}{TE} x100$	RER: Renewable energy rate RE: Renewable energy used TE: Total energy required	WP2
Environmental burden from harmful substances	Emissions Greenhouse Gases (GHG) rate	18-72%[1]	This indicator gives information about the reduction of GHG emissions between the Green-Loop process in comparison with the current situation.	$ERR = \frac{[GE_{Current} - GE_{GL}]}{[GH]_{Current}} x100$	ERR: Emissions reduction rate GE: Greenhouse gasses emissions	WP2
Occupational health and safety	Reduction of incidents	25%	This indicator gives information about the reduction of incidents among the workers comparing the	$RI = \frac{[Inc]_{Current} - [Inc]_{GL}}{[Inc]_{Current}} x100$	RI: Reduction of incidents Inc: Number of incidents that occur	WP2

Funded by the European Union

Sector	KPI name	Percentage [Units]	KPI Description	Formula	Variables	(WP)i
			Green-Loop process with the current situation.			
	Reduction of harmful substances used	80%	This KPI gives information on how many harmful substances are no longer used in the Green-Loop process compared to the current process.	$RHS = \frac{[HS]_{Current} - [HS]_{GL}}{[HS]_{Current}} x100$	RHS: Reduction of harmful substances HS: Number of harmful substances used across the process	WP2
Economic factors	Revenues invested rate	15-60%[1]	This indicator measures the amounts earned from previously invested money (it is mainly interest and dividends earned from a company's investment in shares and bonds of other companies).	$RIR = \frac{[ROI]_{Current} - [ROI]_{GL}}{[ROI]_{Current}} x100$	RIR: Revenues invested rate ROI: Return on Investment	WP7
	Return on Innovation Investment	14-56%[1]	This KPI measures the returns generated from investments in innovation.	$RII = \frac{[NP_{GL} - IC_{GL}]}{[IC]_{GL}} x100$	RII: Return on innovation investment NP: Net profit IC: Innovation costs	WP7
	Final products cost reduction during all life cycle	15%	This indicator is the result of the comparison the cost generated during the life cycle of the Green-Loop process and the current one.	$CR = \frac{[Cost]_{Current} - [Cost]_{GL}}{[Cost]_{Current}} x100$	CR: Cost reduction Cost: cost generated by product	WP2

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

Sector	KPI name	Percentage [Units]	KPI Description	Formula	Variables	$(WP)_i$

Table 2. Proposed KPIs by Consortium for use-case 1

BIO-RUBBER COMPOSITE						
Sector	KPI	Percentage [Units]	KPI Description	Formula	Variables	$(WP)_i$
Smart manufacturing	Monitorization of production	>80%	This KPI establishes how much of the Green-Loop process is monitored during the production of the bio-rubber.	$MP = \frac{[Mon]_{GL} - [Mon]_{Current}}{[Mon]_{GL}} x100$	MP: Monitorization production Mon: Grade of monitorization	WP3
	Ultrasound enhancement: (lignin production & rubber manufacture).	L: 20% R: 15%	This indicator measures the improvement in the Green-Loop process with the application of ultrasound in relation with the current situation.			WP3
	Circularity and sustainable ratio measurement	>90%	In this KPI it is appreciate the growth of the circularity in the Green-Loop process in comparison with the current situation.	$CR = \frac{TAP}{ACF} x100$	CR: Circularity ratio TAP: Total assets purchased ACF: Assets from circular flow (not virgin material)	WP2
Environmental impacts	Reduction of wastes	>85%	In this KPI it is appreciate the decrease of the wastes in the Green-Loop process in comparison with the current situation.	$WRR = \frac{[WRM]_{Current}}{[WRM]_{GreenLoop}} x100$	WRR: Waste Reduction Rate WRM: Wasted Raw Material	WP2
	Reduction of CO_2 emissions	25%	This indicator shows the decrease of the CO2	$RCE = \frac{[CE]_{GreenLoop}}{[CE]_{Current}} x100$	RCE: Reduction of CO_2 emissions	WP2

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

Sector	KPI name	Percentage [Units]	KPI Description	Formula	Variables	(WP)ᵢ
			emissions in the Green-Loop process in comparison with the current situation.		CE: CO_2 emissions	
	Valorisation yield	>95%	This KPI establishes the percentage of usable product; in another words, the amount of material in the final product that is not going to landfill.	$VY = \frac{[UM]}{[TM]} x100$	VY: Valorisation yield UM: Usable material TM: Total material	WP2
	Recyclability	80%	This indicator sets the recyclability of the materials in the process.	$Re = \frac{[RM]}{[TM]} x100$	Re: Recyclability RM: Recyclable material TM: Total material	WP2
	Final product refurbish rate	>50%	This indicator sets the number of final products that has been refurbished in relation to the total produced.	$PRR = \left[\frac{ARP}{TPS}\right] x100$	PRR: Product Refurbish Rate ARP: Amount of refurbished products ATM: Total amount of products sold	WP2
Material properties	Compressive Strength	>80 [MPa]	In this KPI, is set the minimum value that can be collected when performing the Compressive Strength test, number calculated from the failure load divided by the cross-sectional area resisting the load.	$CS = \left[\frac{F}{A}\right]$	CS: Compressive Strength F: Force at the point of failure A: Cross-sectional surface area	WP3
	Smoke production	<1.3 [m^2/s]	This indicator measures the maximum value of the smoke	$TSP(t) = 1.000x \left[\frac{SPR_{av}(t)}{t-300}\right]$	TSP: Total smoke production	WP3

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

Sector	KPI name	Percentage [Units]	KPI Description	Formula	Variables	(WP)i
			generation coefficient after exposing the material to certain conditions of temperature and oxygen concentration.		SPR_{av}: Average smoke production rate T: Time [0 ≤ t ≤ 3.000]	
	Thermal conductivity	<0.3 [W/mK]	This KPI defines the maximum number of Watts conducted per metre thickness of the material, per degree of temperature difference between one side and the other.	$K = \left[\frac{q}{\nabla T}\right]$	K: Thermal conductivity q: Heat flux (per unit time and unit area) ∇T: Temperature gradient	WP3
	Shear Bond Strength	>4.5 [MPa]	This indicator establishes the maximum force which adhesive joint can tolerate before fracture.	$S = \left[\frac{T}{A}\right]$	S: Shear bond strength T: Tension applied A: Bonded area	WP3

Table 3. Proposed KPIs by Consortium for use-case 2.

BIO-PLASTIC						
Smart manufacturing	Monitorization of production	>80%	This KPI establishes how much of the Green-Loop process is	$MP = \frac{[Mon]_{GL} - [Mon]_{Current}}{[Mon]_{GL}} x100$	MP: Monitorization production	WP4

Funded by the European Union

Sector	KPI name	Percentage [Units]	KPI Description	Formula	Variables	(WP)i
			monitored during the production of the bio-plastic.		Mon: Grade of monitorization	
	Manufacture enhancement with microwaves	>20%	This indicator measures the improvement in the Green-Loop process with the addition of microwaves, in relation with the current situation.			
	Circularity and sustainable ratio measurement	>90%	In this KPI it is appreciate the growth of the circularity in the Green-Loop process in comparison with the current situation.	$CR = \frac{TAP}{ACF} x100$	CR: Circularity ratio TAP: Total assets purchased ACF: Assets from circular flow (not virgin material)	WP2
Environmental impacts	Reduction of wastes	>60%	In this KPI it is appreciate the decrease of the wastes in the Green-Loop process in comparison with the current situation.	$WRR = \frac{[WRM]_{Current}}{[WRM]_{GreenLoop}} x100$	WRR: Waste Reduction Rate WRM: Wasted Raw Material	WP2
	Reduction of CO2 emissions	>30%	This indicator shows the decrease of the CO2 emissions in the Green-Loop process in comparison with the current situation.	$RCE = \frac{[CE]_{GreenLoop}}{[CE]_{Current}} x100$	RCE: Reduction of CO_2 emissions CE: CO_2 emissions	WP2
	Reuse of biomaterial	50%	This KPI measures the amount of biomaterial that is reused in the Green-Loop process.	$RoB = \frac{[RB]_{GreenLoop}}{[TM]_{Current}} x100$	RoB: Reuse of Biomaterial RB: Quantity of reusable biomaterial TM: Total material	WP2

Funded by the European Union

Sector	KPI name	Percentage [Units]	KPI Description	Formula	Variables	(WP)i
	Recyclability (organic recycling)	>95%	This indicator sets the organic recyclability of the materials in the Green-Loop process.	$Re = \frac{[ORM]}{[TM]}x100$	Re: Recyclability ORM: Organic recyclable material TM: Total material	WP2
Material properties	Compressive Strength	>80 [MPa]	In this KPI, is showed that 80 MPa is the minimum value that can be collected when performing the Compressive Strength test, number calculated from the failure load divided by the cross-sectional area resisting the load.	$CS = \left[\frac{F}{A}\right]$	CS: Compressive Strength F: Force at the point of failure A: Cross-sectional surface area	WP4
	Compressive Elastic Modulus	>2.5 [GPa]	This indicator fixes the minimum value to refers to the ability of plastic material to withstand compressive forces before it deforms or breaks.	$K = -V \cdot \frac{\Delta p}{\Delta V}$	K: Compressive elastic modulus V: Volume Δp: Pressure change ΔV: Volume change	WP4
	Flexural Modulus	>2.3 [GPa]	This KPI measures the minimum value that this property	$E_{flex} = \left[\frac{L^3 \cdot F}{4 \cdot w \cdot h^3 \cdot d}\right]$	E_{flex}: Flexural Modulus L: Distance between the two out supports F: Load applied at the middle of the beam w: Width of the sample h: Height of the sample	WP4

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

Sector	KPI name	Percentage [Units]	KPI Description	Formula	Variables	(WP)i
					d: Deflection due to the load F	
	Flexural Strength	>71 [MPa]	This KPI sets the minimum value for this intensive property which is calculated as the ratio of stress to strain in flexural deformation, or the tendency for a material to resist bending.	$\sigma_{flex} = \left[\frac{3 \cdot L \cdot F}{2 \cdot w \cdot d^2}\right]$	σ_{flex}: Flexural Strength L: Length of the sample F: Maximum force applied w: Width of the sample d: Depth of the sample	WP4
	Tensile elastic	>2.3 [GPa]	This indicator establishes the minimum value of the ratio between the stress in the direction of application of a force and the corresponding deformation.	$E = \left[\frac{\sigma}{\varepsilon}\right]$	E: Tensile Elastic σ: Force per unit area ε: Proportional deformation	WP4
	Tensile strength	>49 [MPa]	This KPI fixes the amount of force required to pull a specimen to the point of material failure.	$s = \left[\frac{P}{a}\right]$	s: Tensile strength P: Force required a: Cross-sectional area	WP4

Table 4. Proposed KPIs by Consortium for use-case 3.

WOOD COMPOSITE						
Smart manufacturing	Monitorization of production	>80%	This KPI establishes how much of the Green-Loop process is	$MP = \frac{[Mon]_{GL} - [Mon]_{Current}}{[Mon]_{GL}} x100$	MP: Monitorization production	WP5

Funded by the European Union

Sector	KPI name	Percentage [Units]	KPI Description	Formula	Variables	(WP)ᵢ
			monitored during the production of the wood composites.		Mon: Grade of monitorization	
	Manufacture enhancement with microwaves	>20%	This indicator measures the improvement in the Green-Loop process with the addition of microwaves, in relation with the current situation.			
	Circularity and sustainable ratio measurement	>90%	In this KPI it is appreciate the growth of the circularity in the Green-Loop process in comparison with the current situation.	$CR = \frac{TAP}{ACF} x100$	CR: Circularity ratio TAP: Total assets purchased ACF: Assets from circular flow (not virgin material)	WP2
Environmental impacts	Reduction of wastes	>40%	In this KPI it is appreciate the decrease of the wastes in the Green-Loop process in comparison with the current situation.	$WRR = \frac{[WRM]_{GreenLoop}}{[WRM]_{Current}} x100$	WRR: Waste Reduction Rate WRM: Wasted Raw Material	WP2
	Reduction of CO2 emissions	28%	This indicator shows the decrease of the CO2 emissions in the Green-Loop process in comparison with the current situation.	$RCE = \frac{[CE]_{GreenLoop}}{[CE]_{Current}} x100$	RCE: Reduction of CO_2 emissions CE: CO_2 emissions	WP2
	Final product refurbish rate	>50%	This indicator sets the number of final products that has	$PRR = \left[\frac{ARP}{TPS}\right] x100$	PRR: Product Refurbish Rate ARP: Amount of refurbished products	WP2

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them

Sector	KPI name	Percentage [Units]	KPI Description	Formula	Variables	(WP)ᵢ
			been refurbished in relation to the total produced.		ATM: Total amount of products sold	
	Recyclability	70%	This indicator sets the recyclability of the materials in the Green-Loop process.			WP2
Material properties	Retention of bio-lubricant due to open microporosity	5-10%	This KPI establishes the range of losses generated by the retention of bio-lubricant in the wood composites due to the microporosity.	$BLR = \left[\frac{FM - IM}{FM}\right] x100$	BLR: Bio-lubricant retention FM: Final mass IM: Initial mass	WP5
	Wear coefficient	<10^{-5} [mm^3/Nm]	This indicator marks the maximum value of the measured wear coefficient, which is determined as the weight loss measured by a digital scale divided by the sliding distance.	$K = \left[\frac{W}{F \cdot V \cdot T}\right]$	K: Wear coefficient [mm^3/Nm] W: Wear volume [mm^3] F: Force [N] V: Velocity [m/s] T: Elapsed time [s]	WP5
	Friction coefficient (under lubrication)	<0.1	This KPI sets the maximum value that this friction, calculated as a force opposing relative motion, can receive and which can occur at the interface between the bodies, but also inside the bodies.	$\mu = \frac{F_{max}}{F_N}$	μ: frictional coefficient F_{max}: Frictional force [N] F_N: Applied Normal force [N]	WP5

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor the granting authority can be held responsible for them