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D5.3 – Evaluation of sustainability and replicability

WP5

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Project Title	Development of innovative lightweight and highly insulating energy efficient components and associated enabling materials for cost-effective retrofitting and new construction of curtain wall facades
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Executive Summary

The present deliverable reports the outcomes of Task 5.3 “Evaluation of sustainability and replicability” in the framework of the EENSULATE project.

The LCA and LCC described in the present document have been set up on the basis of the inputs provided by partners and the outcomes of the activities carried out or foreseen in the framework of other Work Packages, such as WP2 “Optimization and scale-up of the innovative high insulating material for the spandrel and installation process - EENSULATE Foam”, WP3 “Optimization and scale up of the innovative high insulating and dynamic vision glass component – EENSULATE glass” and WP4 “Detailed design, prototyping and lab characterisation of EENSULATE façade modules”. Moreover, estimations and RINA-C calculations based on secondary data gathered from literature and external sources have been also used.

The analysis focuses on three case studies, depending on the targeted applications of the innovative products developed in the project, i.e. VIG based on innovative getter and sealant, as well as an innovative foam for spandrel application in curtain wall system:

- window in Miejskie Dzierżoniowa Museum, located in an historical building in Dzierżoniów, Poland;
- door-window in San Giovanni Public Library, located in an historical building in Pesaro, Italy;
- façade module to be installed at a Primary School in Dzierżoniów, Poland.

These case studies differ from each other not only for the final application they target, but also for the features required for the EENSULATE product (e.g. lightweight non-laminated VIG for the museum window, laminated VIG for the door-window and for the vision glass of the façade module), for the type of building considered as well as for the climate scenarios (i.e. Poland and Italy).

Moreover, according to the specific targeted application, the EENSULATE solutions are compared with different benchmark products, i.e.:

- single glass pane for museum window (this is mainly due to the requirement for a lightweight solution linked to cultural heritage constraints);
- double-glazing unit for door-window;
- triple-glazing unit and mineral wool respectively for vision glass and spandrel of façade module.

Considering a life cycle along 20 years, from manufacturing until use phase of the targeted products, EENSULATE solutions show lower environmental impacts in almost all of the Environmental Footprint impact categories: however, while in the case of the museum window such improvements are mainly due to the relevant savings foreseen in the use phase (because of the significantly lower U-value of the VIG compared with the benchmark), in the other cases these lower impacts are to be linked to the savings obtained in the VIG manufacturing phase if compared with the benchmarks (i.e. DGU and TGU).

These results are even more significant considering the high potential for further improvements and developments that may be envisaged for the EENSULATE products, especially VIG and one-component foam. The latter, in particular, still shows quite higher impacts if compared with the benchmark considered in the present study, i.e. mineral wool, even though the EENSULATE foam entail higher performances in terms of insulation provided.

As regards the economic perspective, the lower scale of the EENSULATE processes compared with the benchmarks affects the LCC outcomes, resulting in higher production costs in the windows application case studies. However, while in the case of the museum the higher manufacturing costs are partially offset by the relevant savings linked to the use phase, in the case of the door-window for the library the improvement in the U-value of the product does not bring substantial enhancements in terms of economic savings in the use phase.

Unlike the window case studies, the EENSULATE façade module appears as the most promising application, also in terms of cost-competitiveness towards benchmark products based on TGU and mineral wool. Indeed, although foam manufacturing entails higher costs than mineral wool production, VIG production process seems to be able to guarantee relevant savings if compared with the manufacturing of TGU.

For all case studies, it can be shown that the main differences between EENSULATE and benchmark products are mainly based on the manufacturing and the use phase: indeed, assembly and installation in both scenarios essentially consists of the same raw materials and procedures. However, this latter aspect represents a 'conservative' approach, especially considering the façade module case study: indeed, the EENSULATE solution is actually lighter than the benchmark one, thus potentially allowing an easier installation process that entails the use of either more lightweight or a lower amount of additional components like brackets, anchorages, etc.

Considering the better technical performances such as the increased thermal and acoustic insulation, the lower environmental impacts for most of the impact categories and the high potential for further improvements aiming to reduce costs of the developed processes, the EENSULATE solutions show a significant potential for a real market deployment and wide replicability. This latter aspect is particularly proved by the different types of application, typology of buildings and climate scenarios that are analysed in the present study: VIG shows indeed a high versatility, with promising results especially from an environmental sustainability perspective.

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Abbreviations and Acronyms

[ADP] – Abiotic Depletion Potential
[AE] – Accumulated Exceedance
[CAPEX] – CAPital Expenditure
[CO] – Confidential
[CTUe] – Comparative Toxic Unit for ecosystems
[CTUh] – Comparative Toxic Unit for humans
[DGU] – Double Glazed Unit
[E-LCC] – Environmental Life Cycle Costing
[EF] – Environmental Footprint
[EoL] – End-of-Life
[EU] – European Union
[FU] – Functional Unit
[GHG] – Greenhouse gases
[GLO] – Global
[GMD] – Gmina Miejska Dzierzoniow
[GWP] – Global Warning Potential
[ILCD] – International Reference Life Cycle Data System
[IPCC] – Intergovernmental Panel on Climate Change
[ISO] – International Standardisation Organisation
[JRC] – European Commission Joint Research Centre
[LCA] – Life Cycle Assessment
[LCI] – Life Cycle Inventory
[LCIA] – Life Cycle Impact Assessment
[LCC] – Life Cycle Costing
[NPV] – Net Present Value
[OCF] – One-component foam
[ODP] – Ozone Depletion Potential
[OEF] – Organisation Environmental Footprint
[OPEX] – OPerative EXpenditure
[PEF] – Product Environmental Footprint
[PVB] – Polyvinyl butyral
[PM] – Particulate Matter
[RER] – Europe
[SETAC] – Society of Environmental Toxicology and Chemistry
[S-LCA] – Social Life Cycle Assessment
[TGU] – Triple Glazed Unit
[UNEP] – United Nations Environment Programme
[VIG] – Vacuum Insulated Glass
[WP] – Work Package

1 Introduction

The EENSULATE project aims to validate an affordable and lightweight solution for envelope insulation to bring existing curtain wall buildings to “nearly zero energy” standards while complying with the structural limits of the original building structure and national building codes.

Two key innovative insulating products are developed:

• **EENSULATE foam:** highly insulating mono-component and environmentally friendly spray foam for the cost-effective automated manufacturing and insulation of the opaque components of curtain walls as well as for the significant reduction of thermal bridges during installation;

• **EENSULATE glass:** lightweight and thin double pane vacuum glass for the insulation of the transparent component of curtain walls, manufactured through an innovative low temperature process using polymeric flexible adhesives and distributed getter technology, thus allowing to use both annealed and tempered glass as well as low emissivity coatings.

The performances of the EENSULATE insulating solutions are tested at full scale prototype. Three different demo buildings (i.e. museum, library and school), located in two different climates (Poland and Italy), addressing both curtain-wall constructions and windows to be installed in historical buildings are used for validating the achieved results. The focus is on the thermo-acoustic behavior of demo buildings and indoor comfort.

In particular, within EENSULATE project, WP5 “Validation of performance, sustainability and replicability” aims to carry out the validation of performance, sustainability and replicability of the innovative products. In this respect, the present report, output of the Task 5.3 “Evaluation of sustainability and replicability”, performs an assessment of the environmental sustainability as well as cost-effectiveness of the EENSULATE solutions. The outcome of this study may be intended as a steering tool to pave the way towards sustainable development and wide replicability of the innovative products.

Several partners are in charge of the development of the different processes and phases within the three case studies, as summarised below:

- SAES for getter and sealant manufacturing;
- BGTEC for Vacuum Insulated Glass (VIG) manufacturing, assembly and installation of window at the museum and installation of façade modules at the school;
- FOCCHI for assembly and installation of window at the library, assembly of façade modules at the school;
- SELENA for foam manufacturing.

1.1 Identification of the document and its structure

The present document is a WP5 “Validation of performance, sustainability and replicability” deliverable of the European Commission co-funded project EENSULATE (under Grant Agreement no. 723868, in the framework of H2020 programme).

The deliverable D5.3 “Evaluation of sustainability and replicability” contains the results coming out from LCA and LCC analysis.

The document is organised in the following chapters:

- **Chapter 1** specifies the structure of the document and gives an overview of the EENSULATE project;
- **Chapter 2** describes the LCA and LCC methodologies, including a briefly explanation of the LCA phases, i.e. goal and scope, inventory analysis, impact assessment and results interpretation;
- **Chapter 3** reports LCA and LCC related to the case study I: substitution of existing window at Polish museum;
- **Chapter 4** reports LCA and LCC related to the case study II: substitution of existing door-window at Italian library;
- **Chapter 5** reports LCA and LCC related to the case study III: substitution of existing façade module at Polish school;
- **Chapter 6** provides conclusions of the document;
- **Chapter 7** lists the quoted references.

Annexes containing inventory data provided by EENSULATE partners are reported at the end of the document, as listed below:

- Annex I - Museum window
- Annex II - Library door-window
- Annex III - Façade module

2 Methodology

Life Cycle Assessment (LCA) is a structured, comprehensive and internationally recognised technique for assessing the environmental aspects of a product (i.e. good or service) and the potential environmental impacts throughout the product's life cycle.

A product life cycle includes all stages of a product system, from raw material acquisition to the end of life, including extracting and processing of raw materials, manufacturing, distribution, use and final disposal (i.e. 'cradle-to-grave' approach).

Figure 2.1 – Illustration of LCA process

LCA assists in:

- identifying opportunities to improve the environmental aspects of products at various points in their life cycle;
- decision making in industry, governmental or non-governmental organisations (e.g. strategic planning, priority setting, product and process design or redesign);
- selection of relevant indicators of environmental performance;
- marketing (e.g. an environmental claim, eco-labeling scheme or environmental product declarations).

The LCA methodology is regulated by the following standards and guidelines:

- ISO 14040: 2006 - Environmental management — Life Cycle Assessment — Principles and framework [1];
- ISO 14044: 2006 - Environmental management — Life Cycle Assessment — Requirements and guidelines [2];
- ILCD Handbook: General guide for Life Cycle Assessment – Detailed guidance [3];
- PEF/OEF Recommendation 2013/179/EU: Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations [4].

Life Cycle Costing (LCC) is a method that summarises all costs associated with the life cycle of a product (or service) that are directly covered by one, or more, of the actors involved in the product life cycle (e.g. supplier, producer, user/consumer, end-of-life actor) [5].

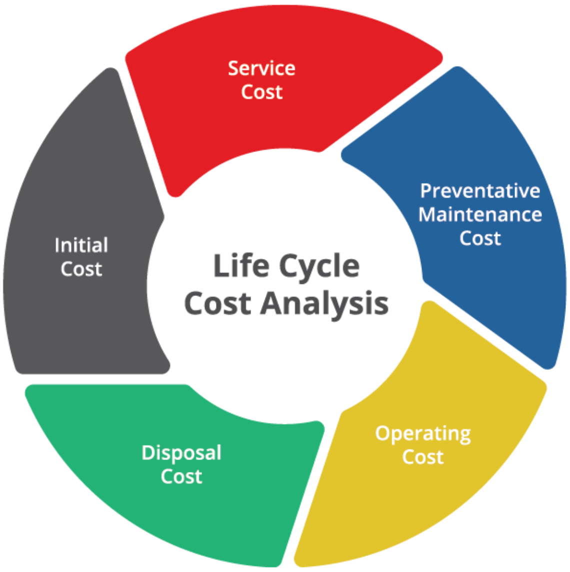


Figure 2.2 – Illustration of LCC process

Life cycle costing can be used as a stand-alone tool or into the broader context of sustainable development of a product, together with environmental LCA and social LCA.

Cost information for the entire life cycle is often useful in combination with LCA. Basically, LCC analysis has a similar structure as an LCA that it is conducted in parallel. Therefore, many aspects need to be defined and aligned with the decisions taken for the LCA in order to obtain an overall consistent analysis.

LCC can be used to understand the cost drivers of a product system, to identify improvement options as well as to validate pricing strategies.

Although the use of LCC is still limited and an ISO standard does not exist yet, the following guidelines and standards have been developed in order to give advice for implementing LCC:

- SETAC Guidelines: Environmental Life Cycle Costing: A code of Practice [5];
- ISO 15686-5:2008: Buildings and constructed assets — Service-life planning — Part 5: Life-cycle costing [6].

LCA and LCC methodologies follow the **Life Cycle Assessment framework** defined in the ISO 14040 [1] and ISO 14044 [2] standards. LCA consists of four steps: Goal and Scope Definition, Life Cycle Inventory, Impact Assessment and Interpretation, as illustrated in Figure 2.3.

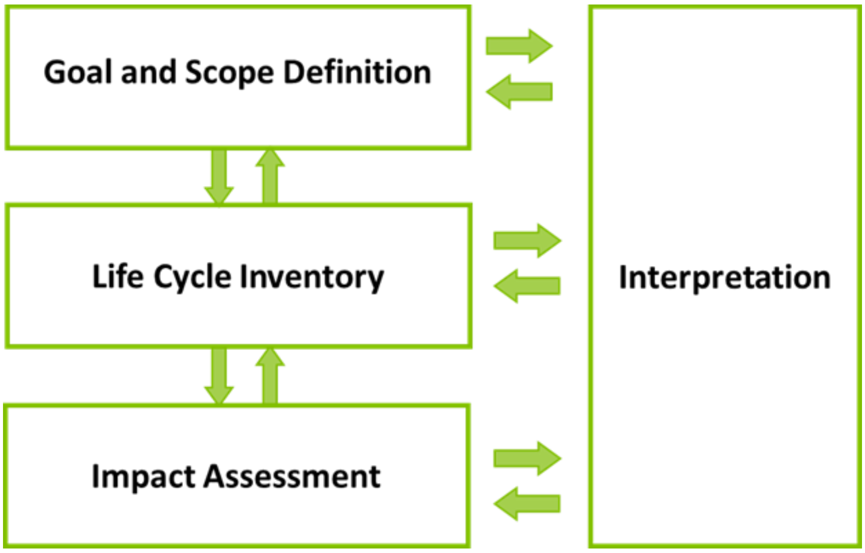


Figure 2.3 – Life Cycle Assessment framework

Goal and Scope Definition

The first phase of an LCA (or LCC) is the definition of the goal and scope. In this step all general decisions for setting up the LCA system are made. The goal and scope should be defined clearly and consistently with the intended application. An LCA is an iterative process and this allows redefining the goal and scope later in the study based on the interpretation of the results.

In the **goal definition**, the intended application, the purpose and the intended audience of an LCA study shall be unambiguously stated.

In the **scope definition,** the product or process system under study is characterised, all assumptions are detailed, and the methodology used to set up the product system is defined. Several aspects shall be considered and stated:

- the product system to be studied;
- the function of the product system and the functional unit;
- system boundary;
- allocation procedures;
- the methods for impact assessment and types of impacts to be considered and the interpretation to be performed;
- data requirement;
- assumptions and limitations;
- data quality requirements.

Life Cycle Inventory

Life Cycle Inventory (LCI) analysis is the phase of LCA/LCC involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

The process of conducting an LCI is iterative. As data are collected and more is learned about the system, data requirements or limitations may be redefined or a change in the data collection procedure in order to meet the goal of the study may be required.

Basically, this phase includes data collection, compilation of the data in Life Cycle Inventory tables, modelling of the system and calculating the LCI results.

Data collection step consists in collecting quantitative and qualitative data for every unit process in the system. After that all process data are collected, LCI tables are created. Subsequently, data are validated and related to the functional unit, in order to generate the LCI results for each unit process and for the overall product system.

Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) identifies and evaluates the amount and significance of the potential environmental/economic impacts arising from the LCI.

The **Impact Assessment of LCA** is composed by mandatory and optional steps:

- **Classification**: assignment of LCI results to one or more impact categories, according to the environmental impacts they are expected to contribute, e.g. CO_2 and CH_4 are assigned to the "Global Warming" impact category, while SO_2 is assigned to the "Acidification" impact category.
- **Characterisation:** conversion of LCI results to common units within each impact category through characterisation factors, so the converted results can be aggregated into category indicator results.
- **Normalisation (optional):** displaying of the magnitude of impact indicator results relative to a reference amount (e.g. a whole country or an average citizen), obtaining dimensionless and normalised LCIA results.
- **Weighting (optional):** weighting of the significance of impact categories by weighting factors, obtaining weighted LCIA results that can be aggregated to a single-value overall impact indicator.

While in the **Impact Assessment of LCC**, costs for each phase of the product's life cycle should be quantified and related to the functional unit. Thus, cost contributions to the total cost of the analysed product need to be evaluated. Likewise, results analysis may include hot spot identification, NPV analysis, calculation of payback period and break-even point as well as sensitivity analysis.

When LCC is applied with an LCA, the evaluation focuses mainly on supply chain effects and on the identifications of trade-offs or win-win situations between the environmental and the economic impacts [7].

Interpretation

The Interpretation is the phase of LCA in which the findings from the other phases are summarised and analysed in order to derive robust conclusions, identify limitations and make recommendations for the intended audience of the study.

The interpretation is an iterative process of reviewing and revising the scope of the LCA, as well as the nature and quality of the data collected consistent with the defined goal. This phase should include:

- identification of significant issues from the results of the LCI and LCIA phases;
- evaluation of the study, considering completeness, sensitivity and consistency checks;
- conclusions, limitations and recommendations.

3 Case study I: substitution of existing window at Polish museum

This chapter reports the LCA and LCC analysis of the case study I, which focuses on the EENSULATE glass used for substituting an existing window on historical building in Dzierżoniów, Poland.

EENSULATE glass is a lightweight and thin double pane vacuum glass, manufactured through an innovative low temperature process using polymeric flexible adhesives (EENSULATE sealant) and distributed getter technology (EENSULATE getter), thus allowing to use both annealed and tempered glass as well as low emissivity coatings. The prototype manufacturing process was developed under Task 3.5 “Prototypes assembly” by ULSTER, while BGTEC was in charge of full-scale prototypes production.

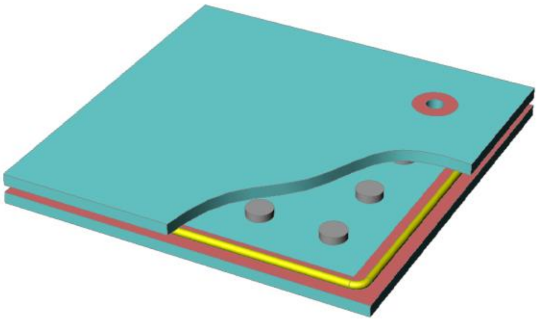


Figure 3.1 – Configuration of EENSULATE glass [8]

- **EENSULATE sealant** is a mono-component epoxy resin dispensable in the range 60-100°C, developed by SAES under Task 3.2 “Innovative sealing development“. The thermal curing allows low processing temperature (below 200 °C). The resin has extremely high barrier performance for Ar, N_2 and O_2 (till two orders of magnitude better than commercial sealants for insulating glasses). The sealant contains also an active filler for moisture absorption. The resin has high yield stress and adhesion strength (> 7MPa) on glass surfaces. It can be processed in air and deposited by an automatized system working with precise erogation.

  In EENSULATE VIG prototype manufacturing, pre-formed sealant strips (50 cm x 10 mm x 0,5 mm) are used in order to simplify the process and avoid the purchase of commercial scale dispensing system.

- **EENSULATE getter**, developed by SAES within Task 3.3 “Innovative getter development”, is a laminated strip (500 m x 8 mm x 0,22 mm) based on zirconium alloy powder (ZAO®02) on both sides of a nickel-plated iron substrate. This solution has a nitrogen and oxide sorption capacity superior than state-of-art getter solutions. Getter is activated by radio frequency heating under vacuum pumping.

The EENSULATE window (area = 3,9 m2) is installed at Museum Miejskie Dzierżoniowa, located in Dzierżoniów, Poland. EENSULATE project planned the retrofitting of a window on the ground floor, maintaining the original window frame. Being an historical building, the renovation activities are subject to severe restrictions to preserve its artistic value. The existing window constituted of a single flat glass pane is replaced with EENSULATE glass of 8,2 mm thickness (4mm+0,2mm+0,4 mm), which has high thermal performances (U = 0,5 W/m^{2}K).

Figure 3.2 – Polish Museum and zoom of the window [9]

3.1 Goal and Scope definition

In this chapter, the goal and scope of the case study I, i.e. substitution of existing window in the Polish museum, is clearly defined, consistently with the intended application. All general decisions for setting up the LCA and LCC are provided: the purpose, the application, the system boundaries, the functional unit as well as assumptions, limits and methodology.

3.1.1 Goal definition

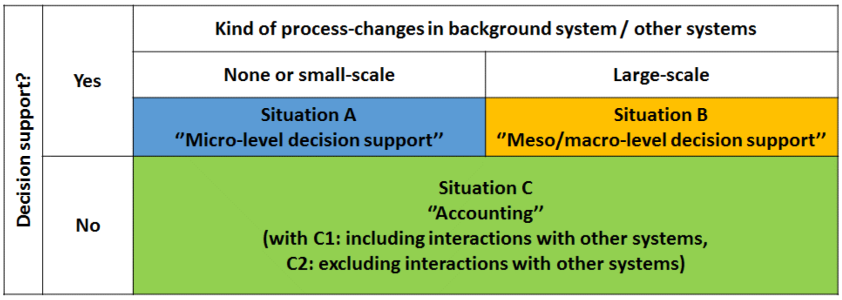
3.1.1.1 Intended application

The intended application of the analysis is a comparison between the EENSULATE solution, i.e. a window made by an innovative VIG, and the selected benchmark product, i.e. flat glass pane, along their life cycle.

3.1.1.2 Reasons for carrying out the study and decision context

The LCA and LCC studies are carried out to assess the effectiveness and sustainability of the developed solutions, both from an environmental and an economic perspective, taking also into account the potential benefits along lifetime linked to the implementation of an innovative window with better insulation performance. The analysis may act as steering tool to pave the way towards a wide replicability and commercialisation of the innovative products.

These studies do not affect the consortium in any decisions, but they are useful to evaluate the environmental and economic impacts of the innovative products. Taking also into account that there are no interactions with other systems, the studies are in the **situation "C2"** (see Figure 3.3), in accordance to ILCD guidelines [10].



Decision support?		Kind of process-changes in background system / other systems	
	Yes	None or small-scale	Large-scale
		Situation A "Micro-level decision support"	Situation B "Meso/macro-level decision support"
	No	Situation C "Accounting" (with C1: including interactions with other systems, C2: excluding interactions with other systems)	

Figure 3.3 – Decision context

3.1.1.3 Target audience

Considering the public feature of the document, the main target audience is composed by:

- European Commission;
- Members of the EENSULATE project's consortium;
- Public bodies and policy makers;
- Stakeholders belonging to the building and construction sector (including architects, building owners, construction companies, etc);
- Stakeholders involved in the retrofitting of different types of glazed buildings (including historical ones);
- Stakeholders involved in the recovery and preservation of cultural heritage.

3.1.2 Scope definition

3.1.2.1 Function and functional unit

The primary function of a window is to provide thermal and acoustic insulation and to protect the building interior against the exterior natural phenomena. The EENSULATE solution has the capacity to provide high insulation performance, keeping weight and thickness in the same order of magnitude as the original components.

The functional unit is the retention of the targeted insulation performance of **1 m^2 of window glass**, with the aim of fulfilling indoor comfort requirements **for 20 years**.

3.1.2.2 System boundaries and cut-offs

A **"cradle-to-gate" analysis** is performed, including the raw materials production, manufacturing of the main components, assembly, installation and use phase of the targeted product.

Figure 3.4 shows the whole life cycle of the EENSULATE window. The system boundaries are outlined by the red line.

The dismantling phase is excluded from the analysis: indeed, no substantial differences are envisaged between EENSULATE and benchmark case. Furthermore, the end-of-life phase is out of the boundary limits of the present analysis.

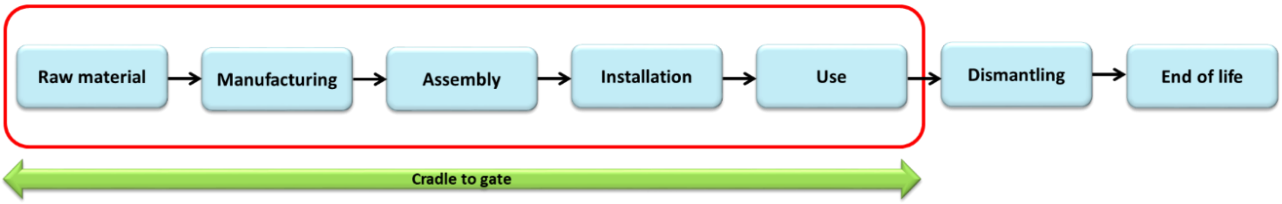


Figure 3.4 – System boundaries of the EENSULATE window's life cycle

The whole system is divided into a **foreground system** and **background system**, as shown in Figure 3.5. The foreground system consists of processes which are under the control of the decision-maker for which the study is carried out, i.e. sealant and getter production, VIG manufacturing as well as window assembly and installation. While the background system represents all up- and downstream processes connected to the foreground system, namely the raw material and energy production, transports, use phase as well as waste treatment and disposal.

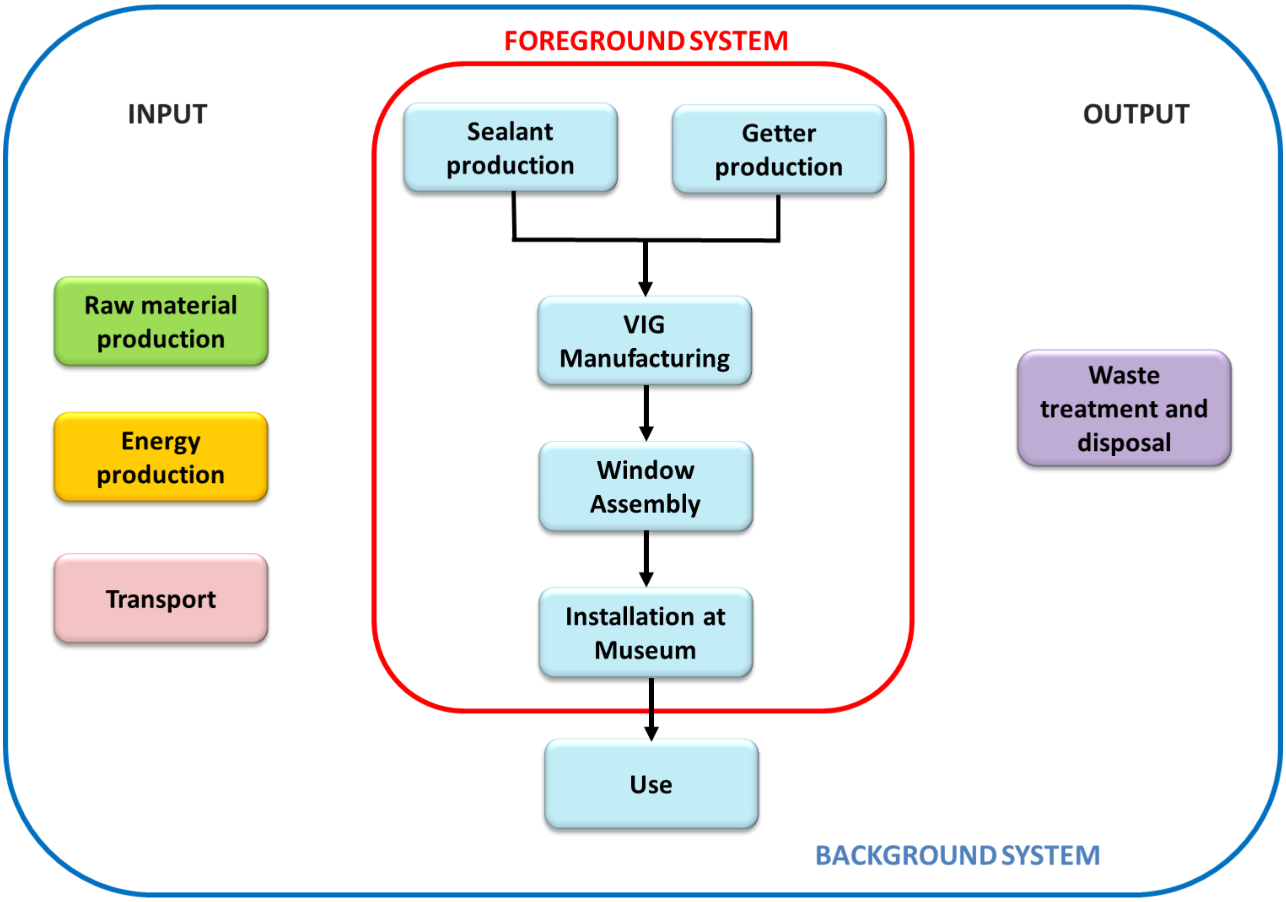


Figure 3.5 – EENSULATE foreground and background system of the case study I

The following cut-off criteria are used in this study to decide the inclusion or exclusion of input or processes:

- **Mass and environmental significance**: inputs that do not contributed to more than 1% of the mass input of the product system and that are estimated to contribute no more than 1% of the total environmental impacts are excluded from the LCA:
  - FEP foils in sealant production;
  - stainless steel pillars in VIG manufacturing;
  - indium in VIG manufacturing;
  - stainless steel cover in VIG manufacturing.
- **Economic significance**: processes or activities estimated to contribute no more than 1% of the total economic impacts are omitted from the LCC study:
  - waste disposal in getter production;
  - waste disposal and energy in sealant production;
  - transport in VIG manufacturing;
  - energy, equipment and transport in assembly, disassembly and installation.

3.1.2.3 Assumption and limitations

Within this study, the following assumptions are included:

- annual maintenance costs are assumed to be 3% of the overall CAPEX for getter and sealant production processes and 2% for VIG manufacturing process;
- the purchasing cost of heating oven in VIG manufacturing is assumed equal to 200 k€ with a depreciation time of 15 years, in place of a renting cost of 17 k€/month;
- in the use phase, calculations are based on the thermal energy needed to balance the heat losses through the window along its life cycle;
- for the use phase, heat losses through the window are estimated through a simplified calculation[1], considering:
    - Wroclaw average monthly outdoor temperatures (T_e) for year 2019[2,] adopted as representative for Dzierżoniów city,
    - average indoor temperature (T_i) in the museum equal to 16 °C,
    - coefficient of heat transmittance for EENSULATE museum window equal to 0,5 W/m^2K,
    - coefficient of heat transmittance for benchmark museum window equal to 5,8 W/m^2K,
    - heating energy consumption for 10 hours/day for the period from 15th October to 15th April;
- packaging is not considered;
- only transportations of EENSULATE products within foreground system are considered;
- for road transport, a truck 3.5 ton with full payload is considered;
- for sealant and getter transport via airplane, a cargo plane 22 ton with full payload is considered for a route from Milan Malpensa to Warsaw airport.

3.1.2.4 Data quality requirements

Specific data, directly measured or collected from processes or activities within the EENSULATE project, are required for inventorying the foreground system. For inventorying the background system, instead, generic data can be gathered from a third-party like: LCI databases (e.g. Ecoinvent v3.5 Databases, GaBi LCA Databases), industry-average, scientific papers as well as government statistics source (e.g. Eurostat).

Data quality requirements for this study are summarised in Table 3.1.

Table 3.1 – Data quality requirements

	Foreground processes	**Background processes**
Temporal coverage	Data shall be valid for 2 years at least.	Data shall be valid for 2 years at least

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[1] Heat loss Q is calculated using the following formula:

$$Q = U \cdot A \cdot (T_i - T_e)$$

where:
U = coefficient of heat transmittance [W/m^2K];
A = window area [m^2];
T_i = average indoor temperature [K];
T_e = average outdoor temperature [K].

[2] https://www.worldweatheronline.com/breslavia-weather-averages/pl.aspx

	Foreground processes	Background processes
Geographical coverage	Data shall refer to the country where the processes within the EENSULATE project effectively occur: Sealant and getter production: Italy VIG manufacturing: Poland Assembly: Poland Installation at museum: Poland	Data shall refer to the country where the processes within the EENSULATE project effectively occurs. In case such data are missing, either averaged data across Europe or data from neighbouring countries should be considered.
Technological coverage	Data shall refer to the innovative technologies developed within the EENSULATE project.	Data should be representative of state-of-the-art technologies involved in upstream and downstream processes. In case such data are missing, production mix or technology mix depending on the processes should be considered.
Reliability	Data shall be based on direct measurements or calculations derived from partners involved in the development of the EENSULATE products.	Data should be based on calculations or computational models. In case of missing data, estimations should be considered.
Completeness	Data shall be representative of the system under study.	Data shall be as representative of the upstream and downstream processes as possible. In case of data gaps, some flows deemed as not relevant may be excluded from the analysis.

3.1.2.5 LCIA methodology and impact categories

The impact categories selected for this study are the ones recommended by the PEF Guide (2013) [11]. These are related to resource use, emissions of environmentally damaging substances (e.g. greenhouse gases and toxic chemicals), which may as well affect human health. Impact assessment methods use models for quantifying the causal relationships between the material/energy inputs and emissions associated with the product life cycle and each impact category considered. Each category hence refers to a certain stand-alone impact assessment model. The inventoried data are grouped and aggregated according to the respective contributions to each impact category [12].

Table 3.2 provides the list of impact categories and related category indicators and characterisation models methods to be used.

Table 3.2 – Recommended models for Environmental Footprint (EF) scheme

Recommendation at midpoint				
Impact category	**Indicator**	**Unit**	**Recommended default LCIA model**	**Source of CFs**
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq	Baseline model of 100 years of the IPCC (based on IPCC 2013)	EF-2017
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11eq	Steady-state ODPs as in (WMO 1999)	EF -2017
Human toxicity, cancer effects*	Comparative Toxic Unit for humans (CTUh)	CTUh	USEtox model (Rosenbaum et al, 2008)	EF -2017

Recommendation at midpoint				
Impact category	Indicator	Unit	Recommended default LCIA model	Source of CFs
Human toxicity, non-cancer effects*	Comparative Toxic Unit for humans (CTUh)	CTUh	USEtox model (Rosenbaum et al, 2008)	EF -2017
Particulate matter/Respiratory inorganics	Human health effects associated with exposure to $PM_{2.5}$	Disease incidences	PM model recommended by UNEP (UNEP 2016)	EF -2017
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	kBq U^{235}	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)	EF -2017
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS (Van Zelm et al, 2008) as applied in ReCiPe 2008	EF -2017
Acidification	Accumulated Exceedance (AE)	mol H^+ eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	EF -2017
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	EF -2017
Eutrophication, aquatic freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe	EF -2017
Eutrophication, aquatic marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe	EF -2017
Ecotoxicity (freshwater)*	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	USEtox model, (Rosenbaum et al, 2008)	EF -2017
Land use	Soil quality index (Biotic production, Erosion resistance, Mechanical filtration and Groundwater replenishment)	Dimensionless, aggregated index of: kg biotic production/ (m^2*a) kg soil/ (m^2*a) m^3 water/ (m^2*a) m^3 groundwater/ (m^2*a)	Soil quality index based on LANCA (Beck et al. 2010 and Bos et al. 2016)	EF -2017
Water scarcity	User deprivation potential (deprivation-weighted water consumption)	kg world eq. deprived	Available WAter REmaining (AWARE) in UNEP, 2016	EF -2017
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	CML Guinée et al. (2002) and van Oers et al. (2002).	EF -2017
Resource use, energy carriers	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML Guinée et al. (2002) and van Oers et al. (2002)	EF -2017

The two optional steps of the Impact Assessment phase, namely normalisation and weighting, are not considered in this analysis.

3.2 Life Cycle Inventory

This phase involves data collection, compilation of Life Cycle Inventory (LCI) tables, modelling of the system and calculating the LCI results.

Figure 3.6 shows the iterative process undertaken for conducting the LCI analysis.

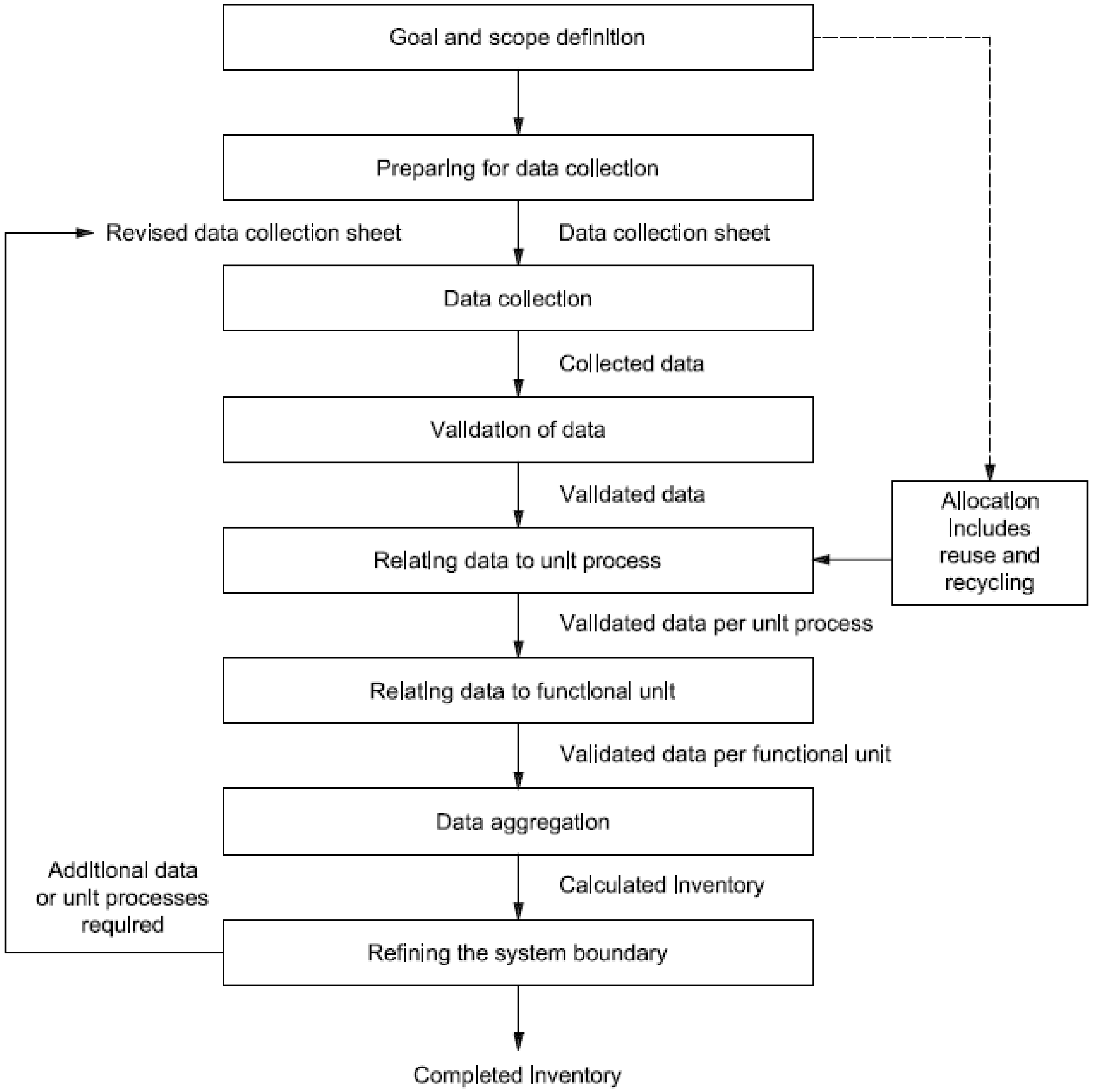

Figure 3.6 – Life Cycle Inventory procedure [2]

Firstly, block flow diagrams of the processes within system boundaries were developed. The following figures report the block flow diagrams for each phase of product's life cycle, showing the unit operations and relative input (raw materials, energy) and output flows (products, waste, emissions, by-products).

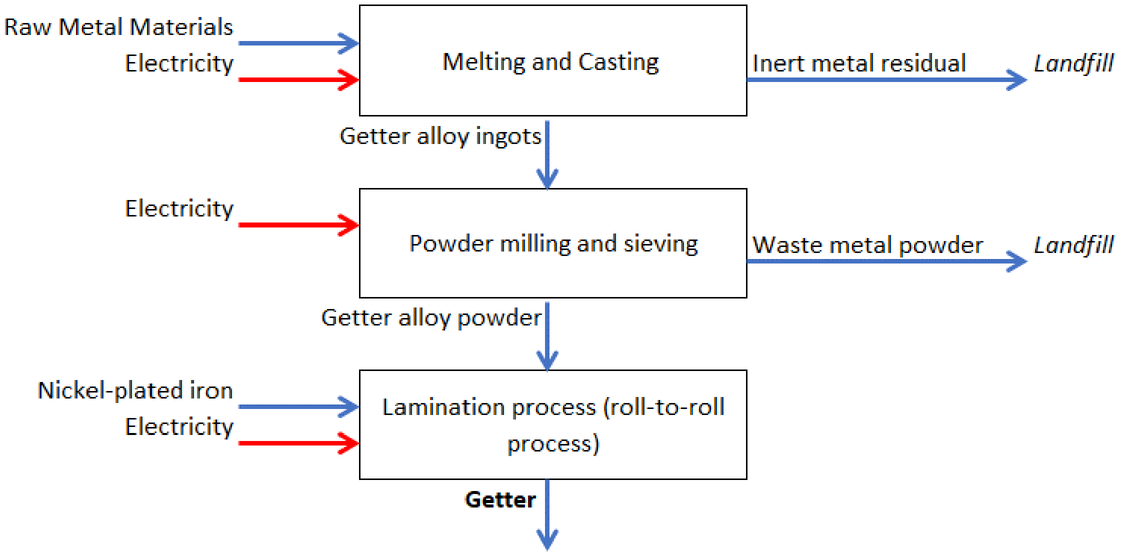

Figure 3.7 – Block flow diagram of getter production

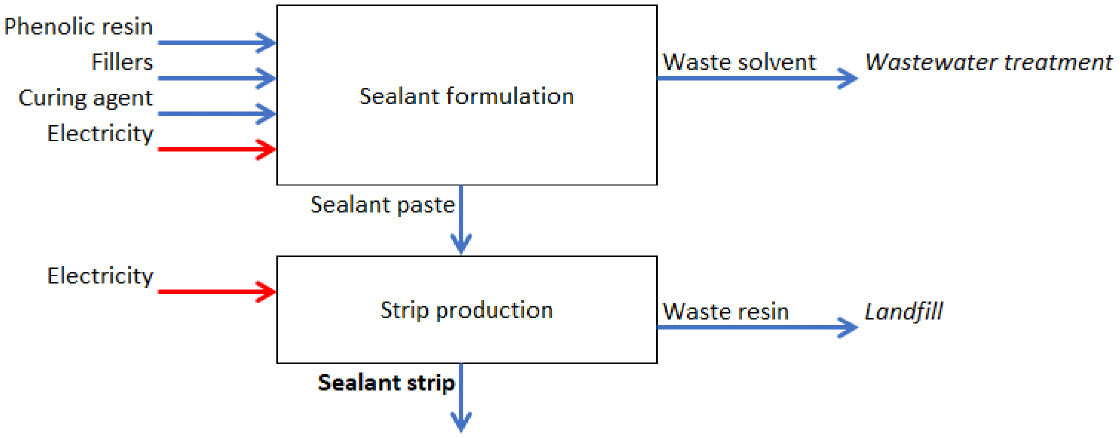

Figure 3.8 – Block flow diagram of sealant production

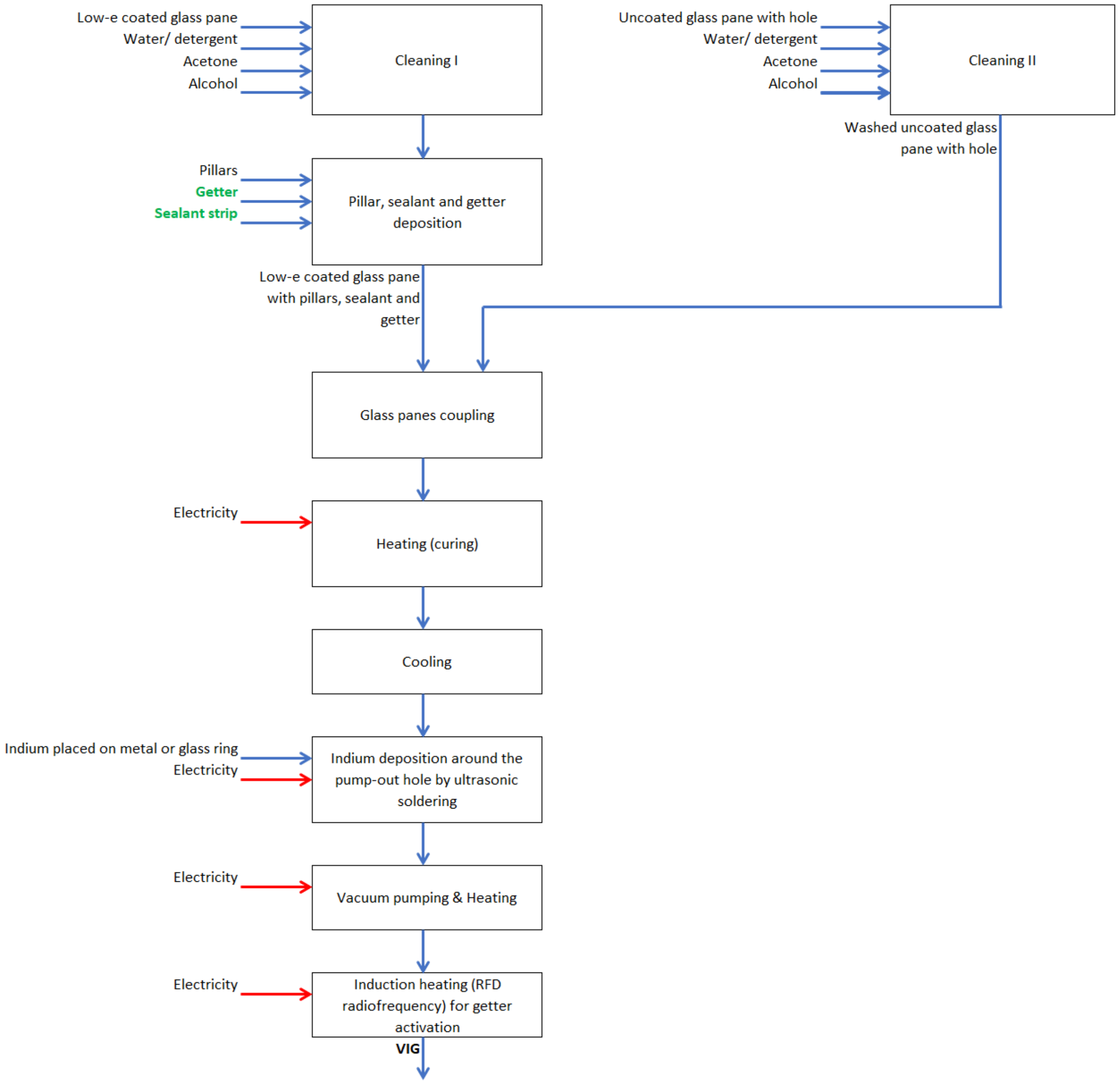

Figure 3.9 – Block flow diagram of VIG manufacturing

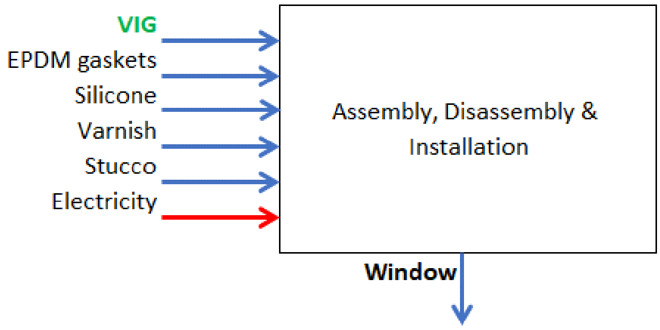

Figure 3.10– Block flow diagram of window assembly, disassembly and installation at the museum

Data collection were performed, according to LCI methodology developed. Primary data were collected from EENSULATE partners through questionnaires, while secondary data were collected through LCI databases (GaBi Database and Ecoinvent Database v3.5) and literature research.

LCI tables, containing all data collected, are reported in **Annex I: Museum window**.

The modelling of the system was performed through a dedicated software, namely GaBi 8, for the LCA and a specific tool based on Microsoft Excel 2016 for LCC. In this step, data must be related to the functional unit, in order to generate the LCI results. In LCA, the latter can be calculated using the GaBi software, which automatically generates the LCI results once the model of the system is set up.

GaBi software

GaBi software automatically tracks all material, energy and emissions flows giving instant performance accounting in the environmental impact categories. With a modular and parameterised architecture, GaBi allows rapid modeling even in case of complex processes and different production options.

GaBi software is complemented by the most comprehensive, up-to-date Life Cycle Inventory databases available compiled by IKP/PE, with over 4500 Life Cycle Inventory datasets based on primary data collection in cooperation with companies, associations and public bodies [13].

In addition, Ecoinvent database version 3.5 is fully integrated in GaBi software. This covers more than 2500 processes for different areas, including energy, transportation, waste disposal, construction, chemicals, detergents, paper and board, agriculture and waste management. It is the most widely used LCI database in Europe, and the data are valid for Swiss and Western European conditions. The different categories of data are updated and maintained by different Swiss institutions.

3.3 Impact Assessment

The following subchapters report the main outcomes of LCA and LCC related to the museum window, **per functional unit** (i.e. 1 m^2 of window glass for 20 years).

3.3.1 LCA results

Table 3.3 reports the LCA results related to the EENSULATE window's life cycle compared with the benchmark, highlighting in particular the resultant potential carbon footprint.

Table 3.3 – LCA results related to the EENSULATE/BENCHMARK window's life cycle

Impact category	EENSULATE	BENCHMARK	Unit
Acidification terrestrial and freshwater	5,22E-01	5,63E-01	Mole of H^+ eq.
Cancer human health effects	6,25E-08	6,51E-08	CTUh
Climate Change	1,46E+02	3,81E+02	kg CO_2 eq.
Ecotoxicity freshwater	9,21E+02	5,54E+02	CTUe
Eutrophication freshwater	5,28E-03	4,07E-03	kg P eq.
Eutrophication marine	9,38E-02	1,57E-01	kg N eq.
Eutrophication terrestrial	1,04E+00	1,72E+00	Mole of N eq.
Ionising radiation - human health	2,73E+00	1,63E+00	kBq U^{235} eq.
Land Use	5,46E+02	2,68E+02	Pt
Non-cancer human health effects	3,08E-06	4,62E-06	CTUh
Ozone depletion	2,80E-06	1,88E-06	kg CFC-11 eq.
Photochemical ozone formation - human health	2,70E-01	4,60E-01	kg NMVOC eq.
Resource use, energy carriers	1,72E+03	5,86E+03	MJ
Resource use, mineral and metals	2,51E-04	1,78E-04	kg Sb eq.
Respiratory inorganics	4,49E-06	4,51E-06	Deaths
Water scarcity	1,19E+01	8,87E+00	m^3 world equiv.

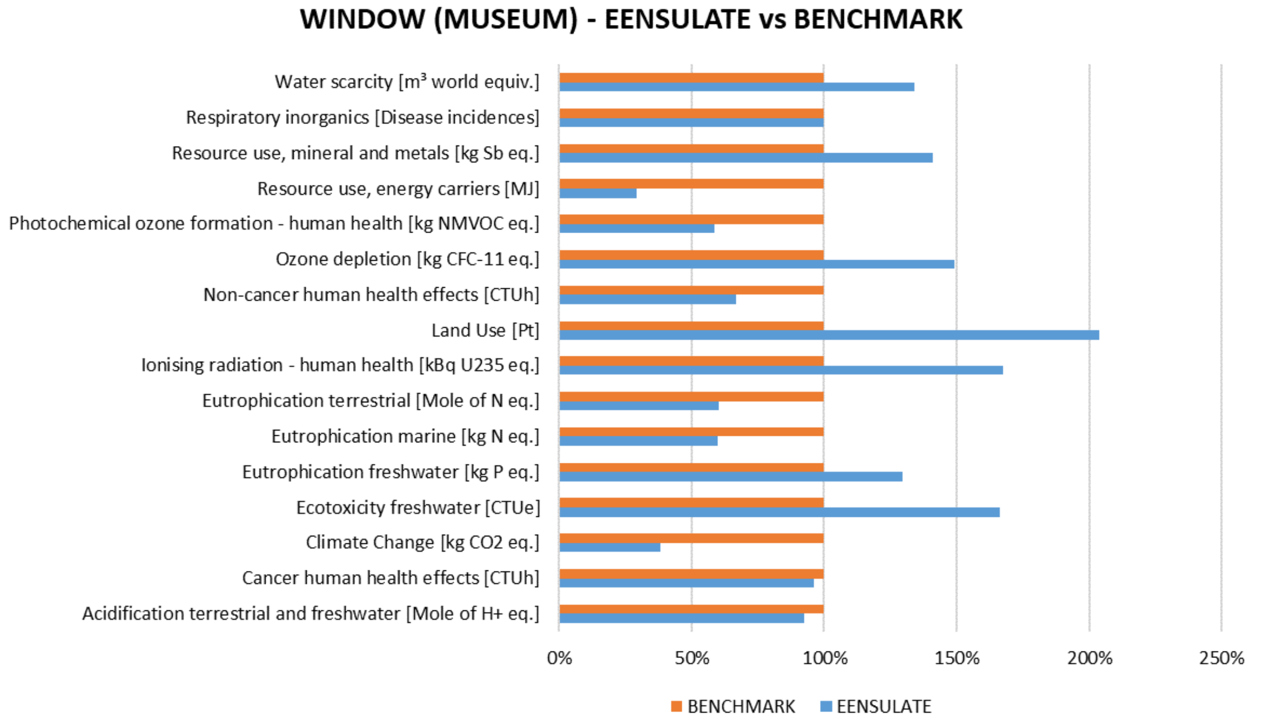

Figure 3.11 – Comparison of LCA results between EENSULATE and BENCHMARK window's life cycle

EENSULATE solution shows relevant benefits in terms of environmental impacts for most of the impact categories: in particular, a reduction up to 62% can be seen for the climate change impact category, while other impact categories present a reduction of environmental impacts ranging from 4% (cancer human effect) to 71% (resource use, energy carriers).

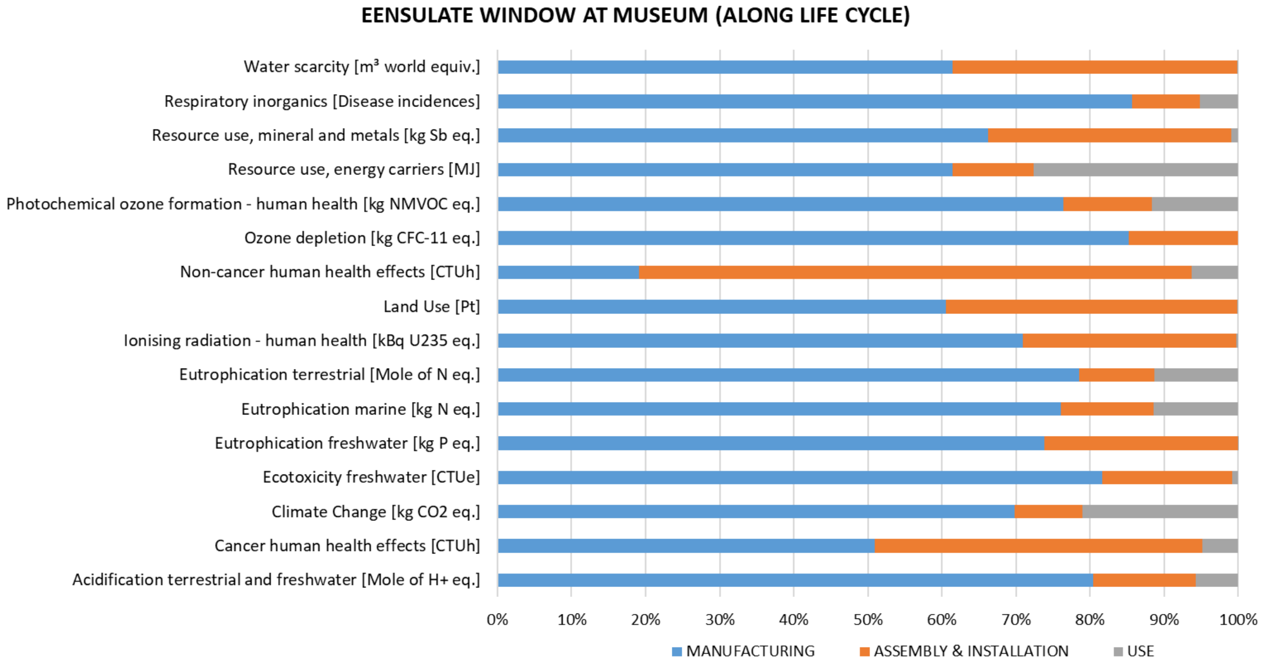

Figure 3.12 – Environmental impact distribution along the EENSULATE window's life cycle

The Figure 3.12 shows how each phase contributes to the environmental impacts along the life cycle of the EENSULATE window (a similar distribution is observed also in the benchmark case). For almost all categories the highest impacts are associated with the manufacturing phase, mainly consisting in the VIG production process (Figure 3.13).

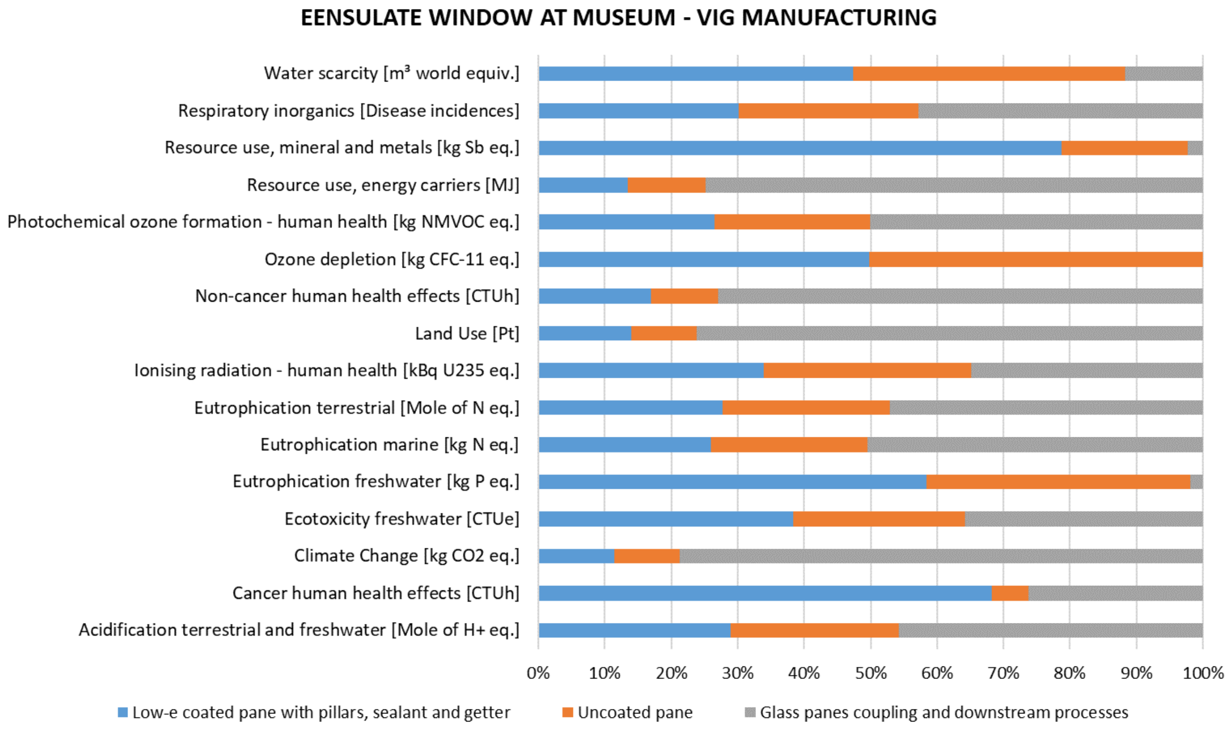

Figure 3.13 – Environmental impact associated with the VIG manufacturing phase (EENSULATE window at museum)

3.3.2 LCC results

Table 3.4 reports the LCC results related to EENSULATE window’s life cycle compared with the benchmark.

Table 3.4 – LCC results per m^2 of window glass related to the EENSULATE/BENCHMARK window’s life cycle

Phase	EENSULATE	BENCHMARK	Unit
Manufacturing	208,08	50	€/m^2
Assembly & Installation	1271,67	1271,67	€/m^2
Use	5,83	67,61	€/m^2
TOTAL	1485,58	1389,28	€/m^2

The VIG production cost is equal to **208,08 €/m^2**. The economic impacts distribution among CAPEX and OPEX costs is reported in Figure 3.14.

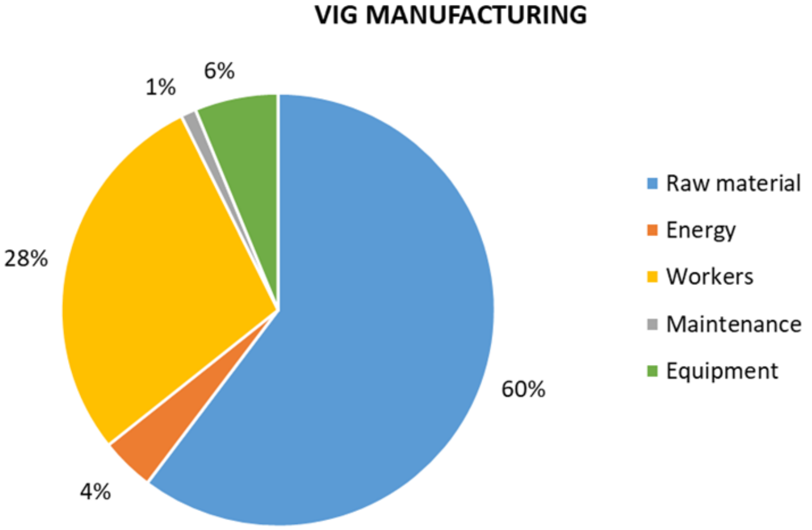

Figure 3.14 – Economic impacts distribution in the VIG manufacturing phase

In the VIG manufacturing phase, the main cost contribution is covered by the raw materials cost (60%), followed by the workers cost (28%); equipment, energy and maintenance costs account for 6%, 4% and 1% respectively. Other cost items (waste disposal and transport) are omitted because they contribute less than 1% of the total cost.

Figure 3.15 shows the cost breakdown among different raw materials in the VIG manufacturing phase. Low-e coated glass pane and uncoated glass pane account for 35% and 28% respectively, while sealant plus getter (components developed within EENSULATE project) for 32% of the total raw materials cost.

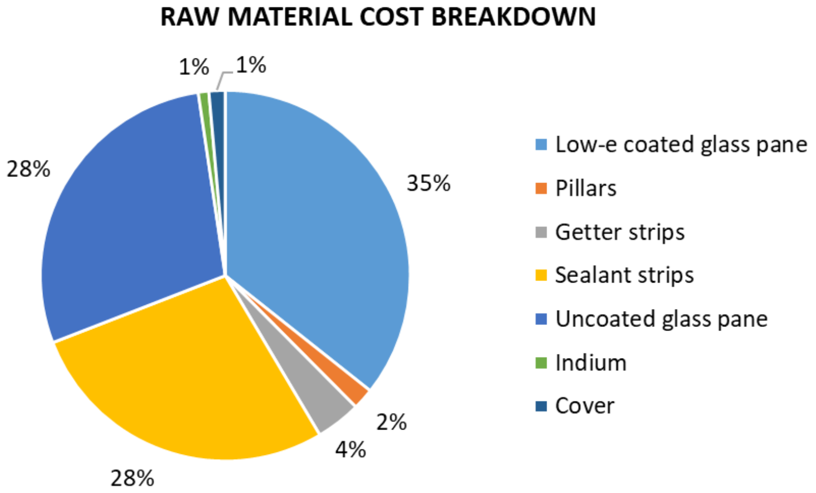

Figure 3.15 – Raw material cost breakdown within VIG manufacturing

Focusing on getter and sealant manufacturing, the economic impacts distribution among different cost items are reported in the figures below (Figure 3.16 and Figure 3.17). Regarding getter production, raw materials cost entails the greatest impact on the total cost (63%), followed by workers cost (30%). Conversely, in the sealant production, 72% of economic impact is related to workers, while raw materials contribute for 24%.

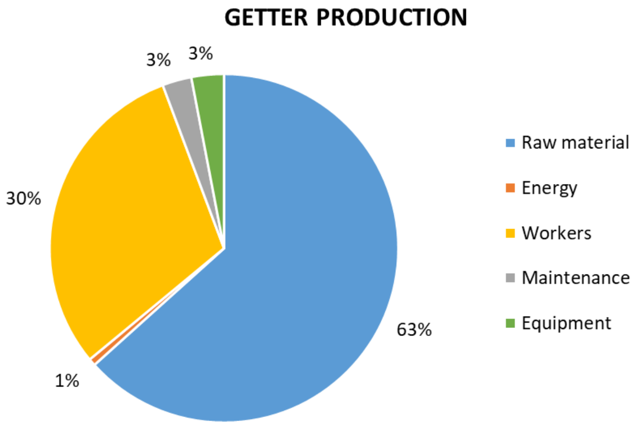

Figure 3.16 – Economic impacts distribution in the getter production process

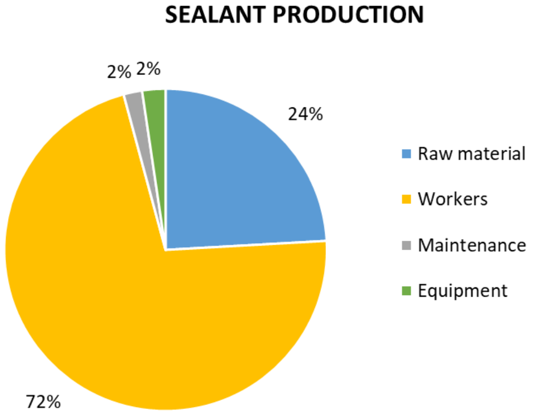

Figure 3.17 – Economic impacts distribution in the sealant production process

In assembly, disassembly and installation phases, almost all economic impacts are due to the workers cost (97%).

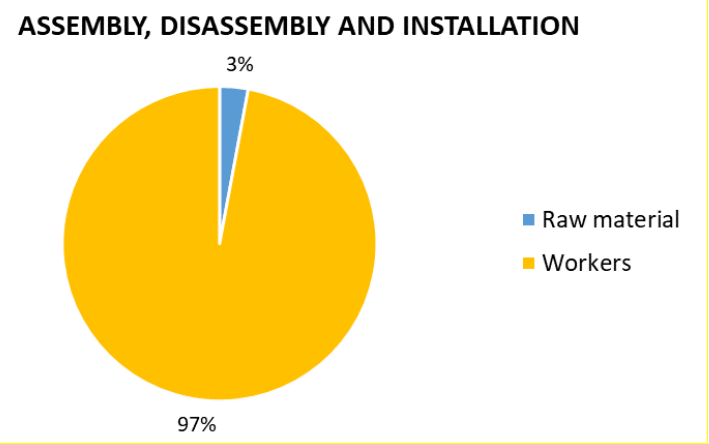

Figure 3.18 – Economic impacts distribution in window assembly, disassembly and installation at the museum

3.4 Interpretation of the results

In the case of the window to be installed at the Polish museum, the EENSULATE solution based on VIG shows a better environmental performance for most of the impact categories compared with the benchmark (i.e.

flat glass window). Although the EENSULATE VIG manufacturing phase entails higher impacts compared with the flat glass production included in the benchmark, the most relevant benefits are associated with the use phase: indeed, the best thermal insulation provided by the EENSULATE window (U = 0,5 W/m^2K) compared with the benchmark's one (U = 5,8 W/m^2K) allows important savings, such as 325 kg CO_2 eq. along the life cycle of the window.

The higher impacts of EENSULATE solution associated with some impact categories (e.g. ozone depletion, land use, ionising radiation) are mainly linked to the production of two flat glass panes (coated and uncoated) used in the VIG manufacturing (while only a single glass pane is foreseen in the benchmark case).

Concerning the VIG manufacturing phase (see Figure 3.13), which mostly contributes to the environmental impacts (see Figure 3.12), the highest contribution is linked to the electric energy required in the heating and vacuum pumping stages.

Regarding the assembly and installation phase, there are no significant discrepancies between the EENSULATE and benchmark case: indeed, the EENSULATE case differs from the benchmark one only for the inclusion of the impacts related to the transport of the window from BGTEC facility to the Polish museum.

Also from the economic point of view, the EENSULATE window shows benefits in the use phase. Indeed, the best thermal insulation performance allows a reduction of energy consumption, which entails a cost saving of 91% compared with the benchmark. However, LCC results show that the VIG manufacturing cost is still much higher (208 €/m^2) than the market price of the benchmark solution (50 €/m^2).

Within VIG manufacturing, the highest contribution is represented by the raw materials cost (60% of the total costs): as it can be seen in the Figure 3.15, this is mainly linked to the two flat glass panes (63%), sealant (28%) and getter (4%).

Regarding the getter production (see Figure 3.16), the cost item entailing the greatest impact is the raw materials cost, corresponding to 63% of the total getter manufacturing cost.

For the sealant production (see Figure 3.17), the major contribution is instead associated with workers cost (72% of the total sealant manufacturing cost). This mainly depends on the strips production step, which requires quite long working times.

4 Case study II: substitution of existing door-window at Italian library

This chapter reports the LCA and LCC analysis of the case study II, which focuses on the EENSULATE glass used for substituting an existing door-window at an historical building in Pesaro, Italy.

The **EENSULATE glass,** as previously described in chapter 3, is a novel Vacuum Insulated Glass manufactured by BGTEC, using innovative sealant and getter solutions developed by SAES. This is then subjected to a lamination process in a facility located in Crema, Italy. The stratification process reduces the risk of debris in case of breakage and the probability of breakage itself. It consists of bonding the two glass panes with a PVB interlayer.

The EENSULATE door-window (total area = 2,2 m^2) is installed at San Giovanni Public Library, located in an historical building in Pesaro (Italy). The retrofitting of the door-window is carried out preserving the overall window frame and replacing only the existing DGU (28 mm thickness) with the EENSULATE glass (structured as follows: 6 mm Mid Iron Toughened/VACUUM 0,25/6 mm Mid Iron Toughened/ PVB 1,52/6 mm Mid Iron Heat Strengthened).

Figure 4.1 – San Giovanni Public Library: door-window [9]

4.1 Goal and Scope definition

In this chapter the goal and scope of the case study II, i.e. substitution of existing door-window at the library in Pesaro, is clearly defined, consistently with the intended application. All general decisions for setting up the LCA and LCC are provided.

4.1.1 Goal definition

4.1.1.1 Intended application

The intended application of the analysis is a comparison between the EENSULATE solution, i.e. a door-window made by an innovative VIG (including lamination step), and the selected benchmark product, i.e. a laminated double-glazed window, along their life cycle.

4.1.1.2 Reasons for carrying out the study and decision context

The LCA and LCC studies are carried out to assess the effectiveness and sustainability of the developed solutions, both from an environmental and an economic perspective, taking also into account the potential benefits along lifetime linked to the implementation of an innovative door-window with better insulation performance. The analysis may act as steering tool to pave the way towards a wide replicability and commercialisation of the innovative products.

These studies do not affect the consortium in any decisions, but they are useful to evaluate the environmental and economic impacts of the innovative products; taking into account also that there are no interactions with other systems, the studies are in the **situation "C2"** (see Figure 3.3), in accordance to ILCD guidelines [10].

4.1.1.3 Target audience

Considering the public feature of the document, the main target audience is composed by:

- European Commission;
- Members of the EENSULATE project's consortium;
- Public bodies and policy makers;
- Stakeholders belonging to the building and construction sector (including architects, building owners, construction companies, etc);
- Stakeholders involved in the retrofitting of different types of glazed buildings (including historical ones);
- Stakeholders involved in the recovery and preservation of cultural heritage.

4.1.2 Scope definition

4.1.2.1 Function and functional unit

The primary function of a window is to provide thermal and acoustic insulation and to protect the building interior against the exterior natural phenomena. EENSULATE solution has the capacity to provide high insulation performance, keeping weight and thickness in the same order of magnitude as the original components.

The functional unit is the retention of the targeted insulation performance of **1 m^2 of window glass**, with the aim of fulfilling indoor comfort requirements **for 20 years**.

4.1.2.2 System boundaries and cut-offs

A **"cradle-to-gate" analysis** is performed, including the raw material production, manufacturing of the main components, assembly, installation and use phase of the targeted product.

Figure 4.2 shows the whole life cycle of the EENSULATE door-window. The system boundaries are outlined by the red line.

The dismantling phase is excluded from the analysis: indeed, no substantial differences are envisaged between EENSULATE and benchmark case. Furthermore, the end-of-life phase is out of the boundary limits of the present analysis.

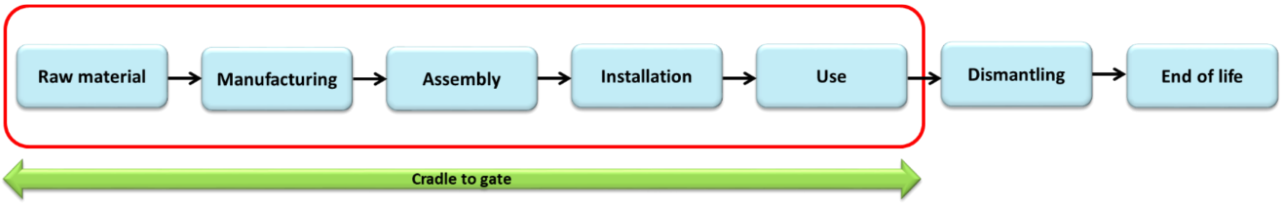

Figure 4.2 – System boundaries of the EENSULATE door-window's life cycle

The whole system is divided into a **foreground system** and **background system**, as shown in Figure 4.3. The foreground system consists of processes which are under the control of the decision-maker for which the study is carried out, i.e. sealant and getter production, VIG manufacturing as well as door-window assembly and installation. While the background system represents all up- and downstream processes connected to the foreground system, namely the raw material and energy production, transports, use phase as well as waste treatment and disposal.

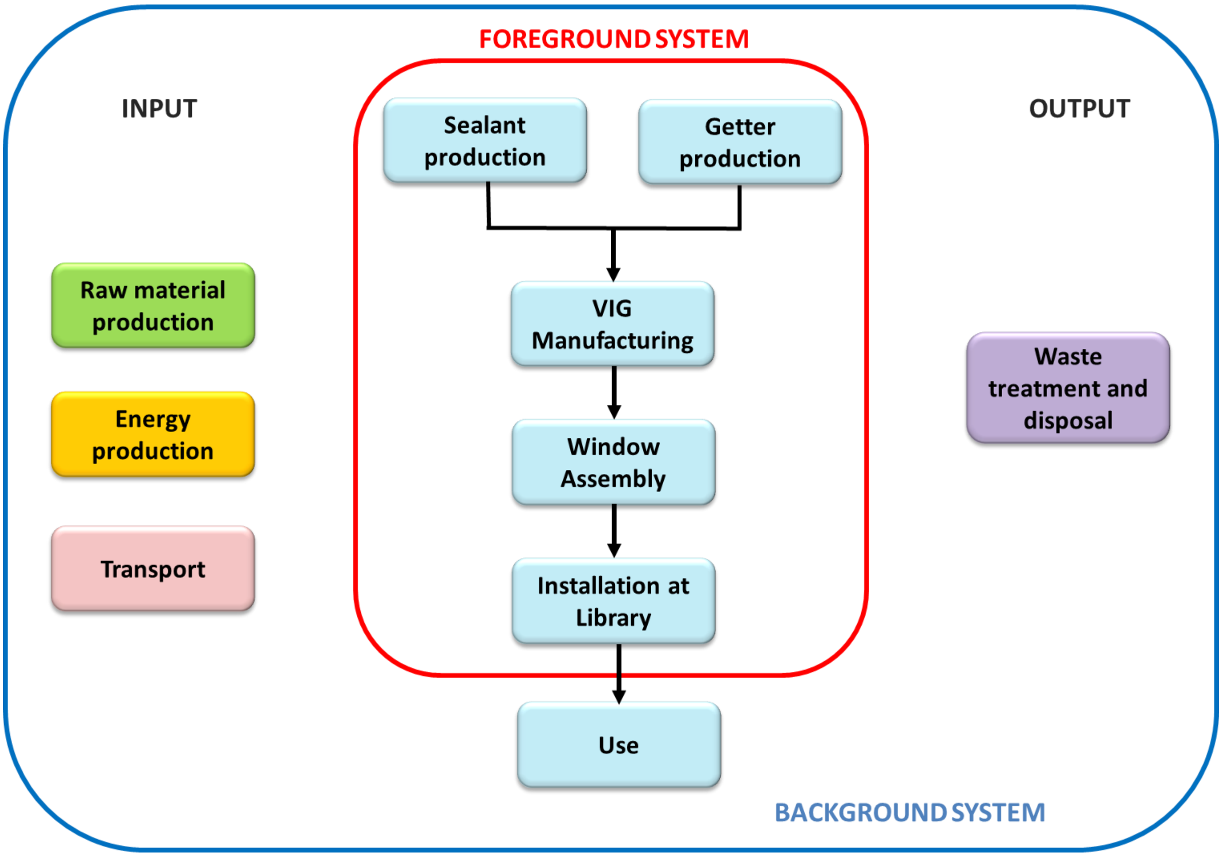

Figure 4.3 – EENSULATE foreground and background system of the case study II

The following cut-off criteria are used in this study to decide the inclusion or exclusion of input or processes:

- **Mass and environmental significance:** inputs that do not contributed to more than 1% of the mass input of the product system and that are estimated to contribute no more than 1% of the total environmental impacts are excluded from the analysis:
    - FEP foils in sealant production;
    - stainless steel pillars in VIG manufacturing;
    - indium in VIG manufacturing;
    - stainless steel cover in VIG manufacturing;
    - PVB bags in lamination process.
- **Economic significance:** processes or activities estimated to contribute no more than 1% of the total economic impacts are omitted from LCC study:
    - waste disposal in getter production;
    - waste disposal and energy in sealant production;
    - energy, equipment in assembly, disassembly and installation.

4.1.2.3 Assumption and limitations

Within this study, the following assumptions are included:

- annual maintenance costs are assumed to be 3% of the overall CAPEX for getter and sealant production processes and 2% for VIG manufacturing process;
- the purchasing cost of heating oven in VIG manufacturing is assumed equal to 200 k€ with a depreciation time of 15 years, in place of a renting cost of 17 k€/month;
- in the use phase, calculations are based on the thermal energy needed to balance the heat losses through the door-window along its life cycle;
- for the use phase, heat losses through the door-window are estimated through a simplified calculation[3], considering:
    - Pesaro average monthly outdoor temperatures (T_e) for year 2019[4],
    - average indoor temperature (T_i) in the library equal to 16° C,
    - coefficient of heat transmittance for EENSULATE library door-window equal to 0,3 W/m^2K,
    - coefficient of heat transmittance for benchmark door-window equal to 1,1 W/m^2K,
    - heating energy consumption for 10 hours/day for the period from 15th October to 15th April;
- packaging is not considered;
- only transportations of EENSULATE products within foreground system are considered;
- for road transport, a truck 3.5 ton with full payload is considered;
- for sealant and getter transport via airplane, a cargo plane 22 ton with full payload is considered for a route from Milan Malpensa to Warsaw airport.

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[3] Heat loss Q is calculated using the following formula:

$$Q = U \cdot A \cdot (T_i - T_e)$$

where:
U = coefficient of heat transmittance [W/m^2K];
A = window area [m^2];
T_i = average indoor temperature [K];
T_e = average outdoor temperature [K].

[4] https://www.worldweatheronline.com/pesaro-weather/marche/it.aspx

4.1.2.4 Data quality requirements

Data quality requirements for this study are summarised in Table 3.1. As explained above (section 3.1.2.4), specific data are required for inventorying the foreground system, while generic data can be gathered for the background system.

Table 4.1 – Data quality requirements

	Foreground processes	Background processes
Temporal coverage	Data shall be valid for 2 years at least.	Data shall be valid for 2 years at least
Geographical coverage	Data shall refer to the country where the processes within the EENSULATE project effectively occur: Sealant and getter production: Italy VIG manufacturing: Poland Assembly and installation at library: Italy	Data shall refer to the country where the processes within the EENSULATE project effectively occurs. In case such data are missing, either averaged data across Europe or data from neighbouring countries should be considered.
Technological coverage	Data shall refer to the innovative technologies developed within the EENSULATE project.	Data should be representative of state-of-the-art technologies involved in upstream and downstream processes. In case such data are missing, production mix or technology mix depending on the processes should be considered.
Reliability	Data shall be based on directly measurements or calculations derived from partners involved in development of the EENSULATE products.	Data should be based on calculations or computational models. In case of missing data, estimations should be considered.
Completeness	Data shall be representative of the system under study.	Data shall be as representative of the upstream and downstream processes as possible. In case of data gaps, some flows deemed as not relevant may be excluded from the analysis.

4.1.2.5 LCIA methodology and impact categories

The impact categories selected for this study are the ones recommended by the PEF Guide (2013) [11], as explained in more details in section 3.1.2.5.

4.2 Life Cycle Inventory

The Inventory analysis for the case study II was carried out similarly to the previous case study (see section 3.2).

The following figures report the block flow diagrams for each phase of product's life cycle, showing the unit operations and relative input (raw materials, energy) and output flows (products, waste, emissions, by-products).

Block flow diagrams related to EENSULATE getter and EENSULATE sealant production are reported in the previous paragraphs (see Figure 3.7 and Figure 3.8).

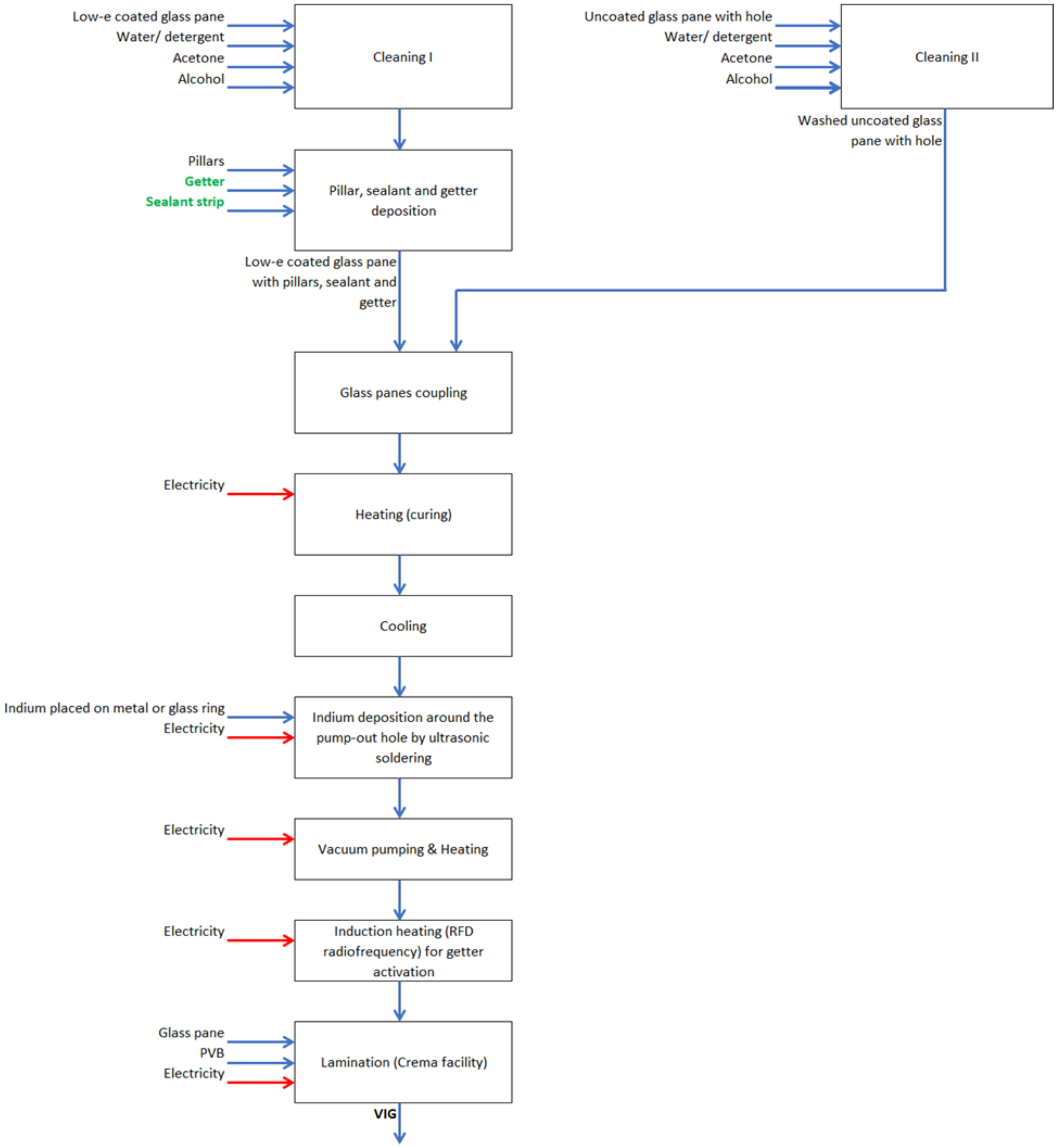

Figure 4.4 – Block flow diagram of VIG manufacturing and lamination process

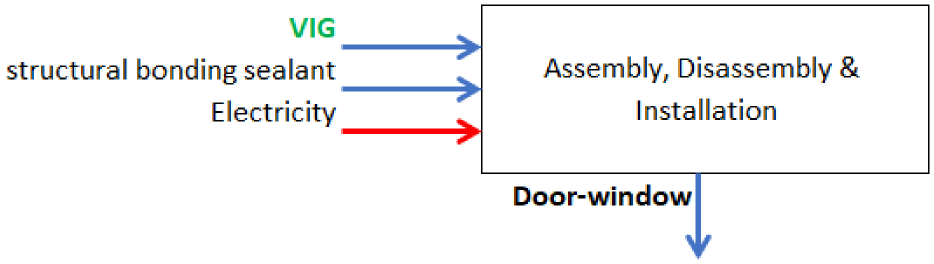

Figure 4.5 – Block flow diagram of door-window assembly, disassembly and installation at library

All data collected during the inventory analysis are included in **LCI tables**, which are reported in **Annex II: Library door-window**.

4.3 Impact Assessment

The following subchapters report the main outcomes of LCA and LCC associated with the door-window at the San Giovanni Public Library, **per functional unit** (i.e. 1 m^2 of window glass).

4.3.1 LCA results

Table 4.2 reports the LCA results related to the EENSULATE door-window's life cycle compared with the benchmark, highlighting in particular the resultant potential carbon footprint.

Table 4.2 – LCA results related to the EENSULATE/BENCHMARK door-window's life cycle

Impact category	EENSULATE	BENCHMARK	Unit
Acidification terrestrial and freshwater	7,72E-01	1,16E+00	Mole of H^+ eq.
Cancer human health effects	2,80E-08	9,75E-08	CTUh
Climate Change	1,74E+02	1,67E+02	kg CO_2 eq.
Ecotoxicity freshwater	1,67E+03	8,02E+03	CTUe
Eutrophication freshwater	8,56E-03	4,29E-02	kg P eq.
Eutrophication marine	1,42E-01	1,97E-01	kg N eq.
Eutrophication terrestrial	1,65E+00	2,33E+00	Mole of N eq.
Ionising radiation - human health	4,59E+00	1,39E+01	kBq U^{235} eq.
Land Use	6,08E+02	5,13E+02	Pt
Non-cancer human health effects	1,17E-06	2,06E-06	CTUh
Ozone depletion	5,44E-06	1,55E-05	kg CFC-11 eq.
Photochemical ozone formation - human health	4,02E-01	5,85E-01	kg NMVOC eq.
Resource use, energy carriers	2,06E+03	2,46E+03	MJ
Resource use, mineral and metals	3,04E-04	4,79E-04	kg Sb eq.
Respiratory inorganics	6,99E-06	1,13E-05	Deaths
Water scarcity	2,58E+01	7,43E+01	m^3 world equiv.

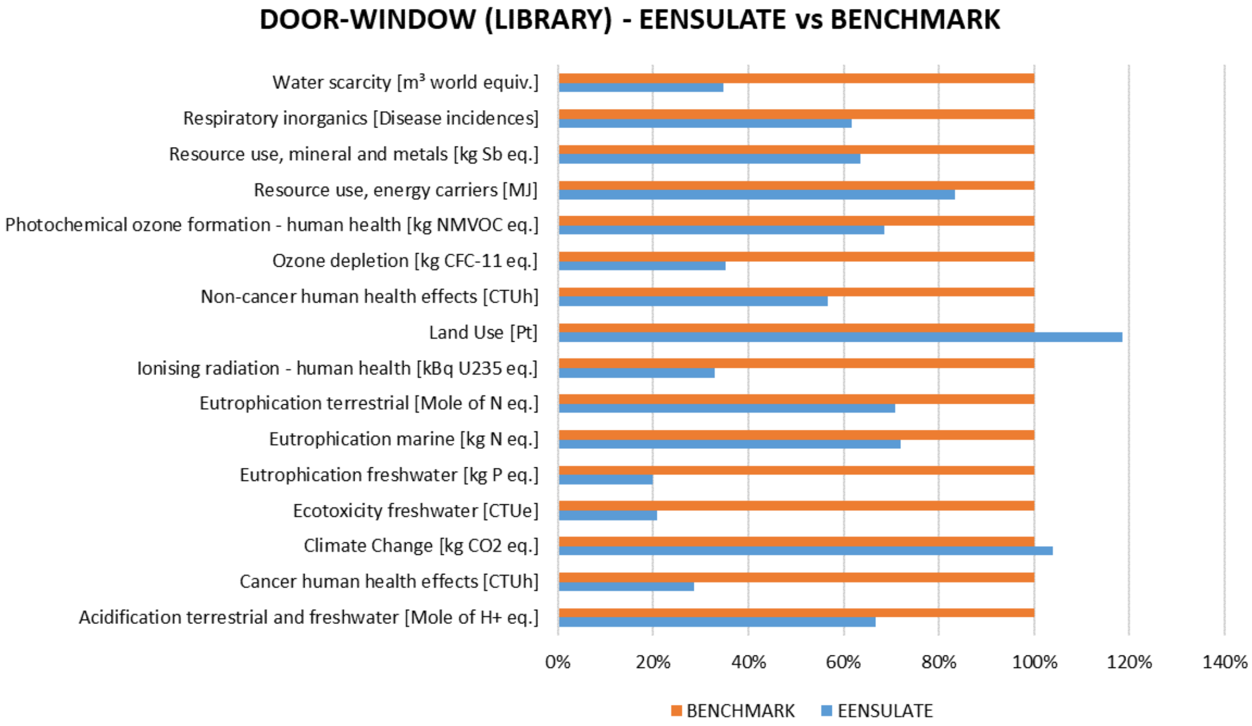

Figure 4.6 – Comparison of LCA results between EENSULATE and BENCHMARK door-window’s life cycle

For almost all of the impact categories, EENSULATE door-window based on VIG shows a better environmental performance compared with the benchmark based on double glazing.

Moreover, in terms of climate change potential, the two solutions are comparable (just 4% of difference between EENSULATE and benchmark door-window).

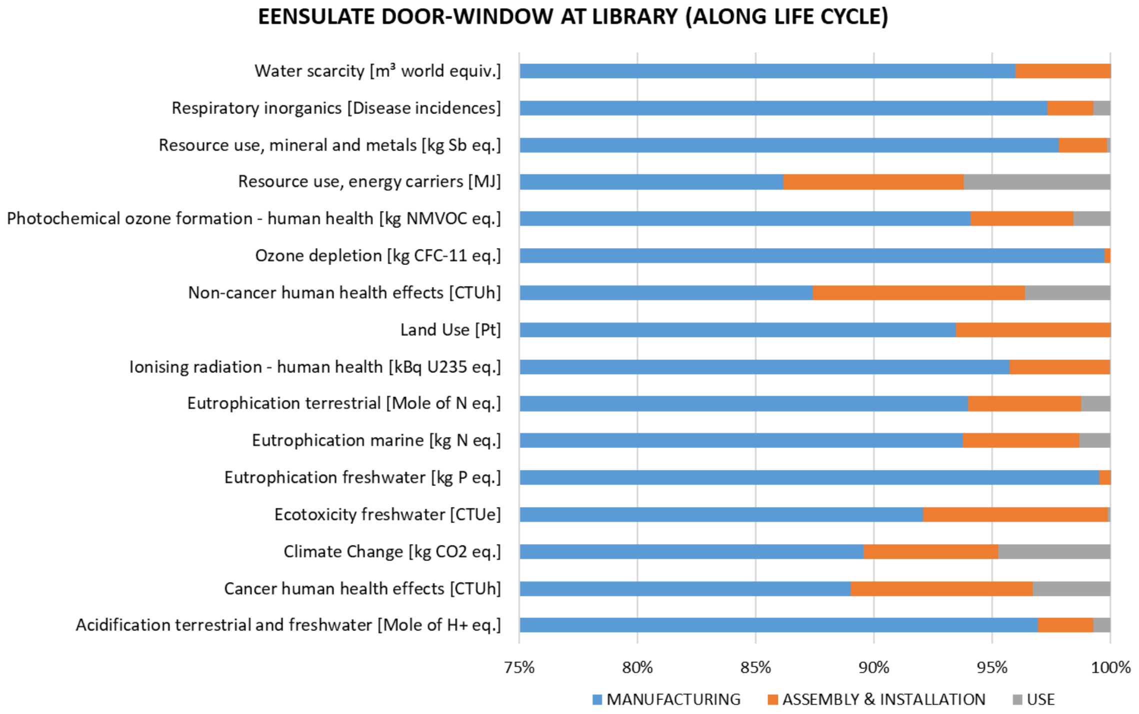

Figure 4.7 – Environmental impact distribution along the EENSULATE door-window's life cycle

As in the case of the window for the Polish museum (see Figure 3.12), the manufacturing phase (including getter, sealant and VIG manufacturing) entails the highest share among the total environmental impacts (above 90% of the impacts are associated with the manufacturing for almost all impact categories).

4.3.2 LCC results

Table 4.3 shows the LCC results related to EENSULATE door-window along life cycle compared with the benchmark.

Table 4.3 – LCC results per m^2 of window glass related to the EENSULATE/BENCHMARK door-window's life cycle

Phase	EENSULATE	BENCHMARK	Unit
Manufacturing	308,79	100	€/m^2
Assembly & Installation	160,51	161,81	€/m^2
Use	2,31	5,21	€/m^2
TOTAL	471,61	267,02	€/m^2

The VIG manufacturing cost is **308,79 €/m^2**, including also the lamination process (i.e. 'other cost' in the Figure 4.8 below). The economic impacts are split between CAPEX and OPEX as follows: raw materials cost (46%), other cost (30%), workers cost (16%), while equipment, energy, transport and maintenance costs count less than 3% each.

Within raw materials cost (see Figure 3.15), sealant and getter account for 28% and 4% respectively. The economic impacts distributions related to sealant and getter production are reported in section 3.3.2.

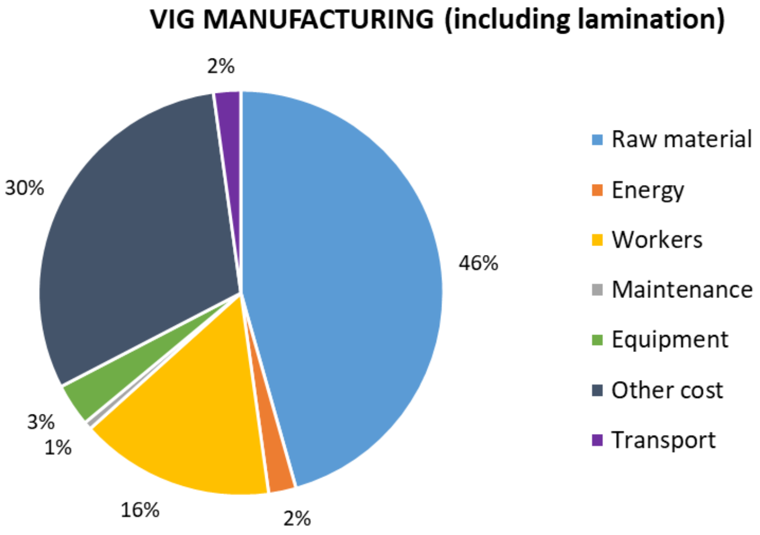

Figure 4.8 – Economic impacts distribution in the VIG manufacturing phase, including lamination process (‘other cost’)

Figure 4.9 shows how each cost categories contributes to the economic impacts related to door-window assembly, disassembly and installation.

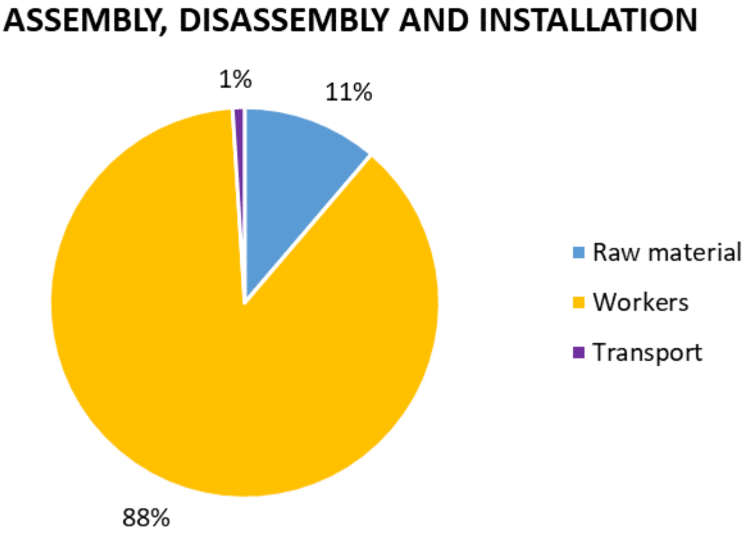

Figure 4.9 – Economic impacts distribution in door-window assembly, disassembly and installation at the library

4.4 Interpretation of the results

The benchmark considered in the case of the door-window to be installed at the San Giovanni Public library in Pesaro (Italy), i.e. the DGU with lamination, entails higher environmental impacts if compared with the flat glass pane considered as benchmark window in the case of the Polish museum.

Apart from two impact categories (i.e. land use and climate change), the EENSULATE solution presents an environmental impacts reduction ranging from 28% (in the case of eutrophication marine) to 80% (in the case of eutrophication freshwater) compared with the benchmark case. This result is mainly linked to the VIG manufacturing phase, which generally entails a reduction of environmental impacts compared with the DGU production process: indeed, while land use and climate change present a slight increase (13% and 16% increase respectively) if compared with the benchmark, the other impact categories show a significant reduction, thus proving the potential environmental sustainability of the developed solution.

Although the VIG manufacturing process requires an amount of energy which is significantly higher than the benchmark case (DGU assembly is mostly performed at room temperature), the innovative VIG represents a lightweight solution entailing also a lower consumption of raw materials if compared with the DGU.

As in the case of the museum, the assembly and installation phases do not entail significant differences between EENSULATE and benchmark solution, apart from the transportation routes that are taken into account only in the EENSULATE case study.

The use phase does not weigh significantly on the overall impacts along life cycle: however, the impacts related to this phase reflect the enhancement in terms of U-value between the benchmark based on DGU (U = 1,1 W/m^{2}K) and the EENSULATE solution based on VIG (U = 0,3 W/m^{2}K).

Concerning LCC results, the lamination step significantly increases the VIG cost, varying from 208,08 €/m^2 in the case of the museum window to 308,79 €/m^2 in the case of the door-window for the library. The cost category associated with the lamination process, denominated ‘other cost’, accounts for 30% of the total VIG manufacturing cost (see Figure 4.8). Its contribution is very high due to the cost of vacuum bags in PVB needed for the lamination (54 €/m^2) as well as the cost of the process itself (40 €/m^2).

Furthermore, transport costs should also be taken into account, considering the long distance between BGTEC facility in Poland and the lamination facility (Crema, Italy).

In this second case study, the gap between VIG manufacturing cost and the market price of DGU is quite relevant (308,79 €/m^2 vs. 100 €/m^2).

In terms of cost savings related to the use phase (20 years), the EENSULATE solution shows a costs reduction of 73% compared with DGU.

5 Case study III: substitution of existing façade module at Polish school

This chapter reports the LCA and LCC analysis of the case study III, which focuses on the EENSULATE façade module used for retrofitting a curtain wall of tertiary building in Dzierżoniów, Poland**.**

The **EENSULATE façade module** (total area = 4,59 m^2) consists of a vision glass (63% of the total area) made of a high performing Vacuum Insulated Glass and of a spandrel component (37% of the total area) manufactured using an innovative spray foam, as it can be seen in Figure 5.1. The EENSULATE module (1261 x 3640 x 19,77 mm) has a high energy efficiency with the overall thermal transmittance equal to 0,64 W/m^{2}K.

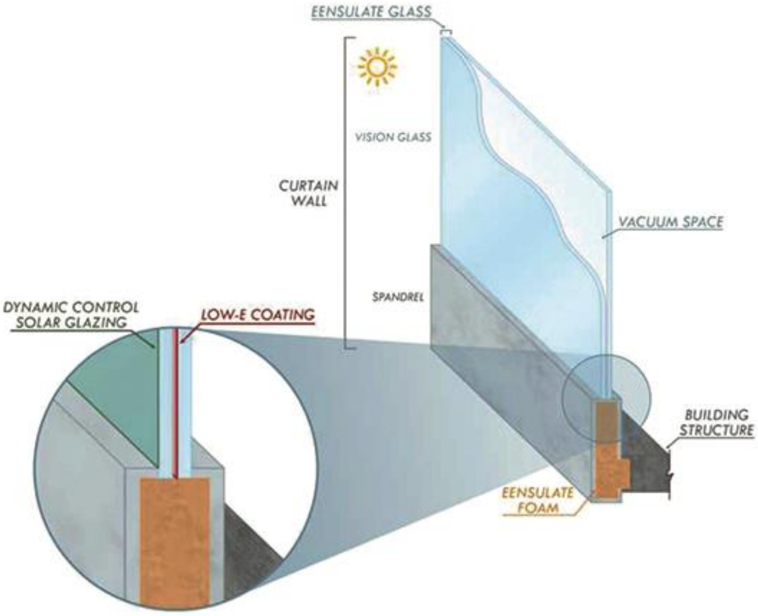

Figure 5.1 – EENSULATE façade module

- **EENSULATE glass**, as previously described in chapter 3, is a novel Vacuum Insulated Glass manufactured by BGTEC, using innovative sealant and getter solutions developed by SAES. As in the case of the door-window, the glass is subjected to a lamination process, in order to meet the safety specification of the public building.

- **EENSULATE foam** is a one-component polyurethane foam (OCF) developed by SELENA under Task 2.3 “Foam formulation production”, with high insulating and fire-retardant properties for the cost-effective manufacturing and insulation of the opaque components of curtain walls.

The EENSULATE façade module is used for retrofitting the demonstration building’s façade (surface = 115,5 m^2), with the aim to increase the energy efficiency of the building in line with EU and national targets for public buildings. The demo is a Primary School located in Dzierżoniów (Poland) owned by Dzierżoniów Municipality (Gmina Miejska Dzierzoniow - GMD).

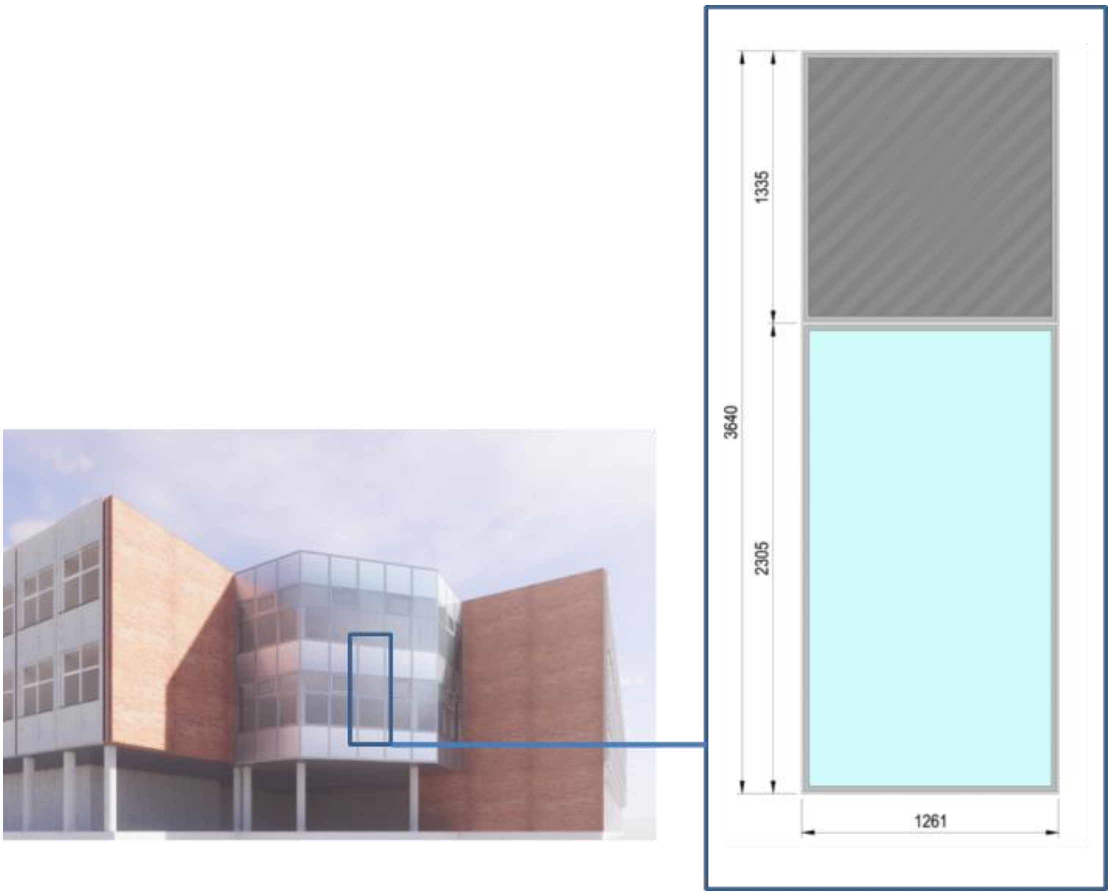

Figure 5.2 – Exterior view of Dzierżoniów School’s façade and zoom on the EENSULATE façade module [14]

5.1 Goal and Scope definition

In this chapter, the goal and scope of the case study III, i.e. substitution of existing façade module, is clearly defined, consistently with the intended application. All general decisions for setting up the LCA and LCC are provided.

5.1.1 Goal definition

5.1.1.1 Intended application

The intended application of the case study III is a comparison between the EENSULATE solution, i.e. a curtain wall module made by an innovative VIG (including lamination step) and a novel one-component foam, and the selected benchmark product, i.e. a façade module constituted by a laminated triple glazing vision glass and mineral wool for spandrel, along their life cycle.

5.1.1.2 Reasons for carrying out the study and decision context

The LCA and LCC studies are carried out to assess the effectiveness and sustainability of the developed solutions, both from an environmental and an economic perspective, taking also into account the potential benefits along lifetime linked to the implementation of an innovative façade module with better insulation performance. The analysis may act as steering stool to pave the way towards a wide replicability and commercialisation of the innovative product.

5.1.1.3 Target audience

Considering the public feature of the document, the main target audience is composed by:

- European Commission;
- Members of the EENSULATE project's consortium;
- Public bodies and policy makers;
- Stakeholders belonging to the building and construction sector (including architects, building owners, construction companies, etc);
- Stakeholders involved in the retrofitting of different types of glazed buildings (including historical ones);
- Stakeholders involved in the recovery and preservation of cultural heritage.

5.1.2 Scope definition

5.1.2.1 Function and functional unit

The primary function of a curtain wall system is to provide thermal and acoustic insulation and to protect the building interior against the exterior natural phenomena. EENSULATE façade module has the capacity to provide high insulation performance and to reduce thermal bridges between curtain wall and sub-structures, keeping weight in the same order of magnitude as the original components.

The functional unit is the retention of the targeted insulation performance of **1 m^2 of curtain wall system,** with the aim of fulfilling indoor comfort requirements **for 20 years**.

5.1.2.2 System boundaries and cut-offs

A **"cradle-to-gate" analysis** is performed, including the raw material production, manufacturing of the main components and assembly of the targeted product.

Figure 5.3 shows the whole life cycle of the EENSULATE façade module. The boundary limits are outlined by the red line.

The dismantling phase is excluded from the analysis: indeed, no substantial differences are envisaged between the two cases (EENSULATE solution and benchmark). The end-of-life phase is also out of the boundary limits of the present analysis.

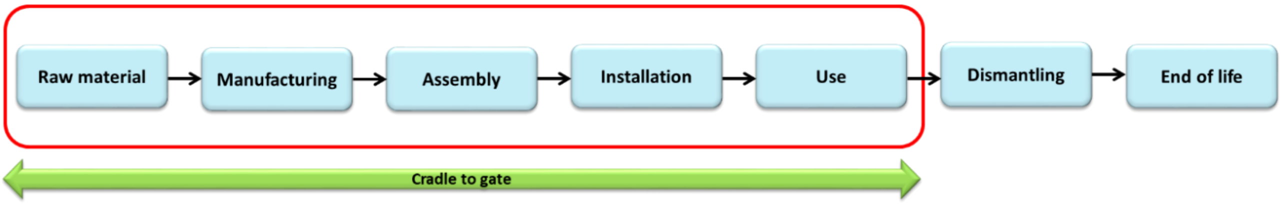

Figure 5.3 – System boundaries of the EENSULATE façade module's life cycle

The whole system is divided into a **foreground system** and **background system**, as shown in Figure 5.4**.** The foreground system consists of processes which are under the control of the decision-maker for which the study is carried out, i.e. sealant and getter production, VIG manufacturing, foam manufacturing as well as façade module assembly and installation. While the background system represents all up- and downstream processes connected to the foreground system, namely the raw material and energy production, transports, use phase as well as waste treatment and disposal.

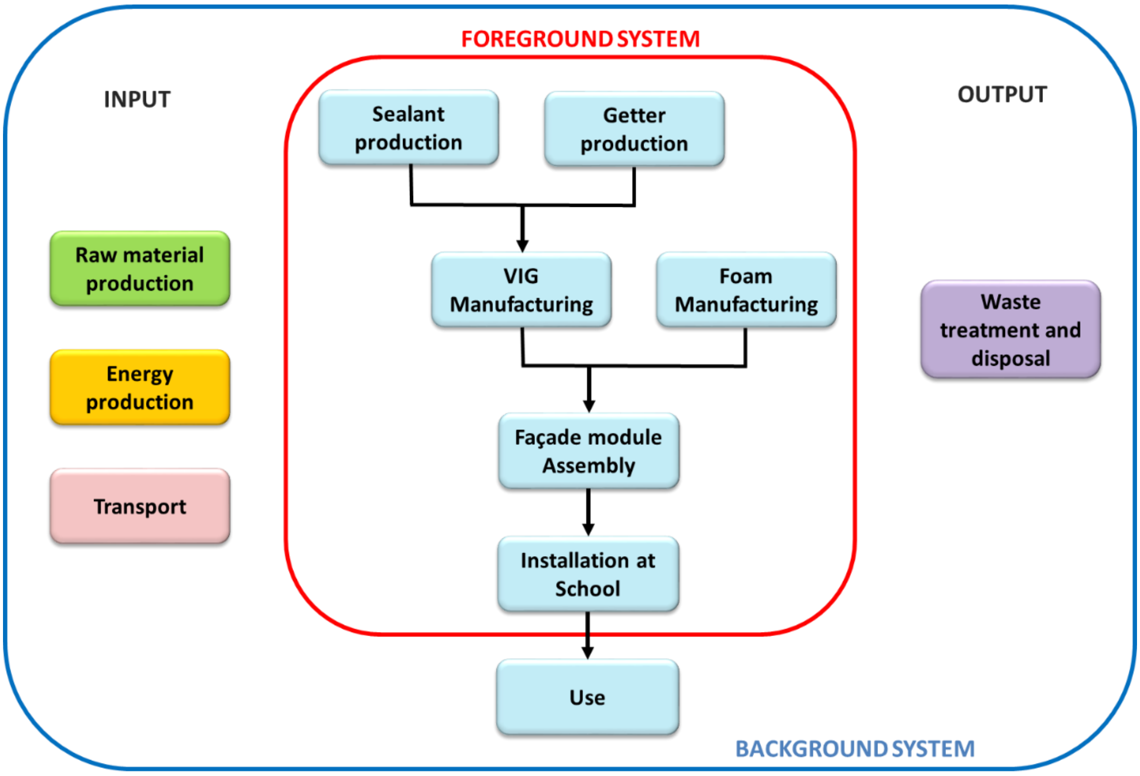

Figure 5.4 – EENSULATE foreground and background system of the case study III

The following cut-off criteria are used in this study to decide the inclusion or exclusion of input or processes:

- **Mass and environmental significance:** inputs that do not contributed to more than 1% of the mass input of the product system and that are estimated to contribute no more than 1% of the total environmental impacts are excluded from the analysis:
  - FEP foils in sealant production;
  - stainless steel pillars in VIG manufacturing;
  - indium in VIG manufacturing;
  - stainless steel cover in VIG manufacturing;
  - PVB bags in lamination process;
  - stainless steel dowels, bolts and screws in installation.

- **Economic significance:** processes or activities estimated to contribute no more than 1% of the total economic impacts are omitted from LCC study:
    - waste disposal in getter production;
    - energy and waste disposal in sealant production;
    - energy, waste disposal, maintenance, equipment and transport in assembly;
    - energy, waste disposal, maintenance, equipment in installation.

5.1.2.3 Assumptions and limitations

Within this study, the following assumptions are included:

- annual maintenance costs are assumed to be 3% of the overall CAPEX for getter and sealant production processes, 2% for VIG manufacturing and 1% for foam manufacturing process;
- the purchasing cost of heating oven in VIG manufacturing is assumed equal to 200 k€ with a depreciation time of 15 years, in place of a renting cost of 17 k€/month;
- in the use phase, calculations are based on the thermal energy needed to balance the heat losses through the façade module along its life cycle;
- for the use phase, heat losses through the façade module are defined by a simplified calculation[5], considering:
    - Wroclaw average monthly outdoor temperatures (T_e) for year 2019[6], adopted as representative for Dzierżoniów city,
    - average indoor temperature (T_i) in the school equal to 20° C,
    - coefficient of heat transmittance for EENSULATE façade module equal to 0,64 W/m^2K,
    - coefficient of heat transmittance for benchmark façade module equal to 0,8 W/m^2K,
    - heating energy consumption for 10 hours/day for the period from 15th October to 15th April.
- packaging is not considered;
- only transportations of EENSULATE products within foreground system are considered;
- for road transport, a truck 3.5 ton with full payload is considered;
- for sealant and getter transport via airplane, a cargo plane 22 ton with full payload is considered for a route from Milan Malpensa to Warsaw airport;
- for foam transport via airplane, a cargo plane 22 ton with full payload is considered for a route from Krakow airport to Milan Malpensa.

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[5] Heat loss Q was calculated using the following formula:

$$Q=UA(T_i-T_e)$$

where:
U=coefficient of heat transmittance;
A=window area;
T_i=average indoor temperature;
T_e: average outdoor temperature.

[6] https://www.worldweatheronline.com/breslavia-weather-averages/pl.aspx

5.1.2.4 Data quality requirements

Data quality requirements for this study are summarised in Table 5.1. Specific data are required for inventorying the foreground system, while generic data can be gathered for the background system (see section 3.1.2.4).

Table 5.1 – Data quality requirements

	Foreground processes	**Background processes**
Temporal coverage	Data shall be valid for 2 years at least.	Data shall be valid for 2 years at least
Geographical coverage	Data shall refer to the country where the processes within the EENSULATE project effectively occur: Sealant and getter production: Italy VIG manufacturing: Poland Assembly: Italy Installation at school: Poland	Data shall refer to the country where the processes within the EENSULATE project effectively occurs. In case such data are missing, either averaged data across Europe or data from neighbouring countries should be considered.
Technological coverage	Data shall refer to the innovative technologies developed within the EENSULATE project.	Data should be representative of state-of-the-art technologies involved in upstream and downstream processes. In case such data are missing, production mix or technology mix depending on the processes should be considered.
Reliability	Data shall be based on directly measurements or calculations derived from partners involved in development of the EENSULATE products.	Data should be based on calculations or computational models. In case of missing data, estimations should be considered.
Completeness	Data shall be representative of the system under study.	Data shall be as representative of the upstream and downstream processes as possible. In case of data gaps, some flows deemed as not relevant may be excluded from the analysis.

5.1.2.5 LCIA methodology and impact categories

The impact categories selected for this study are the ones recommended by the PEF Guide (2013) [11], as explained in more details in section 3.1.2.5.

5.2 Life Cycle Inventory

The Inventory analysis for the case study III was carried out similarly to the previous case studies (see section 3.2).

The following figures report the block flow diagrams for each phase of product's life cycle, showing the unit processes and relative inputs and outputs.

Block flow diagrams related to EENSULATE getter and sealant production, as well as VIG manufacturing plus lamination step are reported above in Figure 3.7, Figure 3.8 and Figure 4.4 respectively.

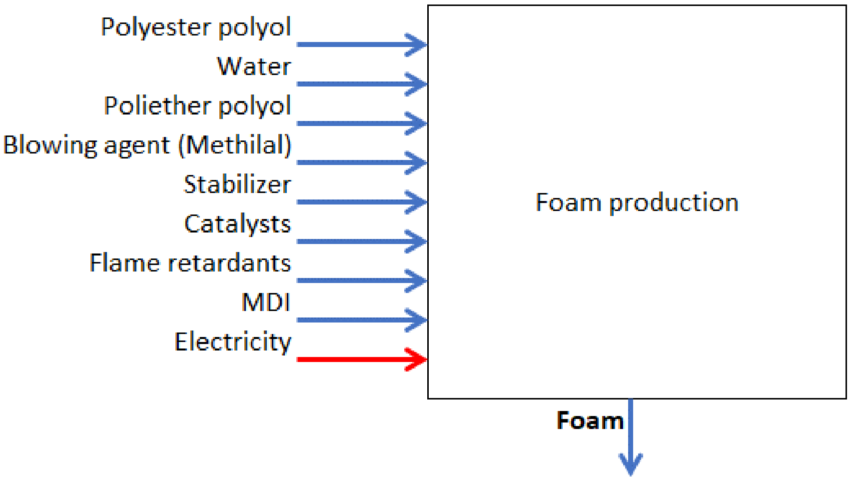

Figure 5.5 – Block flow diagram of foam manufacturing

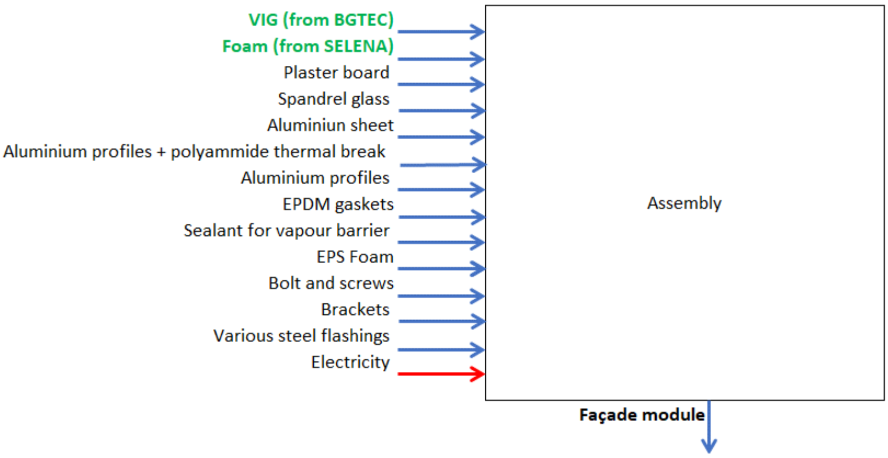

Figure 5.6 – Block flow diagram of façade module assembly

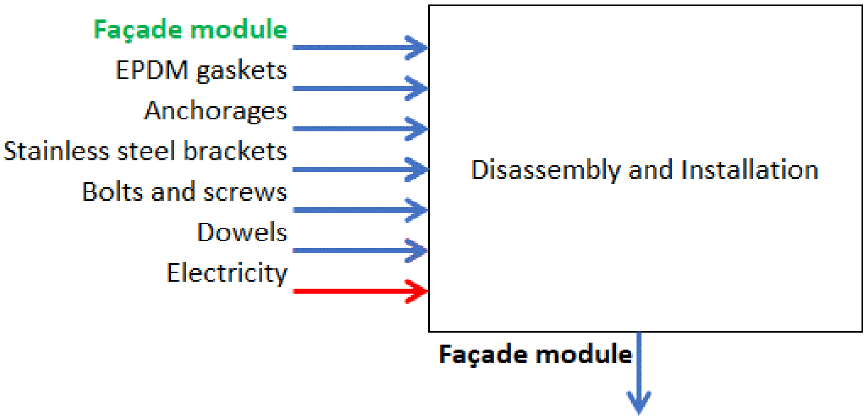

Figure 5.7– Block flow diagram of façade module installation

All data collected during the inventory analysis are included in **LCI tables**, which are reported in **Annex III: Façade module**.

5.3 Impact Assessment

The following subchapters report the main outcomes of LCA and LCC for the façade module, **per functional unit** (i.e. 1 m^2 of curtain wall system).

5.3.1 LCA results

Table 5.2 reports the LCA results related to EENSULATE façade module's life cycle compared with the benchmark, highlighting in particular the resultant potential carbon footprint.

Table 5.2 – LCA results related to the EENSULATE/BENCHMARK façade module's life cycle

Impact category	EENSULATE	BENCHMARK	Unit
Acidification terrestrial and freshwater	1,36E+00	1,40E+00	Mole of H^+ eq.
Cancer human health effects	1,88E-06	1,91E-06	CTUh
Climate Change	3,83E+02	2,92E+02	kg CO_2 eq.
Ecotoxicity freshwater	3,06E+03	3,53E+03	CTUe
Eutrophication freshwater	8,39E-03	2,49E-02	kg P eq.
Eutrophication marine	2,69E-01	2,47E-01	kg N eq.
Eutrophication terrestrial	2,99E+00	2,87E+00	Mole of N eq.
Ionising radiation - human health	1,90E+01	2,33E+01	kBq U^{235} eq.
Land Use	9,30E+02	5,20E+02	Pt
Non-cancer human health effects	3,48E-06	4,43E-06	CTUh
Ozone depletion	1,60E-05	7,37E-06	kg CFC-11 eq.
Photochemical ozone formation - human health	7,40E-01	7,06E-01	kg NMVOC eq.
Resource use, energy carriers	5,02E+03	4,14E+03	MJ
Resource use, mineral and metals	8,03E-04	8,65E-04	kg Sb eq.
Respiratory inorganics	1,21E-05	1,31E-05	Deaths
Water scarcity	4,37E+01	6,02E+01	m^3 world equiv.

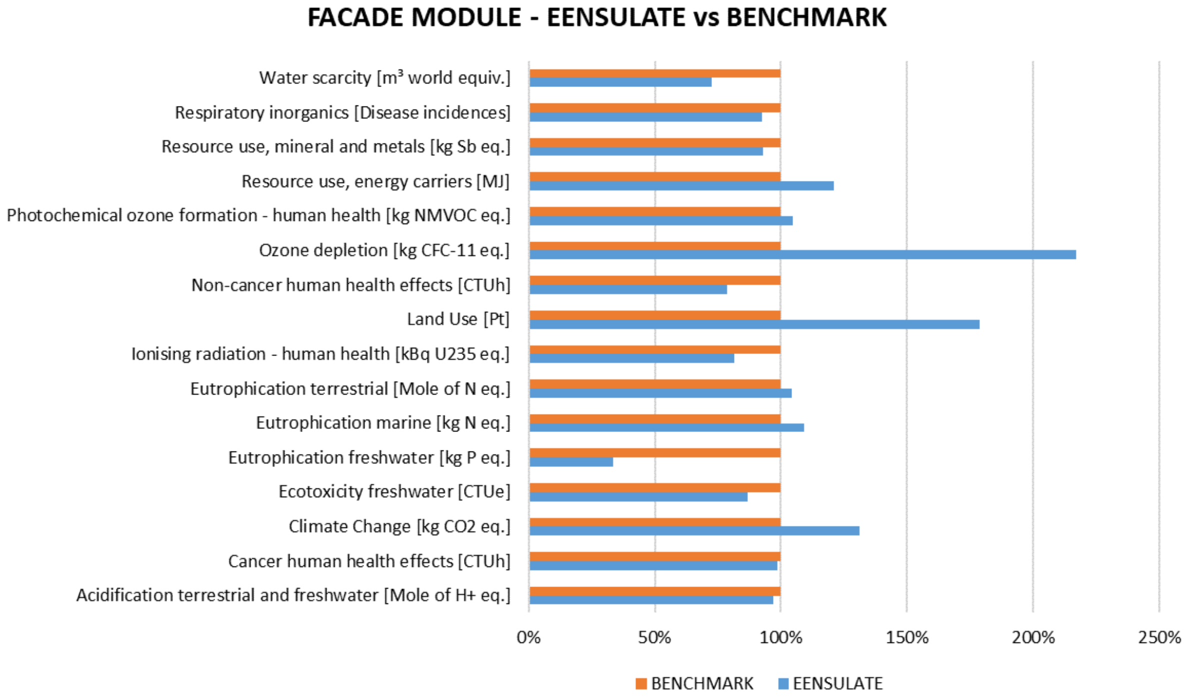

Figure 5.8 – Comparison of LCA results between EENSULATE and BENCHMARK façade module’s life cycle

For most of the impact categories, the EENSULATE façade module based on VIG and innovative foam shows a better or at least comparable environmental performance compared with the benchmark based on triple glazing and mineral wool. As in the case of Pesaro library, the solutions utilised in the façade module (both VIG and TGU) have to undergo a lamination step entailing additional impacts because of the energy required and, only in the case of VIG, the transportation from BGTEC facility to lamination facility in Italy and then to the school in Poland: however, these additional impacts are almost balanced by the ones generated in the benchmark TGU production.

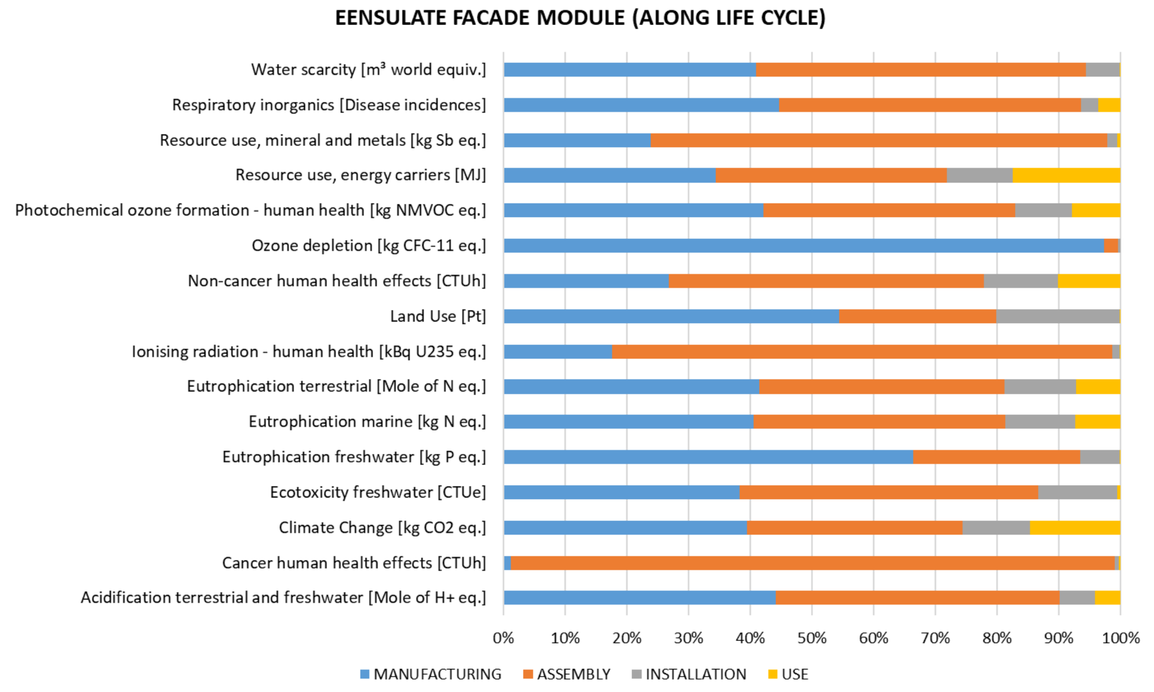

Figure 5.9 – Environmental impact distribution along the EENSULATE façade module’s life cycle

As shown in the Figure 5.9, in the case of the façade module case study, the assembly phase entails the highest share of the environmental impacts, together with the manufacturing phase: indeed, considering an average value among the several impact categories, the assembly and the manufacturing cover respectively an average of 47% and 41% of the environmental impacts.

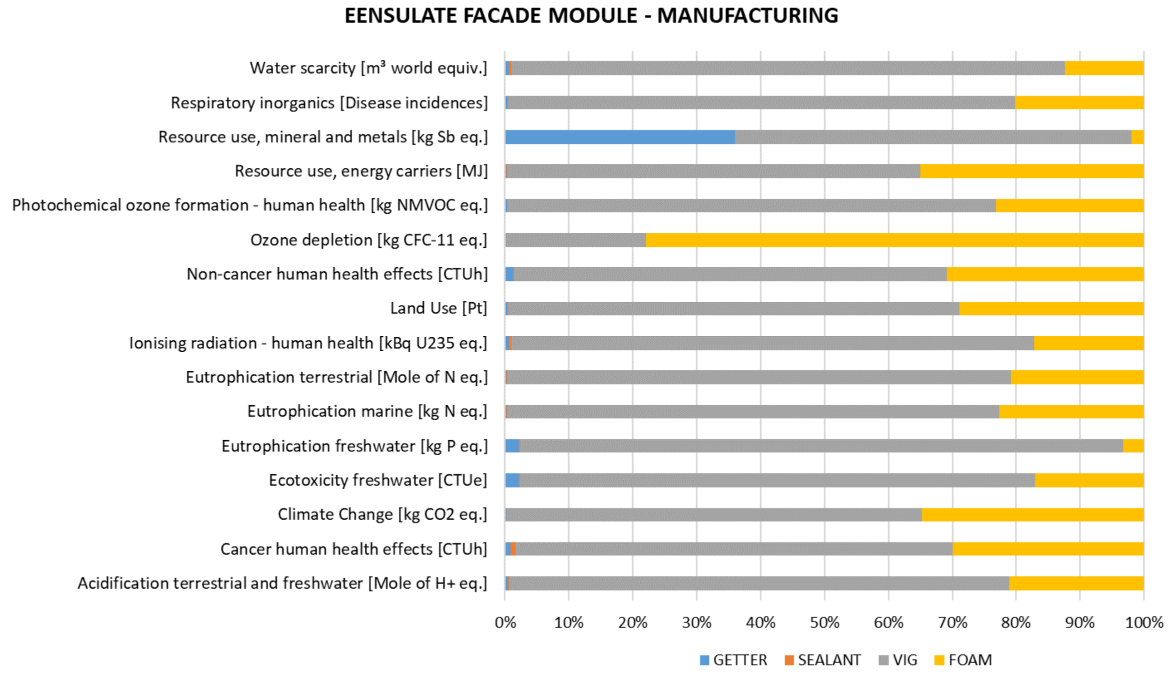

Figure 5.10 – Environmental impact distribution of the façade module manufacturing

The manufacturing phase in the case of the EENSULATE façade module consists in the production processes of the different innovative components developed within the project: getter, sealant, VIG and one-component foam. As it can be seen in the Figure 5.10, the highest impacts are associated with the manufacturing of VIG (including the lamination step) and one-component foam.

5.3.2 LCC results

Table 5.3 reports the LCC results related to EENSULATE façade module along life cycle compared with the benchmark.

Table 5.3 – LCC results per m^2 of façade module related to the EENSULATE/BENCHMARK façade module's life cycle

Phase	EENSULATE	BENCHMARK	Unit
VIG/TGU manufacturing	195,51	239,36	€/m^2
Foam/mineral wool manufacturing	11,82	1,28	€/m^2
Assembly	1368,81	1365,89	€/m^2
Installation	249,19	250,61	€/m^2
Use	10,58	13,35	€/m^2
TOTAL	1835,91	1870,49	€/m^2

The VIG manufacturing cost, which includes also the lamination process, is equal to **195,51 €/m^2 of façade module**. The economic impacts distribution of the VIG manufacturing is reported in the previous chapter (see Figure 4.8).

The **foam manufacturing cost** is equal to **11,82 €/m^2 of façade module,** corresponding to **4,83 €/kg of foam.** The economic impacts related to foam manufacturing (see Figure 5.11) can be attributed mainly to raw materials (59%) and energy (33%). Equipment, workers and maintenance costs account for 5%, 3% and 1% respectively.

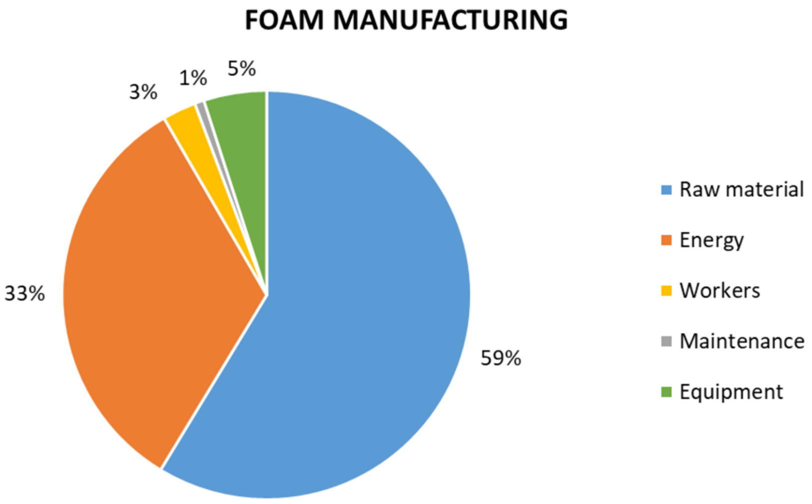

Figure 5.11 – Economic impacts distribution in the foam manufacturing phase

Regarding assembly and installation phases, the economic impacts distributions are reported in the Figure 5.12 below. The economic impacts associated with the assembly step depends on workers and raw materials; while in the case of installation, also the transport has to be considered (4% of the total cost).

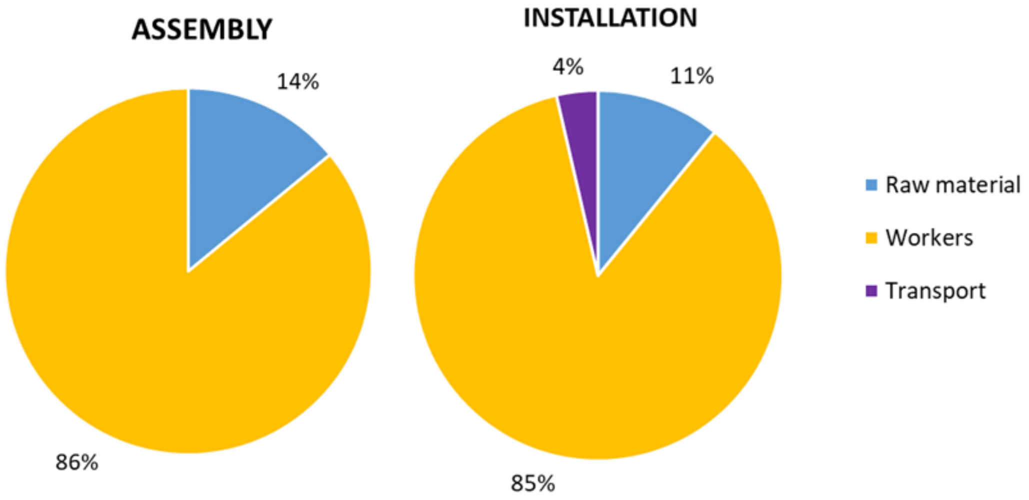

Figure 5.12 – Economic impacts distribution in the façade module assembly and installation phase

5.4 Interpretation of the results

As it can be seen in the Figure 5.8 above, the EENSULATE façade module presents improvements in terms of environmental impacts compared with the benchmark (e.g. up to 73% in the case of eutrophication freshwater).

In particular, VIG production process shows relevant savings in almost all impact categories, if compared with the TGU production. Climate change presents a slight increase in terms of kg CO_2 equivalent (8% increase), which are due to the fact that the EENSULATE case takes also into account the transport of getter and sealant from SAES to BGTEC facility and above all the transport of VIG from BGTEC to the lamination facility located in Crema (Italy).

Without considering these transportation routes, the environmental impacts associated with the EENSULATE solution would be even lower compared with the benchmark.

Although the VIG manufacturing process requires an amount of energy which is significantly higher than the benchmark case (TGU assembly is mostly performed at room temperature), the innovative VIG represents a lightweight solution entailing also a lower consumption of raw materials, including the number of glass panes used, if compared with the TGU.

In the case of the façade module, non-negligible impacts are also linked to the assembly phase, where the VIG (or the TGU in the benchmark case) and the spandrel (based on one-component foam and mineral wool in the EENSULATE and the benchmark case respectively) are joined together with other structural components.

In the assembly phase, most of the impacts (about 70% for many impact categories) are due to the aluminium profiles and to the float glass used as spandrel glass. For some categories (i.e. ozone depletion and eutrophication freshwater) impacts are instead mainly related to the plasterboard (used in the EENSULATE case to improve acoustic insulation properties) and to the steel components like brackets and flashings.

Regarding the climate change impacts, which result higher in the case of the EENSULATE solution compared with the benchmark, they can be mainly linked to two aspects: the transport of the façade module from

FOCCHI facility to the Polish school and the manufacturing of foam. In the latter case, indeed, the electricity used in the process represents the main factor to be improved to make the process more sustainable from this specific environmental perspective.

Moreover, it should be also considered that the energy required during the assembly phase for the foaming step (to be carried out at a constant temperature of 50 °C for 20 minutes) has not been included in the analysis because of the difficulty to estimate it in the current developing situation.

Concerning the use phase, the improvement in the U-value of the innovative façade module (U = 0,64 W/m^{2}K) compared with the benchmark (U = 0,8 W/m^{2}K) entails an environmental impacts reduction of 20% in all impact categories, as well as an equal percentage of cost savings. However, the weight of the use phase in the overall life cycle of the façade module (considering the functional unit 1 m^2 of façade module) is not so high (see Figure 5.9), if compared e.g. with the manufacturing and the assembly phase.

Concerning LCC results, it is estimated a foam manufacturing cost equal to 11,82 €/m^2 of façade module, which is significantly higher than the price of mineral wool (1,28 €/m^2 of façade module): this is mainly due to the costs attributed to raw materials and energy (see Figure 5.11).

On the contrary, the VIG cost referred to the functional unit is lower than the benchmark TGU price (195,51 €/m^2 vs. 239,36 €/m^2).

The assembly is the phase of life cycle entailing higher costs. This mainly depends on the workers cost (86% of the total assembly costs), considering the high number of workers involved in the process. The cost of the components needed for assembling the façade module (e.g. spandrel glass, aluminum profiles, brackets) accounts for about 14% of the total assembly costs.

6 Conclusions

The present deliverable aims at assessing the environmental and economic sustainability of the innovative solutions developed within the EENSULATE project, compared with specific benchmark products.

Such EENSULATE solutions mainly consist in windows and façade modules based on VIG technology. In particular, three different case studies are considered, in order to properly assess the sustainability and the replication potential of the developed concepts in different scenarios in terms of application, type of building and climatic zone.

In the first case study, the VIG is installed within the original windows of a Polish museum. This historical building entails constraints linked to the conservation of the cultural heritage but the VIG technology is able to provide a lightweight solution associated with high performance in terms of thermal and acoustic insulation suitable for this application.

Moreover, the EENSULATE solution shows also a high sustainability potential from an environmental point of view: if compared with the benchmark (i.e. single glass pane), the innovative window based on VIG shows lower values for most of the impact categories, with a reduction of 62% in the climate change category. In particular, the main improvements are associated with the use phase, where the relevant decrease in the U-value of the EENSULATE window compared with the benchmark brings to a decrease of about 90% of the impacts generated along the use phase of the window (i.e. 20 years).

From an economic perspective, VIG manufacturing process entails higher costs compared with the benchmark: this is mainly due to the complexity of the innovative process, which indeed requires further optimisation activities before a full and reliable deployment at a larger scale. However, the EENSULATE process shows a relevant potential in terms of technical performances which could boost its marketability and application in different scenarios, including historical buildings (like the Polish museum) requiring solutions able to meet cultural heritage preservation requirements.

The second case study entailing the substitution of the door-window at a library in Pesaro (Italy) confirms the good environmental performances of VIG shown in the museum case study. In particular, concerning the manufacturing phase, VIG shows lower impacts in almost all impact categories if compared with the benchmark, i.e. DGU. The lamination process required in this case study aims at reducing the risk of debris in case of breakage and the probability of breakage itself. This lamination step together with the higher thickness of the glass panes used in the library compared with the ones needed in the museum, represent the main differences between the VIG typology used in the first and second case study.

The lamination process is also the main responsible for the higher production costs observed in the library's case study compared with the museum case. This aspect, as well as the need of further developments and optimisation required for the VIG manufacturing process, is to be considered when analysing the overall economic results of the present study. Indeed, in case a further cost reduction is obtained thanks to a full industrialisation of the main production steps, the innovative EENSULATE solutions could achieve a good competitiveness towards the benchmark ones, considering their lower environmental impacts and higher technical performances (e.g. U-value reduction up to 73% compared with the DGU).

Along with window and door-window, the present study focuses also on the application of VIG and an innovative foam into a façade module for curtain wall systems. This is what is analysed in the third case study entailing the substitution of 115,5 m^2 of existing façade in a Polish school.

From the environmental point of view, the EENSULATE solution shows lower impacts in most of the impact categories compared with the benchmark, i.e. a façade module constituted by TGU and mineral wool for spandrel, although the EENSULATE case includes also the impacts associated with the transportation routes in the manufacturing, assembly and installation phase. These results could even be lowered in case efficient optimisation activities are carried out, focusing not only on the VIG manufacturing process but especially on the foam process, which indeed entails significantly higher environmental impacts if compared with the mineral wool.

The LCC shows a very promising result in terms of economic sustainability for the VIG manufacturing if compared with the TGU, while the foam production process seems to entail much higher costs than the mineral wool: however, considering the overall life cycle of the EENSULATE façade module (manufacturing, assembly, installation and use phase over 20 years), it entails lower costs compared with the benchmark.

Coupling these economic results with the environmental ones, the EENSULATE façade module shows a high potential for its wide replicability and application, considering both a sustainability- and a performance-based perspective.

Ultimately, the innovative solutions developed within the EENSULATE project, i.e. VIG based on innovative getter and sealant and foam for spandrel, shows a very good performance, especially from the point of view of the environmental sustainability.

Considering an economic perspective, the lower scales of the developed processes compared with the benchmarks and the need for further developments and optimisation activities partially affect the LCC results. However, the optimisation potential for the developed solutions is proved to be high: indeed, it should be also considered that VIG represents a lightweight solution with the opportunity to reduce the costs and the additional components in the assembly and installation phase, both in case of window applications and in case of curtain wall systems.

Moreover, the replication potential of the VIG is much higher than the benchmark solutions. Indeed, EENSULATE VIG is tested and analysed for three different kinds of application (i.e. window without laminated glass pane, door-window including a laminated glass pane, façade module including a laminated glass pane), in different building typologies (i.e. historical buildings like the museum and the library and a tertiary building like the Polish school) and at two different climate scenarios (i.e. Poland and Italy). While in the three case studies three different benchmark solutions are considered, the EENSULATE product in all cases is based on VIG, coupled with an innovative foam in the case of the façade module.

Apart from some discrepancies due to the different solutions envisaged depending on the specific applications, each of the assessed case studies show very promising results for a future and feasible market deployment of the developed EENSULATE products and components.

7 References

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8 Annex I: Museum window

Getter production

Table 8.1 – LCA Inventory of getter production

		LCA INVENTORY – GETTER PRODUCTION					
		Category	Flow	Amount	Unit	Dataset	Source
MELTING AND CASTING	**Input**	Raw material	Raw metal material	2,02	kg	DE: titanium zinc plate production, without pre-weathering ecoinvent 3.5	RINA-C calculation based on primary data from SAES
		Energy	Electricity	7,2	kWh	IT: Electricity grid mix ts	RINA-C calculation based on primary data from SAES
	Output	Waste	Inert metal residual	0,02	kg	EU-28: Ferro metals on landfill ts	RINA-C calculation based on primary data from SAES
		Product	**Getter alloy ingots**	**2**	**kg**	N/A	RINA-C calculation based on primary data from SAES
POWDER MILLING AND SIEVING	**Input**	Raw material	Getter alloy ingots	2	kg	N/A	Primary data from SAES
		Energy	Electricity	21	kWh	IT: Electricity grid mix ts	Primary data from SAES
	Output	Waste	Waste metal powder	0,9	kg	EU-28: Ferro metals on landfill ts	Primary data from SAES
		Product	**Getter alloy powder**	**1,1**	**kg**	N/A	Primary data from SAES
LAMINATION	**Input**	Raw material	Getter alloy powder	1,1	kg	N/A	Primary data from SAES
		Raw material	Nickel plated iron	3,15	kg	GLO: market for selective coat, aluminium sheet, nickel pigmented	Primary data from SAES
		Energy	Electricity	15	kWh	IT: Electricity grid mix ts	Primary data from SAES
	Output	**Product**	**Getter strips**	**4,25**	**kg**	N/A	Primary data from SAES

Table 8.2 – LCC Inventory of getter production

		LCC INVENTORY – GETTER PRODUCTION					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
MELTING AND CASTING	**OPEX**	Raw material	Raw metal material	CO	CO	Confidential information	Primary data from SAES
		Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Waste	Inert metal residual	0,134	€/kg	Landfilling cost	Secondary data (source: European Commission (2012) – Use of economic instruments and waste management performances)
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	Secondary data, assumption
	CAPEX	Equipment	VIM oven	CO	CO	Confidential information	Primary data from SAES
POWDER MILLING AND SIEVING	**OPEX**	Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Waste	Waste metal powder	0,134	€/kg	Landfilling cost	Secondary data (source: European Commission (2012) – Use of economic instruments and waste management performances)
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	Crusher, granulometer, ball mill and siever	CO	CO	Confidential information	Primary data from SAES
LAMINATION	**OPEX**	Raw material	Nickel-plated iron	CO	CO	Confidential information	Primary data from SAES
		Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	Rolling mill	CO	CO	Confidential information	Primary data from SAES

Table 8.3 – LCA Inventory of sealant production

		LCA INVENTORY – SEALANT PRODUCTION					
		Category	Flow	Amount	Unit	Dataset	Source
SEALANT FORMULATION	Input	Raw material	Phenolic resin	4,4	kg	RER: phenolic resin production ecoinvent	Primary data from SAES
		Raw material	Fillers	0,55	kg	GLO: chemical production, inorganic ecoinvent 3.5	Primary data from SAES
		Raw material	Curing agent	0,55	kg	GLO: chemical production, organic ecoinvent 3.5	Primary data from SAES
		Energy	Electricity	26,75	kWh	IT: Electricity grid mix ts	Primary data from SAES
	Output	Waste	Waste solvent	0,5	kg	Europe without Switzerland: treatment of spent solvent mixture, hazardous waste incineration ecoinvent 3.5	Primary data from SAES
		Product	**Sealant paste**	**5**	**kg**	N/A	Primary data from SAES
STRIP PRODUCTION	Input	Raw material	Sealant paste	5	kg	N/A	Primary data from SAES
		Energy	Electricity	100	kWh	EU-28: Electricity grid mix ts	Primary data from SAES
	Output	Waste	Waste resin	1,25	kg	RoW: treatment of spent anion exchange resin from potable water production, municipal incineration ecoinvent 3.5	Primary data from SAES
		Product	**Sealant strips**	**3,75**	**kg**	N/A	Primary data from SAES

Table 8.4 – LCC Inventory of sealant production

		LCC INVENTORY – SELANT PRODUCTION					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
SEALANT FORMULATION	**OPEX**	Raw material	Phenolic resin, fillers and curing agent	CO	CO	Confidential information	Primary data from SAES
		Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Waste	Waste solvent	30	€/m³	Density: 997 kg/m³	RINA-C estimation
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	Oven, speed mixer and powder grinder	CO	CO	Confidential information	Primary data from SAES
STRIP PRODUCTION	**OPEX**	Raw material	FEP foils	CO	CO	Confidential information	Primary data from SAES
		Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Waste disposal	Waste resin	0,134	€/kg	Landfilling cost	Secondary data (source: European Commission (2012) – Use of economic instruments and waste management performances)
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	Needle dispensing tool	CO	CO	Confidential information	Primary data from SAES

Table 8.5 – LCA Inventory of VIG manufacturing

		LCA INVENTORY – VIG MANUFACTURING					
		Category	Flow	Amount	Unit	Dataset	Source
LOW-E COATED PANE PRODUCTION	**Input**	Raw material	Low-e coated glass pane	10	kg	RER: flat glass production, coated ecoinvent 3.5	Primary data from BGTEC
		Raw material	Water/detergent	50	ml	EU-28: Tap water from surface water ts	Primary data from BGTEC
		Raw material	Acetone	20	ml	EU-28: Acetone ts	Primary data from BGTEC
		Raw material	Isopropyl alcohol	20	ml	DE: Isopropanol ts	Primary data from BGTEC
		Raw material	Getter strips	0,0315	kg	N/A	Primary data from BGTEC
		Raw material	Sealant strips	0,00815	kg	N/A	Primary data from BGTEC
		Raw material	Pillars	0,046	g	CUT-OFF	Primary data from BGTEC
		Transport	Truck 3,5t (getter and sealant)	180	km	GLO: Light duty vehicle, Euro 6, up to 3.5t gross weight / up to 1.5t payload capacity ts; EU-28: Diesel mix at refinery ts	Primary data from SAES
		Transport	Cargo plane 22t (getter and sealant)	1100	km	GLO: Cargo plane, 22t payload ts; EU-28: Kerosene / Jet A1 at refinery ts	Primary data from SAES
	Output	**Product**	**Coated pane with pillars, sealant and getter**	**10,04**	**kg**	N/A	Primary data from BGTEC
UNCOATED PANE PRODUCTION	**Input**	Raw material	Uncoated glass pane	10	kg	RER: flat glass production, uncoated ecoinvent 3.5	Primary data from BGTEC
		Raw material	Water/detergent	50	ml	EU-28: Tap water from surface water ts	Primary data from BGTEC
		Raw material	Acetone	20	ml	EU-28: Acetone ts	Primary data from BGTEC
		Raw material	Isopropyl alcohol	20	ml	DE: Isopropanol ts	Primary data from BGTEC
	Output	**Product**	**Coated pane**	**10**	**kg**	N/A	Primary data from BGTEC

		LCA INVENTORY – VIG MANUFACTURING					
		Category	**Flow**	**Amount**	**Unit**	**Dataset**	**Source**
DOWNSTREAM PROCESSES	**Input**	Raw material	Coated pane with pillars, sealant and getter	10,04	kg	N/A	Primary data from BGTEC
		Raw material	Uncoated pane	10	kg	N/A	Primary data from BGTEC
		Raw material	Indium	0,005	kg	CUT-OFF	Primary data from BGTEC
		Raw material	Stainless steel cover	0,01	kg	CUT-OFF	Primary data from BGTEC
		Energy	Electricity	85	kWh	PL: Electricity grid mix ts	Primary data from BGTEC
	Output	**Product**	**VIG**	**20,04**	**kg**	N/A	Primary data from BGTEC

Table 8.6 – LCC Inventory of VIG manufacturing

		LCC INVENTORY – VIG MANUFACTURING					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
VIG MANUFACTURING & LAMINATION	**OPEX**	Raw material	Low-e coated glass pane	50	€/m^2	-	Primary data from BGTEC
		Raw material	Uncoated glass pane	50	€/m^2	-	Primary data from BGTEC
		Raw material	Water/detergent	1,33	€/l	-	Primary data from BGTEC
		Raw material	Acetone	1,4	€/l	-	Primary data from BGTEC
		Raw material	Isopropyl alcohol	12	€/l	-	Primary data from BGTEC
		Raw material	Pillars	270	€/50k pillars	484 pillars per 1 m^2 VIG	Primary data from BGTEC
		Raw material	Getter strips	N/A	N/A	-	RINA-C calculation based on primary data
		Raw material	Sealant strips	N/A	N/A	-	RINA-C calculation based on primary data
		Raw material	Indium solder	0,258	€/g	-	Primary data from BGTEC

LCC INVENTORY – VIG MANUFACTURING

	Category	Flow	Amount	Unit	Comments	Source
	Raw material	Stainless steel cover	0,2	€/g	-	Primary data from BGTEC
	Energy	Electricity	0,0795	€/kWh	-	Secondary data (source: Eurostat)
	Workers	Skilled workers	30	€/h	2 workers; 1920 h/y	Primary data from BGTEC
	Maintenance	-	-	-	2% of CAPEX cost	RINA-C assumption
	Transport	Truck 3,5t	0,1	€/tkm	Transport of getter and sealant from SAES to BGTEC; Transport of VIG from BGTEC to lamination facility	Secondary data (source: European Commission (2017) - Case study analysis of the burden of taxation and charges on transport)
	Transport	Cargo plane 22t	0,12	€/tkm	Transport of getter and sealant from SAES to BGTEC	Secondary data (source: European Commission (2017) - Case study analysis of the burden of taxation and charges on transport)
CAPEX	Equipment	Vacuum wand	200	€	Depreciation time: 1 year	Primary data from BGTEC
	Equipment	Ultrasonic soldering iron	5015	€	Depreciation time: 5 years	Primary data from BGTEC
	Equipment	Vacuum pump	10085	€	Depreciation time: 10 years	Primary data from BGTEC
	Equipment	Vacuum cup device	600	€	Depreciation time: 10 years	Primary data from BGTEC
	Equipment	Induction heater	15000	€	Depreciation time: 5 years	Primary data from BGTEC
	Equipment	Oven	200000	€	Depreciation time: 10 years	RINA-C assumption based on primary data from BGTEC

Table 8.7 – LCA Inventory relating to window assembly & installation

		LCA INVENTORY – ASSEMBLY & INSTALLATION					
		Category	Flow	Amount	Unit	Dataset	Source
ASSEMBLY & INSTALLATION	Input	Raw material	VIG	78,2	kg	N/A	Primary data from BGTEC
		Raw material (benchmark)	Flat glass	48,8	kg	RER: flat glass production, coated ecoinvent 3.5	Primary data from BGTEC
		Raw material	EPDM gaskets	0,7	kg	EU-28: EPDM roofing membranes (EN15804 A1-A3) ts	Primary data from BGTEC
		Raw material	Stucco	3	kg	GLO: market for stucco ecoinvent 3.5	Primary data from BGTEC
		Raw material	Varnish	3	kg	RER: alkyd paint production, white, water-based, product in 60% solution state ecoinvent 3.5	Primary data from BGTEC
		Raw material	Silicone	2	kg	EU-28: Silicone sealing compound (EN15804 A1-A3) ts	Primary data from BGTEC
		Energy	Electricity	12	kWh	PL: Electricity grid mix ts	Primary data from BGTEC
		Transport	Truck 3,5t (window)	273	km	GLO: Light duty vehicle, Euro 6, up to 3.5t gross weight / up to 1.5t payload capacity ts; EU-28: Diesel mix at refinery ts	Primary data from FOCCHI
	Output	**Product**	**VIG module**	**86,9**	**kg**	N/A	Primary data from BGTEC
		Product (benchmark)	**Single glass module**	**57,5**	**kg**	N/A	Primary data from BGTEC

Table 8.8 – LCC Inventory relating to window assembly & installation

		LCC INVENTORY – ASSEMBLY & INSTALLATION					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
ASSEMBLY & INSTALLATION	**OPEX**	Raw material	VIG	N/A	N/A	-	Primary data from BGTEC
		Raw material	EPDM gasket	3	€/m	14 m; 0,05 kg/m	Primary data from BGTEC
		Raw material	Stucco	8	€/kg	-	Primary data from BGTEC
		Raw material	Varnish	15	€/kg	-	Primary data from BGTEC
		Raw material	Silicone	16,67	€/kg	-	Primary data from BGTEC
		Energy	Electricity	0,0795	€/kWh	Reference country: Poland	Secondary data (source: Eurostat)
		Workers	Skilled workers	30	€/h	2 workers; 80 h/window	Primary data from BGTEC
		Transport	Truck 3,5t	0,1	€/tkm	Transport of window from BGTEC to museum	Secondary data (source: European Commission (2017) - Case study analysis of the burden of taxation and charges on transport)
	CAPEX	Equipment	Drill, electric screwdriver, brush, paint sprayer, glass suction cup, scaffolding	300	€	Depreciation time: 5 years	Primary data from BGTEC

Table 8.9 – LCA & LCC Inventory relating to window use phase

					LCA INVENTORY – USE			
		Category	**Flow**	**Amount**	**Unit**	**Comment**	**Dataset**	**Source**
USE	**Input**	Energy	Heating consumption per unit along 20 years	480,87	kWh	0,0473 €/kWh (reference country: Poland); $U_{\text{EENSULATE window}} = 0,5\ \text{W/m}^2\text{K}$	PL: Thermal energy from natural gas ts	RINA-C calculation based on primary and secondary data
		Energy (benchmark)	Heating consumption per unit along 20 years (benchmark)	5578,09	kWh	0,0473 €/kWh (reference country: Poland); $U_{\text{BENCHMARK window}} = 5,8\ \text{W/m}^2\text{K}$	PL: Thermal energy from natural gas ts	RINA-C calculation based on primary and secondary data

9 Annex II: Library door-window

Getter production

Table 9.1 – LCA Inventory of getter production

		LCA INVENTORY – GETTER PRODUCTION					
		Category	**Flow**	**Amount**	**Unit**	**Dataset**	**Source**
MELTING AND CASTING	**Input**	Raw material	Raw metal material	2,02	kg	DE: titanium zinc plate production, without pre-weathering ecoinvent 3.5	RINA-C calculation based on primary data from SAES
		Energy	Electricity	7,2	kWh	IT: Electricity grid mix ts	RINA-C calculation based on primary data from SAES
	Output	Waste	Inert metal residual	0,02	kg	EU-28: Ferro metals on landfill ts	RINA-C calculation based on primary data from SAES
		Product	**Getter alloy ingots**	**2**	**kg**	N/A	RINA-C calculation based on primary data from SAES
POWDER MILLING AND SIEVING	**Input**	Raw material	Getter alloy ingots	2	kg	N/A	Primary data from SAES
		Energy	Electricity	21	kWh	IT: Electricity grid mix ts	Primary data from SAES
	Output	Waste	Waste metal powder	0,9	kg	EU-28: Ferro metals on landfill ts	Primary data from SAES
		Product	**Getter alloy powder**	**1,1**	**kg**	N/A	Primary data from SAES
LAMINATION	**Input**	Raw material	Getter alloy powder	1,1	kg	N/A	Primary data from SAES
		Raw material	Nickel plated iron	3,15	kg	GLO: market for selective coat, aluminium sheet, nickel pigmented	Primary data from SAES
		Energy	Electricity	15	kWh	IT: Electricity grid mix ts	Primary data from SAES
	Output	**Product**	**Getter strips**	**4,25**	**kg**	N/A	Primary data from SAES

Table 9.2 – LCC Inventory of getter production

		LCC INVENTORY – GETTER PRODUCTION					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
MELTING AND CASTING	**OPEX**	Raw material	Raw metal material	CO	CO	Confidential information	Primary data from SAES
		Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Waste	Inert metal residual	0,134	€/kg	Landfilling cost	Secondary data (source: European Commission (2012) – Use of economic instruments and waste management performances)
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	VIM oven	CO	CO	Confidential information	Primary data from SAES
POWDER MILLING AND SIEVING	**OPEX**	Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Waste	Waste metal powder	0,134	€/kg	Landfilling cost	Secondary data (source: European Commission (2012) – Use of economic instruments and waste management performances)
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	Crusher, granulometer, ball mill and siever	CO	CO	Confidential information	Primary data from SAES
LAMINATION	**OPEX**	Raw material	Nickel-plated iron	CO	CO	Confidential information	Primary data from SAES
		Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	Rolling mill	CO	CO	Confidential information	Primary data from SAES

Table 9.3 – LCA Inventory of sealant production

		LCA INVENTORY – SEALANT PRODUCTION					
		Category	**Flow**	**Amount**	**Unit**	**Dataset**	**Source**
SEALANT FORMULATION	**Input**	Raw material	Phenolic resin	4,4	kg	RER: phenolic resin production ecoinvent	Primary data from SAES
		Raw material	Fillers	0,55	kg	GLO: chemical production, inorganic ecoinvent 3.5	Primary data from SAES
		Raw material	Curing agent	0,55	kg	GLO: chemical production, organic ecoinvent 3.5	Primary data from SAES
		Energy	Electricity	26,75	kWh	IT: Electricity grid mix ts	Primary data from SAES
	Output	Waste	Waste solvent	0,5	kg	Europe without Switzerland: treatment of spent solvent mixture, hazardous waste incineration ecoinvent 3.5	Primary data from SAES
		Product	**Sealant paste**	**5**	**kg**	N/A	Primary data from SAES
STRIP PRODUCTION	**Input**	Raw material	Sealant paste	5	kg	N/A	Primary data from SAES
		Energy	Electricity	100	kWh	EU-28: Electricity grid mix ts	Primary data from SAES
	Output	Waste	Waste resin	1,25	kg	RoW: treatment of spent anion exchange resin from potable water production, municipal incineration ecoinvent 3.5	Primary data from SAES
		Product	**Sealant strips**	**3,75**	**kg**	N/A	Primary data from SAES

Table 9.4 – LCC Inventory of sealant production

		LCC INVENTORY – SELANT PRODUCTION					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
SEALANT FORMULATION	**OPEX**	Raw material	Phenolic resin, fillers and curing agent	CO	CO	Confidential information	Primary data from SAES
		Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Waste	Waste solvent	30	€/m^3	Density: 997 kg/m^3	RINA-C estimation
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	Oven, speed mixer and powder grinder	CO	CO	Confidential information	Primary data from SAES
STRIP PRODUCTION	**OPEX**	Raw material	FEP foils	CO	CO	Confidential information	Primary data from SAES
		Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Waste disposal	Waste resin	0,134	€/kg	Landfilling cost	Secondary data (source: European Commission (2012) – Use of economic instruments and waste management performances)
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	Needle dispensing tool	CO	CO	Confidential information	Primary data from SAES

Table 9.5 – LCA Inventory of VIG manufacturing & lamination

		LCA INVENTORY – VIG MANUFACTURING & LAMINATION					
		Category	**Flow**	**Amount**	**Unit**	**Dataset**	**Source**
LOW-E COATED PANE PRODUCTION	**Input**	Raw material	Low-e coated glass pane	15	kg	RER: flat glass production, coated ecoinvent 3.5	Primary data from BGTEC
		Raw material	Water/detergent	50	ml	EU-28: Tap water from surface water ts	Primary data from BGTEC
		Raw material	Acetone	20	ml	EU-28: Acetone ts	Primary data from BGTEC
		Raw material	Isopropyl alcohol	20	ml	DE: Isopropanol ts	Primary data from BGTEC
		Raw material	Getter strips	0,0315	kg	N/A	Primary data from BGTEC
		Raw material	Sealant strips	0,00815	kg	N/A	Primary data from BGTEC
		Raw material	Pillars	0,046	g	CUT-OFF	Primary data from BGTEC
		Transport	Truck 3,5t (getter and sealant)	180	km	GLO: Light duty vehicle, Euro 6, up to 3.5t gross weight / up to 1.5t payload capacity ts; EU-28: Diesel mix at refinery ts	Primary data from SAES
		Transport	Cargo plane 22t (getter and sealant)	1100	km	GLO: Cargo plane, 22t payload ts; EU-28: Kerosene / Jet A1 at refinery ts	Primary data from SAES
	Output	**Product**	**Coated pane with pillars, sealant and getter**	**15,04**	**kg**	N/A	Primary data from BGTEC
UNCOATED PANE PRODUCTION	**Input**	Raw material	Uncoated glass pane	15	kg	RER: flat glass production, uncoated ecoinvent 3.5	Primary data from BGTEC
		Raw material	Water/detergent	50	ml	EU-28: Tap water from surface water ts	Primary data from BGTEC
		Raw material	Acetone	20	ml	EU-28: Acetone ts	Primary data from BGTEC
		Raw material	Isopropyl alcohol	20	ml	DE: Isopropanol ts	Primary data from BGTEC
	Output	**Product**	**Coated pane**	**15**	**kg**	N/A	Primary data from BGTEC

LCA INVENTORY – VIG MANUFACTURING & LAMINATION

		Category	Flow	Amount	Unit	Dataset	Source
DOWNSTREAM PROCESSES	**Input**	Raw material	Coated pane with pillars, sealant and getter	15,04	kg	N/A	Primary data from BGTEC
		Raw material	Uncoated pane	15	kg	N/A	Primary data from BGTEC
		Raw material	Indium	0,005	kg	CUT-OFF	Primary data from BGTEC
		Raw material	Stainless steel cover	0,01	kg	CUT-OFF	Primary data from BGTEC
		Energy	Electricity	85	kWh	PL: Electricity grid mix ts	Primary data from BGTEC
	Output	**Product**	**VIG**	**30,04**	**kg**	N/A	Primary data from BGTEC
LAMINATION	**Input**	Raw material	VIG	30,04	kg	N/A	Primary data from BGTEC
		Raw material	Flat glass	15	kg	RER: flat glass production, uncoated ecoinvent 3.5	Primary data from BGTEC
		Raw material	PVB film	1,63	kg	RER: extrusion, plastic film ecoinvent 3.5; GLO: market for polyvinylchloride, emulsion polymerised ecoinvent 3.5; GLO: market for polyvinylchloride, suspension polymerised ecoinvent 3.5	Primary data from BGTEC
		Energy	Electricity	16,8	kWh	IT: Electricity grid mix ts	Primary data from BGTEC
		Transport	Truck 3,5t (VIG to lamination)	1436	km	GLO: Light duty vehicle, Euro 6, up to 3.5t gross weight / up to 1.5t payload capacity ts; EU-28: Diesel mix at refinery ts	Primary data from BGTEC
	Output	**Product**	**VIG after lamination**	**46,67**	**kg**	N/A	Primary data from BGTEC

Table 9.6 – LCC Inventory of VIG manufacturing & lamination

		LCC INVENTORY – VIG MANUFACTURING & LAMINATION					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
VIG MANUFACTURING & LAMINATION	**OPEX**	Raw material	Low-e coated glass pane	50	€/m^2	-	Primary data from BGTEC
		Raw material	Uncoated glass pane	50	€/m^2	-	Primary data from BGTEC
		Raw material	Water/detergent	1,33	€/l	-	Primary data from BGTEC
		Raw material	Acetone	1,4	€/l	-	Primary data from BGTEC
		Raw material	Isopropyl alcohol	12	€/l	-	Primary data from BGTEC
		Raw material	Pillars	270	€/50k pillars	484 pillars per 1 m^2 VIG	Primary data from BGTEC
		Raw material	Getter strips	N/A	N/A	-	RINA-C calculation based on primary data
		Raw material	Sealant strips	N/A	N/A	-	RINA-C calculation based on primary data
		Raw material	Indium solder	0,258	€/g	-	Primary data from BGTEC
		Raw material	Stainless steel cover	0,2	€/g	-	Primary data from BGTEC
		Energy	Electricity	0,0795	€/kWh	-	Secondary data (source: Eurostat)
		Workers	Skilled workers	30	€/h	2 workers; 1920 h/y	Primary data from BGTEC
		Maintenance	-	-	-	2% of CAPEX cost	RINA-C assumption
		Other costs	Lamination process	94	€/m$^2_{VIG}$	Cost for lamination (including glass pane and PVB layer) and for PVB bags required to carry out the process on VIGs	Primary data from BGTEC
		Transport	Truck 3,5t	0,1	€/tkm	Transport of getter and sealant from SAES to BGTEC; Transport of VIG from BGTEC to lamination facility	Secondary data (source: European Commission (2017) - Case study analysis of the burden of taxation and charges on transport)
		Transport	Cargo plane 22t	0,12	€/tkm	Transport of getter and sealant from SAES to BGTEC	Secondary data (source: European Commission (2017) - Case study analysis of the burden of taxation and charges on transport)

LCC INVENTORY – VIG MANUFACTURING & LAMINATION

		Category	Flow	Amount	Unit	Comments	Source
	CAPEX	Equipment	Vacuum wand	200	€	Depreciation time: 1 year	Primary data from BGTEC
		Equipment	Ultrasonic soldering iron	5015	€	Depreciation time: 5 years	Primary data from BGTEC
		Equipment	Vacuum pump	10085	€	Depreciation time: 10 years	Primary data from BGTEC
		Equipment	Vacuum cup device	600	€	Depreciation time: 10 years	Primary data from BGTEC
		Equipment	Induction heater	15000	€	Depreciation time: 5 years	Primary data from BGTEC
		Equipment	Oven	200000	€	Depreciation time: 10 years	RINA-C assumption based on primary data from BGTEC

Table 9.7 – LCA Inventory relating to window assembly & installation

		LCA INVENTORY – ASSEMBLY & INSTALLATION					
		Category	Flow	Amount	Unit	Dataset	Source
ASSEMBLY & INSTALLATION	Input	Raw material	VIG	103,63	kg	N/A	Primary data from FOCCHI
		Raw material (benchmark)	DGU	155,4	kg	RER: glazing production, double, U<1.1 W/m2K, laminated safety glass ecoinvent 3.5	Primary data from FOCCHI
		Raw material	Structural bonding sealant	1,56	kg	EU-28: Polyurethane flexible foam (PU) - TDI-based, no flame retardant, high density ts	Primary data from FOCCHI
		Energy	Electricity	4	kWh	IT: Electricity grid mix ts	Primary data from FOCCHI
		Transport	Truck 3,5t (VIG)	300	km	GLO: Light duty vehicle, Euro 6, up to 3.5t gross weight / up to 1.5t payload capacity ts; EU-28: Diesel mix at refinery ts	Primary data from FOCCHI
		Transport	Truck 3,5t (window)	40	km	GLO: Light duty vehicle, Euro 6, up to 3.5t gross weight / up to 1.5t payload capacity ts; EU-28: Diesel mix at refinery ts	Primary data from FOCCHI
	Output	**Product**	**VIG module**	**105,2**	**kg**	N/A	Primary data from FOCCHI
		Product (benchmark)	**DGU module**	**156,96**	**kg**	N/A	Primary data from FOCCHI

Table 9.8 – LCC Inventory relating to window assembly & installation

		LCC INVENTORY – ASSEMBLY					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
ASSEMBLY & INSTALLATION	**OPEX**	Raw material	VIG	N/A	N/A	-	Primary data from FOCCHI
		Raw material	Structural bonding sealant	0,033	€/ml	Density: 1,3 g/ml	Primary data from FOCCHI
		Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Workers	Skilled workers	26	€/h	3 workers; 4 h/window	Primary data from FOCCHI
		Transport	Truck 3,5t	0,1	€/tkm	Transport of VIG from lamination facility to FOCCHI; Transport of window from FOCCHI to library	Secondary data (source: European Commission (2017) - Case study analysis of the burden of taxation and charges on transport)
	CAPEX	Equipment	Lifting equipment	6000	€	Depreciation time: 15 years	Primary data from FOCCHI

Table 9.9 – LCA & LCC Inventory relating to window use phase

		LCA & LCC INVENTORY – USE						
		Category	Flow	Amount	Unit	Comment	Dataset	Source
USE	**Input**	Energy	Heating consumption per unit along 20 years	66,73	kWh	0,0769 €/kWh (reference country: Italy); $U_{\text{EENSULATE door-window}} = 0{,}3\ W/m^2K$	IT: Thermal energy from natural gas ts	RINA-C calculation based on primary and secondary data
		Energy (benchmark)	Heating consumption per unit along 20 years (benchmark)	244,69	kWh	0,0769 €/kWh (reference country: Italy); $U_{\text{BENCHMARK door-window}} = 1{,}1\ W/m^2K$	IT: Thermal energy from natural gas ts	RINA-C calculation based on primary and secondary data

10 Annex III: Façade module

Getter production

Table 10.1 – LCA Inventory of getter production

		LCA INVENTORY – GETTER PRODUCTION					
		Category	Flow	Amount	Unit	Dataset	Source
MELTING AND CASTING	**Input**	Raw material	Raw metal material	2,02	kg	DE: titanium zinc plate production, without pre-weathering ecoinvent 3.5	RINA-C calculation based on primary data from SAES
		Energy	Electricity	7,2	kWh	IT: Electricity grid mix ts	RINA-C calculation based on primary data from SAES
	Output	Waste	Inert metal residual	0,02	kg	EU-28: Ferro metals on landfill ts	RINA-C calculation based on primary data from SAES
		Product	**Getter alloy ingots**	**2**	**kg**	N/A	RINA-C calculation based on primary data from SAES
POWDER MILLING AND SIEVING	**Input**	Raw material	Getter alloy ingots	2	kg	N/A	Primary data from SAES
		Energy	Electricity	21	kWh	IT: Electricity grid mix ts	Primary data from SAES
	Output	Waste	Waste metal powder	0,9	kg	EU-28: Ferro metals on landfill ts	Primary data from SAES
		Product	**Getter alloy powder**	**1,1**	**kg**	N/A	Primary data from SAES
LAMINATION	**Input**	Raw material	Getter alloy powder	1,1	kg	N/A	Primary data from SAES
		Raw material	Nickel plated iron	3,15	kg	GLO: market for selective coat, aluminium sheet, nickel pigmented	Primary data from SAES
		Energy	Electricity	15	kWh	IT: Electricity grid mix ts	Primary data from SAES
	Output	**Product**	**Getter strips**	**4,25**	**kg**	N/A	Primary data from SAES

Table 10.2 – LCC Inventory of getter production

		LCC INVENTORY – GETTER PRODUCTION					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
MELTING AND CASTING	**OPEX**	Raw material	Raw metal material	CO	CO	Confidential information	Primary data from SAES
		Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Waste	Inert metal residual	0,134	€/kg	Landfilling cost	Secondary data (source: European Commission (2012) – Use of economic instruments and waste management performances)
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	VIM oven	CO	CO	Confidential information	Primary data from SAES
POWDER MILLING AND SIEVING	**OPEX**	Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Waste	Waste metal powder	0,134	€/kg	Landfilling cost	Secondary data (source: European Commission (2012) – Use of economic instruments and waste management performances)
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	Crusher, granulometer, ball mill and siever	CO	CO	Confidential information	Primary data from SAES
LAMINATION	**OPEX**	Raw material	Nickel-plated iron	CO	CO	Confidential information	Primary data from SAES
		Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	Rolling mill	CO	CO	Confidential information	Primary data from SAES

Table 10.3 – LCA Inventory of sealant production

		LCA INVENTORY – SEALANT PRODUCTION					
		Category	**Flow**	**Amount**	**Unit**	**Dataset**	**Source**
SEALANT FORMULATION	**Input**	Raw material	Phenolic resin	4,4	kg	RER: phenolic resin production ecoinvent	Primary data from SAES
		Raw material	Fillers	0,55	kg	GLO: chemical production, inorganic ecoinvent 3.5	Primary data from SAES
		Raw material	Curing agent	0,55	kg	GLO: chemical production, organic ecoinvent 3.5	Primary data from SAES
		Energy	Electricity	26,75	kWh	IT: Electricity grid mix ts	Primary data from SAES
	Output	Waste	Waste solvent	0,5	kg	Europe without Switzerland: treatment of spent solvent mixture, hazardous waste incineration ecoinvent 3.5	Primary data from SAES
		Product	**Sealant paste**	**5**	**kg**	N/A	Primary data from SAES
STRIP PRODUCTION	**Input**	Raw material	Sealant paste	5	kg	N/A	Primary data from SAES
		Energy	Electricity	100	kWh	EU-28: Electricity grid mix ts	Primary data from SAES
	Output	Waste	Waste resin	1,25	kg	RoW: treatment of spent anion exchange resin from potable water production, municipal incineration ecoinvent 3.5	Primary data from SAES
		Product	**Sealant strips**	**3,75**	**kg**	N/A	Primary data from SAES

Table 10.4 – LCC Inventory of sealant production

		LCC INVENTORY – SELANT PRODUCTION					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
SEALANT FORMULATION	**OPEX**	Raw material	Phenolic resin, fillers and curing agent	CO	CO	Confidential information	Primary data from SAES
		Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Waste	Waste solvent	30	€/m^3	Density: 997 kg/m^3	RINA-C estimation
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	Oven, speed mixer and powder grinder	CO	CO	Confidential information	Primary data from SAES
STRIP PRODUCTION	**OPEX**	Raw material	FEP foils	CO	CO	Confidential information	Primary data from SAES
		Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)
		Waste disposal	Waste resin	0,134	€/kg	Landfilling cost	Secondary data (source: European Commission (2012) – Use of economic instruments and waste management performances)
		Workers	Skilled workers	CO	CO	Confidential information	Primary data from SAES
		Maintenance	-	-	-	3% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	Needle dispensing tool	CO	CO	Confidential information	Primary data from SAES

Table 10.5 – LCA Inventory of VIG manufacturing and VIG/TGU lamination

		LCA INVENTORY – VIG MANUFACTURING AND VIG/TGU LAMINATION					
		Category	**Flow**	**Amount**	**Unit**	**Dataset**	**Source**
LOW-E COATED PANE PRODUCTION	**Input**	Raw material	Low-e coated glass pane	15	kg	RER: flat glass production, coated ecoinvent 3.5	Primary data from BGTEC
		Raw material	Water/detergent	50	ml	EU-28: Tap water from surface water ts	Primary data from BGTEC
		Raw material	Acetone	20	ml	EU-28: Acetone ts	Primary data from BGTEC
		Raw material	Isopropyl alcohol	20	ml	DE: Isopropanol ts	Primary data from BGTEC
		Raw material	Getter strips	0,0315	kg	N/A	Primary data from BGTEC
		Raw material	Sealant strips	0,00815	kg	N/A	Primary data from BGTEC
		Raw material	Pillars	0,046	g	CUT-OFF	Primary data from BGTEC
		Transport	Truck 3,5t (getter and sealant)	180	km	GLO: Light duty vehicle, Euro 6, up to 3.5t gross weight / up to 1.5t payload capacity ts; EU-28: Diesel mix at refinery ts	Primary data from SAES
		Transport	Cargo plane 22t (getter and sealant)	1100	km	GLO: Cargo plane, 22t payload ts; EU-28: Kerosene / Jet A1 at refinery ts	Primary data from SAES
	Output	**Product**	**Coated pane with pillars, sealant and getter**	**15,04**	**kg**	N/A	Primary data from BGTEC
UNCOATED PANE PRODUCTION	**Input**	Raw material	Uncoated glass pane	15	kg	RER: flat glass production, uncoated ecoinvent 3.5	Primary data from BGTEC
		Raw material	Water/detergent	50	ml	EU-28: Tap water from surface water ts	Primary data from BGTEC
		Raw material	Acetone	20	ml	EU-28: Acetone ts	Primary data from BGTEC
		Raw material	Isopropyl alcohol	20	ml	DE: Isopropanol ts	Primary data from BGTEC
	Output	**Product**	**Coated pane**	**15**	**kg**	N/A	Primary data from BGTEC

		LCA INVENTORY – VIG MANUFACTURING AND VIG/TGU LAMINATION					
		Category	**Flow**	**Amount**	**Unit**	**Dataset**	**Source**
DOWNSTREAM PROCESSES	**Input**	Raw material	Coated pane with pillars, sealant and getter	15,04	kg	N/A	Primary data from BGTEC
		Raw material	Uncoated pane	15	kg	N/A	Primary data from BGTEC
		Raw material	Indium	0,005	kg	CUT-OFF	Primary data from BGTEC
		Raw material	Stainless steel cover	0,01	kg	CUT-OFF	Primary data from BGTEC
		Energy	Electricity	85	kWh	PL: Electricity grid mix ts	Primary data from BGTEC
	Output	**Product**	**VIG**	**30,04**	**kg**	N/A	Primary data from BGTEC
LAMINATION	**Input**	Raw material	VIG	30,04	kg	N/A	Primary data from BGTEC
		Raw material (benchmark)	*TGU*	*54*	*kg*	*RER: glazing production, triple, U<0.5 W/m2K ecoinvent 3.5*	*Secondary data (source: Ecoinvent database)*
		Raw material	Flat glass	15	kg	RER: flat glass production, uncoated ecoinvent 3.5	Primary data from BGTEC
		Raw material (benchmark)	*Flat glass*	*18*	*kg*	*RER: flat glass production, uncoated ecoinvent 3.5*	*Secondary data (source: Ecoinvent database)*
		Raw material	PVB film	1,63	kg	RER: extrusion, plastic film ecoinvent 3.5; GLO: market for polyvinylchloride, emulsion polymerised ecoinvent 3.5; GLO: market for polyvinylchloride, suspension polymerised ecoinvent 3.5	Primary data from BGTEC
		Raw material (benchmark)	*Plastic film*	*3*	*kg*	*RER: extrusion, plastic film ecoinvent 3.5; GLO: market for polyvinylchloride, emulsion polymerised ecoinvent 3.5; GLO: market for polyvinylchloride, suspension polymerised ecoinvent 3.5*	*Secondary data (source: Ecoinvent database)*
		Energy	Electricity	16,8	kWh	IT: Electricity grid mix ts	Secondary data (source: Ecoinvent database)
		Energy (benchmark)	*Electricity*	*26,92*	*kWh*	*IT: Electricity grid mix ts*	*Secondary data (source: Ecoinvent database)*

		LCA INVENTORY – VIG MANUFACTURING AND VIG/TGU LAMINATION					
		Category	**Flow**	**Amount**	**Unit**	**Dataset**	**Source**
		Transport	Truck 3,5t (VIG to lamination)	1436	km	GLO: Light duty vehicle, Euro 6, up to 3.5t gross weight / up to 1.5t payload capacity ts; EU-28: Diesel mix at refinery ts	Primary data from BGTEC
	Output	**Product**	**VIG after lamination**	**46,67**	**kg**	N/A	Primary data from BGTEC
		Product (benchmark)	*TGU after lamination*	*75*	*kg*	*N/A*	*Secondary data (source: Ecoinvent database)*

Table 10.6 – LCC Inventory of VIG manufacturing and VIG lamination

		LCC INVENTORY – VIG MANUFACTURING AND VIG LAMINATION					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
VIG MANUFACTURING AND VIG LAMINATION	**OPEX**	Raw material	Low-e coated glass pane	50	€/m^2	-	Primary data from BGTEC
		Raw material	Uncoated glass pane	50	€/m^2	-	Primary data from BGTEC
		Raw material	Water/detergent	1,33	€/l	-	Primary data from BGTEC
		Raw material	Acetone	1,4	€/l	-	Primary data from BGTEC
		Raw material	Isopropyl alcohol	12	€/l	-	Primary data from BGTEC
		Raw material	Pillars	270	€/50k pillars	484 pillars per 1 m^2 VIG	Primary data from BGTEC
		Raw material	Getter strips	N/A	N/A	-	RINA-C calculation based on primary data
		Raw material	Sealant strips	N/A	N/A	-	RINA-C calculation based on primary data
		Raw material	Indium solder	0,258	€/g	-	Primary data from BGTEC

LCC INVENTORY – VIG MANUFACTURING AND VIG LAMINATION

	Category	Flow	Amount	Unit	Comments	Source
	Raw material	Stainless steel cover	0,2	€/g	-	Primary data from BGTEC
	Energy	Electricity	0,0795	€/kWh	Reference country: Poland	Secondary data (source: Eurostat)
	Workers	Skilled workers	30	€/h	2 workers; 1920 h/y	Primary data from BGTEC
	Maintenance	-	-	-	2% of CAPEX cost	RINA-C assumption
	Other costs	Lamination process	94	€/m^2_{VIG}	Cost for lamination (including glass pane and PVB layer) and for PVB bags required to carry out the process on VIGs	Primary data from BGTEC
	Transport	Truck 3,5t	0,1	€/tkm	Transport of getter and sealant from SAES to BGTEC; Transport of VIG from BGTEC to lamination facility	Secondary data (source: European Commission (2017) - Case study analysis of the burden of taxation and charges on transport)
	Transport	Cargo plane 22t	0,12	€/tkm	Transport of getter and sealant from SAES to BGTEC	Secondary data (source: European Commission (2017) - Case study analysis of the burden of taxation and charges on transport)
CAPEX	Equipment	Vacuum wand	200	€	Depreciation time: 1 year	Primary data from BGTEC
	Equipment	Ultrasonic soldering iron	5015	€	Depreciation time: 5 years	Primary data from BGTEC
	Equipment	Vacuum pump	10085	€	Depreciation time: 10 years	Primary data from BGTEC
	Equipment	Vacuum cup device	600	€	Depreciation time: 10 years	Primary data from BGTEC
	Equipment	Induction heater	15000	€	Depreciation time: 5 years	Primary data from BGTEC
	Equipment	Oven	200000	€	Depreciation time: 10 years	RINA-C assumption based on primary data from BGTEC

Table 10.7 – LCA Inventory of foam manufacturing

		LCA INVENTORY – FOAM MANUFACTURING					
		Category	**Flow**	**Amount**	**Unit**	**Dataset**	**Source**
SEALANT FORMULATION	**Input**	Raw material	Polyester polyol	0,26	kg	RER: Aromatic Polyester Polyol (APP) (European average, including flame retardant) PU Europe	Primary data from SELENA
		Raw material	Water	0,004	kg	EU-28: Tap water from surface water ts	Primary data from SELENA
		Raw material	Polyether polyol	0,015	kg	RER: Polyether polyol PlasticsEurope	Primary data from SELENA
		Raw material	Blowing agent	0,04	kg	GLO: chemical production, organic ecoinvent 3.5	Primary data from SELENA
		Raw material	Stabiliser	0,004	kg	GLO: chemical production, organic ecoinvent 3.5	Primary data from SELENA
		Raw material	Catalyst	0,01	kg	GLO: chemical production, inorganic ecoinvent 3.5	Primary data from SELENA
		Raw material	Flame retardants	0,02	kg	GLO: chemical production, organic ecoinvent 3.5	Primary data from SELENA
		Raw material	MDI	0,65	kg	EU-28: Methylenediphenyl diisocyanate ((p)MDI) ISOPA	Primary data from SELENA
		Energy	Electricity	20	kWh	PL: Electricity grid mix ts	Primary data from SELENA
	Output	**Product**	**Foam**	**1**	**kg**	N/A	Primary data from SELENA

Table 10.8 – LCC Inventory of foam manufacturing

		LCC INVENTORY – SELANT PRODUCTION					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
SEALANT FORMULATION	**OPEX**	Raw material	Polyester polyol	2,1	€/kg	-	Primary data from SELENA
		Raw material	Tap water	0,00025	€/kg	-	Primary data from SELENA
		Raw material	Polyether polyol	2,137	€/kg	-	Primary data from SELENA
		Raw material	Blowing agent	2	€/kg	-	Primary data from SELENA
		Raw material	Stabiliser	8,78	€/kg	-	Primary data from SELENA
		Raw material	Flame retardants	25	€/kg	-	Primary data from SELENA
		Raw material	Catalysts	28,05	€/kg	-	Primary data from SELENA
		Raw material	Isocyanate	2,09	€/kg	-	Primary data from SELENA
		Energy	Electricity	0,0795	€/kWh	Reference country: Poland	Secondary data (source: Eurostat)
		Workers	Skilled workers	20	€/h	2 workers; 1600 h/y	Primary data from SELENA
		Maintenance	-	-	-	1% of CAPEX cost	RINA-C assumption
	CAPEX	Equipment	Mixer, dosing pumps, balance	600	€/d	200 d/y	Primary data from SELENA

Table 10.9 – LCA Inventory relating to façade module assembly

		LCA INVENTORY – ASSEMBLY					
		Category	**Flow**	**Amount**	**Unit**	**Dataset**	**Source**
ASSEMBLY	**Input**	Raw material	VIG	135,65	kg	N/A	Primary data from FOCCHI
		Raw material (benchmark)	*TGU*	*217,99*	*kg*	*N/A*	*Primary data from FOCCHI*
		Raw material	Foam	11,245	kg	N/A	Primary data from FOCCHI
		Raw material (benchmark)	*Mineral wool*	*19,2*	*kg*	*EU-28: Mineral wool (Facades) (EN15804 A1-A3) ts*	*Primary data from FOCCHI*
		Raw material	Plaster board	37	kg	GLO: market for gypsum plasterboard ecoinvent 3.5	Primary data from FOCCHI
		Raw material	Spandrel glass	46,29	kg	EU-28: Float flat glass ts	Primary data from FOCCHI
		Raw material	Aluminium sheets	4,46	kg	EU-28: Stainless steel sheet (EN15804 A1-A3) ts	Primary data from FOCCHI
		Raw material	Aluminium profiles + polyamide	40,89	kg	EU-28: Aluminium frame profile, thermically isolated, powder coated (EN15804 A1-A3) ts; EU-28: Polyamide 6.6 fibres (PA 6.6) ts	Primary data from FOCCHI
		Raw material	Aluminium profiles	7,65	kg	EU-28: Aluminium frame profile, thermically isolated, powder coated (EN15804 A1-A3) ts	Primary data from FOCCHI
		Raw material	EPDM gaskets	1	kg	EU-28: EPDM roofing membranes (EN15804 A1-A3) ts	Primary data from FOCCHI
		Raw material	Sealant for vapour barrier	1,56	kg	EU-28: Polyurethane flexible foam (PU) - TDI-based, no flame retardant, high density ts	Primary data from FOCCHI
		Raw material	Bolts & screws	1	kg	EU-28: Fixing material screws stainless steel (EN15804 A1-A3) ts	Primary data from FOCCHI
		Raw material	Brackets	45	kg	RER: section bar rolling, steel ecoinvent 3.5	Primary data from FOCCHI
		Raw material	Various steel flashings	6,01	kg	RER: section bar rolling, steel ecoinvent 3.5	Primary data from FOCCHI
		Energy	Electricity	46,96	kWh	IT: Electricity grid mix ts	Primary data from FOCCHI

LCA INVENTORY – ASSEMBLY

	Category	Flow	Amount	Unit	Dataset	Source
	Transport	Truck 3,5t (VIG)	300	km	GLO: Light duty vehicle, Euro 6, up to 3.5t gross weight / up to 1.5t payload capacity ts; EU-28: Diesel mix at refinery ts	Primary data from BGTEC
	Transport	Truck 3,5t (foam)	1240	km	GLO: Light duty vehicle, Euro 6, up to 3.5t gross weight / up to 1.5t payload capacity ts; EU-28: Diesel mix at refinery ts	Primary data from BGTEC
Output	**Product**	**Façade module**	**337,76**	**kg**	N/A	Primary data from FOCCHI
	Product (benchmark)	***Benchmark façade module***	***391,05***	***kg***	***N/A***	***Primary data from FOCCHI***

Table 10.10 – LCC Inventory relating to façade module assembly

		LCC INVENTORY – ASSEMBLY					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
ASSEMBLY	**OPEX**	Raw material	VIG	N/A	N/A	Dimensions: 1261 mm x 2305 mm x 19,77; 6 mm Mid Iron Toughened/VACUUM 0,25/6 mm Mid Iron Toughened/ PVB 1,52/6 mm Mid Iron Heat Strenghtened	RINA-C calculation based on primary data
		Raw material (benchmark)	*TGU*	*378*	*€/m^2*	*Dimension: 1261 mm x 2305 mm x 30 mm*	*Primary data from FOCCHI*
		Raw material	Foam	N/A	N/A	Dimension: 1261 mm x 1335 mm x 167 mm	RINA-C calculation based on primary data
		Raw material (benchmark)	*Mineral wool*	*3,5*	*€/m^2*	*Dimensions: 1261 mm x 1335 mm x 190 mm*	*Primary data from FOCCHI*
		Raw material	Plaster board	4,71	€/m^2	Dimension: 1261 mm x 1335 mm x 12 mm	Primary data from FOCCHI
		Raw material	Spandrel glass	78	€/m^2	Dimensions: 1261 mm x 1335 mm x 11 mm	Primary data from FOCCHI
		Raw material	Aluminium sheets	8,5	€/kg	-	Primary data from FOCCHI
		Raw material	Aluminium profiles + polyamide	81,25	€/$m^2_{\text{facade module}}$	8,9 kg/$m^2_{\text{facade module}}$	Primary data from FOCCHI
		Raw material	Aluminium profiles	20,42	€/$m^2_{\text{facade module}}$	1,67 kg/$m^2_{\text{facade module}}$	Primary data from FOCCHI
		Raw material	EPDM gaskets	3	€/m	20 m; 0,05 kg/m	Primary data from FOCCHI
		Raw material	Sealant for vapour barrier	0,033	€/ml	Density: 1,3 g/ml	Primary data from FOCCHI
		Raw material	Bolts and screws	4,78	€/kg	-	Primary data from FOCCHI
		Raw material	Brackets	2,71	€/kg	-	Primary data from FOCCHI
		Raw material	Various steel flashings	1,2	€/$m^2_{\text{facade module}}$	1,31 kg/$m^2_{\text{facade module}}$	Primary data from FOCCHI
		Energy	Electricity	0,0952	€/kWh	Reference country: Italy	Secondary data (source: Eurostat)

		LCC INVENTORY – ASSEMBLY					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
		Workers	Skilled workers	26	€/h	12 workers; 1752 h/y	Primary data from FOCCHI
		Transport	Truck 3,5t	0,1	€/tkm	Transport of VIG from lamination facility to FOCCHI; Transport of foam from SELENA to FOCCHI	Secondary data (source: European Commission (2017) - Case study analysis of the burden of taxation and charges on transport)
	CAPEX	Equipment	Control machine, foaming machine, forklift	5,8	€/$m^2_{facade\ module}$	-	Primary data from FOCCHI

Table 10.11 – LCA Inventory relating to façade module installation at school

		LCA INVENTORY – INSTALLATION					
		Category	**Flow**	**Amount**	**Unit**	**Dataset**	**Source**
INSTALLATION AT SCHOOL	**Input**	Raw material	Façade module	337,76	kg	N/A	Primary data from FOCCHI
		Raw material (benchmark)	*BENCHMARK façade module*	*391,05*	*kg*	*N/A*	*Primary data from FOCCHI*
		Raw material	EPDM gaskets	0,49	kg	EU-28: EPDM roofing membranes (EN15804 A1-A3) ts	Primary data from FOCCHI
		Raw material	Anchorages	5	kg	RER: section bar rolling, steel ecoinvent 3.5	Primary data from FOCCHI
		Raw material	Stainless steel brackets	20	kg	RER: section bar rolling, steel ecoinvent 3.5	Primary data from FOCCHI
		Raw material	Dowels, bolts & screws	N/A	N/A	CUT-OFF	Primary data from FOCCHI
		Energy	Electricity	2,29	kWh	PL: Electricity grid mix ts	Primary data from BGTEC
		Transport	Truck 3,5t (façade module)	1224	km	GLO: Light duty vehicle, Euro 6, up to 3.5t gross weight / up to 1.5t payload capacity ts; EU-28: Diesel mix at refinery ts	Primary data from FOCCHI

Table 10.12 – LCC Inventory relating to façade module installation at school

		LCC INVENTORY – FAÇADE MODULE INSTALLATION AT SCHOOL					
		Category	**Flow**	**Amount**	**Unit**	**Comments**	**Source**
INSTALLATION AT SCHOOL	**OPEX**	Raw material	Façade module	N/A	N/A	-	Primary data from FOCCHI
		Raw material	EPDM gasket	3	€/m	9,8 m; 0,05 kg/m	Primary data from FOCCHI
		Raw material	Anchorages	15	€/piece	2 pieces per façade module	Primary data from FOCCHI
		Raw material	Stainless steel brackets	30	€/piece	2 pieces per façade module	Primary data from FOCCHI
		Raw material	Dowels, bolts and screws	5	€/unit	-	Primary data from FOCCHI
		Energy	Electricity	0,0795	€/kWh	Reference country: Poland	Secondary data (source: Eurostat)
		Workers	Skilled workers	32	€/h	4 workers; 24 day/façade; façade: 115,5 m^2	Primary data from BGTEC
		Transport	Truck 3,5t	0,1	€/tkm	Transport of façade module from FOCCHI to school	Secondary data (source: European Commission (2017) - Case study analysis of the burden of taxation and charges on transport)
	CAPEX	Equipment	Crane, platform, drill, electric screwdriver, glass suction cup, spirit level	3000	€	Depreciation time: 10 years	Primary data from BGTEC

Table 10.13 – LCA & LCC Inventory relating to façade module use phase

		LCA & LCC INVENTORY – USE						
		Category	**Flow**	**Amount**	**Unit**	**Comment**	**Dataset**	**Source**
USE	**Input**	Energy	Heating consumption per unit along 20 years	26093,76	kWh	0,0473 €/kWh (reference country: Poland); $U_{\text{EENSULATE facade module}}$ = 0,64 W/m^{2}K	PL: Thermal energy from natural gas ts	RINA-C calculation based on primary and secondary data
		Energy (benchmark)	Heating consumption per unit along 20 years (benchmark)	32617,2	kWh	0,0473 €/kWh (reference country: Poland); $U_{\text{BENCHMARK facade module}}$ = 0,8 W/m^{2}K	PL: Thermal energy from natural gas ts	RINA-C calculation based on primary and secondary data