SEVENTH FRAMEWORK PROGRAMME
THEME 4
FP7-2010-NMP-ENV-ENERGY-ICT-EeB

Project no.: 260086

Deliverable Report

Submission Date: July 2014

D6.2 – Comparative environmental impact assessment report, version 0.1

Prepared by:
GAIKER

Project co-funded by the European Commission within the Seventh Framework Programme		
Dissemination level		
PU	Public	X
PP	Restricted to other programme participants (including Commission Services)	
RE	Restricted to a group specific by the consortium (including Commission Services)	
CO	Confidential, only for members of the consortium (including Commission Services)	

1 Acknowledgements

I wish to thank all my colleagues at GAIKER involved in this work, especially Ainara Pocheville who has contributed to the Life Cycle Inventory step. We also thank Oliver Missbauer from Fraunhofer IVV, Yoash Carmi of HANITA Coatings, Marc Fricke and Dirk Weinrich of BASF, Mónica García of ACCIONA, Adrian Pargeter and Malcolm Rochefort of KINGSPAN and Dr. Roland Caps of va-Q-tec for their collaboration by providing information on materials and production processes.

This report has been referenced from confidential information determined from research under the NANOINSULATE Project as well as from published information on LCA of insulation materials-in buildings.

2 Document Control

Version	Change Made	Reason For Change	Date of Change	Change By
0.1	First issue		03/07/14	C.Delgado

3 Executive Summary

Deliverable 6.2 "Comparative environmental impact assessment report" is a deliverable of Workpackage 6 "Lifecycle assessment, safety of the advanced insulation systems, and service-life costing analysis". It is delivered from the Task 6.2 (Simplified lifecycle assessment (LCA) of advanced VIPs), which aimed at carrying out a comparison of the environmental impacts between the currently-available alternatives used as insulation material (in window applications and roof/wall applications); and the different advanced VIPs developed in the project. The analysis has been done using simplified lifecycle analysis (LCA) methodologies for both TVIPs and OVIPs.

In the case of novel OVIPs with organic nanofoam core, the analysis performed is intended to conduct comparative assertions on the basis of a simplified LCA, for internal communication. Benchmarks in the comparison are insulation boards made of rigid foam polyurethane and silica VIPs. The functional unit for this analysis have been "amount of insulation material for achieving **U=0.20 W/m^{2}K** in 1 m^2 area of building wall **over 30 years**". The analysis comprises the product, construction, use and end-of-life stages for the three insulation elements compared. Several transport, use and end-of-life scenarios have been studied. Sensitivity analysis has been conducted on the choice of data and assumptions for modelling the product stage of the novel OVIP. The LCA results conclude that OVIP's impacts in the production stage are smaller than those originated by the silica VIP benchmark, but the silica VIP performs better in the use stage. If recycled cores are used for manufacturing silica VIPs, the environmental profile of this option over the lifecycle is the best among the several alternatives evaluated.

In the case of TVIP intended to be integrated into triple glazing windows, the lack of data has forced a change in the scope of the LCA planned (comparison with triple glazing windows with gas filler in the IGU (Insulating Glass Unit)) to a stand-alone simplified LCA of the transparent VIPs, including only its production and end-of-life stages. The purpose of this study is to identify the materials and processes that contribute in a higher degree to the environmental impacts of the panel. It has been concluded that the silica aerogel core is the determining component from an environmental point of view and the TEOS precursor and the CO_2 used for the SCD in the manufacture of the aerogel explains how it scores in the several environmental indicators assessed.

4 Contents

5 Introduction

As denoted in DoW, Deliverable Report D6.2 will show the results of the assessment of the environmental impacts associated to the entire lifecycle of the advanced Vacuum Insulation Panels (opaque (O-VIP) and transparent (T-VIP)) in comparison to the impacts originating from the current insulation materials used for the same applications (PUR rigid foam insulation boards and silica VIPs for walls or roof and triple glazing in windows).

Following provisions in relevant standards and guidelines for the LCA of a construction product, the current analysis has been designed to cover four stages in the lifecycle of the novel insulation panels: product stage, construction, use and end of life stages. The assessment of the production stage has been mostly based on information collected from the partners in the project participating in the development and application of the VIPs (material producers, VIP producers, etc.) about material and energy inputs and outputs in the manufacturing processes. Construction stage has been modelled from assumptions about the transport of insulation products to the construction site, based on indications given by the manufacturers and consensus on installation operations for the different products. The use stage considers a twofold perspective (material and energy-efficiency) to estimate the impacts derived from relevant use aspects such as durability, thermal conductivity aging, etc. that translates into material consumption and waste generation in maintenance operations, energy losses during use... Finally, the End-of-Life (EOL) stage has been assessed through evaluation of scenarios (BAU and alternative based on the most plausible options identified in Task 6.3), calculating impacts associated with the EOL processes and the benefits achieved by material/energy recovered.

Although the task proposes a simplified LCA, mainly owing to aspects such as limitations in data common in newly-developed products and processes, it takes into account recommendations from ISO 14040 & 14044 and the International Reference Lifecycle Data System (ILCD) Handbook launched from the European Platform of LCA. Other EN and ISO standards dealing with methodological issues in sustainability assessment of building and construction (B/C) works have been reviewed for practical rules on: impact categories most relevant to building applications; impact assessment models; selection of functional units for BMCCs; and setting system boundaries for B/C LCA studies.

5.1 Terms of reference

The present Deliverable is linked to Task 2 (Simplified lifecycle assessment (LCA) of advanced VIPs), of Workpackage 6 "Lifecycle assessment, safety of the advanced insulation systems, and service-life costing analysis". The main objectives in this task are:

- To carry out a comparison of the environmental impacts between the currently available alternatives used and the different advanced VIPs developed in the project: (insulation material for roof and wall applications for OVIPs and triple glazing in windows applications in the case of TVIP).
- To perform the environmental analysis using simplified lifecycle analysis (LCA) methodologies for both TVIPs and OVIPs, to cover all lifecycle stages in each case, including: Production, Construction, Use and End-of-Life.

The evaluation and interpretation of lifecycle analysis results has enabled the calculation and dissemination of key LCA results, e.g. contribution to anthropogenic global warming (AGW), energy savings, etc.

5.2 Life Cycle Assessment (LCA) of construction products. General aspects

Life Cycle Assessment (LCA) is an internationally standardized technique for assessing the environmental aspects associated with a product (goods/processes/services) over its life cycle and their effects on the environment and human health. It is a "Cradle to grave" analysis, that's mean, from raw materials extraction to disposal of final waste, considering production, distribution, use and disposal/recycling of product.

As a rule, a LCA consists of four phases (ref. ISO 14040 series) as depicted in the figure below.

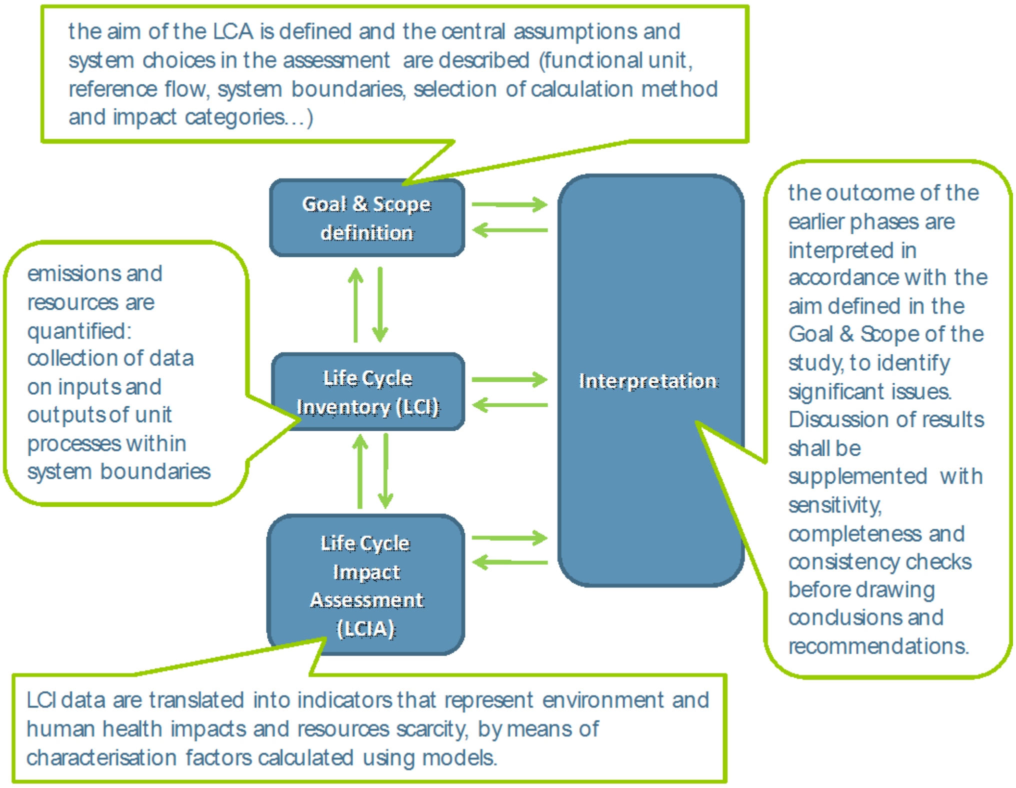

Figure 1. The four phases of a Life Cycle Assessment according to ISO 14040.

The structure of the LCA studies for OVIPs and TVIPs in the present report follows the four-phase schedule set out by the ISO standards and the recommendations by the ILCD Handbook launched from the European Platform of LCA:

- Phase 1 – Goal & Scope definition.

  (1) Literature review: investigation of methodological LCA approaches specific to B/C products and applications

  (2) Definition of functional unit, relevant impact categories, setting system boundaries, benchmarking against state-of-the-art insulation and selection of reference materials (and production technology) for window and roof/wall applications... Gaiker with the support of the rest of partners, especially va-Q-tec & Kingspan, has defined the life cycle assessment framework for novel VIPs in B/C.

- Phase 2 – LCI.

  Collecting data and modelling processes:

  – Partners in charge of production of VIPs and their components have provided/validated the corresponding process flowcharts
  – Production, use and EOL inventories (input, outputs) of advanced VIPs and their components have been gathered from consortium partners.

– Gaiker has gathered production, use and EOL inventories of conventional insulation materials from literature and consortium partners. Generic industry data, available in LCI databases, are used for upstream processes, when needed.

- Phase 3 – LCIA.

  Calculation of LCIA, based on data collected in Phase 2 and decisions on impact categories and characterisation models, for evaluating comparatively environmental profile of OVIPs, TVIPs and benchmarks.

- Phase 4 – Interpretation.

  (1) Identification of significant issues and completeness-consistency-sensitivity checks, to quantify how the choices about data and calculation parameters and processes included in the product system influence on the results.

  (2) Discussion of results to draw conclusions on overall impact of VIPs and to offer ecodesign recommendations.

For LCA studies in the construction sector, various standards are a source of specific rules and additional guidance for the environmental assessment of construction products and have been consulted for this work:

- EN 15804 Sustainability of construction works –Environmental product declarations – Core rules for the product category of construction products.
- ISO 21930 Sustainability in building construction –Environmental declaration of building products.
- CEN/TR 15941:2010 Sustainability of construction works -Environmental product declarations - Methodology for selection and use of generic data
- EN 15978 –Sustainability of construction works –Assessment of environmental performance of buildings –Calculation method.

European standards for assessment of environmental performance (product level and works level) are being developed by CEN/TC 350 (Sustainability of construction works). The Modularity principle proposed by CEN TC 350 for the environmental evaluation is as follows:

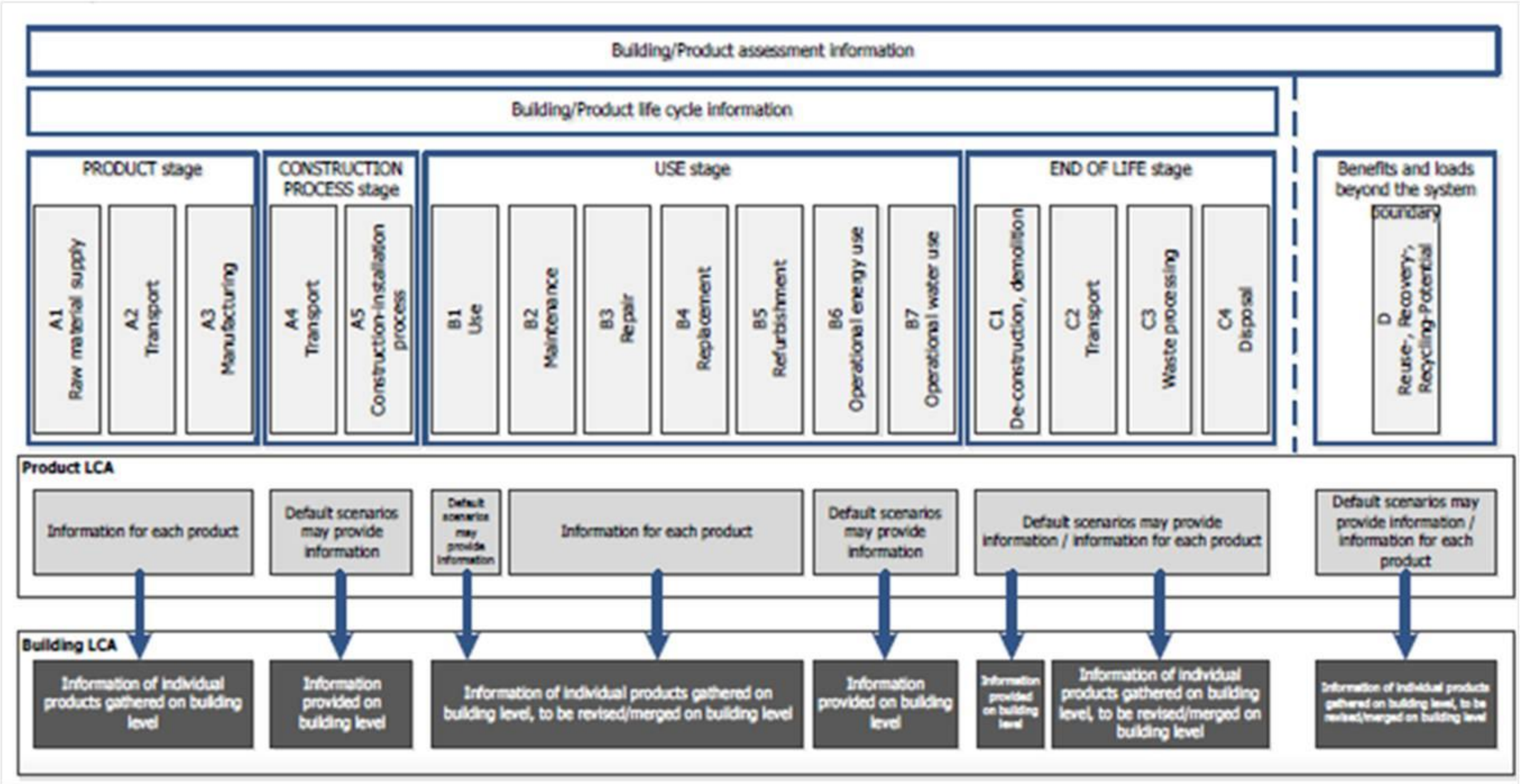

Figure 2. Modularity principle proposed by CEN TC 350 for the environmental evaluation in the EN standards.

The European research project 'EeBGuide – Operational guidance for Life Cycle Assessment Studies of the Energy-Efficient Buildings Initiative', which ran from November 2011 to October 2012 and was co-funded as a coordination and support action (CSA) by the European Commission under the Seventh Framework Programme, has produced the EeBGuide. The EeBGuide[1], provides information on calculation rules, metrics, provisions and instructions for LCA studies of energy-efficient buildings and building products for European research projects of the E2B Initiative. This guide has also been used as reference document for the LCA in NanoInsulate project.

In principle, the life cycle stages to be considered for the LCA of VIPs are (ref. EN 15804 and Figure 2):

1. Product stage, comprising production of VIP components, manufacture of T-VIPs & O-VIPs and assembly with other materials and products to make building components (incl. transport up to production gate, production waste management and all upstream processes from cradle to gate: e.g. raw materials supply). Modules A1-A2-A3.
2. Construction process stage: transport from factory to construction site; on-site integration of VIPs into building elements, transformation of the product (if any) and installation into the building. Modules A4-A5.
3. Use stage: operation of the product in the building and maintenance. B modules.
4. End of life: including deconstruction of the building components with VIPs and end of life routes of VIPs (recycling/recovery/final disposal). C modules. The potential benefits gained by recycling and recovery of materials and energy (Module D) are also evaluated in the EOL scenarios examined.

The precise stages and modules included in the LCA studies of the OVIP and TVIP are described in the next sections of the report.

[1] EeBGuide Guidance Document. Part A: Products. Operational Guidance for Lifecycle Assessment studies of the Energy Efficient Buildings Initiative (EU FP7 project).Available at: http://www.eebguide.eu/

6 Environmental impact assessment of advanced Opaque Vacuum Insulation Panels: LCA of OVIPs

The environmental profile of the novel OVIPs developed in the project, when used in wall insulation applications has been estimated through its whole lifecycle and is described in the next chapters, that follow the four phases structure of LCA studies.

The results obtained are compared with the environmental impacts of currently available alternatives used: PUR rigid foam boards and silica VIPs.

6.1 Goal and Scope of the LCA study

The aim of this study is the calculation and interpretation of the LCA results for the novel OVIP product system to be used as wall insulation in buildings, by means of a simplified LCA aimed at comparative assertions (benchmarks for the comparison: PUR rigid foam boards and silica VIPs). The study is part of a confidential report: results are intended for internal communication purposes within the project Consortium.

6.1.1 Functional unit and reference flows

With respect to thermal insulation products, the thermal resistance R (or its inverse, the thermal transmittance U=1/R) has to be chosen as operational parameter. The thermal transmittance (U) is the heat flow in watts (W) through 1 m² of a building component when the temperature difference between the surfaces in the direction of heat flow is 1K.

Therefore, the basis for comparison in the LCA study is the equivalent thermal performance (in terms of *U-value*) of the wall insulation product during a given service life period. By consensus in the consortium, and as specified in other project Deliverables (e.g., D4.1 v06), service life time is established as 30 years.

Functional unit (F.U.):
Amount of insulation material for achieving **U=0.20 W/m^{2}K** (i.e. thermal resistance R=5 m^{2}K/W) in 1 m^2 area of building wall **over 30 years**

Product system to be evaluated: advanced VIP with organic nanofoam core ("OVIP").
Benchmark(s) for environmental performance comparisons:

- Boards of Polyurethane rigid foam ("PUR foam boards")
- VIPs with fumed silica core ("silica VIPs")

Reference flows of insulation materials for performing "the same function"

- 1 m^2 PUR foam board 12.5 cm thick (λ= 0.025 W/mK, d= 30 kg/m^3) → 3.75 kg needed
- 1 m^2 VIP with fumed silica core, 2 cm thick (λ< 0.004 W/mK)
- 1 m^2 OVIP with PU nanofoam core, 2.5 cm thick (λ= 0.005 W/mK)

6.1.2 Description of the product systems

The main characteristics of the insulation products considered in the LCA study are shown in the tables below.

Table 1. Description of PUR rigid foam board (average)

λ, W/mK	0.025
d, kg/m^3	30
unit size	custom made: 1 m^2 x thickness upon request so that U-value=0.20 W/m^{2}K
(λ) service life, years	30
composition	industry average polyurethane rigid foam (ref. ISOPA)

(source: consensus value for d & λ, Va-Q-Tec and Kingspan at project meetings)

Table 2. Description of silica VIP

λ, W/mK	<0.004 (initial, @1mbar) 0.005 (after 30 years of service)
d, kg/m^3	200 kg/m^3(thickness 20mm: 4.0 kg/m^2)
unit size	1 m^2 panel, thickness 2.0 cm (U-value=0.20 W/m^{2}K) standard sizes (ref. Kingspan): 120 /60 cm × 120 cm × 2 cm
(λ) service life, years	30 increase of gas pressure: ca. 1 mbar/year the predicted change of the thermal conductivity after 30 years is 1.0 mW/(m K) (20% increase)
composition	• core: ➢ pressed fumed silica powder λ= 0.02 W/mK in air, bulk d= 180-210 kg/m^3 (a-SiO_2 d=2200 kg/m^3) ➢ opacifier (silicon carbide (SiC)) ➢ fibre fleece (polyester (PET) fibres) • envelope: high barrier film 50 µm PE, 36 µm PET • "Va-Q-check" sensor: ➢ metal chip for sensor (aluminium disk) ➢ glass fibre fleece for sensor
other considerations	for LCA calculations inventory data for production of 3-layer metallised film by HANITA (VO8621) are used (VO8621 trilaminate= 3 layers of metallised 12 µm PET + 1 layer 50 µm PE) product *va-Q-plus* by va-Q-tech used as silica VIP benchmark

Table 3. Description of OVIP

λ, W/mK	0.005 (initial, @0.1mbar) 0.014 (after 30 years of service) 0.035 (atmospheric pressure)
d, kg/m^3	130-180
unit size	demo panels 40 cm × 45 cm, thickness 3 cm
(λ) service life, years	30 yearly gas pressure increase of 0.25 mbar/year the predicted change of the thermal conductivity after 30 years is 9 mW/(m K) (200% increase)
composition	• core: PU nanofoam slab (BASF formulation 174-1) λ=0.0048 W/mK, d=130 kg/m^3 • envelope: opaque laminate (HANITA) "Standard PET 23 µm / Al / AlOx / ORMOCER System 1 / AlOx / Al / adhesive / HDPE 50 µm" • desiccant (calcium oxide) • "Va-Q-check" sensor
other considerations	for LCA calculations inventory data provided for manufacturing 1 m^2 panel of thickness 2.5 cm (→ U=0.20 W/m^2K)

6.1.3 System boundaries

The present LCA uses the attributional approach. The system boundaries for this simplified LCA of wall insulation products follow the modular design defined by standard EN 15804. The modules which are within the scope of this study are described below.

- For the PRODUCT STAGE: raw materials supply (Mod.A1) and manufacturing processes (Mod.A3) are included in the study. Transport of OVIP components to VIP manufacturer's factory (Mod.A2) is not included, to avoid misrepresentation of transport of pilot-scale materials between partners in the scope of the project.

- CONSTRUCTION STAGE: Transport from factory to construction site (Mod.A4), including production of packaging and its EOL. Consensus reached on not to include the Installation phase: no data available on non-negligible differences in the installation activities (consumption of auxiliaries, product rejects or offcuts, etc.).

- USE STAGE: consensus reached on not to include maintenance/repair/refurbishment activities for installed insulation products during the 30 yr. service life. Use phase (Mod.B1) is evaluated by the simplified analysis of operational energy in use, based on the calculation of requirements of delivered energy for space heating associated to heat losses per unit area due to heat transfer by thermal conductance of the material.

- EOL STAGE: it is assumed within the consortium that differences in de-installation of the analysed insulation products are negligible; therefore Deconstruction module (C1) is not considered. Modules C2 (transport from deconstruction site to waste treatment facilities), C3 (waste process for reuse, recovery or recycling) and C4 (waste treatment processes for disposal) are included in the study. Also Mod.D (Reuse, recycling, recovery potential).

Capital goods and equipment have not been included in the foreground processes for manufacturing, use and waste treatment operations modelled from specific data collected for the study. In the case of generic data used for the background processes or average operations in the industry, capital equipment and machinery may be included in the datasets. For the consistency of the consideration of infrastructure in the study generic datasets have been selected from the same LCI database (*Ecoinvent System process v2.2*).

6.1.3.1 Cut-off rules

In principle, all inputs and outputs to every unit process within the system boundaries for which data are available are included in the calculations. Data gaps are filled by conservative assumptions with average or generic data, based on unit processes with similar outputs or technologies.

In case of insufficient data, materials or processes can be omitted if they contribute with less than 1% to the total mass or energy flows and provided that the sum of all the excluded materials and processes will not exceed 5% of total mass or energy use of product system.

6.1.3.2 Allocation

The provisions in ISO 14040 and ILCD Handbook have been followed for allocating flows and impacts when modelling multi-output processes has been needed.

Components for reuse and materials for recycling and energy recovery are considered as potential resources for future use, which result in benefits (avoidance of production of primary fuels and raw materials) but that entail certain environmental loads due to the recovery process. The net benefits are quantified in Module D of the LCA study and are compared to the production of the substituted item.

6.1.4 Data quality requirements

Representativeness:

- Technological and geographical: average European technology, average European transport conditions and European average Electricity mix.
- Temporal coverage. : 2000-2014.

Foreground Data: specific data based on production data provided by companies involved in the project

Background data: generic data from LCI databases providing average datasets: Ecoinvent v2.2 (system process), except for operational energy in use from fuels burned in boilers (ELCD datasets considered better representatives). Missing standard datasets for background processes have been modelled from average industry data provided by European manufacturers associations, if possible. Alternatively, industry data from individual companies are used.

References are appropriately reported in the LCI chapter. Datasets from LCI databases used in the study are listed in the Appendices.

6.1.5 LCIA methodology, impact categories and environmental indicators

Literature review on B/C LCA has been conducted by GAIKER, in order to check the recommendations on: selection of impact categories relevant to building applications and impact assessment models. The literature review includes EN and ISO standards dealing with methodological issues in sustainability and environmental performance assessment of construction works (ISO 21931-1, EN 15643-1, EN 15978 (buildings), EN 15804 (products), CEN/TR 15941), as well as the EeBGuide. According to the practical rules given in the aforementioned standards and guidelines the following environmental indicators have been included in the assessment:

- environmental impact categories of LCIA (mid-point indicators):
  - Climate change (expressed as Global Warming Potential),
  - Stratospheric Ozone Depletion,
  - Acidification Potential,
  - Eutrophication Potential,
  - Formation of Tropospheric Ozone (as photochemicals oxidants),
  - Abiotic Resources Depletion (materials & fossil fuels)
- environmental aspects (LCI):
  - inputs data: use of Renewable & Non-renewable energy resources (Primary Energy & Secondary Fuels), use of Fresh Water;
  - waste data: Hazardous, Non-hazardous & Radioactive waste to final disposal;
  - outputs data: Components for re-use, Materials for recycling, Materials for energy recovery, Exported energy

Table 4. List of environmental indicators used for the assessment and expression of results

Impact category indicator	**Unit**	**Method ref.**
Climate change expressed as GWP (GWP)	kg CO_2 equiv.	ILCD 2011
Destruction of the stratospheric ozone layer (ODP)	kg CFC-11 equiv.	ILCD 2011
Acidification of land & water resources as Acidification Potential (AP)	kg SO_2 equiv.	CML 2001
Eutrophication (EP)	kg PO_4 equiv.	CML 2001
Formation of ground level ozone expr.as photochemical oxidants (POCP)	kg C_2H_4 equiv.	CML 2001
Use of non-renewable resources (as Abiotic Depletion) (ADP)	kg Sb eq	CML 2001
Use of non-renewable primary energy (PENRT)	MJ	CED 1.08
Use of renewable primary energy (PERT)	MJ	CED 1.08
Water resource depletion (WRD)	m^3 water eq	ILCD 2011
components for reuse (CfR)	kg	inventory
materials for recycling (MfR)	kg	inventory
material for energy recovery (MfER)	kg	inventory
hazardous waste to final disposal (HWD)	kg	inventory
non-hazardous waste to final disposal (NHWD)	kg	inventory

The LCA software used for the environmental calculations has been SimaPro 7.3.3. Mid-point indicators for the selected impact categories have been selected from the relevant methods included in the software, as indicated in Table 4. Indicators of environmental aspects derived from the inventory have been calculated from the analysis of the inventory, by computing the corresponding flows addressed to disposal operations or to reuse/recycling/recovery.

6.2 Life Cycle Inventory (LCI)

In order to collect all the necessary information about consumptions and outputs through the life cycle of the product to be investigated, which has been later considered in the assessment of their environmental repercussions, a systematic inventory of the inflows and outflows of the different aspects and operations associated with the production, distribution-installation, use and end-of-life of the product has been made.

- For the PRODUCT STAGE the inventory of input and output flows has been made from process flowcharts and mass and energy data supplied by the partners involved in the synthesis of the materials, supplemented with average industry data and literature values when needed.
- CONSTRUCTION STAGE: Transport to construction site modelled using average data and packaging description given by va-Q-tec and Kingspan for silica VIPs. Consensus reached on not to include the Installation phase.
- USE STAGE: consensus reached on not to include maintenance/repair/refurbishment activities for installed insulation products during their service life. Use phase has been evaluated by the simplified analysis of operational energy in use, based on the calculation of requirements of delivered energy for space heating associated to heat losses per unit area due to heat transfer by thermal conductance of the material.
- EOL STAGE: modelled from current EOL routes for building insulation materials and conclusions of the study of recyclability and recovery potential of the novel materials conducted by GAIKER in Task 6.3.

6.2.1 PRODUCT Stage

<u>PUR RIGID FOAM BOARDS</u>

In the case of PUR boards, source of data for the inventory of the Product stage are the Eco-profile of the European Plastics Industry for POLYURETHANE RIGID FOAM (Plastics Europe, 2005) and the Eco-profiles for the precursors (MDI-TDI and Polyether Polyols) by ISOPA (2012). The corresponding LCI dataset is available in the Ecoinvent v2.2 database.

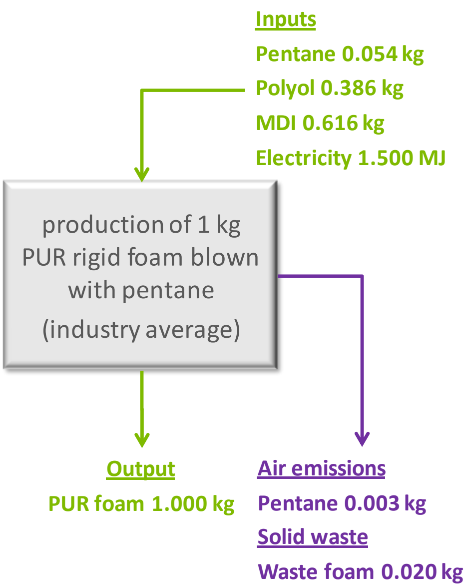

Figure 3. Input-output flowchart for production of 1 kg PUR rigid foam.

SILICA VIPS

The inventory for the production of 1 m^2 of silica vacuum insulation panels has been provided by va-Q-tec. The manufacturing process comprises the following operations: weighing of components, mixing of components, pressing boards from powder, cutting boards to size, wrapping board with fibre fleece, drying board by heating, wrapping board into high barrier film, evacuating, sealing, storing VIP for several days, testing gas pressure, packaging.

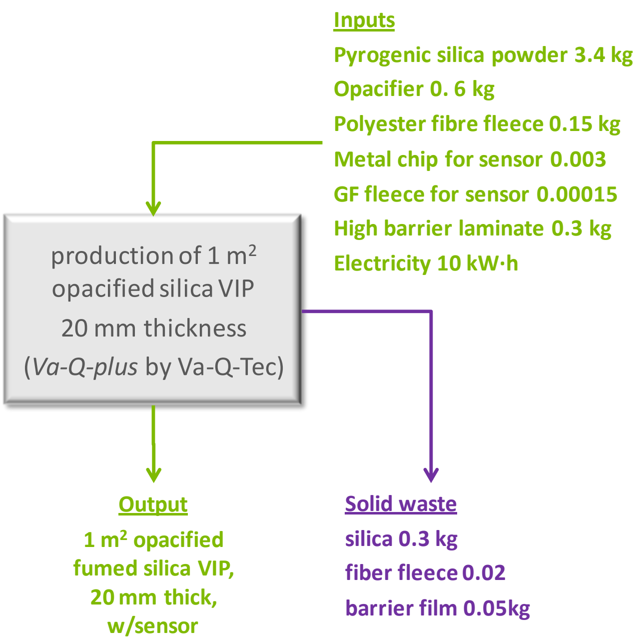

Figure 4. Input-output flowchart for production of 1 m^2 silica VIP.

The following waste treatments are assumed for disposal of manufacturing waste:

- Silica: inert waste landfill
- Polyester fibre fleece: non-hazardous waste incineration
- Barrier film: non-hazardous waste incineration

Supply of most of the raw materials for silica VIPs can be represented with standard LCI datasets available in the Ecoinvent v2.2 database. Production of synthetic amorphous pyrogenic silica has been modelled using average industry data provided by CEFIC-ASASP (*Source: European Commission. Integrated Pollution Prevention and Control. Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals - Solids and Others industry. July 2007*).

The inventory for the production of the high barrier trilaminate (VO8621 film) for the VIP envelope has been supplied by HANITA. Production of VO8621 trilaminate is done in two consecutive steps: first, aluminium vapour metallisation of individual PET layers by physical vapour deposition. Second step: lamination of 3 layers of aluminium metallised PET and one layer of LDPE, using MEK-based PU adhesive. PU adhesive has been modelled as a mixture of one third MDI and two thirds polyether polyol (*Source: Edward M. Petrie. Training Courses on Polyurethane Adhesives Part I: Formulation. SpecialChem Adhesives & Sealants*).

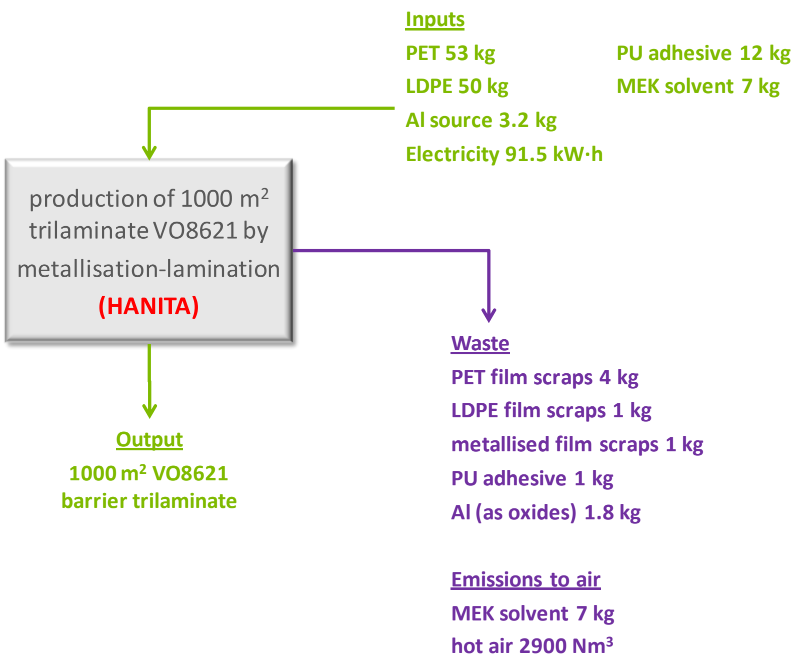

Figure 5. Aggregated input-output flowchart for production of 1000 m^2 VO8621 trilaminate film.

Assumptions about destination of waste generated in the production of barrier trilaminate:

- PET film, LDPE film, metallised film: non-hazardous waste incineration
- PU adhesive (not cured): hazardous waste incineration
- Aluminium losses in deposition process: non-hazardous waste landfill. Alternative EOL: recycling of aluminium

PRODUCT STAGE - Alternative Scenario – silica VIP
VIPs manufactured with (100%) recycled silica with opacifier content, from cores of collected EOL VIPs. Density may be 10-20% higher. Silica and opacifier not needed, rest of raw materials the same as in the baseline scenario. Consumption of energy: 10 kWh/m² as for regular silica VIPs + 2 kWh/m² for additional work (recycling process: removal of envelope, sensor and fibre fleece wrapping, sent to disposal (barrier film, fibre fleece, glass fibre fleece) and recycling (aluminium disk)). Service life time and thermal conductivity: the same as of regular silica VIPs.

OVIPS

The inventory for the production of 1 m^2 of the advanced opaque vacuum insulation panels has been estimated considering that the nanofoam cores are supplied to the VIP manufacturer as slabs of the required size. The operations in the manufacturing process: drying slab by heating, desiccant addition, wrapping core into high barrier film, evacuating, sealing, storing VIP for several days, testing gas pressure, (packaging). Consumption of energy in the manufacturing of OVIPs has been estimated by va-Q-tec at 5 kWh/m^2. The barrier film waste generated is sent to non-hazardous waste incineration.

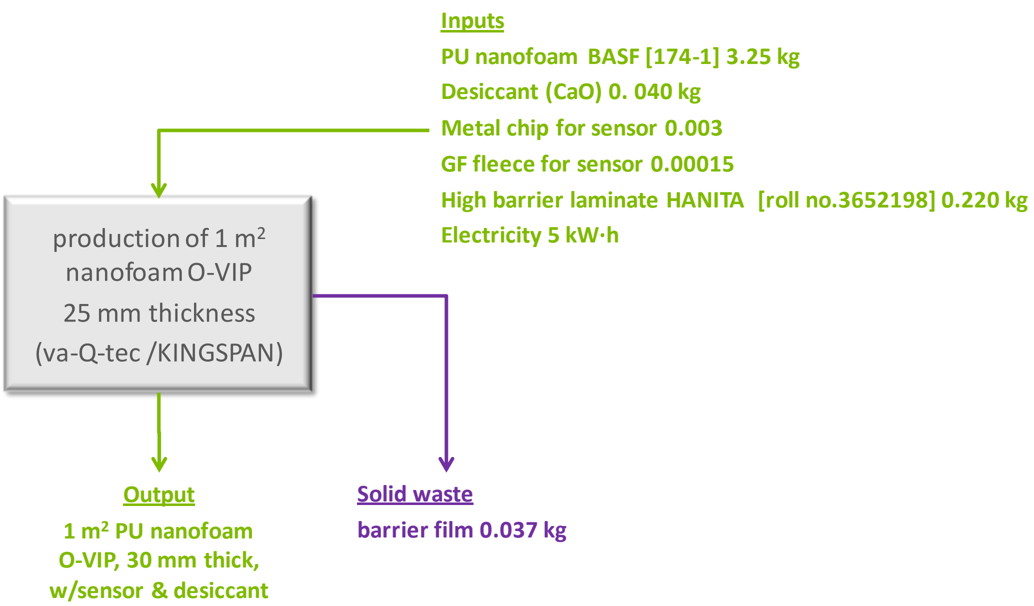

Figure 6. Input-output flowchart for production of 1 m^2 OVIP.

The inventories for production of the PU nanofoam core and the opaque barrier laminate for the envelope have been gathered from data provided by BASF and HANITA, respectively.

Production of PU nanofoam is done by sol-gel chemistry, followed by a drying step. For the isocyanate and polyol standard datasets in LCI databases are used. The LCI datasets for amine catalysts and solvent have been modelled from proxies proposed by BASF (not disclosed due to confidentiality terms). When no standard dataset is readily available for those chemicals, the stoichiometric quantities of raw materials in their synthesis, without inclusion of energy term, and taking into account reaction yield (as reported in literature) have been used. According to BASF, 99% of solvent used in the batch process is recovered; the remaining 1% is combusted. Additives account for less than 1% of mass inputs to product system and can be neglected. Energy used for mixing and drying: electricity and natural gas.

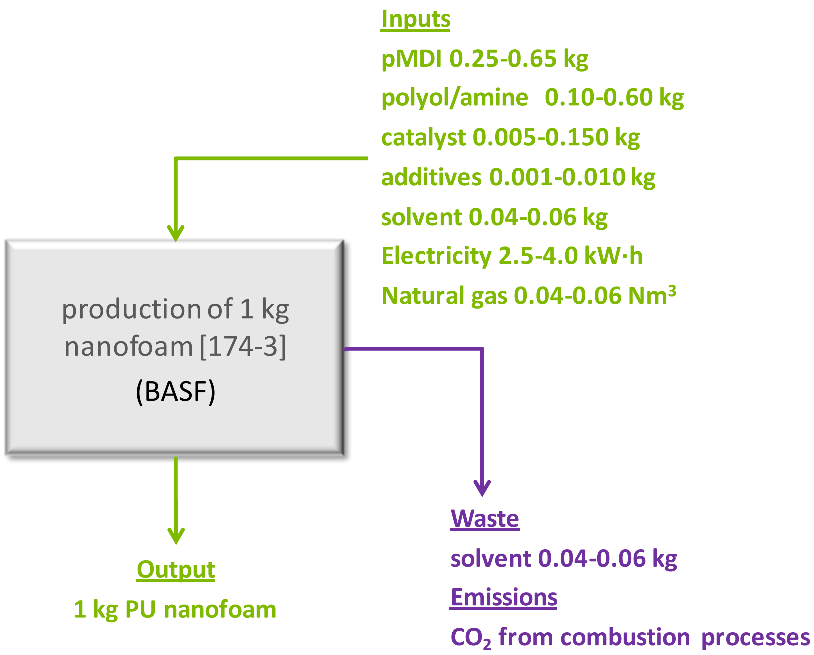

Figure 7. Input-output flowchart for production of 1 kg PU nanofoam.

Two different combinations of the mass and energy inputs in the declared ranges of values have been worked out (case A and case B) to check their influence in the LCA results.

LCI - case A

assumptions:

ratio MDI:polyol = pMDI min : polyol max
additives: avg. --> neglible (<1%)
catalyst = avg.
solvent = min.
energy = electricity avg. & natural gas min.
CO2 emissions = max.

LCI - case B

assumptions:

ratio MDI:polyol = pMDI max : polyol min
additives: 3/4max--> neglible (<1%)
catalyst = max
solvent = min.
energy = electricity avg. & natural gas min.
CO2 emissions = max.

Regarding production of the opaque high-barrier laminate, it is done in four consecutive steps: PET is, firstly, coated by thermal deposition of aluminium and then undergoes a second metallisation step (reactive deposition of AlOx). The coating process of Ormocer Sys1 has been assimilated to the lamination step, in terms of energy and net mass consumption of films. Two additional metallisation steps are applied later (in the order: reactive deposition of AlOx and, then, PVD of Al metal). Final step is the wet lamination of the high barrier structure to the sealing HDPE film, using solvent based PU adhesive (solvent: Methyl Ethyl Ketone). Destination of waste generated in the production of the high-barrier trilaminate is assumed as follows:

- PET film, HDPE film, metallised films: non-hazardous waste incineration
- PU adhesive (not cured): hazardous waste incineration
- ORM Sys1 lacquer remains: proxy = paint incineration in non-hazardous waste incineration
- Aluminium losses in deposition process: non-hazardous waste landfill. Alternative EOL: recycling of aluminium

1. Metallisation of PET film (2 stage process, 2nd stage of Al_2O_3)
2. Wet layer coating ORMOCER® System 1 lacquer
3. Deposition (2 stage process) of upper layers of AlOx & Aluminium onto the structure Nano 544 “Standard PET / Al / AlOx /ORMOCER® Sys1”
4. Lamination of 1 layer of high-barrier structure and 1 layer of HDPE seal film

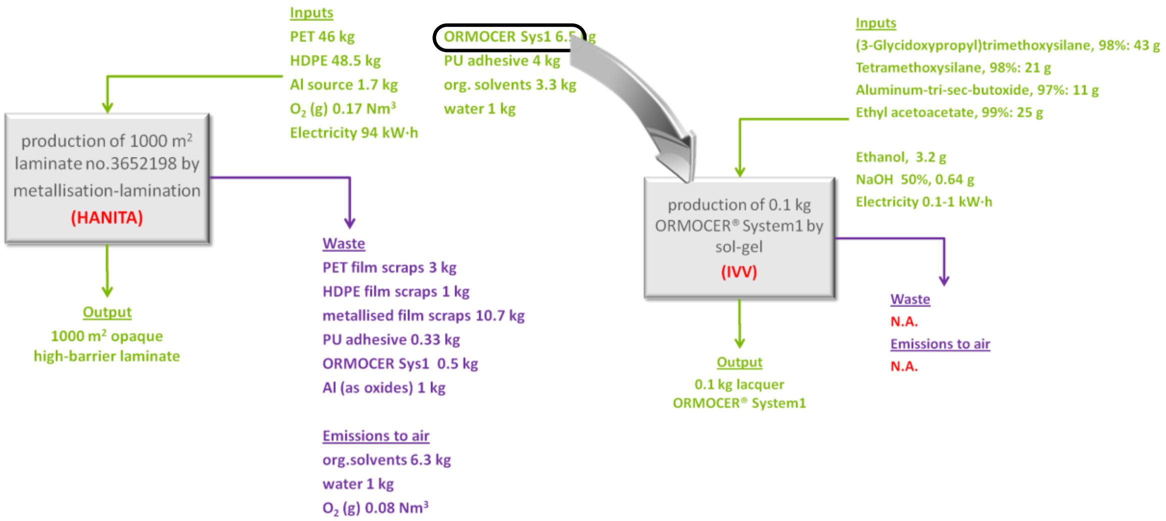

Figure 8. Input-output (aggreg.) flowchart for production of 1000 m^2 of advanced high-barrier laminate (opaque)

The LCI for supply of the ORMOCER® System1 lacquer is based on the description of process and data about raw materials consumption provided by Fraunhofer IVV for production at lab-scale and on a larger scale (output: 50 kg). The LCI datasets for chemicals not included in LCI databases have been prepared from information about organic synthesis reactions, using the stoichiometric quantities of the reactants as raw materials and considering the yield of the reactions. No data about energy consumption in the preparation of the lacquer have been made available. Electricity consumption for stirring have been estimated from literature references about power requirements for mixing in industrial bioreactors and from rated power figures in specifications of pilot-scale equipment. A sensitivity check has been carried out, considering two different values for electricity consumption 1 and 0.1 kWh per 100 g lacquer.

PRODUCT STAGE - Alternative Scenario – OVIP
Nanofoam is delivered to VIP manufacturer in blocks (1,25×1,25×1 m3) and cores are cut to size (1,20×1,20×0,025 m3) Manufacturing process comprises: cutting slabs to size from nanofoam block, drying slabs by heating, desiccant addition, wrapping slab into high barrier film, evacuating, sealing, storing VIP for several days, testing gas pressure, packaging. Foam losses by cutting estimated at 13wt%. Rest of raw materials the same as in manufacturing of OVIP in the baseline scenario. Consumption of energy: 7.5 kWh/m² (assumed 2.5 kWh/m^2 additional for the cutting step). Foam cut-offs sent to non-hazardous waste incineration.

6.2.2 CONSTRUCTION Stage

Only transport module. It includes the lifecycle of associated packaging (production of packaging materials and end-of-life of packaging after delivery of products to construction site). For all the products the following assumptions apply:

- Transport of packaged product from factory gate to construction site by road. Distance: 300 km. Truck 16t (fleet average)
- Transport of waste to disposal facilities by road. Distance: 30 km. Truck 16t (fleet average). Load factor 50% (return trip: empty).

PUR RIGID FOAM BOARDS

Packaging for PUR rigid foam boards: PE film. No palletised (*Source: PU Europe. Environmental Product Declaration Polyurethane (PU) Boards: Foam without facing R=5*)

Table 5. LCI for Packaging in transport module (PUR boards)

packaging	kg per reference flow kg/m² PUR boards R5	EOL of packaging material
LDPE film	0.0439	non-hazardous waste incineration
total packaging	**0.0439**	
total transported good	**3.7939**	

SILICA VIPS

Two alternative packaging options considered, based on information provided by partners in the consortium:

- **Option V** (Source: va-Q-tec): individually, with PE film and in a cardboard box. 50 units/pallet
- **Option K** (Source: Kingspan): Multiple panels in vertical position in a cardboard box with EPS dividers. Amount per box varies on size and thickness of VIP but typically for 20 mm 1200 x 600 panel, 16 panels per box (box size 245x625x645). 1 box/pallet.

Based on those indications, amounts of packaging materials have been estimated for the two alternative packaging options, using own assumptions about dimensions of EPS dividers, cardboard grammage, PE wrapping film thickness, etc. The two packaging options are modelled as opposed alternatives to detect relevant environmental differences in a theoretical exercise. In practice, multiple VIPs are packaged per box and then palletised by both companies and no major differences in packaging materials per square metre of VIP are envisaged.

Table 6. Estimated LCI for packaging in transport module (silica VIPs, option V)

packaging	kg per reference flow kg/m² silica VIP R5	EOL of packaging material
LDPE film	0.211	recycling 50% + disposal to MSWI 50%
corrugated cardboard (box)	0.886	recycling 75% + disposal to MSWI 25%
pallet (EUR-flat pallet)	0.44	reuse 80% + disposal to MSWI 20%
total packaging	**1.537**	
total transported good	**5.537**	

Table 7. Estimated LCI for packaging in transport module (silica VIPs, option K)

packaging	kg per reference flow kg/m² silica VIP R5	EOL of packaging material
EPS	0.202	disposal to MSWI 100%
corrugated cardboard (box: 16u)	0.233	recycling 75% + disposal to MSWI 25%
pallet (EUR-flat pallet)	1.91	reuse 80% + disposal to MSWI 20%
total packaging	**2.344**	
total transported good	**5.824**	

OVIPS

The two packaging options considered for silica VIPs have been also applied to OVIPs. Size of the cardboard box is assumed the same; for option K this means that number of panels and EPS dividers in each box is smaller than for silica VIPs (due to panel thickness).

Table 8. Estimated LCI for packaging in transport module (OVIPs, option V)

packaging	**kg per reference flow kg/m^2 OVIP R5**	**EOL of packaging material**
LDPE film	0.213	recycling 50% + disposal to MSWI 50%
corrugated cardboard (box)	0.886	recycling 75% + disposal to MSWI 25%
pallet (EUR-flat pallet)	0.44	reuse 80% + disposal to MSWI 20%
total packaging	**1.539**	
total transported good	**5.019**	

Table 9. Estimated LCI for packaging in transport module (OVIPs, option K)

packaging	**kg per reference flow kg/m^2 OVIP R5**	**EOL of packaging material**
EPS	0.204	disposal to MSWI 100%
corrugated cardboard (box: 14u)	0.266	recycling 75% + disposal to MSWI 25%
pallet (EUR-flat pallet)	2.18	reuse 80% + disposal to MSWI 20%
total packaging	**2.652**	
total transported good	**6.132**	

6.2.3 USE Stage

Performance of insulation products in their service life (30 yr.) is evaluated by the calculation of operational energy in use:

- Simplified comparative analysis based on annual heat transfer by transmission per unit area of insulation material, estimated from thermal conductivity of material and Heating Degree Days. No heat storage (based on heat capacity of materials) nor thermal bridges considered.
- The annual heat transfer per 1 m^2 area of insulation materials is estimated as q=U*HDD. U-value corresponding to each year in service of the product is calculated by estimation of the annual value of thermal conductivity, depending on the thermal aging characteristics of each product.
- Heating Degree Days: proxy for the energy demand needed to heat a home or a business; it is derived from measurements of outside air temperature. HDD are

defined relative to a base temperature, the outside temperature below which a building is assumed to need heating. For estimating heating needs for the use stage, an annual value of 3000 K·d has been used, as EU-27 average in the next 30 yr. (*Source: Eurostat. Trend in heating degree days in the EU-27*)

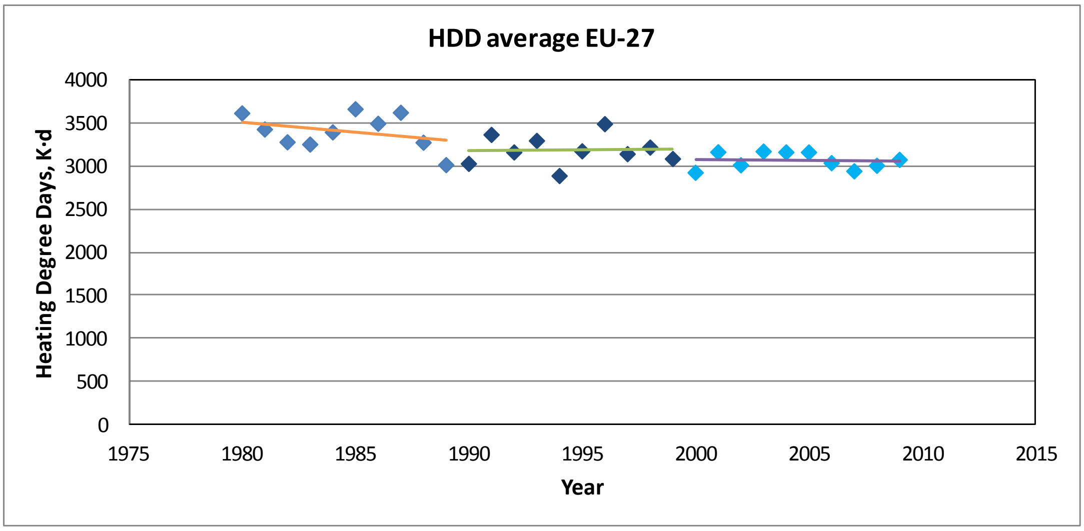

Figure 9. Average EU-27 heating degree-days over period 1980 – 2009 (*Source: Eurostat*)

- Space heating is delivered to end users in different ways (individual boilers fuelled by oil, gas, and coal, and electricity and district heating). For the evaluation of the Use stage in the project, 3 potential energy carriers, with different heating efficiencies, have been considered:
    - Electricity – heat pump 10 kW (electr.)
    - Natural gas – condensing boiler 14.9 kW (NG)
    - Fuel oil – light fuel oil condensing boiler 14.9 kW (oil)
- The efficiencies by fuel used for calculation purposes are the following: electricity 97%, fuel oil 75%, gas 80% (*Ref. Data on households (Fact sheet ENER22: Households energy consumption and emissions). ODYSEE*)

PUR RIGID FOAM BOARDS

As explained in (BING, 2006)[2], in addition to the thermal conductivity of the solid material structure and the heat radiation in the foam cells, the thermal conductivity of rigid polyurethane foam (PUR/PIR) depends for the most part on heat transfer through the cell gas. The relatively sharp increase in thermal conductivity at the beginning of the service life is due to the gas exchange between blowing agent and air (thermal conductivity c. 0.024 W/(m·K). After approximately 3 years, cell gas composition reaches stable equilibrium and thermal conductivity changes minimally thereafter. In general, insulation materials of greater thicknesses achieve lower long-term thermal conductivity values. The time curves show that the 'fixed increments' in accordance with EN 13165 for pentane are:

- 5.8 mW/(m·K) at thicknesses < 80 mm
- 4.8 mW/(m·K) at thicknesses > 80 mm and < 120 m

The declared values of thermal conductivity (λ_D) will not be exceeded even over very long periods.

Assumptions:

- Thermal conductivity virtually constant in service life: declared λ, W/(m·K) = 0,025 → λ, W/(m·K) ≈ constant after 3 yr.(=0,025).
- Modelled variation of thermal conductivity for pentane blown foam boards with thickness >80 mm: initial $\lambda \approx$ 0.0202 W/(m·K), λ increment 0,0048 W/(m·K). See Figure 10.
- Average values: annual heat transfer = 14.4 kWh/(m^2·a); cumulative heat transfer after 30 yr.= 432 kWh/m^2

[2] Thermal insulation materials made of rigid polyurethane foam (PUR/PIR). Properties - Manufacture. Report no.1. Federation of European Rigid Polyurethane Foam Associations. October 06

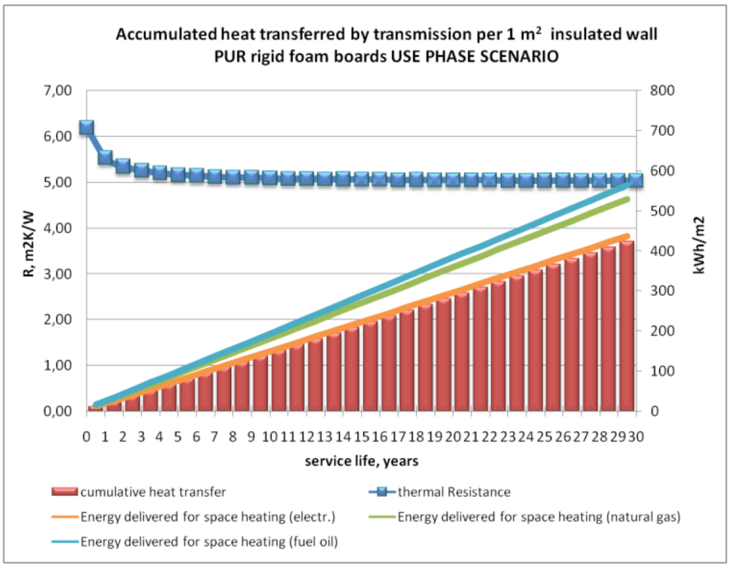

Figure 10. Variation of thermal resistance of PUR boards over service life for declared λ=0.025 W/(m·K) *vs* cumulative heat transfer and energy delivered for space heating (3 energy carriers)

SILICA VIPS

Assumptions:

- Linear increase of thermal conductivity over the years:
  - Initial λ <0.004 W/(m·K) (@1mbar)
  - $\nabla\lambda = 2.67 \cdot 10^{-5}$ W/(m·K·a)
  - predicted change of the thermal conductivity after 30 years is 0.001 W/(m K) (20% increase): λ =0.005 W/(m·K) (after 30 years of service)
- Thermal conductivity of silica VIP in air: λ =0.02 W/(m·K)
- Two scenarios (see Figure 11):
  - **SCENARIO 1**: annual linear increase during 30 years.

    Average values: λ = 0.0045 W/(m·K), U= 0.23 W/(m^2·K), annual heat transfer = 16.2 kWh/(m^2·a); cumulative heat transfer after 30 yr.= 486 kWh/m^2
  - **SCENARIO 2**: total failure after 3 years in service.

    Average values: annual heat transfer = 14.6 kWh/(m^2·a) in the first 3 years and 72 kWh/(m^2·a) in the rest of service life years; cumulative heat transfer after 30 yr. = 1988 kWh/m^2

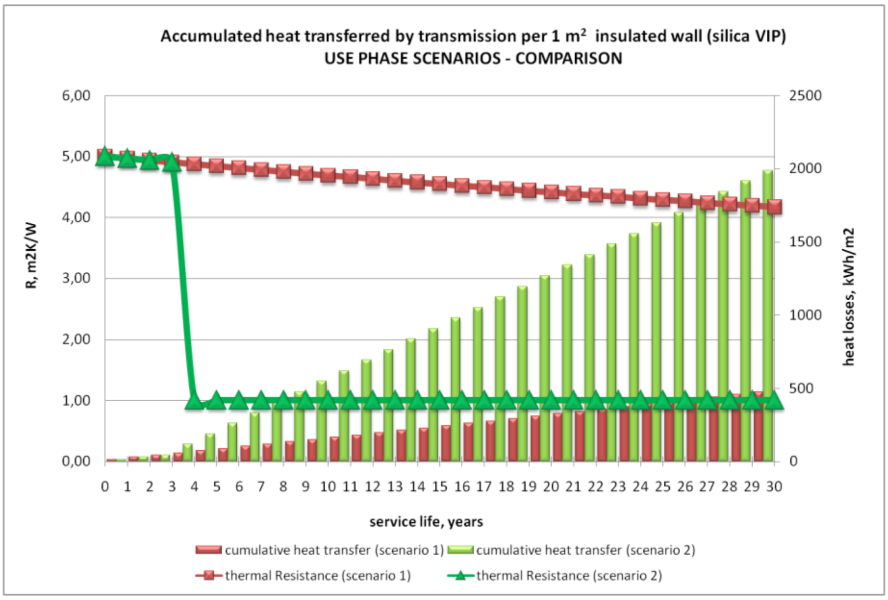

Figure 11. Variation of thermal resistance of silica VIPs over service life *vs* cumulative heat transfer. Scenarios 1 and 2 compared.

OVIPS

Assumptions:

- Linear increase of thermal conductivity over the years:
  - Initial λ =0.0048 W/(m·K) (@0.1mbar)
  - $\nabla\lambda$= 0.0003 W/(m·K·a)
  - predicted change of the thermal conductivity after 30 years is 0.009 W/(m K) (200% increase): λ =0.0138 W/(m·K) (after 30 years of service)
- Thermal conductivity of OVIP in air: λ =0.035 W/(m·K)
- Two scenarios (see Figure 12):
  - **SCENARIO 1**: annual linear increase during 30 years.

    Average values: λ = 0.0094 W/(m·K), U= 0.38 W/(m^2·K), annual heat transfer = 27.1 kWh/(m^2·a); cumulative heat transfer after 30 yr.= 812 kWh/m^2
  - **SCENARIO 2**: total failure after 3 years in service.

    Average values: annual heat transfer = 31 kWh/(m^2·a) in the first 3 years and 101 kWh/(m^2·a) in the rest of service life years; cumulative heat transfer after 30 yr.= 2770 kWh/m^2

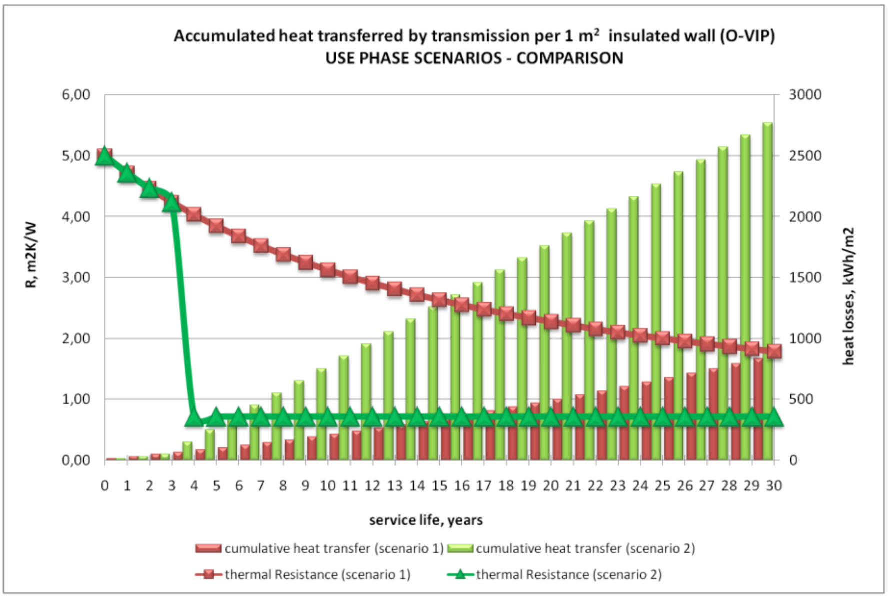

Figure 12. Variation of thermal resistance of OVIPs over service life *vs* cumulative heat transfer. Scenarios 1 and 2 compared.

6.2.4 EOL Stage

Common assumptions:

- Transport of waste from (de-)construction site to disposal facilities by road. Distance: 30 km. Truck 16t (fleet average). Load factor 50% (return trip: empty).
- Transport of waste from (de-)construction site to recycling facilities (manufacturer's factory) by road. Distance: 300 km. Truck 16t (fleet average). Load factor 100%.

PUR RIGID FOAM BOARDS

waste material	**kg per reference flow kg/m² PUR boards R5**	**EOL route**
PUR foam	3.75	non-hazardous waste incineration
total waste	**3.75**	

SILICA VIPS

Baseline scenario:

waste material	kg per reference flow kg/m^2 silica VIP R5	EOL route
core (silica + SiC opacifier + fibre fleece wrapping)	3.83	inert waste landfill
envelope (barrier trilaminate)	0.25	non-hazardous waste incineration
glass fibre fleece for sensor	0.00015	inert waste landfill
aluminium disk for sensor	0.003	aluminium recycling
total waste	**4.08**	

Alternative scenario: core recycling (for remanufacturing VIPs)

waste material	kg per reference flow kg/m^2 silica VIP R5	EOL route
core mix (silica + SiC opacifier)	3.7	recycling [pyrogenic silica & SiC]
polyester fibre fleece	0.13	non-hazardous waste incineration
envelope (barrier trilaminate)	0.25	non-hazardous waste incineration
glass fibre fleece for sensor	0.00015	inert waste landfill
aluminium disk for sensor	0.003	aluminium recycling
total waste	**4.08**	

OVIPS

waste material	kg per reference flow kg/m^2 OVIP R5	EOL route
core (PU nanofoam)	3.25	non-hazardous waste incineration
desiccant	0.0396	non-hazardous waste landfill
envelope (high barrier laminate)	0.18	non-hazardous waste incineration
glass fibre fleece for sensor	0.00015	inert waste landfill
aluminium disk for sensor	0.003	aluminium recycling
total waste	**3.48**	

6.3 Life Cycle Impact Assessment (LCIA)

The evaluation of the environmental performance of the three wall insulation products considered in the study, for the set of impact categories selected (section 6.1.4, Table 4), has been conducted for each stage of their life cycles and their contribution to the entire lifecycles is examined.

In a preliminary assessment the impacts of disposal and recycling/recovery treatments of waste and EOL material/energy outputs are included in the calculation of the indicators for the impact assessment categories, with the aim of simplifying the interpretation of results in the graphs (i.e., disposal and recycling/recovery operations accounted within the system boundaries). The indicators for LCI analysis with regards to waste to disposal and material for recycling/energy recovery are separately evaluated in the cases in which in-depth analysis is undertaken. Lifecycle results are shown (by default) for use stage scenarios that use natural gas (NG) for delivering energy for space heating. During the analysis of the use stage, the different environmental implications of the three energy carriers are discussed.

6.3.1 Environmental profile of PUR rigid foam board R5

As shown in the table and graph below, PRODUCT and USE stages are the main contributors to overall impact in the lifecycle of PUR insulation boards. Those stages are analysed subsequently, to identify the flows causing the greatest impacts.

Table 10. LCIA results for lifecycle of 1 sq.m PUR rigid foam boards (R5) 125 mm (NG energy carrier in USE stage). LCIA results breakdown per lifecycle stage

Impact category	Unit	PRODUCT stage	CONSTRUCTION stage	USE stage	EOL stage	Total
GWP	kg CO2 eq	16.152	0.300	6.843	9.270	**32.566**
ODP	kg CFC-11 eq	8.40E-08	2.63E-08	2.61E-07	3.03E-08	**4.02E-07**
AP	kg SO2 eq	0.067	1.17E-03	0.062	0.005	**0.136**
EP	kg PO4--- eq	0.014	3.29E-04	0.007	0.004	**0.025**
POCP	kg C2H4	0.008	3.88E-05	0.009	6.93E-05	**0.017**
ADP	kg Sb eq	0.161	0.002	0.886	0.002	**1.051**
WRD	m3 water eq	0.047	1.48E-04	-0.005	9.13E-04	**0.043**
PENRT	MJ	375.111	4.953	1669.107	4.937	**2054.107**
PERT	MJ	9.609	0.157	2.450	0.171	**12.387**

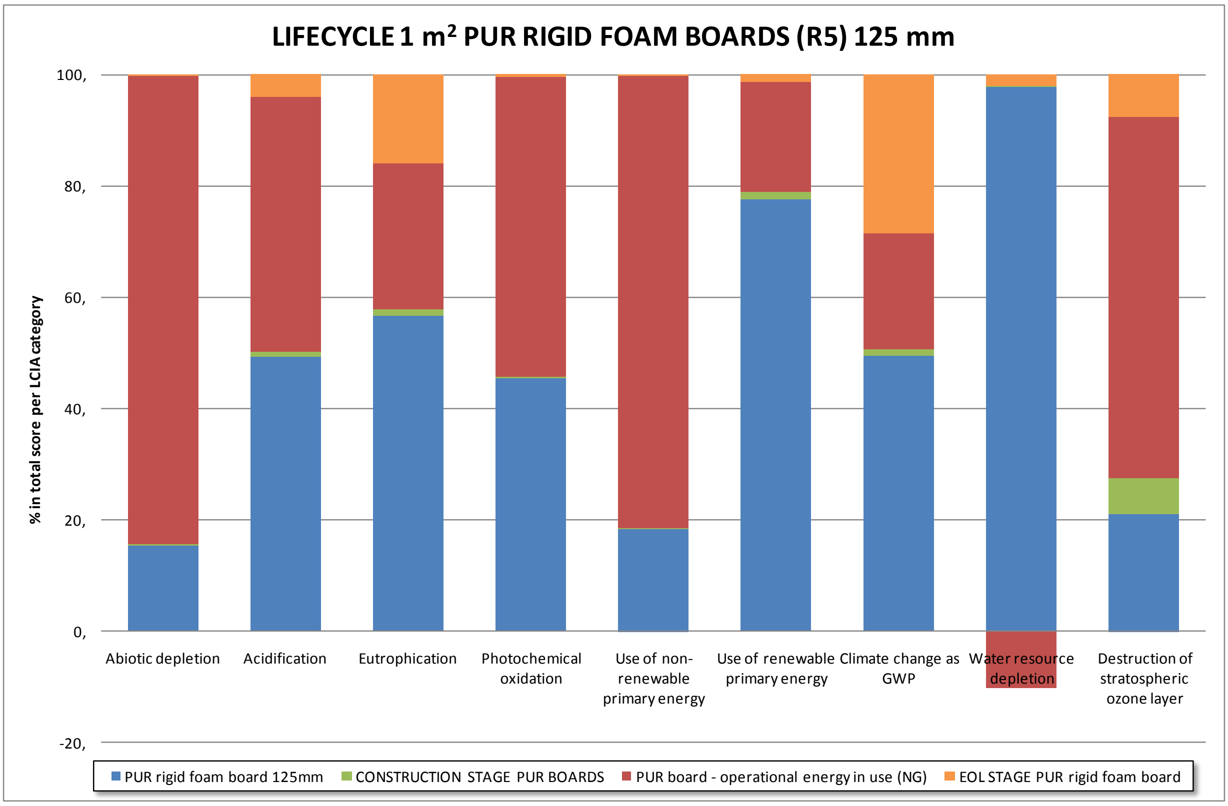

Figure 13. Lifecycle of f 1 sq.m PUR rigid foam boards (R5) 125 mm (NG energy carrier in USE stage) – Relative contribution of lifecycle stages to total LCIA results.

In the PRODUCT stage, the two precursors (polyols and MDI) have the greatest share in most of the impact categories, except for:

- Ozone layer depletion potential: consumption of electricity is the LCI input with the highest value of ODP indicator
- Formation of photochemical oxidants: the impact is mainly due to the blowing agent (pentane) emissions

Table 11. LCIA results for production of 1 sq.m PUR rigid foam boards (R5) 125 mm

Impact category	Unit	Pentane	Polyols	MDI	Electricity, MV	pentane emissions	waste foam to incineration
GWP	kg CO2 eq	1.277	30.357	53.060	4.738	0.000	10.569
ODP	kg CFC-11 eq	0.078	16.414	5.689	68.095	0.000	9.724
AP	kg SO2 eq	1.310	31.099	59.951	6.000	0.000	1.640
EP	kg PO4--- eq	0.492	47.381	26.543	19.793	0.000	5.791
POCP	kg C2H4	0.589	12.715	25.929	2.036	58.553	0.179
ADP	kg Sb eq	4.821	34.089	57.002	3.829	0.000	0.259
WRD	m3 water eq	0.061	28.273	68.910	2.363	0.000	0.393
PENRT	MJ	4.721	34.635	55.876	4.509	0.000	0.259
PERT	MJ	0.227	67.430	20.065	11.912	0.000	0.367

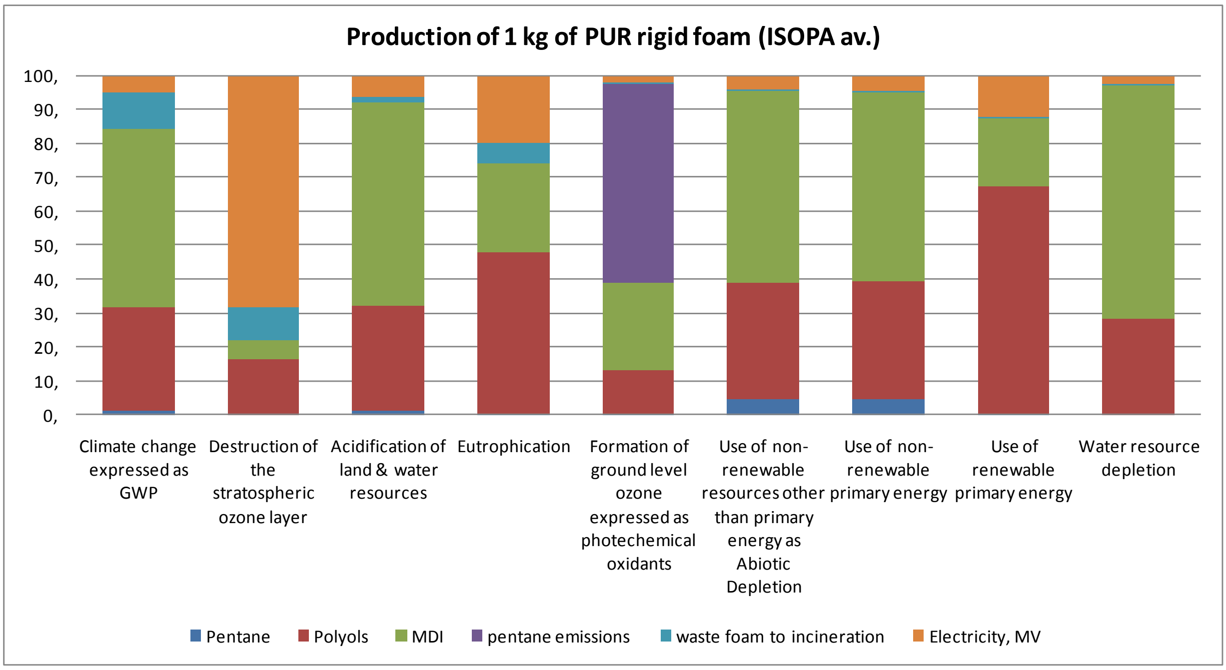

Figure 14. Relative contribution of LCI flows to LCIA results in the Production stage of PUR board.

In the USE stage, it has been assumed that the operational energy in use for compensating heat losses (ca. 430 kWh after 30 years) can be optionally delivered by electricity (heat pump), by natural gas burned in boiler or by fuel oil burned in boiler. The different impacts associated to each of the options for space heating are gathered in the table below and their relative scores can be observed in Figure 15.

Table 12. LCIA results for production of 1 sq.m PUR rigid foam boards (R5) 125 mm

Impact category	Unit	Electricity	Natural Gas	Fuel oil
GWP	kg CO2 eq	102.090	6.843	3.877
ODP	kg CFC-11 eq	1.22E-04	2.61E-07	1.04E-06
AP	kg SO2 eq	0.448	0.062	0.149
EP	kg PO4--- eq	0.318	0.007	0.018
POCP	kg C2H4	0.018	0.009	0.010
ADP	kg Sb eq	0.667	0.886	0.986
WRD	m3 water eq	0.120	-0.005	7.17E-06
PENRT	MJ	1822.562	1669.107	2032.880
PERT	MJ	120.184	2.450	6.502

As a whole, electricity is the energy carrier for space heating with the highest environmental impacts of the three options evaluated. The associated impacts to it are so high, that in the lifecycle perspective, they become the main ones and, when electricity is used for space heating, the USE stage turns into the principal responsible for the overall impacts of the PUR board in wall insulation applications (compare Figure 13 and Figure 16).

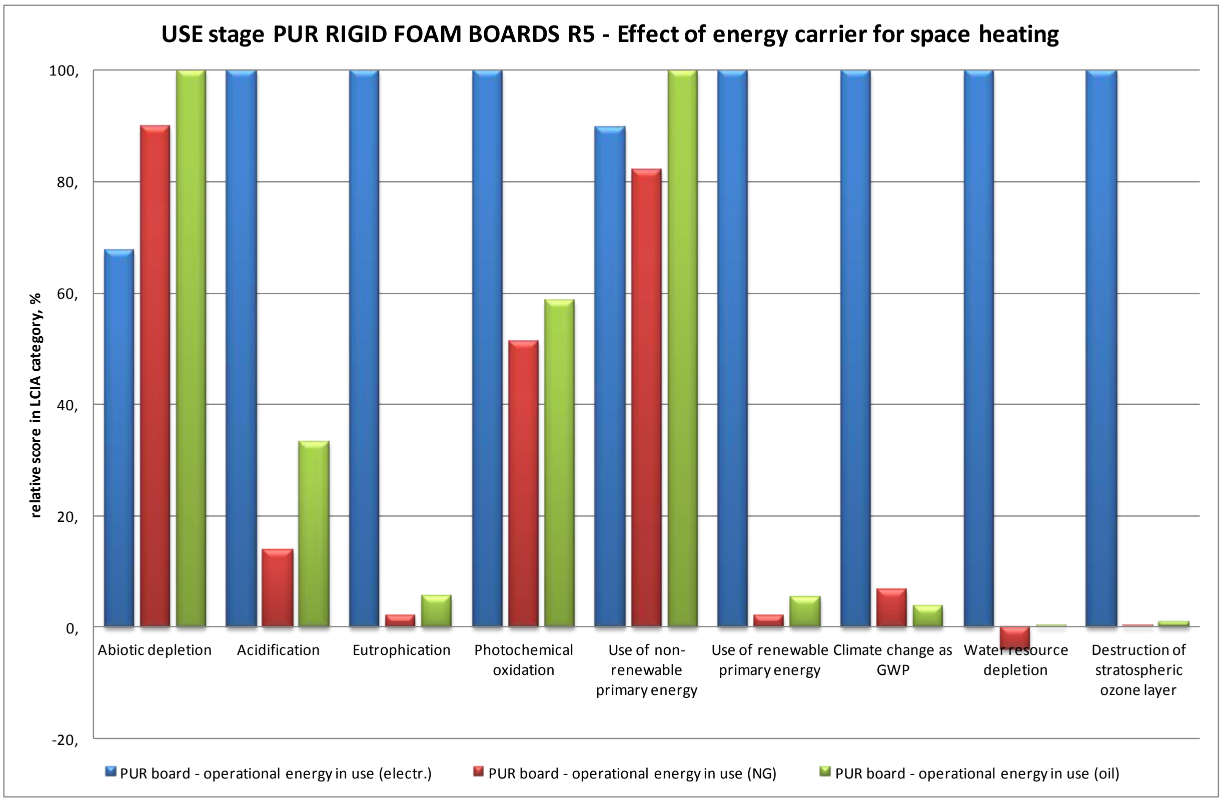

Figure 15. Relative score of each space heating system in the category impact indicators for the USE stage of PUR insulation board.

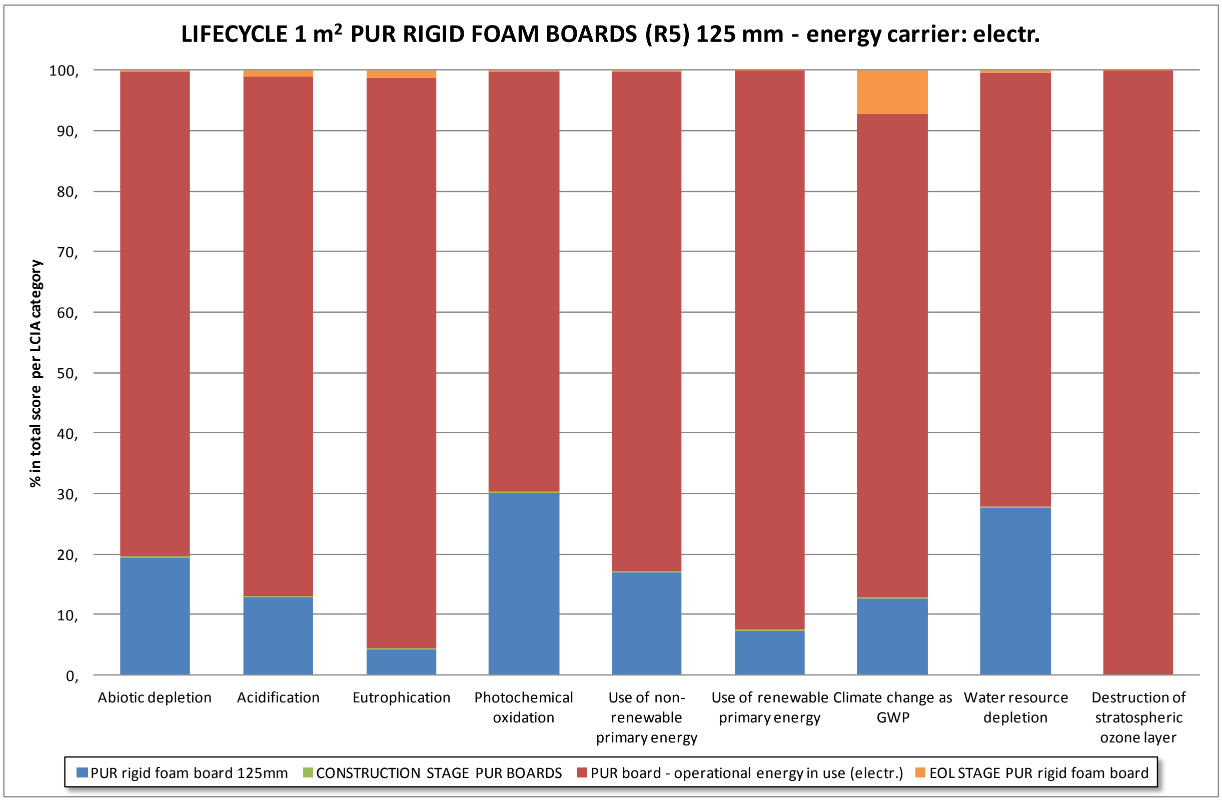

Figure 16. Lifecycle of f 1 sq.m PUR rigid foam boards (R5) 125 mm (electr. energy carrier in USE stage) – Relative contribution of lifecycle stages to total LCIA results.

In all the alternatives examined, the CONSTRUCTION stage has a minor contribution to the overall impacts of the lifecycle of the PUR boards (Figure 13, Figure 16). Within this stage, on average, transport and packaging contribute in similar proportion to the environmental impacts. The impact of the EOL stage, also significantly lower than PRODUCT and USE stages, is mainly due to the impact of the disposal (incineration) of the boards.

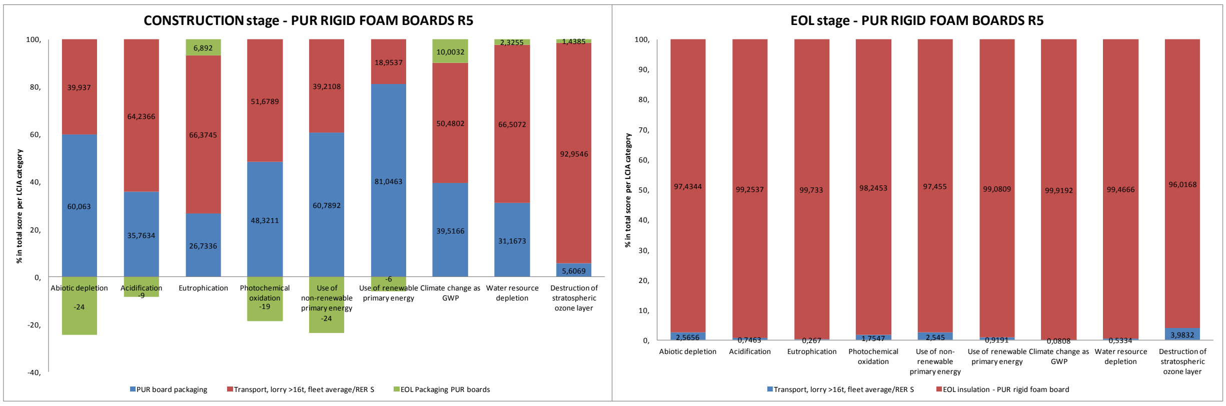

Figure 17. Relative contribution of LCI flows to LCIA results in the Construction and EOL stages of PUR insulation boards.

6.3.2 Environmental profile of silica VIP R5

Figure 18 depicts the contribution of the four lifecycle stages to the overall impact of 1 sq.m silica VIP in wall insulation applications, for a baseline scenario defined as follows:

- PRODUCT stage: manufacture of VIP from virgin raw materials
- CONSTRUCTION stage: packaging option V
- USE stage: linear increase of thermal conductivity over time (Scenario 1), with NG for energy delivery
- EOL stage: waste from EOL silica VIPs (core & envelope) to disposal (landfill, incineration)

Under those assumptions, PRODUCT stage scores higher in seven out of nine of the impact categories evaluated. The impacts derived from energy delivery (NG) for space heating in the USE stage in the categories *Abiotic Depleition* and *Use of Non-renewable Primary Energy* are larger than those associated to manufacturing of the insulation panel. CONSTRUCTION and EOL stages (as formulated in the baseline scenario) have little repercussion in the total environmental profile of the silica VIP (Figure 18, Table 13).

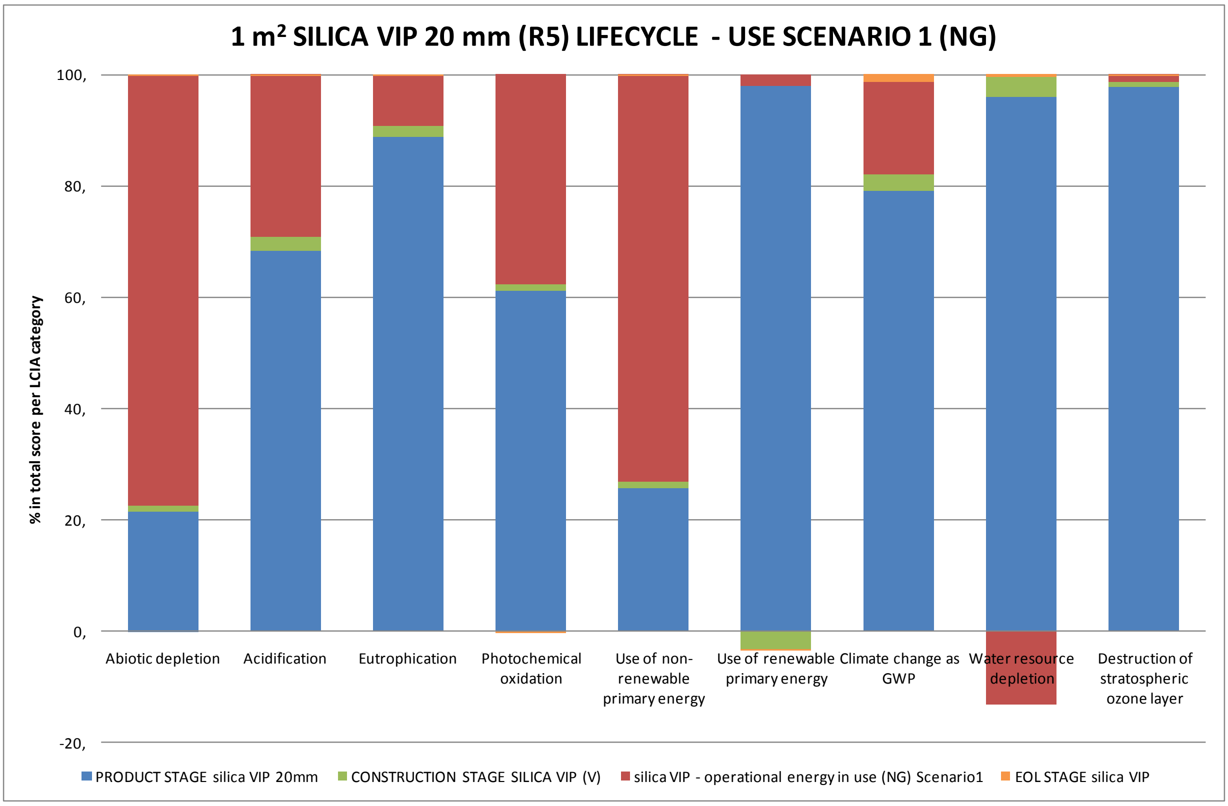

Figure 18. Lifecycle of f 1 sq.m silica VIP (R5) 20 mm (Construction stage: option V; USE Scenario 1, NG energy carrier) – Relative contribution of lifecycle stages to total LCIA results.

Table 13. LCIA results for lifecycle of 1 sq.m silica VIPs (R5) 20 mm (Construction stage: option V; USE Scenario 1, NG energy carrier). LCIA results breakdown per lifecycle stage

Impact category	Unit	PRODUCT stage	CONSTRUCTION stage (option V)	USE stage (SCN.1, NG)	EOL stage	**Total**
GWP	kg CO2 eq	36,589	1,346	7,701	0,586	**46,223**
ODP	kg CFC-11 eq	2,09E-05	1,54E-07	2,94E-07	8,17E-09	**2,14E-05**
AP	kg SO2 eq	0,164	0,006	0,070	1,44E-04	**0,240**
EP	kg PO4--- eq	0,074	0,002	0,007	1,25E-04	**0,084**
POCP	kg C2H4	0,016	2,79E-04	0,010	-3,34E-06	**0,027**
ADP	kg Sb eq	0,277	0,015	0,997	2,51E-04	**1,289**
WRD	m3 water eq	0,040	1,48E-03	-0,005	1,45E-04	**0,036**
PENRT	MJ	660,277	31,832	1878,361	0,590	**2571,059**
PERT	MJ	132,334	-4,359	2,757	-0,086	**130,646**

Considering the PRODUCT stage, the core constituents (especially, the pyrogenic silica) and the electricity consumption account, altogether, for 90% or more of the total impact in all the categories except for *Photochemical Oxidation*, to which the barrier laminate contributes by ca. 50% (Figure 19, Table 14).

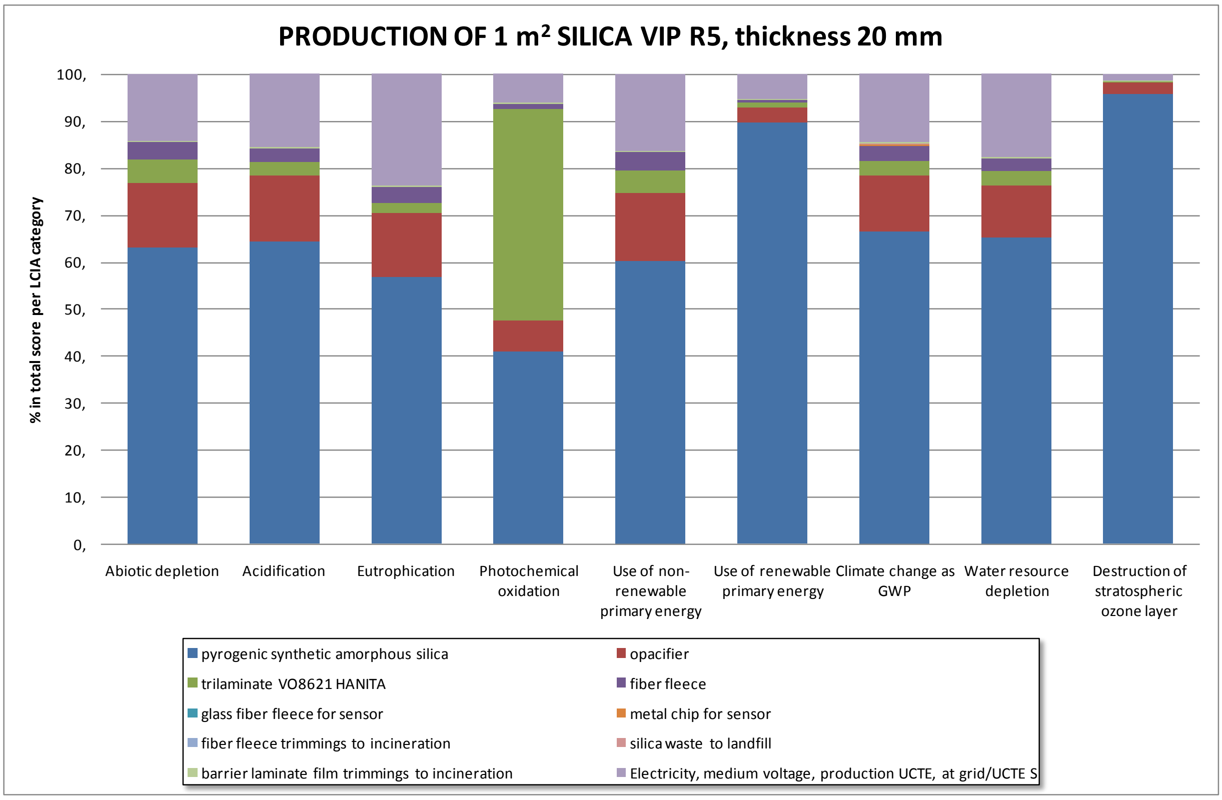

Figure 19. Relative contribution of LCI flows to LCIA results in the Production stage of silica VIP.

For the CONSTRUCTION stage two alternative ways of packaging VIPs have been devised: option V, for cardboard boxing of single VIP and, then, 50 box/pallet, and option K, that entails multiple panels (16u) in one cardboard box, which is palletised. When comparing both alternatives (Table 15), option V scores better in GWP and POCP categories and, above all, in PERT (impact avoidance). Option K performs slightly better in the rest. Nevertheless, the relative impact of the Construction stage is so low in comparison with Production and Use stages, that the differences between the two packaging options are not relevant if the whole lifecycle is taken.

In the USE stage, as discussed earlier, the choice of the heating system plays a key role to explain the magnitude of the impacts during the service life. In Scenario 1 (linear increase of thermal conductivity over the 30 yr.), for energy delivered by natural gas or fuel oil, PRODUCT stage surpasses USE in most impact categories (ADP and PENRT, exc.). However, if the USE Scenario 2 (failure of VIP after 3 years) is considered, the energy effects become dominant also in other impact categories, e.g., acidification potential, potential contribution to photochemical ozone formation (Figure 20). That trend is more noticeable if electricity is used as energy carrier instead. In fact, electric heating makes the impacts of USE stage dominant in the whole lifecycle for both scenarios.

Table 14. LCIA results for production of 1 sq.m silica VIP (R5) 20 mm

Impact category	Unit	pyrogenic SAS	opacifier	trilaminat e VO8621	fiber fleece	GF fleece for sensor	ALU chip for sensor	fiber fleece trimmings to incineration	silica waste to landfill	barrier laminate trimmings to incineration	Electricity, MV
GWP	kg CO2 eq	24.349	4.299	1.223	1.245	3.95E-04	1.07E-03	0.041	0.002	0.117	5.311
ODP	kg CFC-11 eq	2.01E-05	4.83E-07	3.71E-08	7.43E-08	3.42E-11	1.07E-09	3.45E-11	6.38E-10	1.76E-10	2.61E-07
AP	kg SO2 eq	0.105	0.023	0.005	0.005	2.38E-06	4.41E-05	6.40E-06	1.27E-05	2.16E-05	0.025
EP	kg PO4--- eq	0.042	0.010	0.002	0.003	6.43E-07	2.00E-06	8.38E-06	3.09E-06	2.65E-05	0.018
POCP	kg C2H4	0.007	1.11E-03	0.007	2.35E-04	8.87E-08	1.90E-06	1.80E-07	4.66E-07	7.11E-07	9.88E-04
ADP	kg Sb eq	0.175	0.038	0.014	0.011	2.87E-06	5.28E-05	2.13E-06	2.57E-05	1.39E-05	0.039
WRD	m3 water eq	0.026	0.004	1.24E-03	1.22E-03	7.29E-07	3.15E-06	3.57E-06	8.31E-06	1.12E-05	0.007
PENRT	MJ	396.576	96.252	32.564	27.568	0.007	0.140	0.005	0.059	0.034	107.045
PERT	MJ	118.827	4.173	1.215	1.069	0.000	0.031	7.91E-05	4.39E-04	0.002	7.017

Table 15. LCIA results for packaging & transport of 1 sq.m silica VIP (R5) 20 mm. Alternatives compared

Impact category	Unit	CONSTRUCTION STAGE – PACKAGING OPTION K				CONSTRUCTION STAGE – PACKAGING OPTION V			
		CONSTRUCTION Total	Packaging (K)	Transport, lorry >16t	EOL Packaging (K)	CONSTRUCTION Total	Packaging (V)	Transport, lorry >16t	EOL Packaging (V)
GWP	kg CO2 eq	**1.909**	1.383	0.233	0.293	**1.346**	0.739	0.221	0.386
ODP	kg CFC-11 eq	**1.01E-07**	8.35E-08	3.75E-08	-2.01E-08	**1.54E-07**	8.74E-08	3.57E-08	3.12E-08
AP	kg SO2 eq	**5.64E-03**	6.21E-03	1.27E-03	-1.83E-03	**6.00E-03**	5.62E-03	1.20E-03	-8.28E-04
EP	kg PO4--- eq	**1.52E-03**	1.69E-03	3.35E-04	-5.02E-04	**1.82E-03**	1.22E-03	3.19E-04	2.82E-04
POCP	kg C2H4	**1.51E-03**	1.73E-03	3.78E-05	-2.59E-04	**2.79E-04**	3.10E-04	3.59E-05	-6.72E-05
ADP	kg Sb eq	**0.014**	0.016	1.69E-03	-3.64E-03	**0.015**	0.015	1.61E-03	-1.48E-03
WRD	m3 water eq	**1.03E-03**	1.52E-03	1.51E-04	-6.36E-04	**1.48E-03**	1.71E-03	1.44E-04	-3.65E-04
PENRT	MJ	**31.326**	36.524	3.902	-9.100	**31.832**	33.714	3.710	-5.592
PERT	MJ	**7.058**	45.252	0.049	-38.243	**-4.359**	17.503	0.046	-21.909

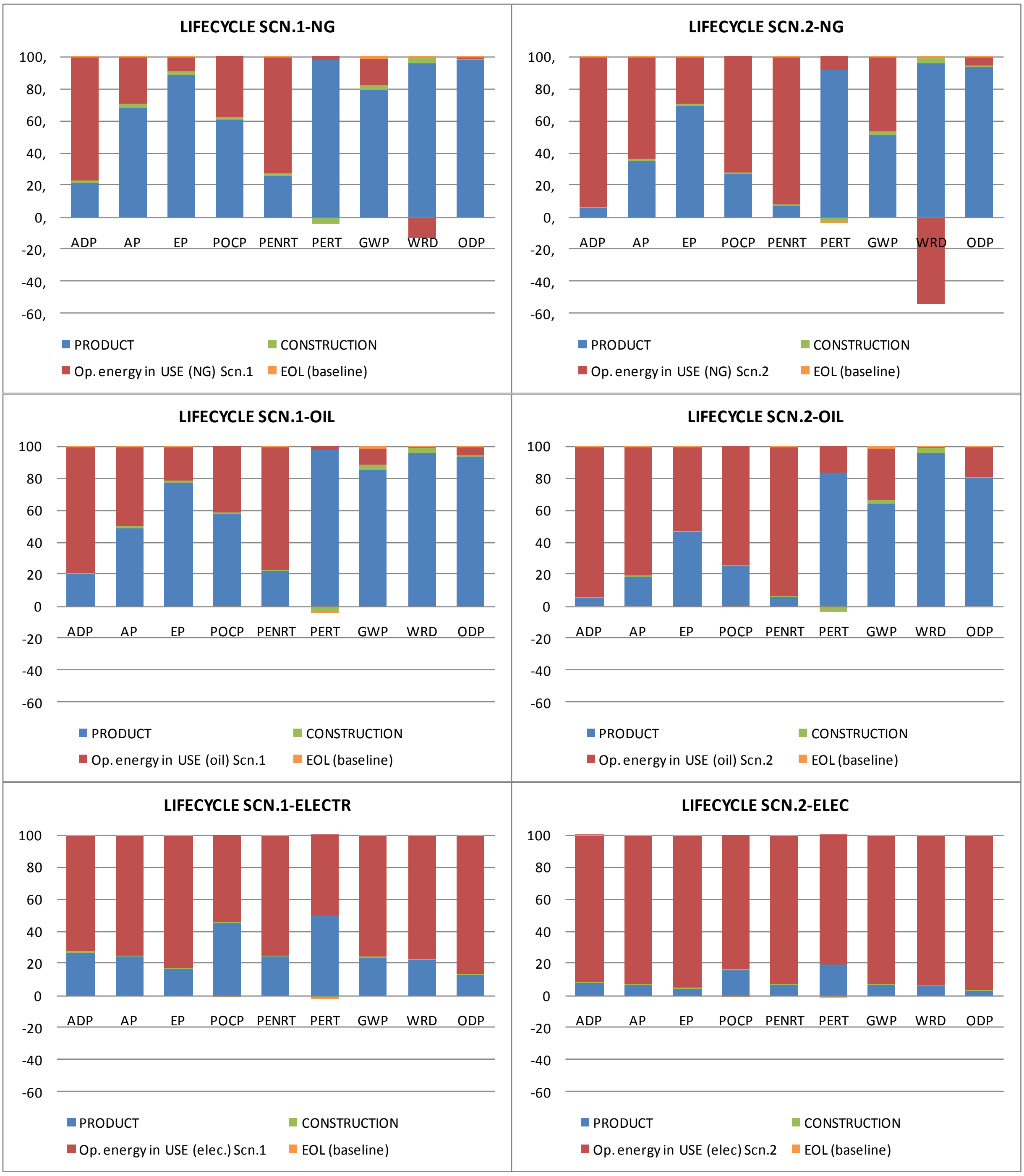

Figure 20. Lifecycle of f 1 sq.m silica VIP (R5) 20 mm (Construction stage: option V). USE stage: Scenario 1 *vs* 2, 3 energy carriers – Relative contribution (%) of lifecycle stages to total LCIA results.

As regards the EOL stage, when materials of core and envelope of end-of-life silica VIPs are directed to disposal (landfill for inert core and incineration for plastic components), there is some contribution to increasing the environmental impacts of the silica VIP lifecycle (only the destination of aluminium disk of sensor to recycling brings about some benefits).

Alternatively, a CORE RECYCLING Scenario has been proposed. It entails a take-back system for EOL VIPs, that returns the product to manufacturer, who disposed of the envelope, sensor and fibre fleece inner bag and use the reclaimed cores in the manufacture of new panels.

If the waste indicators are computed from the inventory of the lifecycle of silica VIPs in the two EOL scenarios drawn, the net values shown in Table 16 are obtained when comparing the core recycling scenario versus the baseline scenario.

Table 16. Environmental indicators from inventory (waste & outputs)

LCI environmental indicators	unit	Variation in waste indicators [Recycling core scenario] vs [Baseline scenario]
materials for recycling (MfR)	kg	+3.700
material for energy recovery (MfER)	kg	0.000
hazardous waste to final disposal (HWD)	kg	-0.008
non-hazardous waste to final disposal (NHWD)	kg	-4.029

The comparison of the alternative EOL scenarios in terms of the LCIA indicators produces the results exposed in the table below. The potential environmental benefits gained by recycling the fumed silica and the silicon carbide are represented as negative values in the several impact categories (avoided impacts). The entire lifecycle for a silica VIP with core recycling at its EOL (packaging option V in the Construction stage, Use scenario 1 – NG energy carrier) is depicted in Figure 21.

Table 17. LCIA results for EOL stage of 1 sq.m silica VIPs (R5) 20 mm. Scenarios compared

Impact category	Unit	EOL baseline	EOL core recycling
GWP	kg CO2 eq	0.586	-29.378
ODP	kg CFC-11 eq	8.17E-09	-2.26E-05
AP	kg SO2 eq	1.44E-04	-0.136
EP	kg PO4--- eq	1.25E-04	-0.053
POCP	kg C2H4	-3.34E-06	-8.40E-03
ADP	kg Sb eq	2.51E-04	-0.225
WRD	m3 water eq	1.45E-04	-0.032
PENRT	MJ	0.590	-517.813
PERT	MJ	-0.086	-134.256

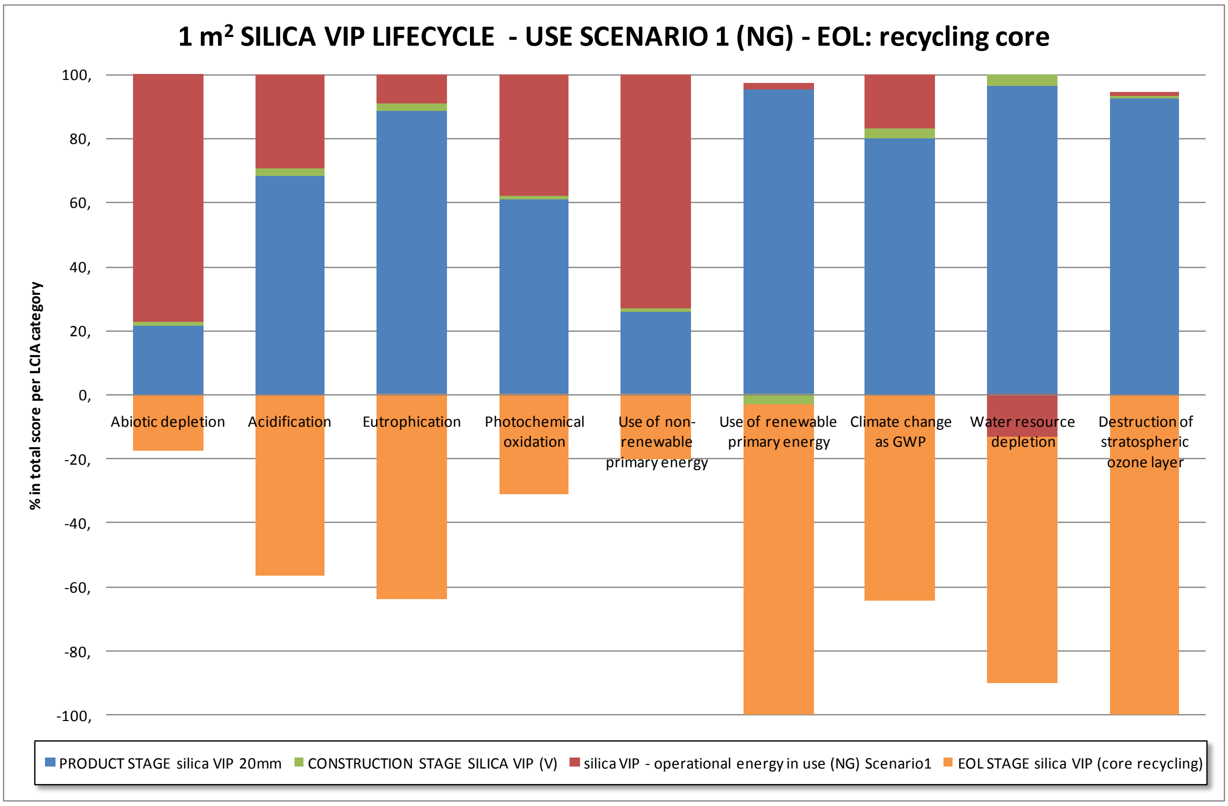

Figure 21. Lifecycle of f 1 sq.m silica VIP (R5) 20 mm with core recycling at EOL (Constr.stage: option V; USE Scenario 1, NG energy carrier) – Relative contribution of lifecycle stages to total LCIA results.

6.3.3 Environmental profile of OVIP R5

Equivalently to the baseline scenario defined for the silica VIP, the following is established for the novel opaque VIP:

- PRODUCT stage: manufacture of VIP from virgin raw materials (nanofoam core delivered as slabs of the required size)
- CONSTRUCTION stage: packaging option V
- USE stage: linear increase of thermal conductivity over time (Scenario 1), with NG for energy delivery
- EOL stage: waste from EOL OVIPs (core & envelope) to disposal (incineration)

Under those frame conditions the environmental profile pictured in Figure 22 is obtained. The relative contribution of PRODUCT and USE stages to the overall impact of the OVIP lifecycle is comparable.

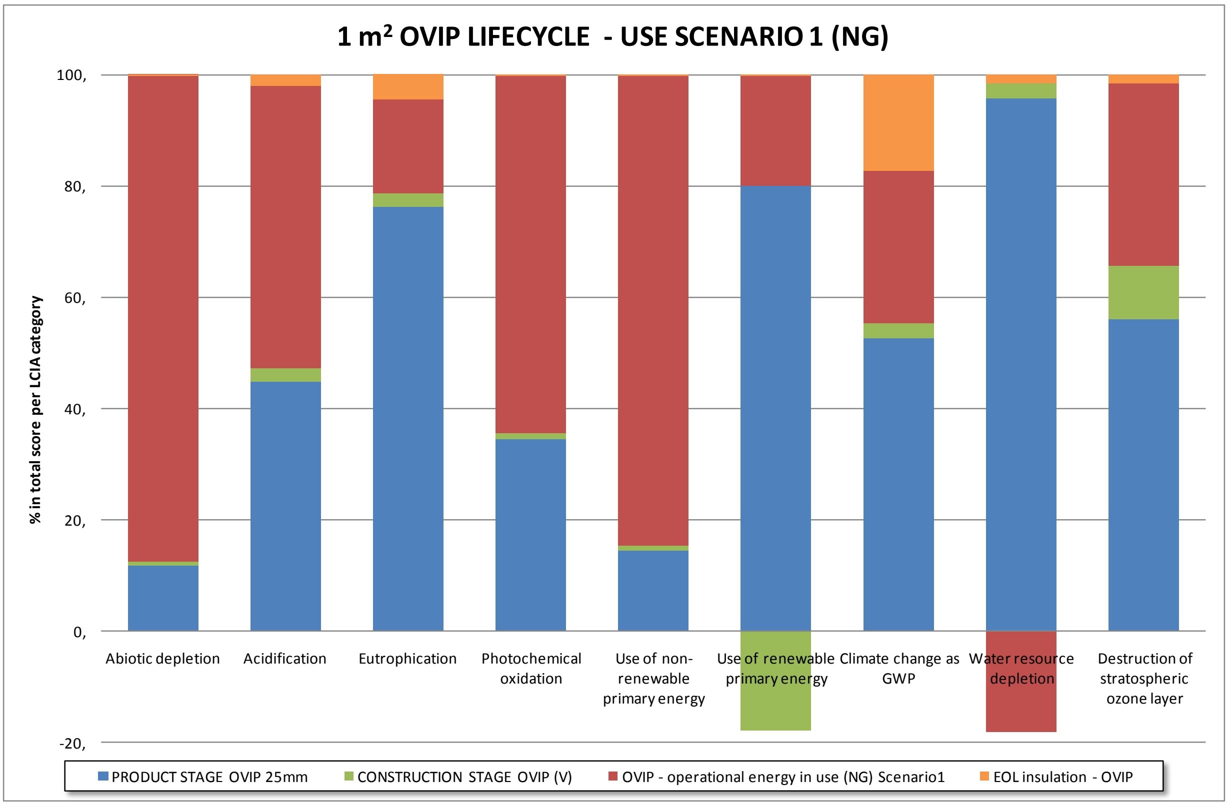

Figure 22. Lifecycle of f 1 sq.m OVIP (R5) 25 mm (Construction stage: option V; USE Scenario 1, NG energy carrier) – Relative contribution of lifecycle stages to total LCIA results.

Table 18. LCIA results for lifecycle of 1 sq.m OVIPs (R5) 25 mm (Construction stage: option V; USE Scenario 1, NG energy carrier). LCIA results breakdown per lifecycle stage

Impact category	Unit	PRODUCT stage	CONSTRUCTION stage (option V)	USE stage (SCN.1, NG)	EOL stage	Total
GWP	kg CO2 eq	25.866	1.332	13.468	8.422	49.089
ODP	kg CFC-11 eq	8.74E-07	1.51E-07	5.14E-07	2.38E-08	1.56E-06
AP	kg SO2 eq	0.108	5.90E-03	0.122	4.61E-03	0.241
EP	kg PO4--- eq	0.059	1.79E-03	0.013	3.53E-03	0.077
POCP	kg C2H4	0.010	2.76E-04	0.018	4.75E-05	0.028
ADP	kg Sb eq	0.233	0.015	1.744	1.64E-03	1.993
WRD	m3 water eq	0.050	1.47E-03	-0.009	8.07E-04	0.043
PENRT	MJ	562.538	31.595	3285.024	3.831	3882.988
PERT	MJ	19.617	-4.358	4.822	0.051	20.132

The PRODUCT stage of the OVIP has been comprehensively analysed, in order to assess the environmental performance of the novel materials developed in the project and draw conclusions for improvement and further research.

As shown in Figure 23, nanofoam is responsible for the higher share of impacts in the production stage. Another relevant flow in the various impact categories is electricity consumption and, in the case of the POCP impact category, the barrier laminate.

However, some data of the LCI of the novel materials are subjected to large uncertainty and some data have been inventoried from extrapolated values or assumptions. Sensitivity checks have been run for quantifying the effect of those choices in the calculations and their results are commented in the following pages. The results in Figure 23 correspond to the combination of the worst cases modelled for the various components. As it will be indicated later, results of worst and best cases examined do not differ too much and, especially, do not influence the overall environmental performance of the OVIP in its lifecycle significantly. For that reason, the chosen combination seems a fine representation of the PRODUCT stage of OVIP.

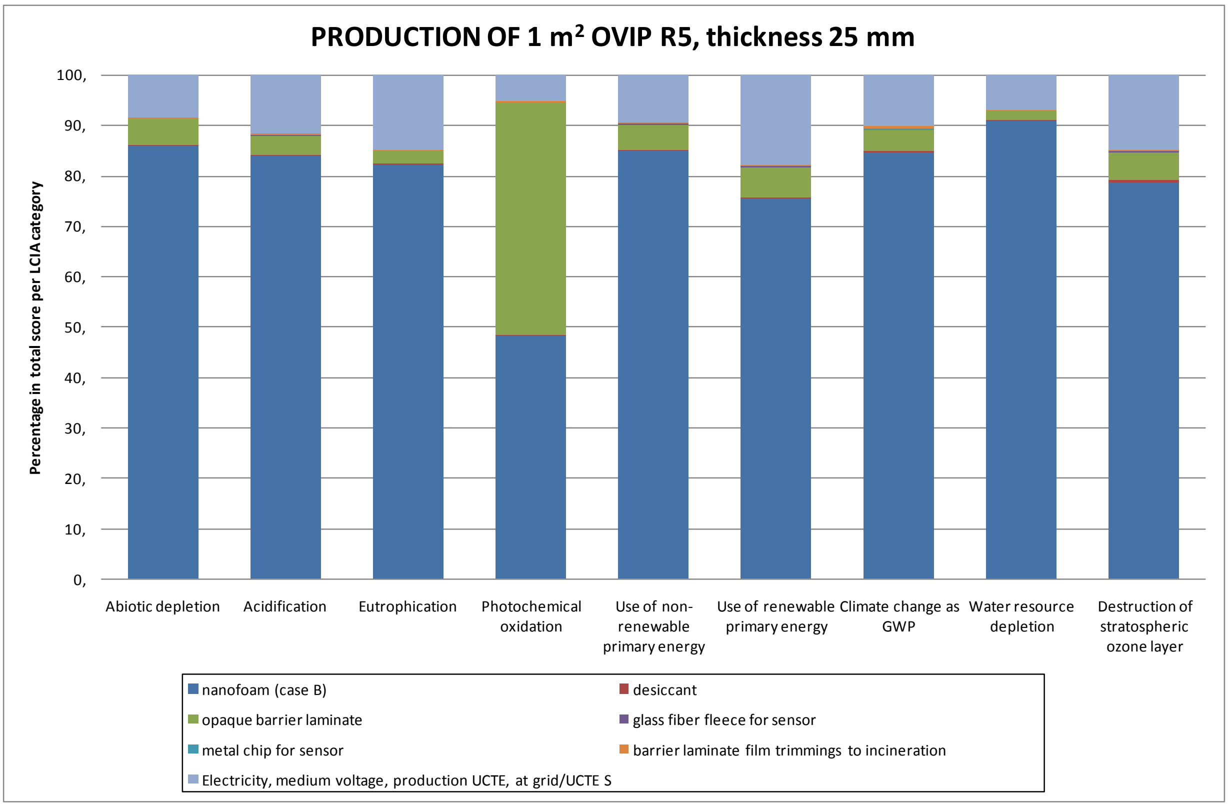

Figure 23. Relative contribution of LCI flows to LCIA results in the Production stage of OVIP.

An alternative manufacturing procedure has been proposed for OVIPs in which the PU nanofoam is delivered in blocks to the VIP manufacturer, who has to cut them to core size. Such procedure involves material losses (with its additional waste management) and some supplementary electricity consumption. All that results in incremented impacts. The estimated values of the environmental indicators for that solution are shown in Table 20. Figure 24 depicts the compared environmental profiles of OVIP manufactured following each of the two procedures.

Table 19. LCIA results for production of 1 sq.m OVIP (R5) 25 mm (baseline)

Impact category	Unit	nanofoam (case B)	desiccant	opaque barrier laminate	glass fiber fleece for sensor	metal chip for sensor	barrier laminate film trimmings to incineration	Electricity, MV
GWP	kg CO2 eq	21.907	0.039	1.175	0.000	0.001	0.087	2.655
ODP	kg CFC-11 eq	6.88E-07	2.72E-09	5.13E-08	3.42E-11	1.07E-09	1.30E-10	1.30E-07
AP	kg SO2 eq	0.091	3.57E-05	4.29E-03	2.38E-06	4.41E-05	1.60E-05	0.013
EP	kg PO4--- eq	0.049	5.87E-06	1.61E-03	6.43E-07	2.00E-06	1.96E-05	0.009
POCP	kg C2H4	0.005	6.66E-06	4.43E-03	8.87E-08	1.90E-06	5.26E-07	4.94E-04
ADP	kg Sb eq	0.201	9.08E-05	0.012	2.87E-06	5.28E-05	1.03E-05	0.020
WRD	m3 water eq	0.046	5.73E-06	1.02E-03	7.29E-07	3.15E-06	8.26E-06	3.49E-03
PENRT	MJ	479.365	0.222	29.224	0.007	0.140	0.025	53.523
PERT	MJ	14.834	0.023	1.217	2.16E-04	0.031	1.22E-03	3.508

Table 20. LCIA results for production of 1 sq.m OVIP (R5) 25 mm (nanofoam cores cut from blocks)

Impact category	Unit	nanofoam (case B)	desiccant	opaque barrier laminate	glass fiber fleece for sensor	metal chip for sensor	barrier laminate film trimmings to incineration	Electricity, MV
GWP	kg CO2 eq	25.075	0.039	1.128	0.000	0.001	0.089	1.161
ODP	kg CFC-11 eq	7.88E-07	2.72E-09	4.88E-08	3.42E-11	1.07E-09	1.34E-10	3.65E-09
AP	kg SO2 eq	0.104	3.57E-05	4.03E-03	2.38E-06	4.41E-05	1.64E-05	6.79E-04
EP	kg PO4--- eq	0.056	5.87E-06	1.39E-03	6.43E-07	2.00E-06	2.01E-05	5.05E-04
POCP	kg C2H4	0.005	6.66E-06	4.54E-03	8.87E-08	1.90E-06	5.40E-07	8.53E-06
ADP	kg Sb eq	0.230	9.08E-05	0.012	2.87E-06	5.28E-05	1.05E-05	2.59E-04
WRD	m3 water eq	0.052	5.73E-06	9.43E-04	7.29E-07	3.15E-06	8.49E-06	1.14E-04
PENRT	MJ	548.689	0.222	28.445	0.007	0.140	0.026	0.603
PERT	MJ	16.980	0.023	1.145	0.000	0.031	0.001	0.021

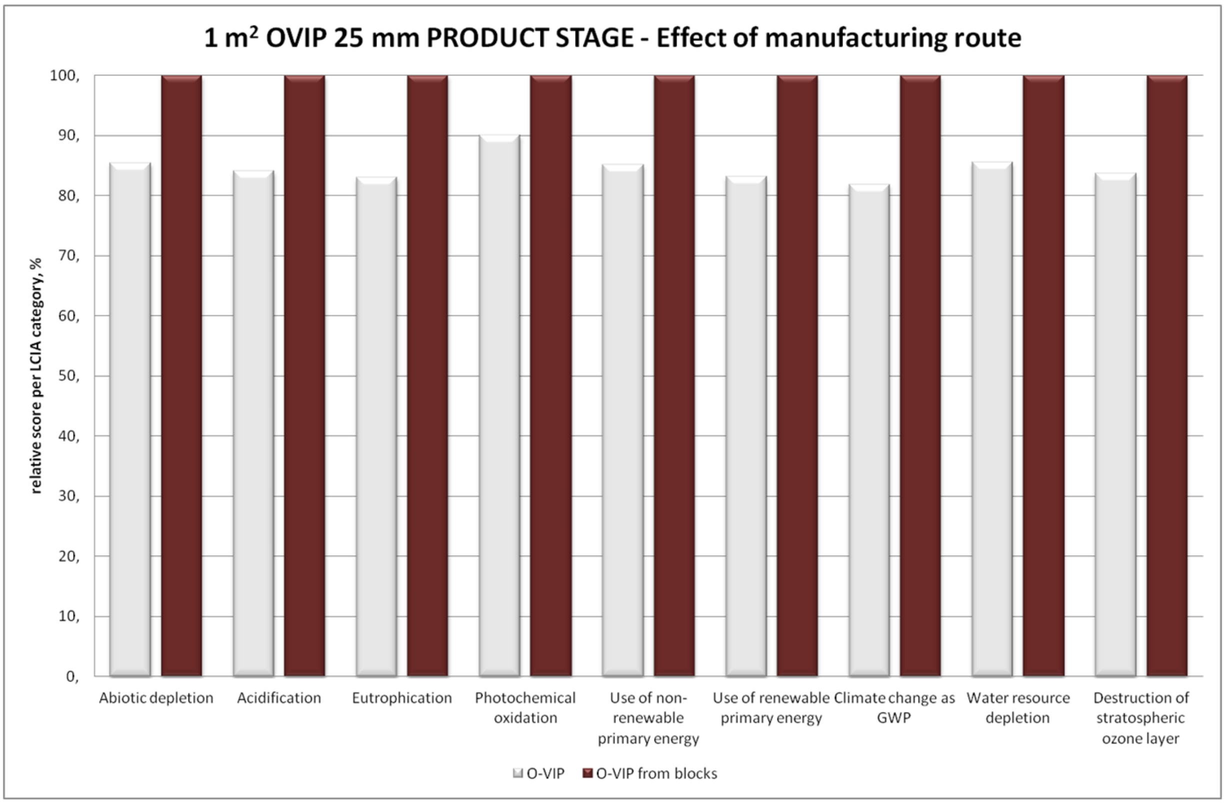

Figure 24. Relative score in LCIA categories of the two manufacturing routes of OVIP.

Considering the two novel components of the OVIP developed in the course of the project, in the production of novel PU nanofoam, polyol, catalyst and electricity seem to be the main contributors to the environmental impacts. In the manufacturing of the high barrier laminate by successive metallisation steps of the PET substrate, followed by a final lamination with HDPE film, the two polymers and the ORMOCER lacquer show the highest shares in the indicators assessed.

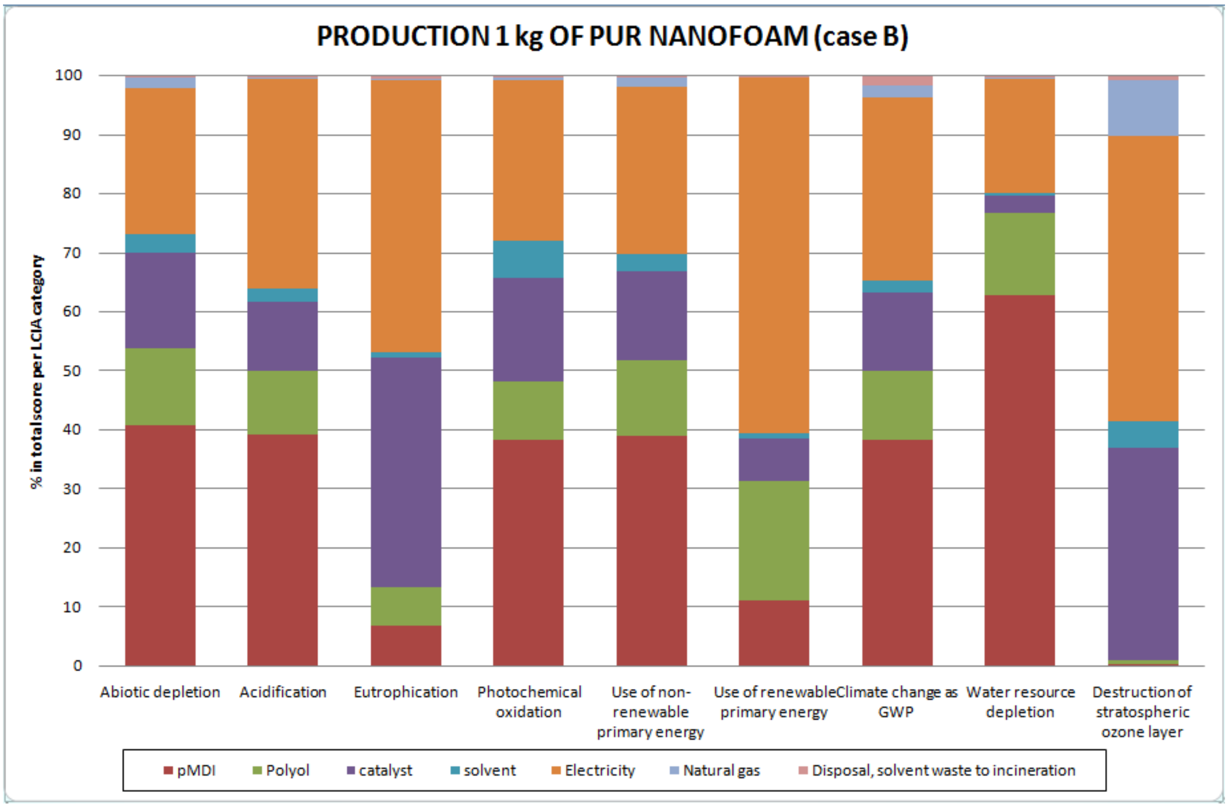

Figure 25. Relative contribution of LCI flows to LCIA results in the Production of 1 kg PU nanofoam.

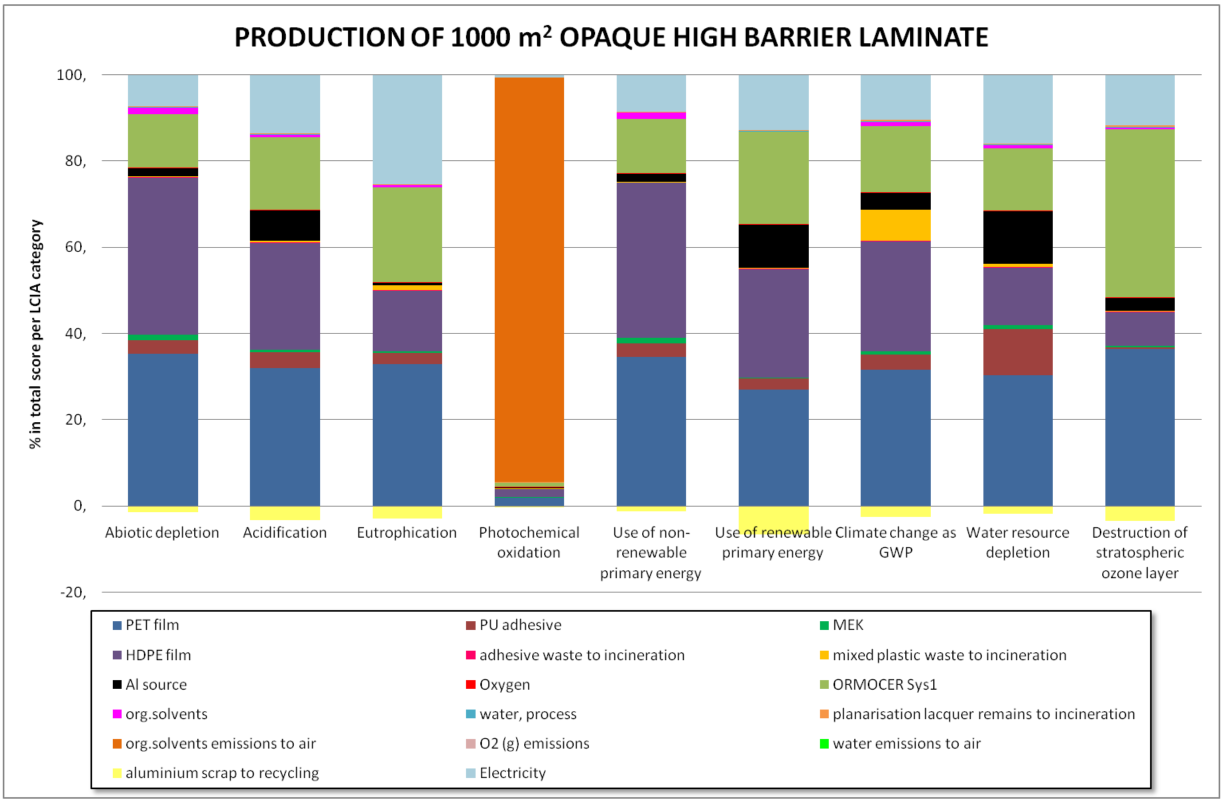

Figure 26. Relative contribution of LCI flows to LCIA results in the Production of 1000 m^2 advanced opaque laminate PET/Al/AlOx/ORM1/AlOx/Al/HDPE.

In the CONSTRUCTION stage the two alternative ways of packaging VIPs evaluated for silica VIPs have also been considered. Slight differences are found in the associated impacts. As concluded previously, the relative impact of the Construction stage is so low in comparison with Production and Use stages, that those minor differences between the two packaging options are not relevant if the whole lifecycle is regarded.

Table 21. LCIA results for CONSTRUCTION stage of 1 sq.m OVIP (R5) 25 mm. Alternatives compared

Impact category	Unit	CONSTRUCTION Total Packaging Option V	CONSTRUCTION Total Packaging Option K
GWP	kg CO2 eq	1.332	1.963
ODP	kg CFC-11 eq	1.51E-07	1.08E-07
AP	kg SO2 eq	5.90E-03	5.92E-03
EP	kg PO4--- eq	1.79E-03	1.62E-03
POCP	kg C2H4	2.76E-04	1.54E-03
ADP	kg Sb eq	0.015	0.015
WRD	m3 water eq	1.47E-03	1.11E-03
PENRT	MJ	31.595	32.628
PERT	MJ	-4.358	7.764

In the USE stage, once more, the choice of the heating system is decisive for the magnitude of the impacts originated during the service life. In Scenario 1 (linear increase of thermal conductivity over the 30 yr.), for energy delivered by natural gas or fuel oil, PRODUCT stage rank as the main contributor in approximately half the number of total impact categories and the USE stage in the other half. For instance, when the four stages of the life cycle of the OVIP are considered (for a USE Scenario 1 and natural gas as energy carrier for space heating), estimations indicate that the accumulated 13.5 kg CO_2 equiv. associated with space heating to compensate for the increasing heat losses over 30 years are roughly the half of the kg CO_2 equiv. linked to the PRODUCT stage. However in other impact categories, the poor performance of the OVIP in terms of thermal resistance aging, means that the USE stage constitutes the main originator of its overall impact.

If the USE Scenario 2 (failure of VIP after 3 years) is considered, the energy effects of the USE stage become dominant in all impact categories, except in Water Resource Depletion (Figure 27). For electric heating the impacts of USE stage are dominant in the whole lifecycle of OVIP for both scenarios.

The EOL of the OVIP has been modelled as disposal of organic nanofoam and barrier laminate by incineration. The impact of this stage in the complete lifecycle of OVIP is significant only in two of the impact categories assessed: eutrophication and, more notoriously, climate change.

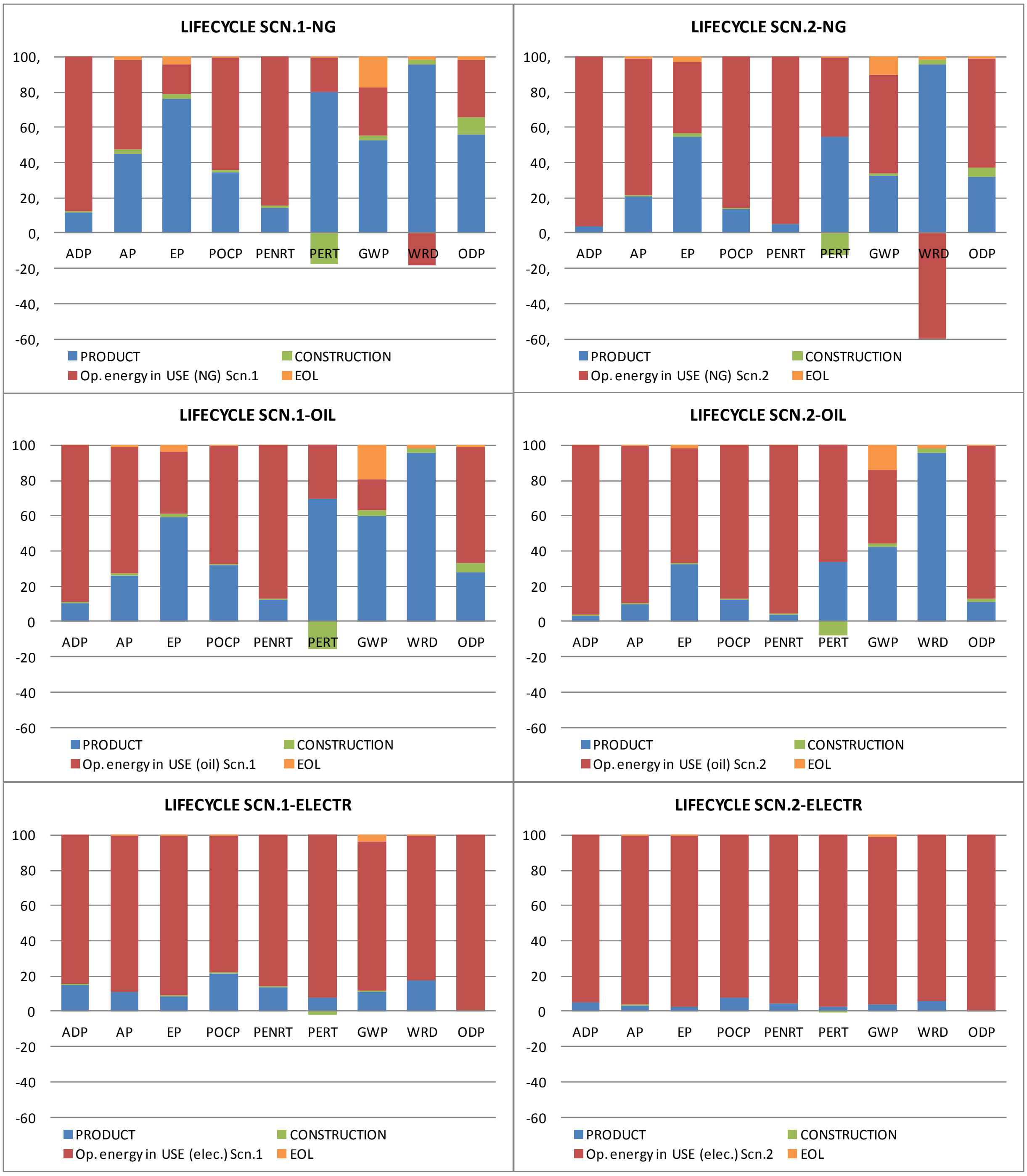

Figure 27. Lifecycle of f 1 sq.m OVIP (R5) 25 mm (Construction stage: option V). USE stage: Scenario 1 *vs* Scenario 2, 3 energy carriers – Relative contribution (%) of lifecycle stages to total LCIA results.

6.4 Interpretation of LCA results

After examining individually the environmental performance of the wall insulation products, by lifecycle stage, in the previous section, the comparison among the three products is now performed, in order to identify the environmental benefits and drawbacks of the novel opaque VIP developed, with regards the benchmark insulations. Also in this chapter, the conclusions of some sensitivity checks are discussed.

6.4.1 OVIP vs benchmarks

When comparing the PRODUCT stage of the opaque VIP with the production of PUR rigid foam boards and silica VIPs, the OVIP scores better than silica VIP in almost all categories of impact. However, the rigid foam insulation boards show better environmental performance than both VIPs in all categories, except for water resource depletion (Figure 28). In the case that silica VIPs were manufactured with recycled silica cores of EOL VIPs collected and returned to the producer, its global impact would be significantly reduced (approx. by 3 times), due to the credits gain by avoiding production of new amounts of primary pyrogenic silica and silicon carbide, and would become lower than the impacts associated to production of the OVIP (Figure 29).

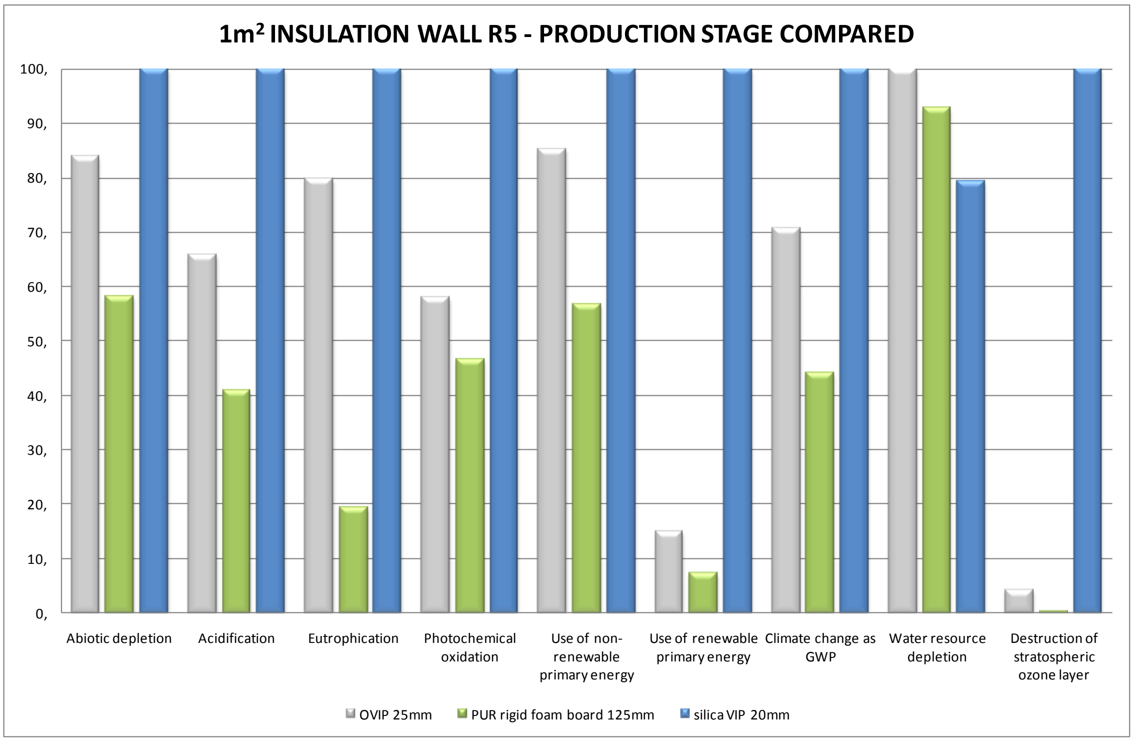

Figure 28. Compared PRODUCT stage of f 1 sq.m of wall insulation products of R=5 m^2K/W.

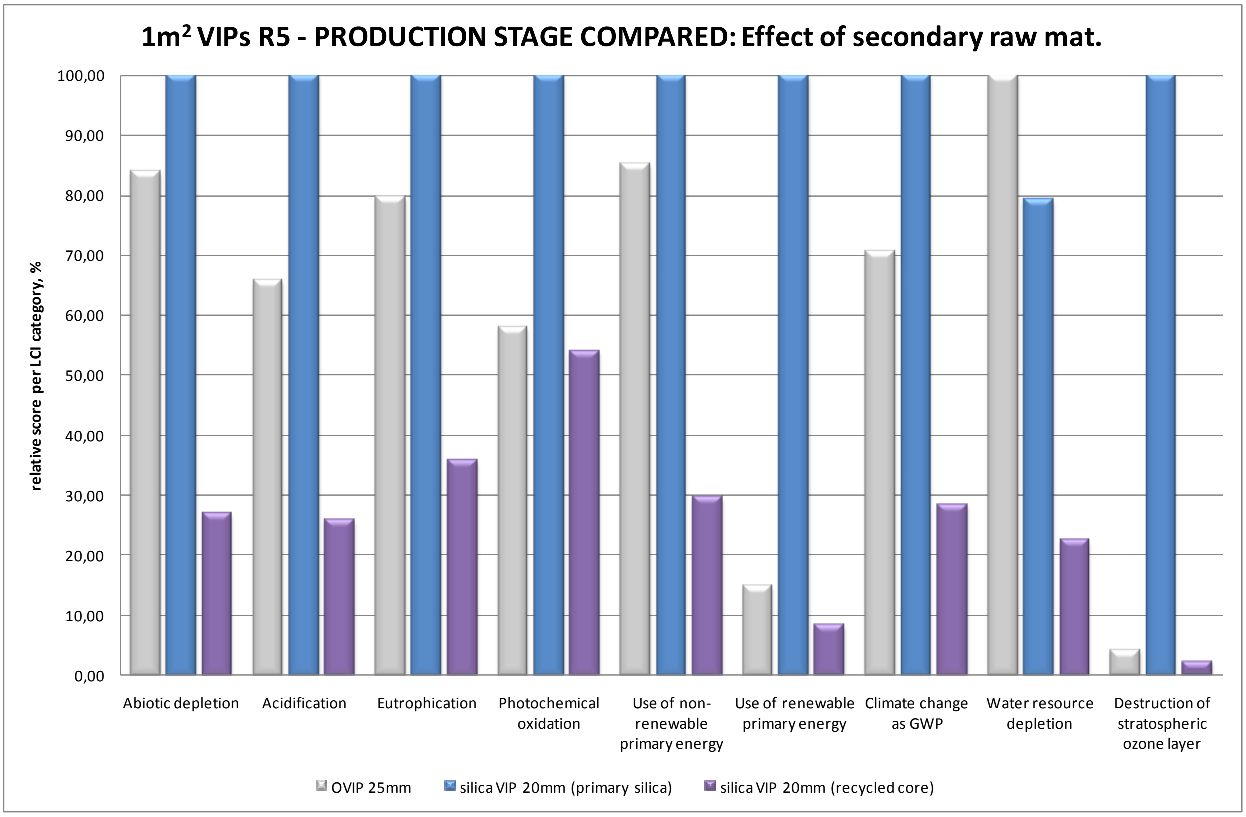

Figure 29. Compared PRODUCT stage of f 1 sq.m of VIPs (R5). Silica VIP production: primary vs secondary raw materials.

Table 22. LCIA results for PRODUCT stage of 1 sq.m wall insulation products (R5).

Impact category	Unit	PUR rigid foam board 125mm	OVIP 25mm	silica VIP 20mm (primary silica)	silica VIP 20mm (recycled core)
GWP	kg CO2 eq	16.152	25.866	36.589	10.374
ODP	kg CFC-11 eq	8.40E-08	8.74E-07	2.09E-05	4.67E-07
AP	kg SO2 eq	0.067	0.108	0.164	0.042
EP	kg $PO4^{3-}$ eq	0.014	0.059	0.074	0.027
POCP	kg C2H4	0.008	0.010	0.016	0.009
ADP	kg Sb eq	0.161	0.233	0.277	0.075
WRD	m3 water eq	0.047	0.050	0.040	0.011
PENRT	MJ	375.111	562.538	660.277	195.909
PERT	MJ	9.609	19.617	132.334	10.937

Attending merely to the Climate Change impact category, this means dropping from 36,6 kg CO_2 equiv./m^2 to 10.4, a value even lower than the one estimated for production of 1m^2 of PUR rigid foams (16.2 kg CO_2 equiv./m^2) and the one associated with production of the OVIP (25.9 kg CO_2 equiv./m^2)

Comparing the environmental profile of the three insulation products, throughout the entire life cycle, leads to the conclusion that none of the VIPs evaluated surpass the environmental performance of the insulation boards made of PUR rigid foam, especially if during the service life the panels result damaged and the vacuum is lost (see Figure 30). In spite of having less impact during production, the total impact scores of the OVIPs are higher than those of silica VIP in most categories for the scenarios assessed, due to the higher increase in thermal conductivity that OVIP experiences. In terms of embodied energy and energy payback periods, that means that after 5 years in service, silica VIPs would have saved, with regard to OVIPs, as much primary energy resources for space heating as the amount that OVIPs production saves versus silica VIP production (-212,1 MJ).

If silica cores of EOL silica VIPs are sent for material recycling, instead of being sent for disposal (landfill), the performance of the silica VIP with secondary cores equals and, even improves, the impact indicator scores of PUR boards in some categories, as depicted in the graph at Figure 31.

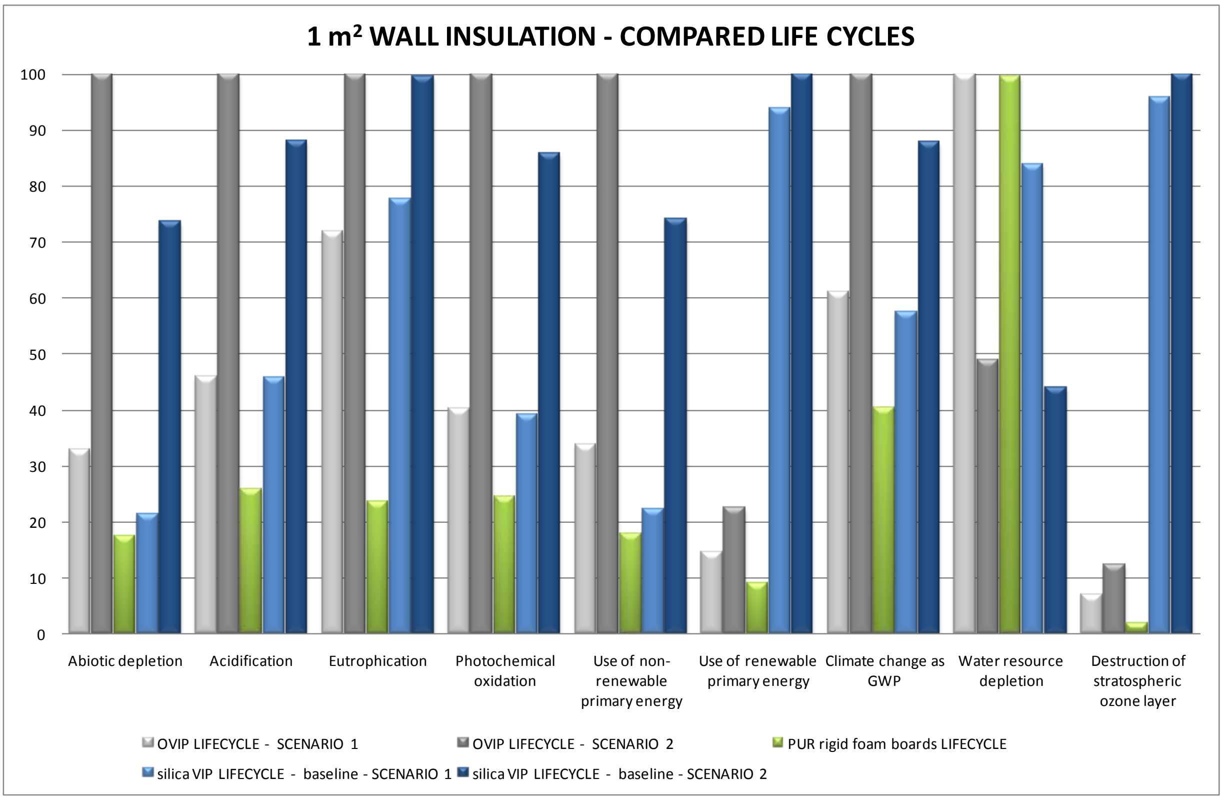

Figure 30. Compared LIFECYCLEs of 1 sq.m of wall insulation products R5 (USE stage: 2 possible USE Scenarios considered for VIPs; energy carrier NG for 3 products).

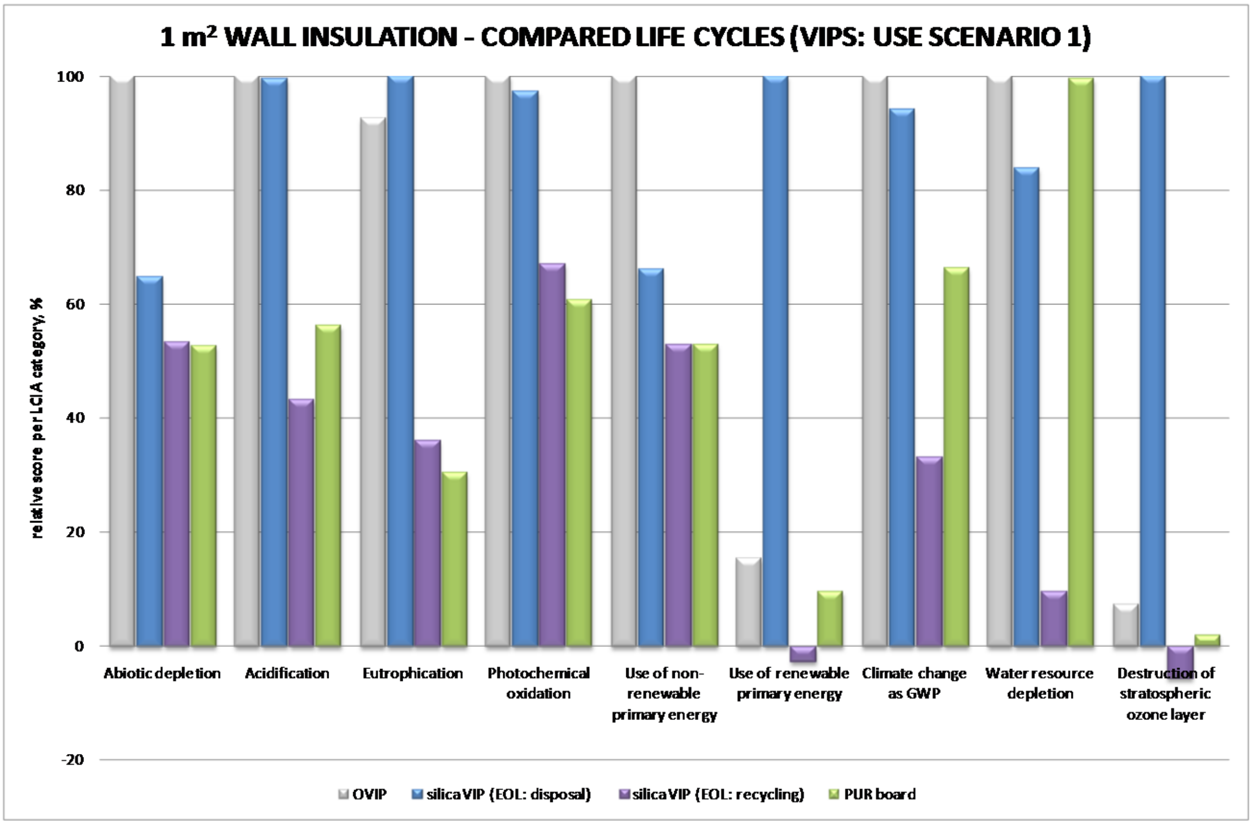

Figure 31. Compared LIFECYCLEs of 1 sq.m of wall insulation products R5 (only USE Scenario 1 considered for VIPs, energy carrier NG for 4 products).

Table 23. LCIA results for LIFECYCLE of 1 sq.m wall insulation products (R5). USE stage: NG energy carrier; VIPs Scenario 1

Impact category	Unit	OVIP	silica VIP (EOL: disposal)	silica VIP (EOL: recycling core)	PUR boards
GWP	kg CO2 eq	49.089	46.223	16.258	32.566
ODP	kg CFC-11 eq	1.56E-06	2.14E-05	0.000	4.02E-07
AP	kg SO2 eq	0.241	0.240	0.104	0.136
EP	kg $PO4^{3-}$ eq	0.077	0.084	0.030	0.025
POCP	kg C2H4	0.028	0.027	0.019	0.017
ADP	kg Sb eq	1.993	1.289	1.064	1.051
WRD	m3 water eq	0.043	0.036	0.004	0.043
PENRT	MJ	3882.988	2571.059	2052.657	2054.107
PERT	MJ	20.132	130.646	-3.524	12.387

This comparison is made using one of the most favourable scenarios for the impacts due to the USE stage (linear decrease of thermal resistance of VIPs along the service life and heating space with NG burned at boiler). If the less favourable scenario is included in the analysis (VIPs failure after 3 years and electric space heating), the PUR insulation boards are clearly the solution with better environmental profile (Figure 32; compare results in Table 24 and Table 23).

Table 24. LCIA results for LIFECYCLE of 1 sq.m wall insulation products (R5). USE stage: electricity energy carrier; VIPs Scenario 2

Impact category	Unit	OVIP	silica VIP (EOL: disposal)	silica VIP (EOL: recycling core)	PUR boards
GWP	kg CO2 eq	703.071	517.550	487.588	127.812
ODP	kg CFC-11 eq	7.98E-04	5.93E-04	0.001	1.22E-04
AP	kg SO2 eq	3.048	2.273	2.137	0.522
EP	kg PO_4^{3-} eq	2.143	1.568	1.514	0.337
POCP	kg C2H4	0.125	0.099	0.091	0.025
ADP	kg Sb eq	4.613	3.424	3.198	0.833
WRD	m3 water eq	0.839	0.606	0.574	0.168
PENRT	MJ	12513.568	9244.684	8726.222	2207.562
PERT	MJ	801.049	691.821	557.654	130.121

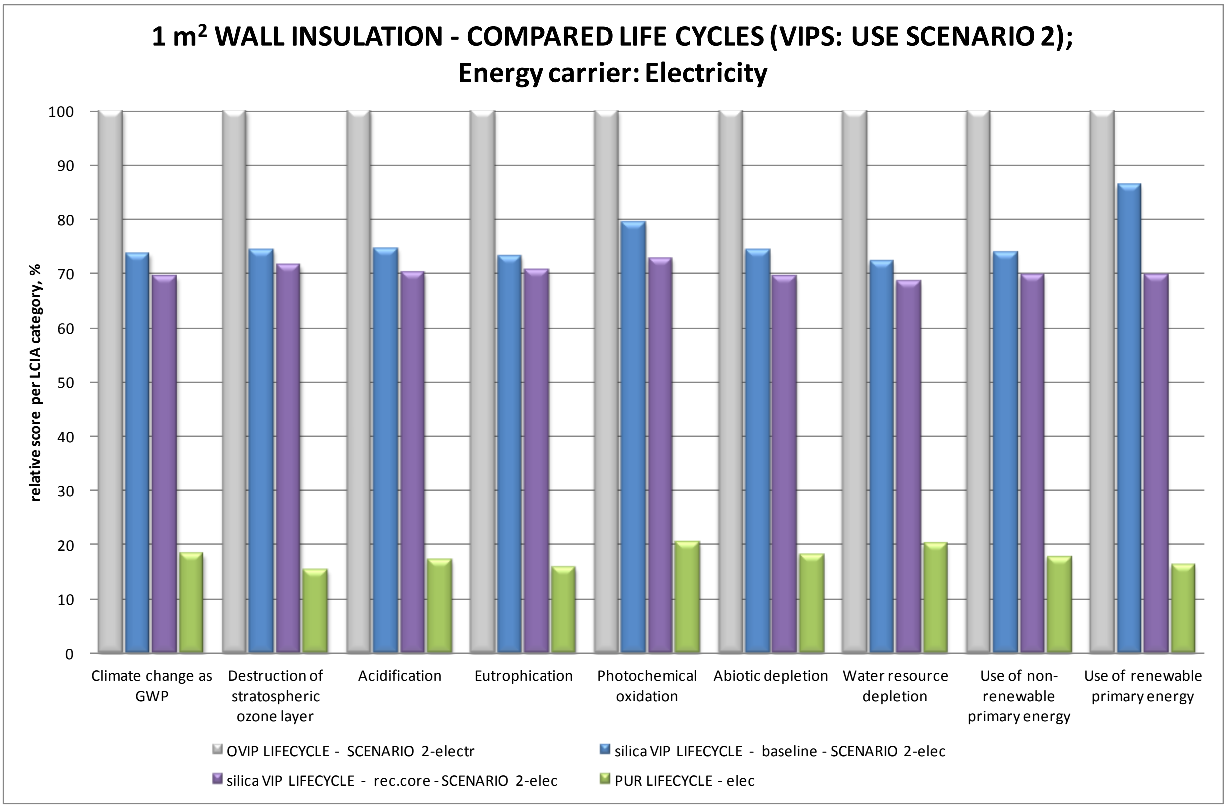

Figure 32. Compared LIFECYCLEs of 1 sq.m of wall insulation products R5 (only USE Scenario 2 considered for VIPs, energy carrier electricity for 4 products).

Therefore, it is concluded that further research would be needed to optimise either barrier properties of the new opaque envelope or the pore size of the core (or both), to ensure improved thermal resistance over time, if the OVIP is to compete with existing insulation solutions, when insulation thickness is not an issue.

In renovation works with space restrictions or when floor prices are high, VIPs have advantages over conventional wall insulation materials requiring thicker layers for achieving the specified thermal resistance. For instance, if a maximum thickness of insulation of only 25 mm is allowed, the R-value for the PUR boards evaluated will be just 1 m^2K/W and then, VIPs will be superior in the USE stage —provided that no failure takes place. On that condition, silica VIPs are the best option.

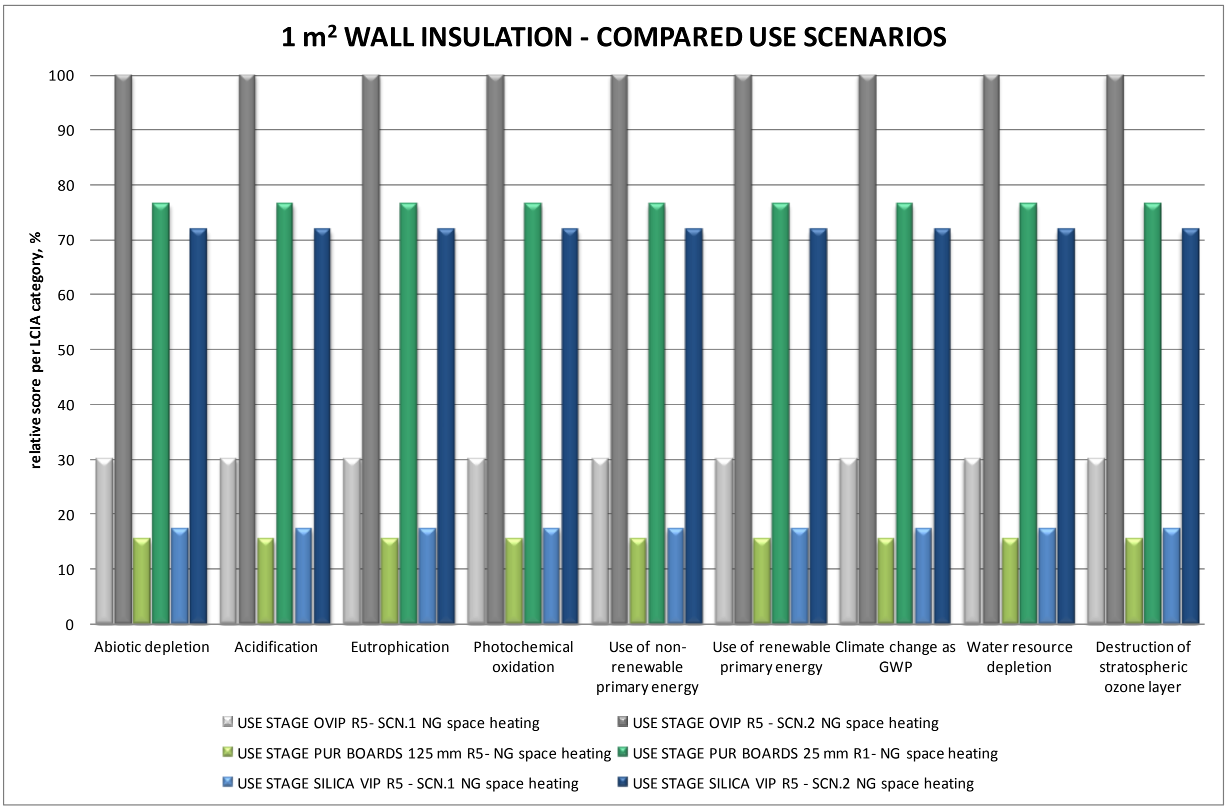

Figure 33. Compared USE stage of 1 sq.m of PUR insulation board R1 and wall insulation products R5 (two possible USE Scenarios considered for VIPs, energy carrier NG for 4 products).

6.4.2 Novel components developed for OVIP vs benchmarks

In the project a new laminate has been produced as envelope of the advanced VIP, of structure [PET(23 μm)/Al(0.1 μm)/AlOx(0.01 μm)/ORM.1(1 μm)/AlOx(0.01 μm)/Al(0.1 μm)/ PU adh./HDPE(50 μm)].

The environmental profile of the industrial-scale production of this laminate is compared with that of the trilaminate VO8621 by HANITA, which has been used as benchmark for the technical performance as barrier material, as well.

In general, they appear to generate similar environmental impacts. The novel laminate scores somewhat lower in several of the environmental indicators examined, but only significantly in the categories of *Formation of Photochemical oxidants* (POCP) and *Water Resource Depletion* (WRD). Conversely, the value of VO8621 trilaminate for the indicator *Ozone Depletion Potential* (ODP) is ca.30% lower.

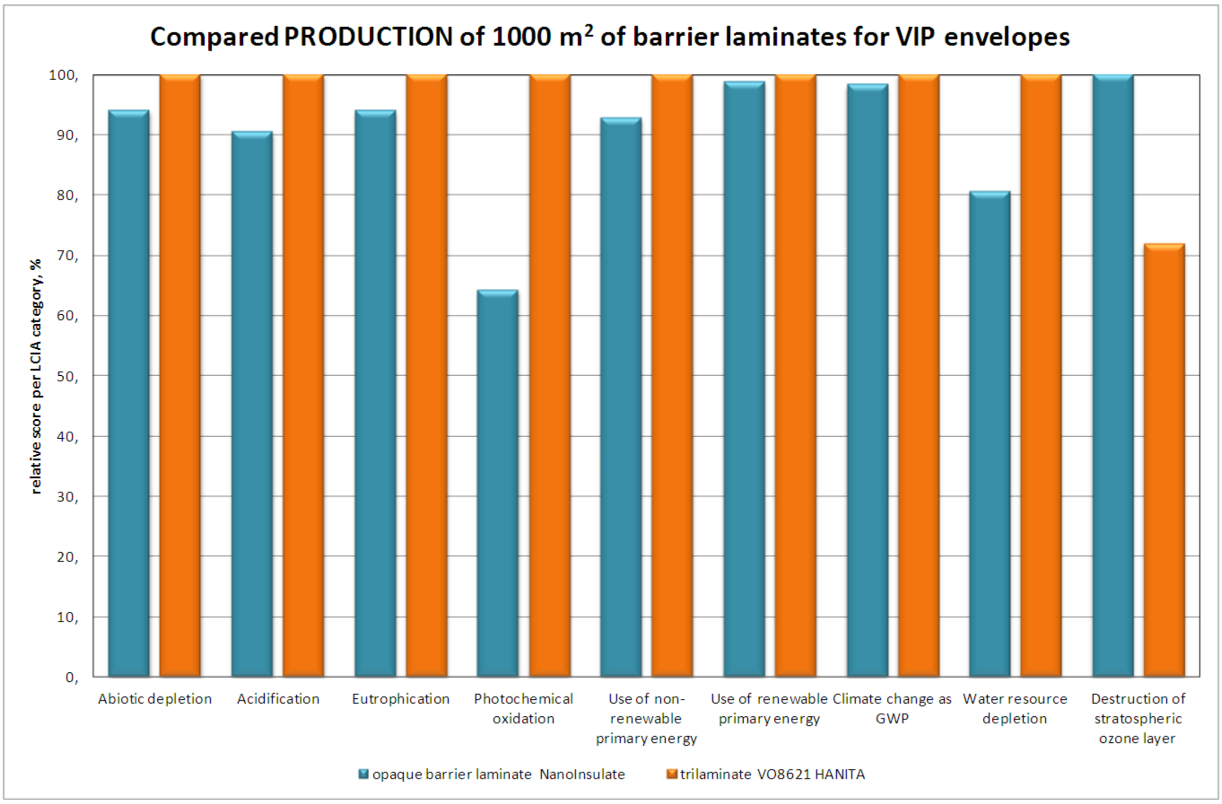

Figure 34. Compared production of 1000 m^2 of advanced opaque laminate and VO8621 trilaminate

In order to explain those results, the inventory flows that contribute to the impact categories are examined. In the case of POCP indicator, the impact is almost exclusively caused by the organic solvent emissions. The impacts associated to the MEK emissions to air inventoried in the lamination step of trilaminate film exceed those accounted in the lamination and lacquer coating steps in the novel barrier laminate. In the WRD indicator, greater contributions from aluminium and adhesive explain, for the most part, the differences. The impact share of ORMOCER® System 1 is the main difference that explains the disparity in the values of the indicator ODP.

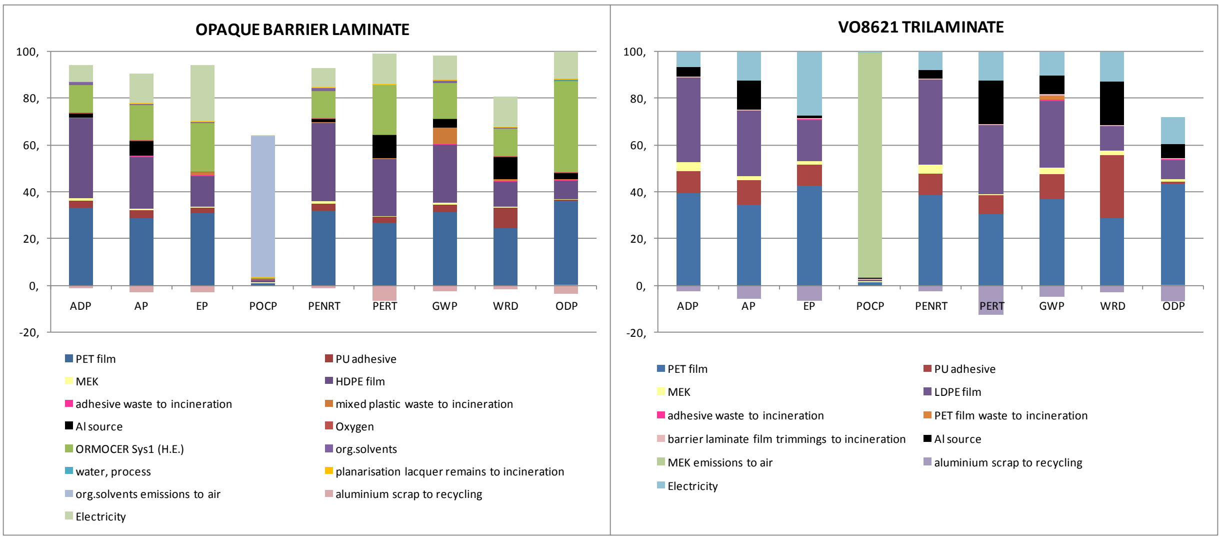

Figure 35. Compared production of 1000 m^2 of advanced opaque laminate and VO8621 trilaminate, showing LCI flows contribution to environmental indicators.

The environmental impacts caused by the production of 1 kg PU nanofoam have been compared with the impacts associated to the production of 1 kg PUR rigid foam (industry average). Although no pentane is used as blowing agent in the nanofoam synthesis, its overall impacts are higher than for the average foam.

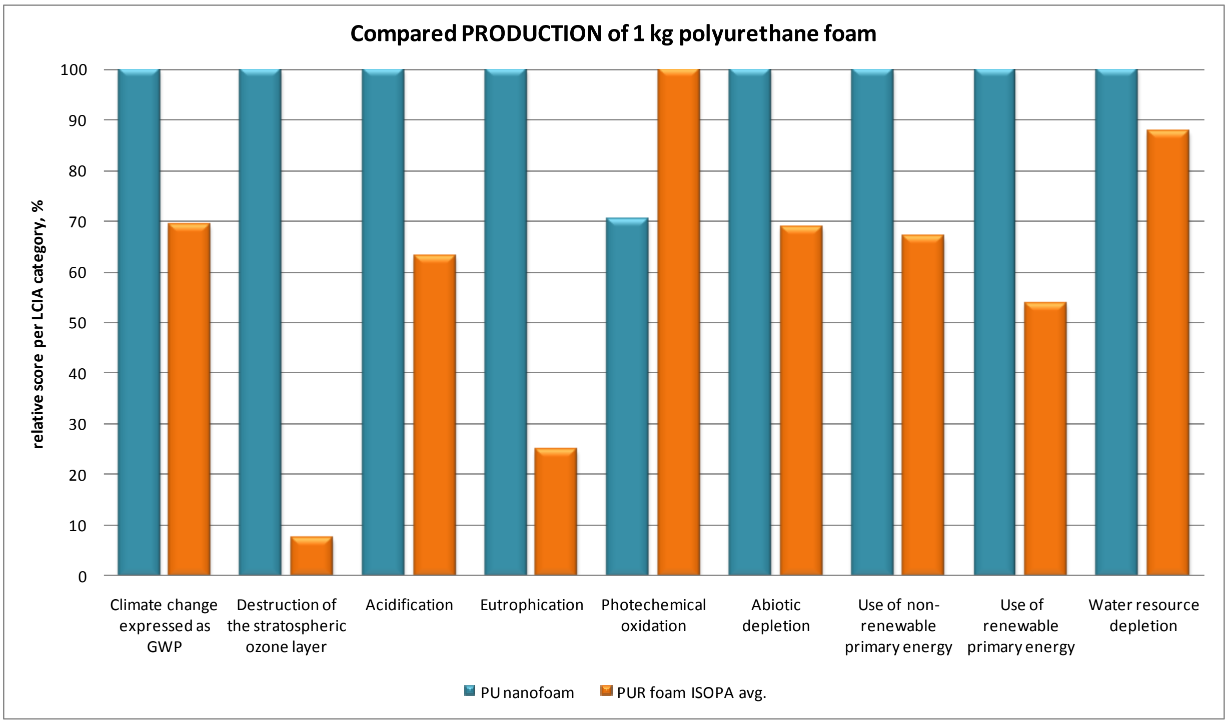

Figure 36. Compared production of 1 kg advanced PU nanofoam and 1 kg industry avg. PUR rigid foam

The observation of the relative contribution of LCI flows to each environmental indicator makes it evident that the share of electricity impact in the indicators in the case of the nanofoam is much higher than in the case of average PUR foam. Most probably, these results are a consequence of upscaling issues, since nanofoam has been synthesised on a small scale in the framework of the NanoInsulate project and inventory data for the average PUR rigid foam come from industrial scale production.

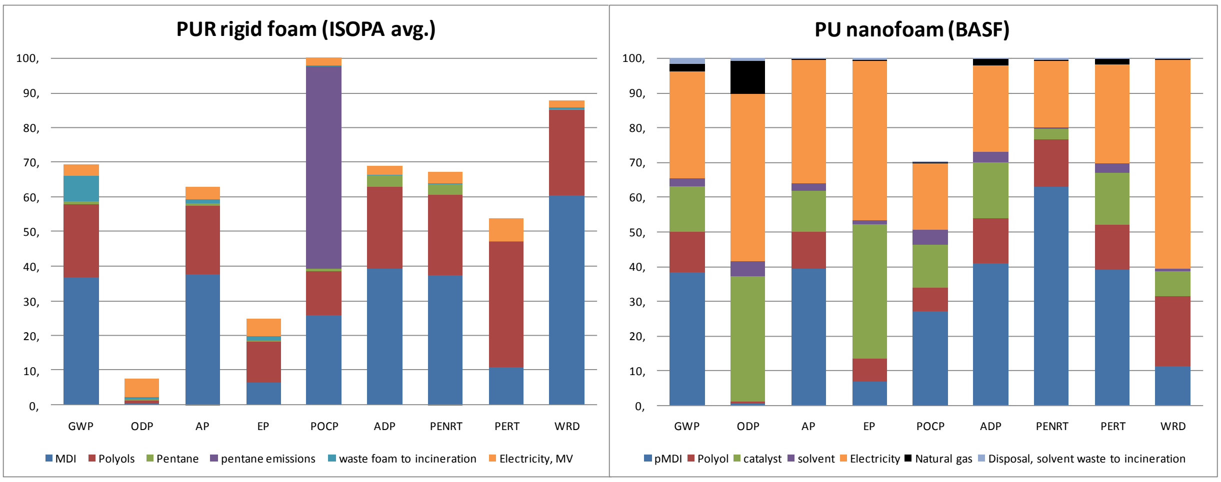

Figure 37. Compared production of 1 kg advanced PU nanofoam and 1 kg industry avg. PUR rigid foam, showing LCI flows contribution to environmental indicators

6.4.3 Sensitivity checks

In the LCI of the production of the novel components developed for the project there is large uncertainty. Several assumptions have been made for filling data gaps and figures for mass and energy flows have been selected within ranges of possible values.

<u>PU NANOFOAM</u>

Regarding the synthesis of nanofoam, two different combinations of the mass and energy flows within the declared ranges of values in the LCI provided by BASF have been worked out (case A and case B, see section 6.2.1). As the comparison between the LCIA results of both cases reveals, the impacts associated to each of them differ by less than 10% in most of the indicators. Given this and the magnitude of the numeric indicators, little influence in the final results is expected due to the choices in the inventory.

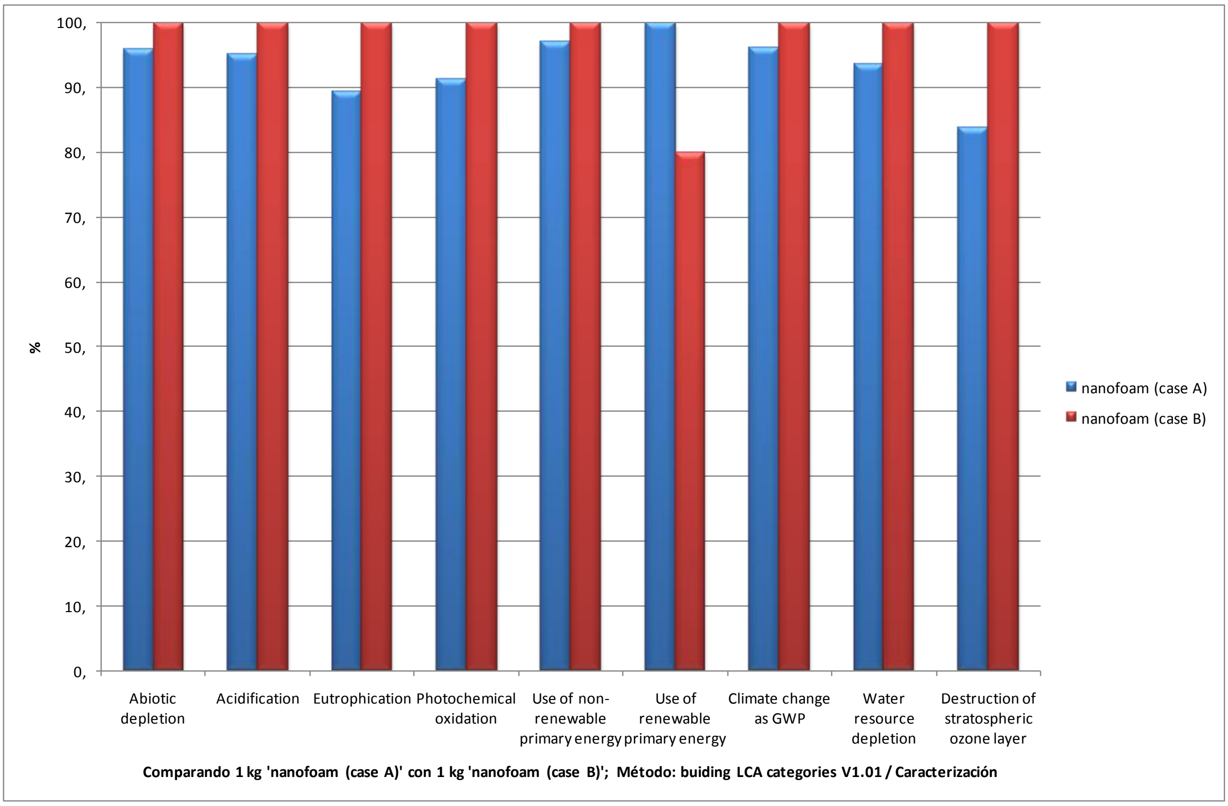

Figure 38. Compared production of 1 kg advanced PU nanofoam (case A *vs* case B)

Table 25. LCIA results for Production of 1 kg PU nanofoam. Sensitivity check

Impact category	Unit	Case A	Case B
GWP	kg CO2 eq	6.477	6.741
ODP	kg CFC-11 eq	1.78E-07	2.12E-07
AP	kg SO2 eq	0.027	0.028
EP	kg PO4--- eq	0.013	0.015
POCP	kg C2H4	1.30E-03	1.42E-03
ADP	kg Sb eq	0.059	0.062
WRD	m3 water eq	0.013	0.014
PENRT	MJ	143.041	147.497
PERT	MJ	5.708	4.564

<u>OPAQUE BARRIER LAMINATE</u>

In the opaque barrier laminate, much of the uncertainty is related to ORMOCER®, either to consumptions and emissions during the application of ORM Sys1, or to the LCI of its production:

- Lacquering metallised film: in the industrial-scale production of laminate films ORMOCER® will be applied onto the metallised substrate by wet layer coating at

HANITA's lacquering machine. According to HANITA, the coating process of ORMOCER® should have numbers similar to the numbers of the lamination processes. Therefore, inputs and outputs of film and energy have been extrapolated from the data for the lamination process. Inputs of ORMOCER® and solvent for thinning and outputs of solvent emissions are modelled according to information provided by Fraunhofer IVV on lacquer composition and application conditions.

- Production of ORMOCER® System 1. Data for lab-scale production have been provided, together with a description of the procedure for larger scale production (50 kg). Energy inputs to the system are data gaps. Data about power requirements for stirring vessels of different volume have been gathered from literature and OEMs and estimates for electricity consumption in the synthesis of 1 kg ORMOCER® System 1 have been calculated, ranging from 1 kWh to 10 kWh. Two sets of LCI data with the minimum and maximum energy values have been worked out and used, alternatively in the LCIA calculations, to check the influence of the energy assumptions.

Other source of uncertainty in the environmental evaluation of metallised laminates is the yield of the metallisation steps and the EOL destination of the losses of the metallic/inorganic sources not deposited onto the substrate. Two possible alternatives have been considered in the calculations: evaporated aluminium deposited out of the film is recovered and can be recycled into new evaporation sources; or it is lost and ends up disposed of. Those assumptions apply also to the trilaminate benchmark, so that bias in LCIA calculation is consistently introduced in their comparative assessment.

Two models of barrier laminate have been made: one with the most favourable assumptions (low energy consumption and aluminium recycling) and another for the worst case (high energy consumption, aluminium losses to disposal). As deduced from the compared columns chart (Figure 39), no significant differences are originated in the LCIA results. Taking into account that the contribution of barrier laminate to the total impact of OVIP is around 5% in most of the categories assessed, except for the *Photochemical Oxidation* (for which best and worst case score the same), it can be concluded that no significant influence in the final results is expected as a consequence of the choices in the inventory of barrier laminate production.

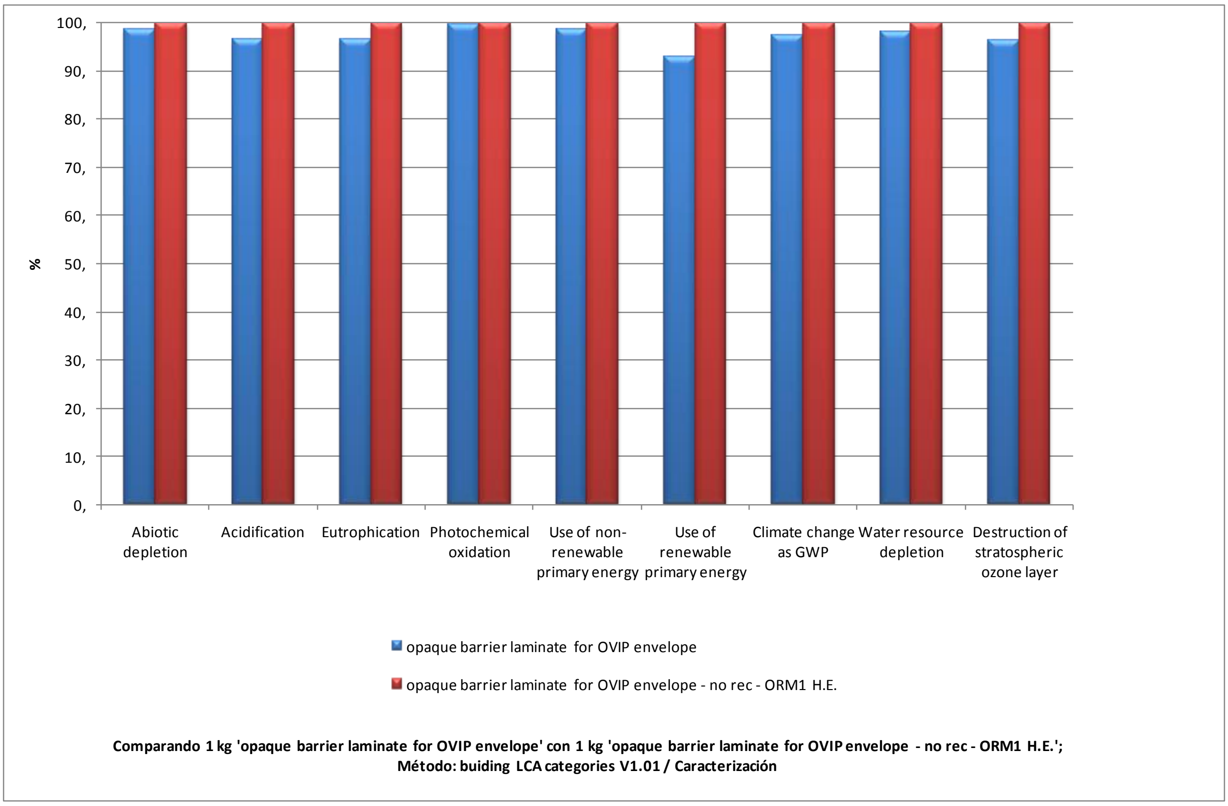

Figure 39. Compared production of 1000 m^2 opaque barrier laminate (best case *vs* worst case)

6.4.3.1 Background LCI datasets for operational energy

Operational energy in use drives most of the impacts of the lifecycle of the products. Relevant differences have been found depending on the energy carrier for delivering the energy for heating, being electricity the responsible for larger impacts. Since background data for heat from boilers fuelled with natural gas and fuel oil have been sourced from a different LCI database (ELCD) than electric heating by heat pumps (Ecoinvent), a sensitivity check has been conducted to verify if the choices of background data are relevantly changing the overall LCIA results.

To this end a comparison is made between the ELCD database processes for heating by boilers using NG and oil and the corresponding processes available at Ecoinvent v2.2, applied to the amount of energy delivered to compensate for heat transfer with OVIP insulation in USE Scenario 1.

Table 26. Background LCI data for residential heating available in LCI databases.

ELCD v2.0 database	Ecoinvent v2.2 database
Heat, from resid. heating systems from NG, consumption mix, at consumer, temperature of 55°C EU-27 S	Heat, natural gas, at boiler condensing modulating <100kW/RER S
Heat, from resid. heating systems from LFO, consumption mix, at consumer, temperature of 55°C EU-27 S	Heat, light fuel oil, at boiler 10kW condensing, non-modulating/CH S

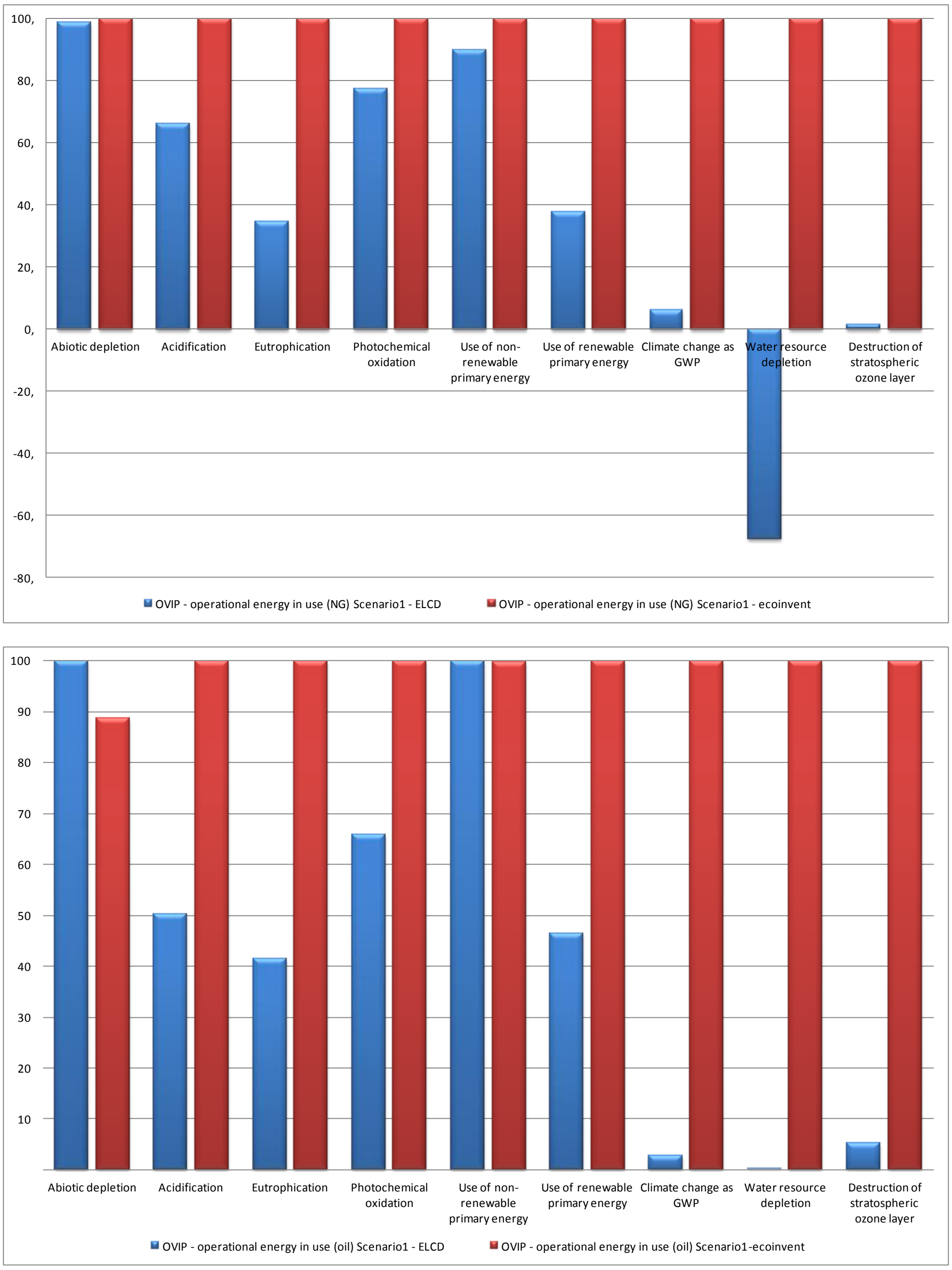

Figure 40. Compared impacts for delivered heat with NG at boiler (top) and light fuel oil at boiler (bottom), calculated using generic background processes from two LCI databases

Table 27. LCIA results for supplying 834 kWh of heat (OVIP, Use Scn.1). Sensitivity check

Impact category	Unit	NG at boiler ELCD	NG at boiler Ecoinvent	LFO at boiler ELCD	LFO at boiler Ecoinvent
GWP	kg CO2 eq	13.468	215.592	7.630	267.980
ODP	kg CFC-11 eq	5.14E-07	3.32E-05	2.04E-06	3.91E-05
AP	kg SO2 eq	0.122	0.185	0.293	0.584
EP	kg PO4--- eq	0.013	0.038	0.035	0.085
POCP	kg C2H4	0.018	0.023	0.020	0.031
ADP	kg Sb eq	1.744	1.768	1.941	1.721
WRD	m3 water eq	-0.009	0.014	1.41E-05	0.064
PENRT	MJ	3285.024	3649.717	4000.978	3991.040
PERT	MJ	4.822	12.803	12.796	27.523

In general, by using the datasets from Ecoinvent database, the estimated impacts are higher. As clearly denoted in the figure, in three impact categories the differences are especially relevant for the values of their numeric indicators: GWP, ODP and WRD. Among them, differences in the associated kg CO2 eq are outstanding.

This means that, if Ecoinvent processes were used for modelling the delivery of operational energy for the three energy carriers in the USE Scenario 1 of OVIP, the USE stage would become undisputedly the dominant phase in the lifecycle impacts.

Regarding the comparison with the payback period between the silica and novel opaque VIPs, the results are not significantly changed with the use of Ecoinvent datasets: the silica VIP would compensate the embodied energy savings in production of OVIP in 4.5 years instead of in the 5 years estimated previously.

7 Environmental impact assessment of advanced Transparent Vacuum Insulation Panels: LCA of TVIPs

The scheduled objectives in the environmental assessment of TVIPs were to carry out a comparison of the environmental impacts between the currently available alternatives used in triple glazing in window applications and triple glazing integrating TVIP in the cavity between panes, using simplified lifecycle analysis (LCA) methodologies to cover all lifecycle stages, including: Production, Construction, Use and End-of-Life.

With the aim of establishing benchmark values for insulating windows, various window rating systems and sets of labelling criteria currently available for windows in Europe, regarding their thermal performance, as well as standards, have been revised, among others: German Window Technology Institute in Rosenheim, Denmark's window rating scheme in efficiency classes, WER system by the British Fenestration Ratings Council, Nordic Ecolabelling v3, PassivHaus (DE), Minergie (CH), IGU certification by the Danish glass industry, EN 1279-5 - *Glass in building - Insulating glass units - Part 5: Evaluation of conformity to create a basis for CE labelling of insulating glass units in accordance with the Construction Products Directive*. Also the guidelines for applying LCA methodology to the product “Windows” and its building application in a recently expired PCR in the EPD® System have been checked to learn how the energetic performance of the window is represented in the Use Phase.

From the information conveyed in the aforementioned documents, it is established that the energetic performance of windows results from the sum of thermal transfer, solar contribution and air permeability effects. The definition of an efficient window involves the fulfilment of some requirements regarding thermal performance, but also the ability to admit daylight. Therefore, a minimum value of the following parameters should be achieved:

- Thermal transmittance (U-value)
- Solar heat gain (G-value), a measure of how much heat from the external environment is transferred through a window into the interior of a building
- Air leakage or air infiltration, which is the amount of air that a window allows to enter or leave a building.
- Day light transmittance (a measure of the amount of daylight that passes through a window and enters a room). Successfully achieving acceptable or high levels of daylight transmission will mean that minimal energy will be used for artificial lighting of the interior of the building

Given that the performance of the window is the result of the effects of the glazing, the frame, the spacers, etc., for simplification of the analysis, the LCA should focus only on evaluating glazing units (IGU) with equivalent performance, based on the cited parameters.

International Standard ISO 10077-1 gives tabulated values for thermal transmittance of double and triple glazing filled with different gases (for vertical glazing), for several types of glass and for various thickness values of glass panes and cavities. That same standard gives typical values of thermal transmittance of windows of given dimensions (1.23 m × 1.48 m) and characteristics (frame area, frame material).

The benchmark IGU to be compared with the triple glazing integrating TVIPs can be set from the tabulated values in ISO 10077-1, once the characteristics of the advanced TVIP-glazing are communicated.

In the framework of activities developed in the project, up to three TVIP-windows are described:

- Prototype TVIP-window (600 mm × 600 mm × 100 mm) constructed and built at IGF/Inwido. Double glazing: 2 glass panes (thickness 4 mm), 1 TVIP panel: 500mm × 500 mm × 15 mm, made by va-Q-tec. $U_w \leq 0.5$ (calculated); g-value = n.a.; daylight transmittance = n.a.
- 'Real' TVIP-window constructed and built at IGF/Inwido. Triple glazing (4-15-4-15-4): three glass panes, thickness 4 mm; inner: common float glass; middle: energy glass; outer: safety glass. Cavity 1 (outer): Ar(g); cavity 2 (inner): T-VIP, 2 panels. T-VIP panel size: 476 mm × 388 mm × 15 mm. U-value= n.a.; g-value = n.a.; daylight transmittance= n.a.
- 'Proof-of-concept' TVIP-window constructed and built at IGF/Inwido: Airglass® Aerogel TVIP 3-Glass Windows, with the characteristics shown in the table below.

Table 28. Characteristics and product data of TVIP-window for LCA analysis

window type	fixed frame/non-opening vertically positioned
U-value, W/m^{2}K	n.a.*
g-value	n.a.*
daylight transmittance	n.a.*
window dimensions	n.a.*
frame	wood Elitfönster® standard wood type (Elitfönster® construction www.elitfonster.se)
frame area*	n.a. (%)*
IGU: type of glazing	triple glazing
IGU: glass	3 glass panes, thickness 4 mm: Outer*: energy glass middle: common float glass

	inner*: common float glass
IGU: glazing dimensions	4-12-4-20-4 unit size*: ?? mm × ?? mm, thickness: 44 mm
IGU: space filler	cavity 1 (outer): Ar(g) cavity 2 (inner): T-VIP, 2 panels* T-VIP panel size*: ?? mm × ?? mm × 20 mm
IGU: glass spacer*	n.a.
weather stripping gasket	n.a.

(*) missing data: to be supplied/confirmed by Airglass

Unfortunately, the lack of sufficient data about the integration of TVIPs developed in the project into triple glazing windows and its thermal properties and performance has forced a change in the scope of the LCA planned (comparison with triple glazing windows with gas filler in the *Insulating Glass Unit*, IGU) to a stand-alone simplified LCA of the transparent VIPs.

7.1 Goal and Scope of the LCA study

The aim of this study is the calculation and interpretation of the LCA results for the novel TVIP product system to be used in triple glazing windows in buildings, by means of a stand-alone simplified LCA of the transparent VIP, including only its production and end-of-life stages. The purpose of this study is to identify the materials and processes that contribute in a higher degree to the environmental impacts of the panel. The study is part of a confidential report: results are intended for internal communication purposes within the project Consortium.

7.1.1 Functional unit and reference flows

As no comparative assertions will be done and the performance in the USE phase has been excluded of the LCA study, the evaluation will be referenced to a unit amount (mass, sq.m panel, panel units...) of transparent VIP.

<u>Declared unit & reference flow:</u>
1 m^2 TVIP 15 mm thickness.

7.1.2 Description of the product system

The main characteristics of the transparent panel considered in the LCA study are shown in the table below.

Table 29. Characteristics and product data of T-VIP developed (for demo activities)

λ, W/mK	0.009 (evacuated, @10mbar)
daylight transmittance	daylight quality, transparent/translucent
d, kg/m^3	185
unit size	panels 476 mm × 388 mm, thickness 15 mm (U-value=0.64 W/m^2K)* (2 panels per inner cavity of sealed glazing unit of T-VIP window)
service life, years	20*
composition	• Core*: 100% silica aerogel (Airglass hydrophilic panel) λ=0.009 W/mK, d=160 kg/m^3 • envelope: laminate (HANITA, roll 3727939) "PET / SiO_2 / adhesive / SiO_2 / PET / adhesive / HDPE"

(*) uncertainty in data: source of data project report, assumptions not confirmed by Airglass at the time of conducting the LCA and writing the present report

7.1.3 System boundaries

The present LCA uses the attributional approach. The unit processes within the system boundaries for this simplified LCA are described below.

- For the PRODUCT STAGE: raw materials supply and manufacturing processes are included in the study. Transport of TVIP components to VIP manufacturer's factory is not included, to avoid misrepresentation of transport of pilot-scale materials between partners in the scope of the project.
- EOL STAGE: only waste processes for reuse, recovery or recycling and waste treatment processes for disposal are included in the study. Reuse, recycling, recovery potential is addressed.

Capital goods and equipment have not been included in the foreground processes for manufacturing and waste treatment operations modelled from specific data collected for the study. In the case of generic data used for the background processes or average operations in the industry, capital equipment and machinery may be included in the datasets. For the consistency of the consideration of infrastructure in the study generic datasets have been selected from the same LCI database (*Ecoinvent System process v2.2*).

7.1.3.1 Cut-off rules

See chapter 6.1.3.1

7.1.3.2 Allocation

See chapter 6.1.3.2

7.1.4 Data quality requirements

See chapter 6.1.4

7.1.5 LCIA methodology, impact categories and environmental indicators

See chapter 6.1.5

7.2 Life Cycle Inventory (LCI)

For manufacturing TVIPs roughly the same operations as for OVIPs are assumed: reception of delivered components (aerogel silica panels of the required core size), drying panels by heating, wrapping core into high barrier film, evacuating, sealing, storing VIP for several days, testing gas pressure, (packaging). Consumption of energy as estimated in the manufacturing of OVIPs by va-Q-tec: 5 kWh/m^2. The barrier film waste generated is sent to non-hazardous waste incineration.

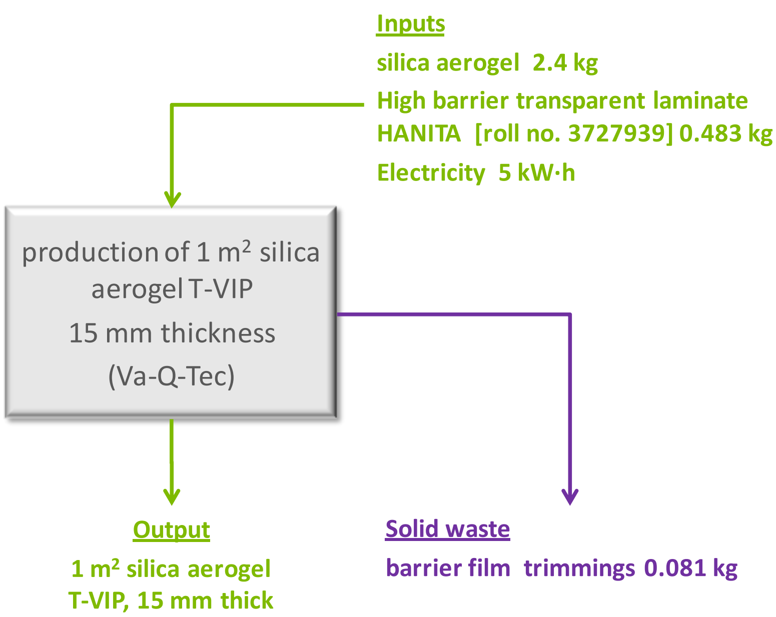

Figure 41. Input-output flowchart for production of 1 m^2 TVIP.

The Production stage of transparent cores has been modelled from "recipes" and description of manufacturing process of pure silica aerogel cores, reported by partner Airglass for batch production on a small industrial scale in Deliverable D1.1 and D1.2 and in WP1 presentations at several project meetings (M18, M30, M36). When needed, data has been supplemented with "recipes" for lab-scale production reported by KOÇ (e.g., acid and basic catalyst concentrations) in project Deliverable reports and thesis produced in the framework of the project. Energy consumption in the manufacturing process at Airglass has been estimated from the reported energy costs (50€ for 12 silica aerogel panels 14 mm thick (equiv. 3 sq.m panel), *source: D1.1 report*) and published data about the price of electricity in Sweden in year 2010.

The production comprises mixing precursor, solvent and catalyst and formation of alcogel, aging in moulds, washing baths, solvent extraction by SCD and final heat treatment to remove remains of ethanol in the aerogel pores.

For the Super Critical Drying (SCD) process with CO_2, ca. 20% losses of "polluted" CO_2 are assumed (700 kg CO_2 per 12 panels equivalent to 49 L aerogel), following claims by Airglass about 80% recycling of CO_2, with solvent recovery. Saturated solvent used in ageing and washing baths is 100% recovered for further runs; therefore, no additional amount of solvent is considered in the calculations.

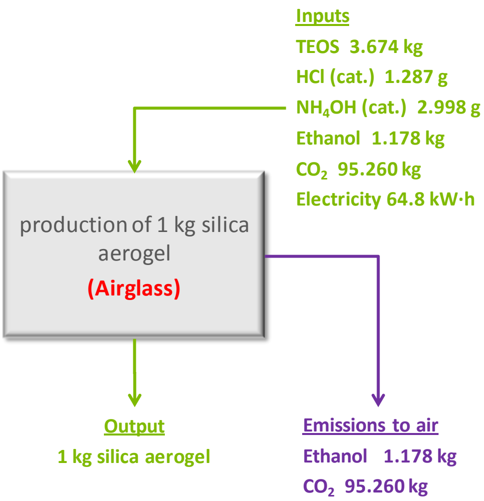

Figure 42. Aggregated input-output flowchart for production of 1 kg pure silica aerogel, with 80% recycling of CO_2 and solvent in SCD system

The manufacturing of the transparent barrier has been modelled from data supplied by HANITA about lamination and from values estimated from literature references on Electron Beam (EB) deposition of SiOx and other inorganic oxides on film (to deal with non-available data about commercial CERAMIS® coating of PET film by AMCOR). Several references have been obtained by OEMs and in scientific literature about coating speed, thickness of layer and power of electron beam sources that have allowed to calculate rough estimates of energy consumed for the deposition of a 0.1 μm layer of SiOx. Also, a LCI datasheet about SiOx coating on PET foil existing in the BUWAL250 database (by the *Swiss Packaging Institute*) have been considered as a source of energy data for the EB coating process. Information by AMCOR[3] about the raw material evaporated ("essentially sand") for the SiOx coating and any other chemicals ("no solvents or other chemicals, which could result in harmful emissions to the environment") used in the process has helped to establish the nature of the material inputs. Regarding material yield of the process, no data have been found about amount of evaporant that does not end deposited onto the film substrate. Two hypotheses have been considered: ca. 50wt% of input material (as in thermal evaporation of Al and reactive deposition of AlOx, *source HANITA*) and 15% (as in sputtering process, *source Ecoinvent v2.2 database*). Similarly, two potential yield percentages of PET film are envisaged: either film losses after coating amount to 7.5wt% of input PET film (as in PVD process, *source HANITA*) or to 100 m^2 per every 1000m^2 of coated PET produced (*BUWAL250 database*).

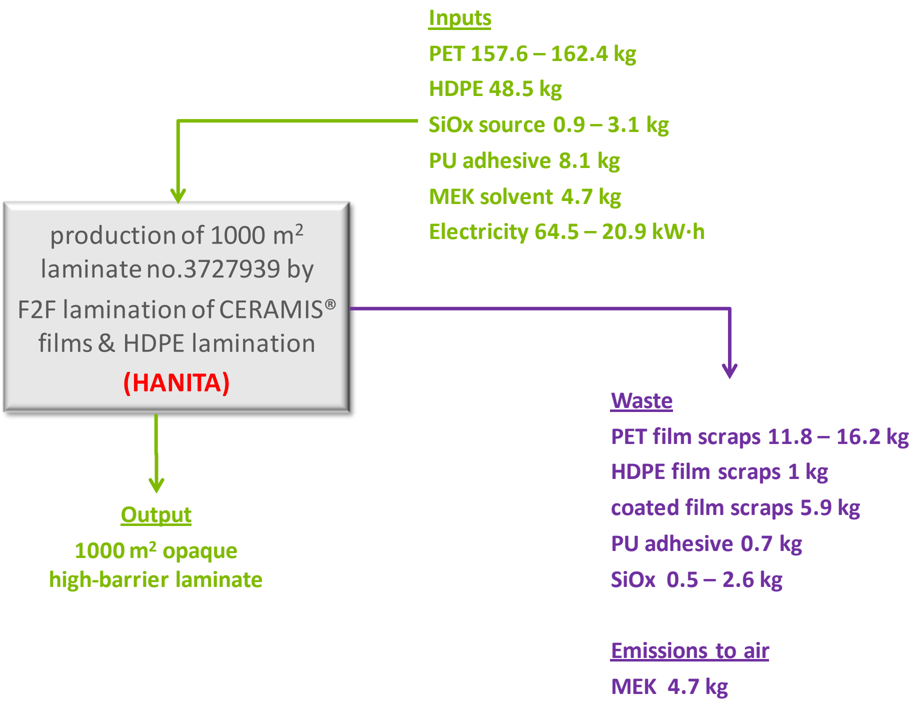

Figure 43. Input-output (aggreg.) flowchart for production of 1000 m^2 of advanced high-barrier laminate (transparent)

[3] AMCOR. CERAMIS® Barrier Films – Brochure 20111 & Ceramis® Coating Technology – Brochure 2012. (available at http://www.amcor.com/businesses/amcor-flexibles/industrial/Ceramis_Publications.html)

Given the ranges of values for energy and material inputs/outputs handled, a sensitivity check has been conducted to quantify the effect of the diverse assumptions on the final environmental results of the barrier film. Three cases, defined for different hypotheses of energy consumption, PET yield and SiOx deposition yield, have been compared. Resulting differences are negligible, as discusses in a later section of this report. For modelling PRODUCT Stage of transparent VIP, the values under Case A hypothesis have been taken.

Table 30. LCI flows for 1000 sq.m coated film (thickness SiOx layer 0.1 μm). Three case hypothesis.

CASE A		
PET losses	7.50wt%	ref. HANITA, PVD thermal evap. of Al
SiOx losses	ca. 50wt%	ref. HANITA, PVD thermal evap. and AlOx reactive deposition
energy input	26.46 kWh	ref. own estimations based on data about material evaporated, Coating Speed [m/min]/layer thickness, Max. coating widths and Max. Electron Beam power in *TOPBEAM 1100 S Datasheet - Applied Materials*
CASE B		
PET losses	9% input area	ref. BUWAL250 datasheet "Production of SiOx coated PET foil"
SiOx losses	ca. 50wt%	ref. HANITA, PVD thermal evap. and AlOx reactive deposition
energy input	5.50 kWh	ref. BUWAL250 datasheet "Production of SiOx coated PET foil"
CASE C		
PET losses	9% input area	ref. BUWAL250 datasheet "Production of SiOx coated PET foil"
SiOx losses	ca. 85wt%	ref. Ecoinvent v2.2
energy input	5.50 kWh	ref. BUWAL250 datasheet "Production of SiOx coated PET foil"

Regarding the end-of-life phase for the TVIPs this is the baseline scenario considered:

Transport of waste to disposal facilities: By road. Distance: 30 km. Truck 16t (fleet average). Load factor 50% (return trip: empty).		
waste material	**kg per reference flow kg/m^2 TVIP 15mm**	**EOL route**
core (silica aerogel)	2.400	inert waste landfill
envelope (transparent barrier)	0.402	non-hazardous waste incineration
total waste	**2.802**	

7.3 Life Cycle Impact Assessment (LCIA)

The environmental profile of production and EOL of the transparent VIP has been evaluated for the set of impact categories selected in the present study (section 6.1.4, Table 4). In a preliminary assessment the impacts of disposal and recycling/recovery treatments of waste and EOL material/energy outputs are included in the calculation of the indicators for the impact assessment categories, with the aim of simplifying the interpretation of results in the graphs (i.e., disposal and recycling/recovery operations accounted within the system boundaries). The indicators for LCI analysis with regards to waste to disposal and material for recycling/energy recovery are separately evaluated later.

The PRODUCT stage of the TVIP has been comprehensively analysed, in order to assess the environmental performance of the novel materials developed in the project and draw conclusions for improvement and identify needs for further research. As shown in Figure 44, aerogel core is almost exclusively the responsible for the overall impacts in the production stage.

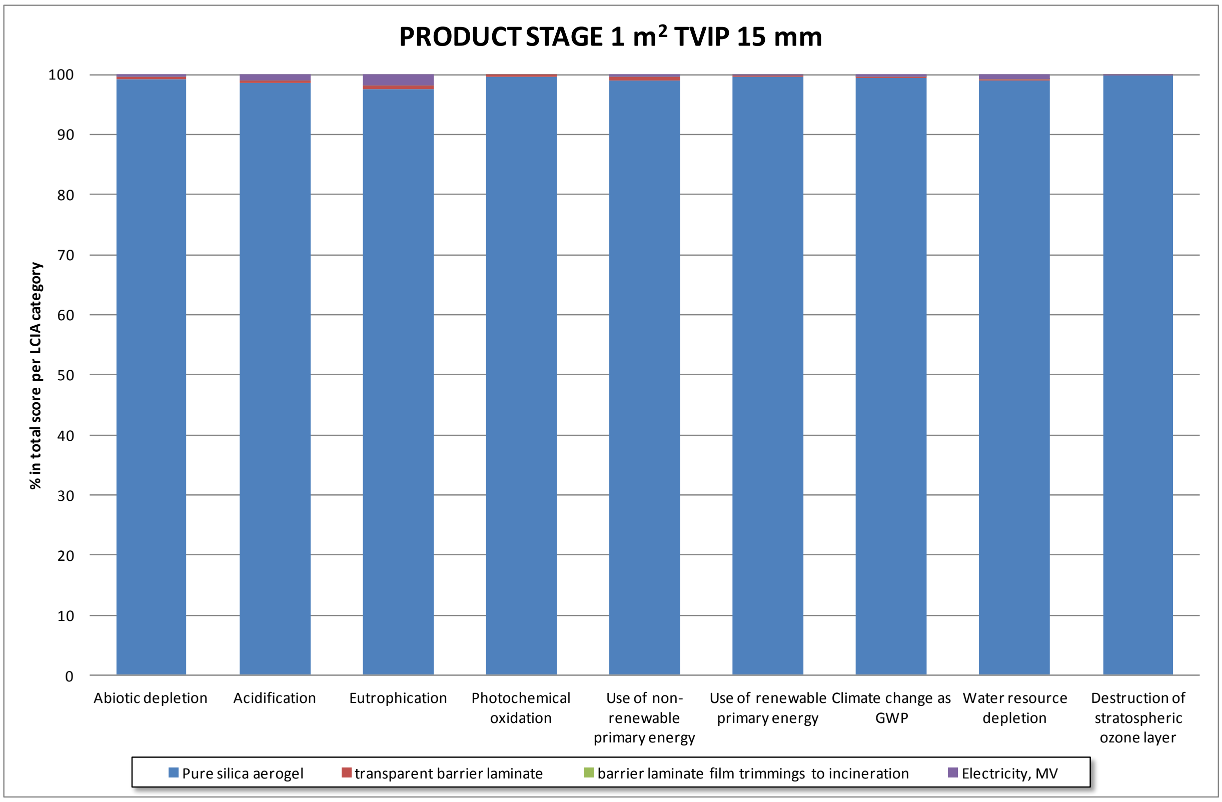

Figure 44. Relative contribution of LCI flows to LCIA results in the Production of 1 m^2 TVIP.

Table 31. LCIA results for production of 1 sq.m transparent VIP 15 mm thickness

Impact category	Unit	Pure silica aerogel	transparent barrier laminate	barrier laminate film trimmings to incineration	Electricity, MV
GWP	kg CO2 eq	888.325	1.879	0.190	2.655
ODP	kg CFC-11 eq	7.56E-05	7.40E-08	2.85E-10	1.30E-07
AP	kg SO2 eq	1.326	6.62E-03	3.51E-05	0.013
EP	kg $PO4^{3-}$ eq	0.460	2.46E-03	4.28E-05	0.009
POCP	kg C2H4	1.243	4.74E-03	1.15E-06	4.94E-04
ADP	kg Sb eq	4.790	0.021	2.25E-05	0.020
WRD	m3 water eq	0.472	1.56E-03	1.81E-05	3.49E-03
PENRT	MJ	11096.673	49.345	0.055	53.523
PERT	MJ	1746.803	1.674	2.67E-03	3.508

Regarding environmental impacts caused in the production of the individual components of the transparent panel, in the case of silica aerogel, the main contributors to the overall impact are:

- TEOS (Tetraethyl orthosilicate) precursor, mainly in use of primary energy, ozone depletion potential, abiotic depletion and acidification potential.
- Ethanol emissions to air for Photochemical oxidation.
- Carbon dioxide (as consumed chemical and emission to air) in Eutrophication Potential, Water Resource Depletion, Climate Change and Acidification, specifically. This circumstance stresses the importance of recycling as much CO_2 as possible in the supercritical drying system, to reduce significantly the impacts associated with the production of aerogel. For instance, every kg of CO_2 recycled and not emitted means avoiding impacts for 1.82 kg CO_2 equiv. (GWP) and 10.53 MJ (primary energy use); apart from the reduction in the different impact categories due to the parallel recovery of the ethanol extracted with the $scCO_2$ (minimising its relative contribution to the POCP category in which the EtOH emitted with the CO_2 losses accounts for the greatest share).

As for the transparent barrier laminate, the amount of PET film present (2 layers of 50 μm thickness each) causes the highest impacts in the total environmental profile. Following it, HDPE film and electricity consumption contribute significantly to the various LCIA categories, on average. For the Photochemical Oxidation indicator, “MEK emissions to air” LCI flow shows the highest score of all input/output flows to the product system.

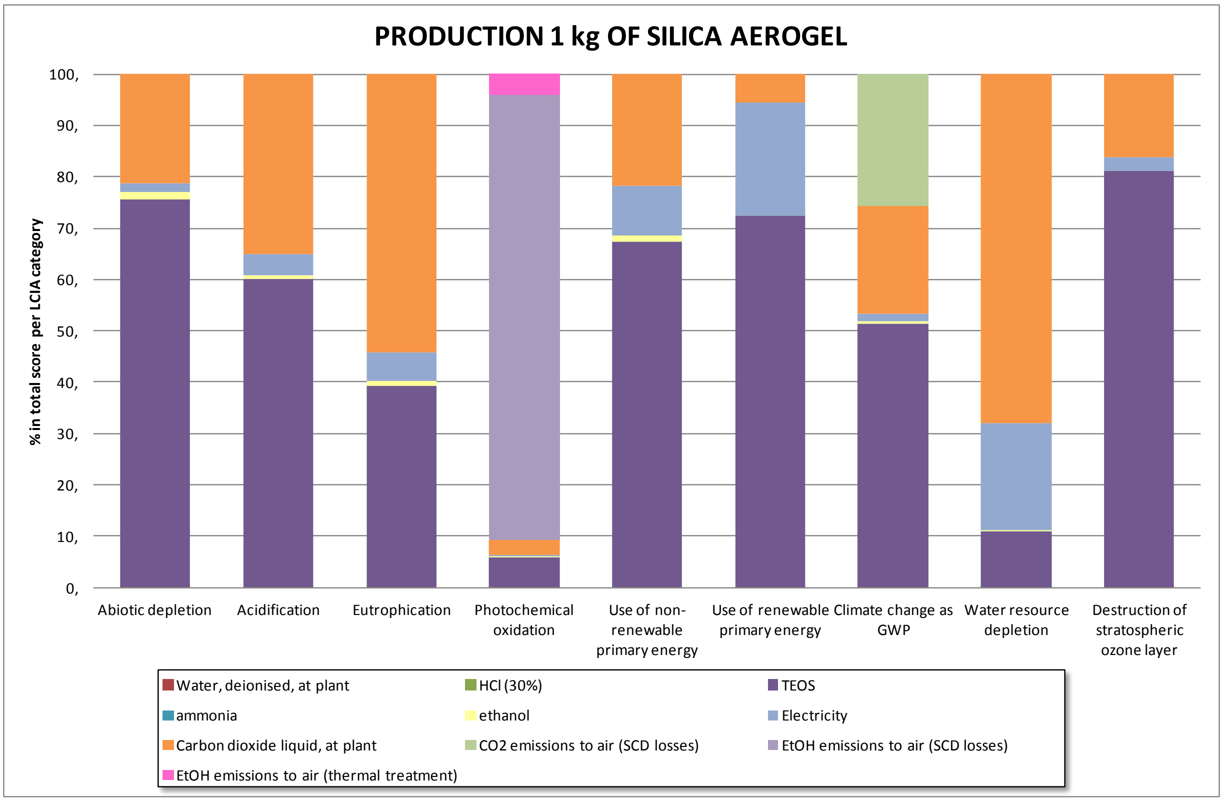

Figure 45. Relative contribution of LCI flows to LCIA results in the Production of 1 kg silica aerogel.

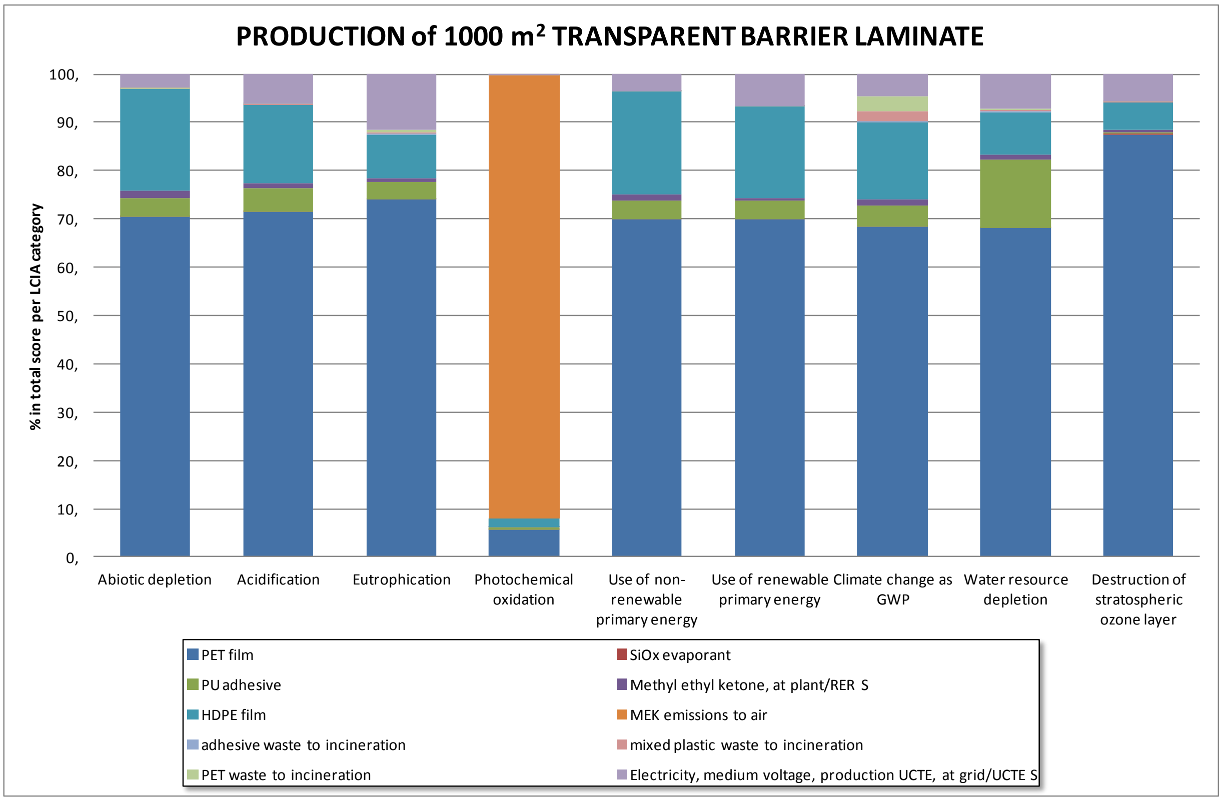

Figure 46. Relative contribution of LCI flows (aggregated values) to LCIA results in the Production of 1000 m^2 of transparent barrier laminate for TVIP envelope

Table 32. LCIA results for production of 1 kg silica aerogel

Impact category	Unit	Water, deionised	HCl (30%)	TEOS	ammonia	ethanol	Electricity, MV	Carbon dioxide liquid	CO_2 emissions to air (SCD)	EtOH emissions to air (SCD)	EtOH emissions to air (thermal)
GWP	kg CO2 eq	1.01E-03	3.66E-03	190.019	6.28E-03	1.471	5.692	77.683	95.260	0.000	0.000
ODP	kg CFC-11 eq	4.91E-10	3.68E-09	2.55E-05	1.01E-09	4.60E-08	8.05E-07	5.10E-06	0.000	0.000	0.000
AP	kg SO2 eq	4.94E-06	1.91E-05	0.331	1.96E-05	4.27E-03	0.023	0.194	0.000	0.000	0.000
EP	kg PO4--- eq	2.94E-06	1.14E-05	0.075	3.17E-06	2.02E-03	0.010	0.104	0.000	0.000	0.000
POCP	kg C2H4	2.53E-07	7.97E-07	0.031	1.04E-06	1.71E-03	9.02E-04	0.015	0.000	0.449	0.021
ADP	kg Sb eq	7.07E-06	2.74E-05	1.510	5.80E-05	0.025	0.034	0.426	0.000	0.000	0.000
WRD	m3 water eq	2.60E-04	8.66E-06	0.021	1.95E-06	5.93E-04	0.041	0.134	0.000	0.000	0.000
PENRT	MJ	0.022	0.071	3108.830	0.125	56.097	455.448	1003.021	0.000	0.000	0.000
PERT	MJ	0.002	0.004	526.867	0.001	0.346	161.102	39.512	0.000	0.000	0.000

Table 33. LCIA results for production of 1000 m^2 advanced transparent barrier laminate

Impact category	Unit	PET film	SiOx evaporant	PU adhesive	MEK	HDPE film	MEK emissions to air	adhesive waste to incineration	mixed plastic waste to incineration	PET waste to incineration	Electricity, MV
GWP	kg CO2 eq	521.181	0.019	32.895	8.297	122.275	0.000	1.625	16.059	24.025	34.266
ODP	kg CFC-11 eq	2.62E-05	2.77E-09	1.29E-07	1.69E-07	1.62E-06	0.000	7.08E-08	2.40E-08	2.04E-08	1.68E-06
AP	kg SO2 eq	1.914	5.36E-05	0.132	0.022	0.435	0.000	1.97E-03	2.96E-03	3.78E-03	0.164
EP	kg PO4--- eq	0.736	9.64E-06	0.034	7.04E-03	0.091	0.000	1.94E-03	3.62E-03	4.95E-03	0.114
POCP	kg C2H4	0.110	2.51E-06	0.006	1.31E-03	0.035	1.757	8.48E-05	9.72E-05	1.06E-04	0.006
ADP	kg Sb eq	6.079	1.25E-04	0.322	0.129	1.831	0.000	3.86E-03	1.90E-03	1.26E-03	0.252
WRD	m3 water eq	0.428	2.22E-04	0.089	7.16E-03	0.055	0.000	9.75E-04	1.53E-03	2.11E-03	0.045
PENRT	MJ	13947.485	0.301	756.805	288.781	4251.041	0.000	9.269	4.646	2.697	690.655
PERT	MJ	472.772	4.92E-03	27.031	2.474	128.917	0.000	0.262	0.225	0.047	45.271

The two graphs below depict the contribution of the various operations (transport of waste to disposal plant, waste disposal treatments) to the total impact of the EOL phase of transparent VIPs. In the graph on the left side, red colour represents % contribution of waste treatments to total score of environmental indicators and blue colour transportation's contribution. The part of impacts due to waste treatments is detailed in the graph on the right, where light colour is for the disposal of inert silica aerogel in landfill and the dark colour for non-hazardous waste incineration of barrier envelope.

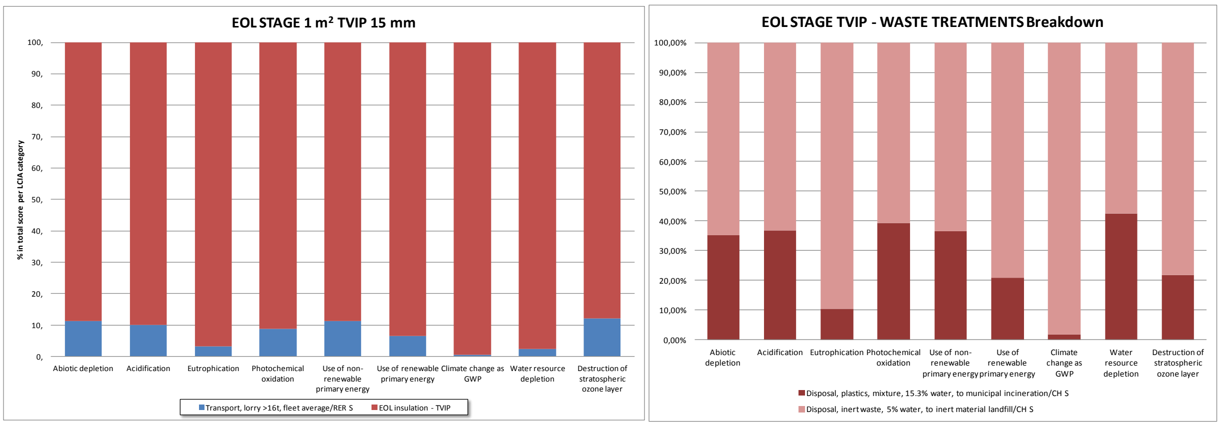

Figure 47. Relative contribution of transport and waste treatments to LCIA results in the EOL stage (left) and relative impacts of core and envelope disposal treatments (right), for 1 m^2 of TVIP 15 mm

All in all, the impact contribution of the EOL is negligible in comparison with the impacts originated during the PRODUCT stage. The major contribution by EOL is for the GWP indicator and, even in this case, EOL only accounts for 0.11% of total impact.

Table 34. LCIA results for lifecycle of 1 sq.m TVIPs 15 mm (Product & EOL stages only). LCIA results breakdown per lifecycle stage

Impact category	Unit	PRODUCT stage	EOL stage	Total
GWP	kg CO2 eq	893.057	0.969	894.025
ODP	kg CFC-11 eq	7.58E-05	7.43E-09	7.58E-05
AP	kg SO2 eq	1.346	3.06E-04	1.346
EP	kg PO4--- eq	0.472	2.46E-04	0.472
POCP	kg C2H4	1.248	1.04E-05	1.248
ADP	kg Sb eq	4.831	3.58E-04	4.831
WRD	m3 water eq	0.477	1.60E-04	0.477
PENRT	MJ	11199.718	0.840	11200.558
PERT	MJ	1751.993	0.018	1752.011

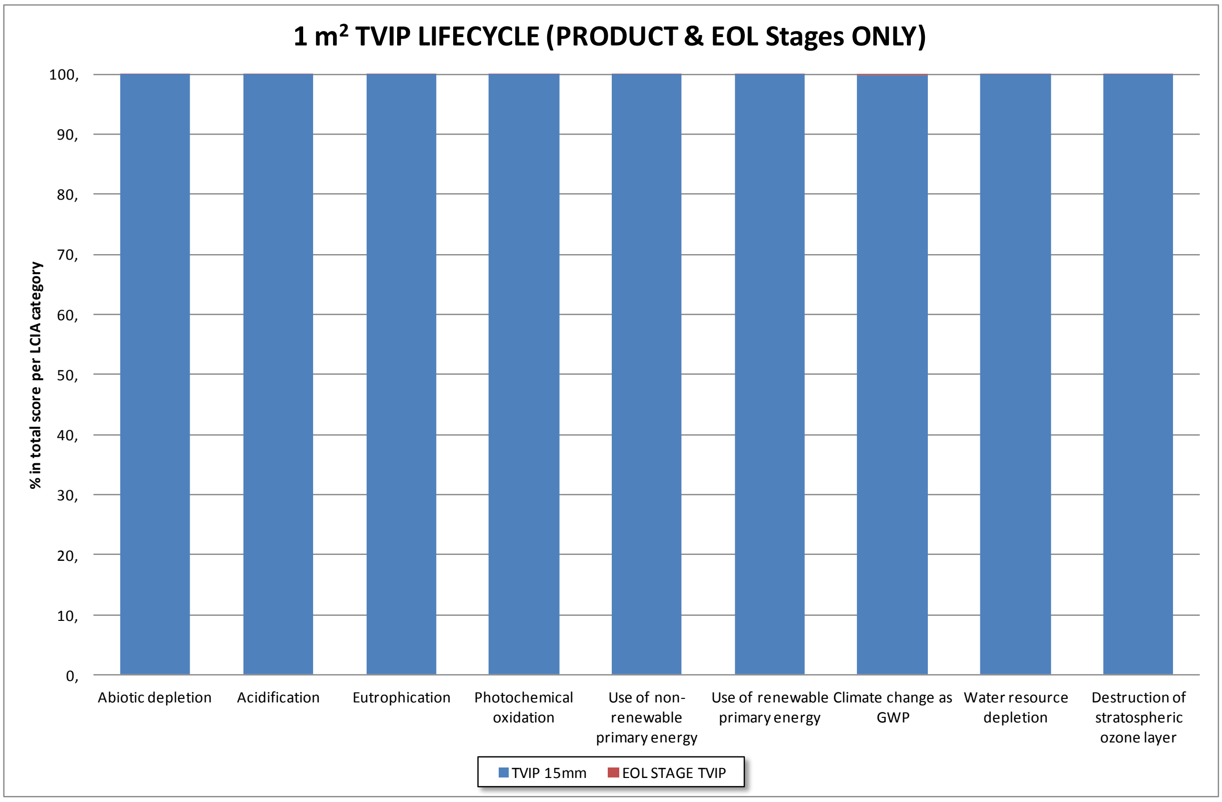

Figure 48. Lifecycle of f 1 sq.m TVIP 15 mm – Relative contribution (%) of lifecycle stages (Product & EOL) to total LCIA results.

7.4 Interpretation of LCA results

After examining the environmental performance of the lifecycle stages considered in the study of TVIP and the overall environmental profile of its novel components (silica aerogel and transparent barrier laminate), further assessment is conducted to understand the environmental profile of the transparent barrier and the implications of the several steps in their manufacture in its overall impacts. The transparent and the opaque barrier laminates developed in the project are compared in terms of environmental impacts. Also in this chapter, the conclusions of the sensitivity check for assumptions made in modelling EB coating of PET film with SiOx are discussed.

7.4.1 Silica aerogel core

With regards to the silica aerogel core, as it has been discussed previously, the precursor TEOS and the CO_2 used for the SCD step are the two main responsible for the impact of the aerogel production. Maximizing the CO_2 recycling in a closed loop system, so that amounts lost (and emitted) per drying run approach zero and additional feeding of CO_2 to the system is barely needed, is key to optimise the environmental profile of the silica aerogel manufacturing. From the LCIA results obtained for the production of 1 kg aerogel (Table 32), it can be concluded that just by increasing CO_2 recycling from 80% to 95%, the total impacts of the production phase could be reduced in the following percentages:

Table 35. Influence of increasing amount of CO_2 recycling in the SCD system in the LCIA results for production of 1 kg silica aerogel

Impact category	Unit	production of 1 kg silica aerogel (rec. 80%)	production of 1 kg silica aerogel (rec. 95%)	% reduction
GWP	kg CO2 eq	370.136	240.428	35%
ODP	kg CFC-11 eq	3.15E-05	2.77E-05	12%
AP	kg SO2 eq	0.553	0.407	26%
EP	kg PO4--- eq	0.192	0.114	41%
POCP	kg C2H4	0.518	0.507	2%
ADP	kg Sb eq	1.996	1.676	16%
WRD	m3 water eq	0.197	0.096	51%
PENRT	MJ	4623.614	3871.348	16%
PERT	MJ	727.835	698.201	4%

7.4.2 Transparent barrier laminate

In section 7.3, the contribution of the several input/output flows in the (aggregated) inventory of the production stage of the transparent laminate has been examined. Now, the breakdown per production step is evaluated. The transparent barrier laminate is manufactured following three consecutive steps:

1. EB deposition of SiOx onto PET film
2. Face-to-face lamination of two layers of PET/SiOx film
3. Lamination of the PET/SiOx//SiOx/PET bilaminate with the sealing layer (HDPE film)

Step 2 and 3 have been made by HANITA within the NanoInsulate project. The EB coating step is external to the project consortium (SiOx coated PET film have been supplied by AMCOR and confidential information about LCI is not available for the LCA analysis; data gaps have been covered with literature values and OEM's brochure information).

In the case of the step 3, final lamination of HDPE with face-to-face bilaminate, the highest impacts correspond to the amount of face-to-face bilaminate consumed (see Figure 49).

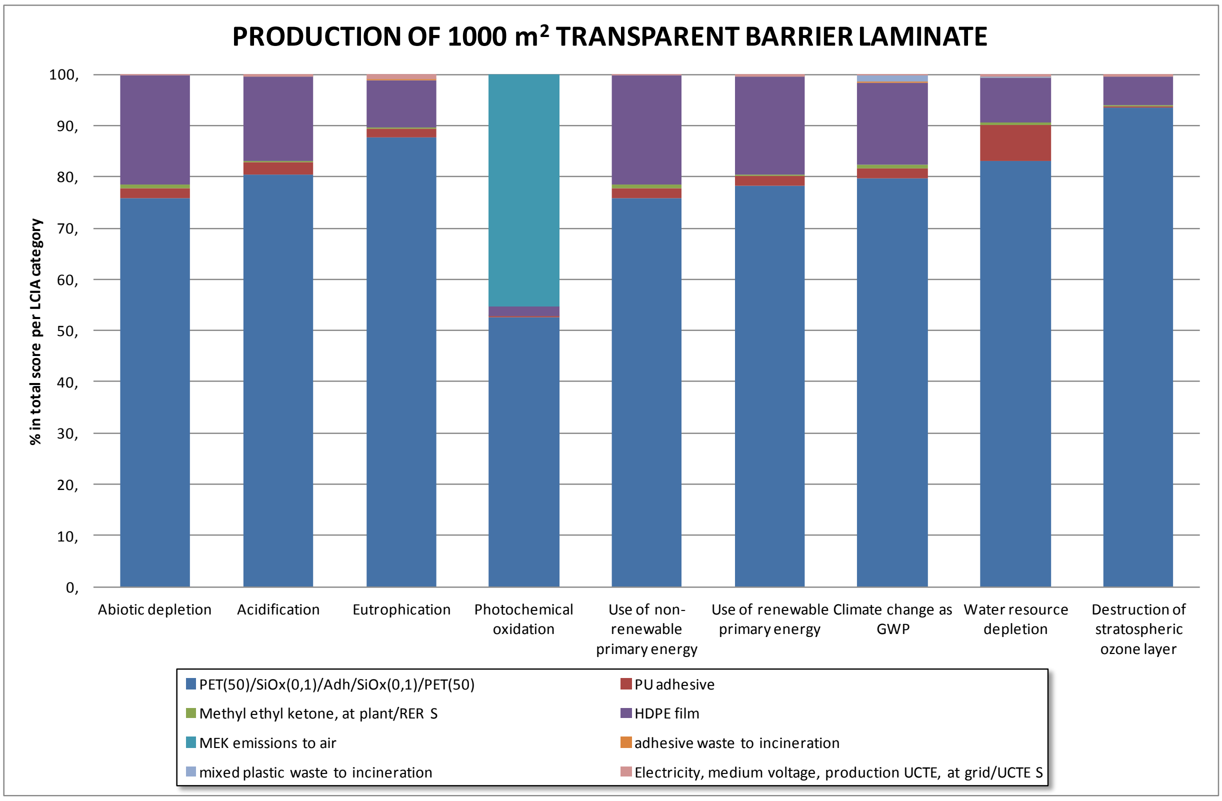

Figure 49. Relative contribution of LCI flows to LCIA results in the Lamination of HDPE and PET/SiOx//SiOx/PET bilaminate to produce 1000 m^2 of transparent barrier laminate

In the face-to-face lamination process, electricity and chemicals used (solvent and PU adhesive) only account for ca. 5% on average of the total impacts (ranging 1% to 10% depending on the environmental indicator evaluated). The amount of coated film used makes up the remaining 95% (except in the POCP impact category, essentially due to the organic solvent emissions in the curing/drying process). This means that, excluding Photochemical oxidation category, the coated film comprises ca.75% of the impact categories assessed for the final barrier laminate.

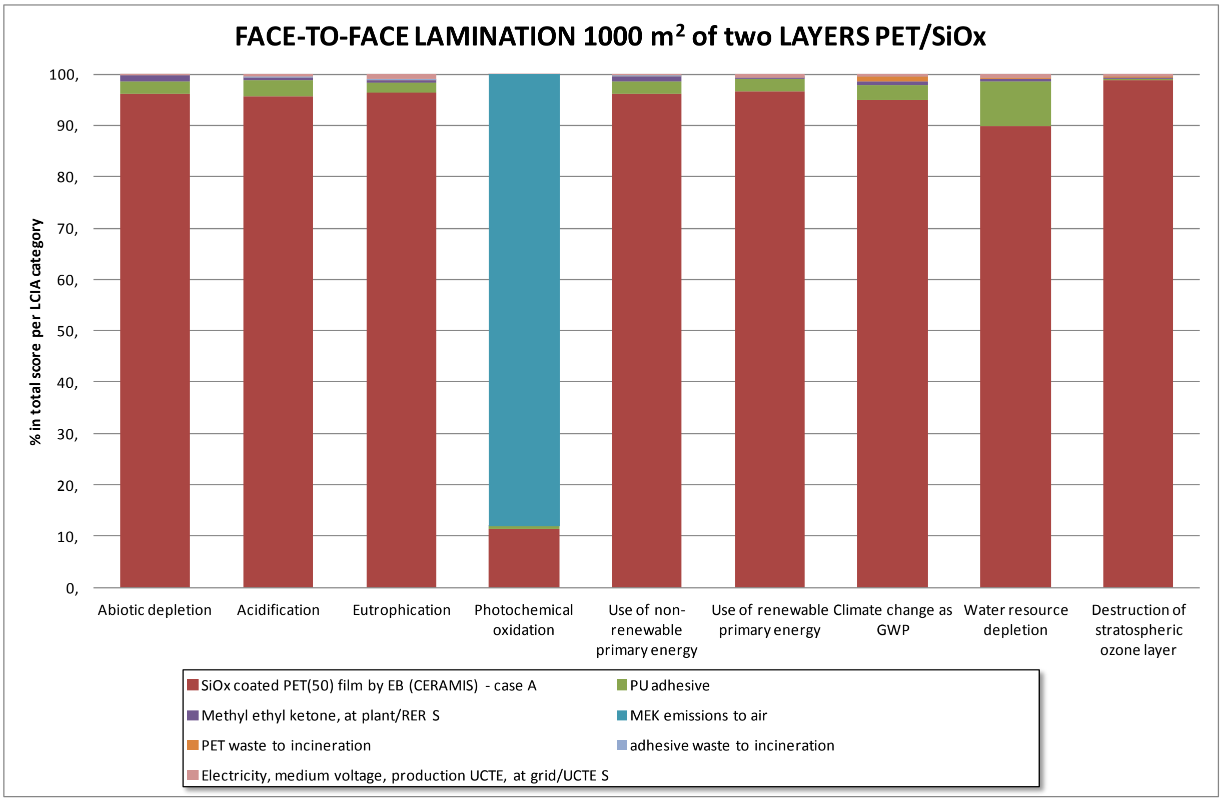

Figure 50. Relative contribution of LCI flows to LCIA results in the face-to-face Lamination of two layers of PET/SiOx film to produce 1000 m^2 of transparent PET/SiOx//SiOx/PET bilaminate

Focusing on the SiOx coating of PET film by Electron Beam deposition technology, more than 90% of the impacts seem to come from the use of PET film and the rest is caused basically by the consumption of electricity, being the silica sand used as evaporation source no relevant from the environmental point of view.

Since there is large uncertainty in data, as a result of estimations of energy input for the EB process based on different reported values and the lack of information about material losses of film and SiOx source during the deposition, three case studies have been evaluated, that represents different combinations of energy and material hypotheses (Table 30). As demonstrated in the next section, the general conclusions about the impacts in the SiOx coating process are not affected by the assumptions made. The LCIA results obtained for the *Case A* hypothesis are shown in Table 36 and Figure 51.

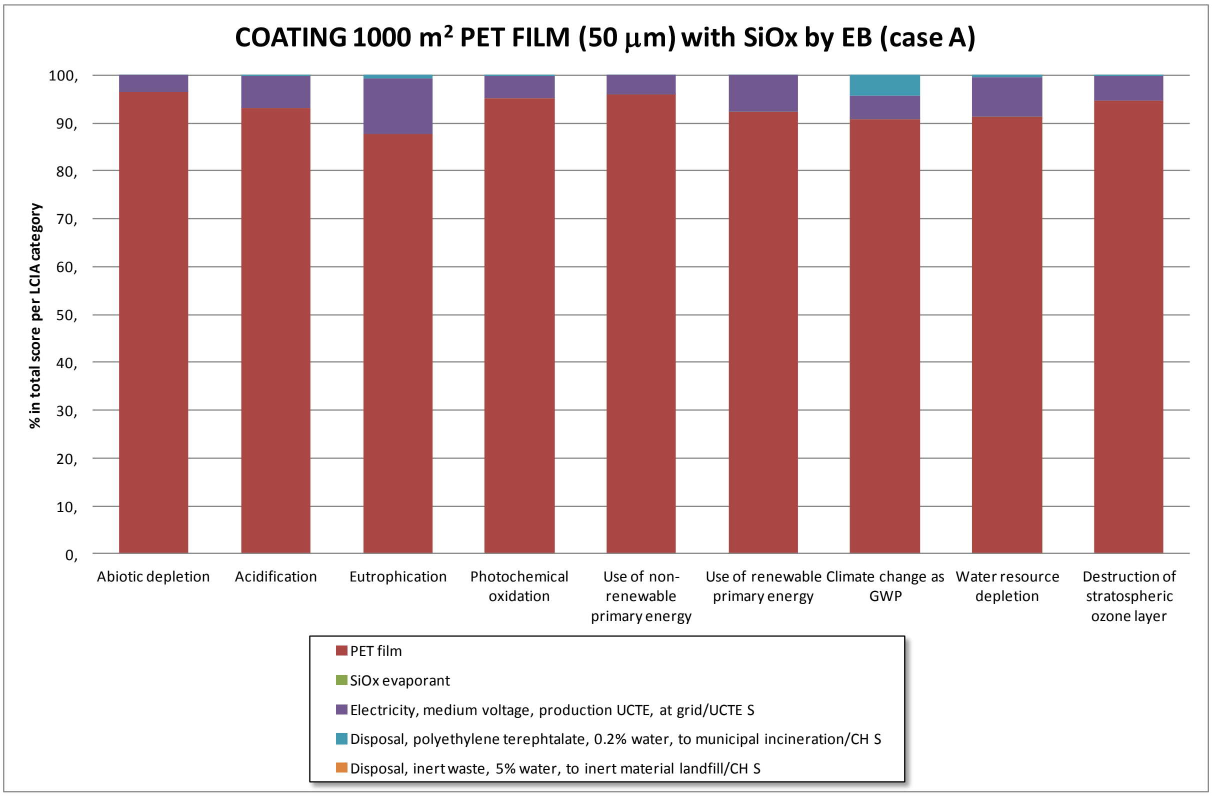

Figure 51. Relative contribution of LCI flows to LCIA results in the SiOx (0.1 μm) coating by EB of PET film (50 μm) to produce 1000 m^2 of transparent PET/SiOx film.

Table 36. LCIA results for production of 1000 m^2 of SiOx (0.1 μm) coated PET film (50 μm) – Case A

Impact category	Unit	PET film	SiOx evaporant	Electricity, MV	Disposal, PET to incineration	Disposal, inert waste to landfill
GWP	kg CO2 eq	250.272	0.009	14.050	11.537	0.002
ODP	kg CFC-11 eq	1.26E-05	1.33E-09	6.90E-07	9.79E-09	4.70E-10
AP	kg SO2 eq	0.919	2.5717E-05	0.067	1.82E-03	9.34E-06
EP	kg PO4--- eq	0.354	4.6277E-06	0.047	2.38E-03	2.27E-06
POCP	kg C2H4	0.053	1.2077E-06	2.61E-03	5.10E-05	3.43E-07
ADP	kg Sb eq	2.919	5.9909E-05	0.103	6.03E-04	1.89E-05
WRD	m3 water eq	0.206	1.07E-04	0.018	1.01E-03	6.12E-06
PENRT	MJ	6697.616	0.145	283.181	1.295	0.044
PERT	MJ	227.026	2.36E-03	18.562	0.022	3.23E-04

7.4.3 Sensitivity check: EB coating

Following the analysis of the EB coating step, a sensitivity check has been conducted to compare the LCIA results achieved when different values are taken for the electric energy input and for the material losses (and, therefore, material inputs). See section 7.2, (Table 30).

As depicted in the figure below, average difference in the scores of environmental indicators is around 2%. Thus, no significant effect in the global results of TVIP envelope is expected as a consequence of the selected calculation assumptions. Based on a precautionary principle, the hypothesis with the highest overall scores have been chosen for modelling the EB coating step (*Case A*) in the manufacturing of the advanced transparent barrier laminate.

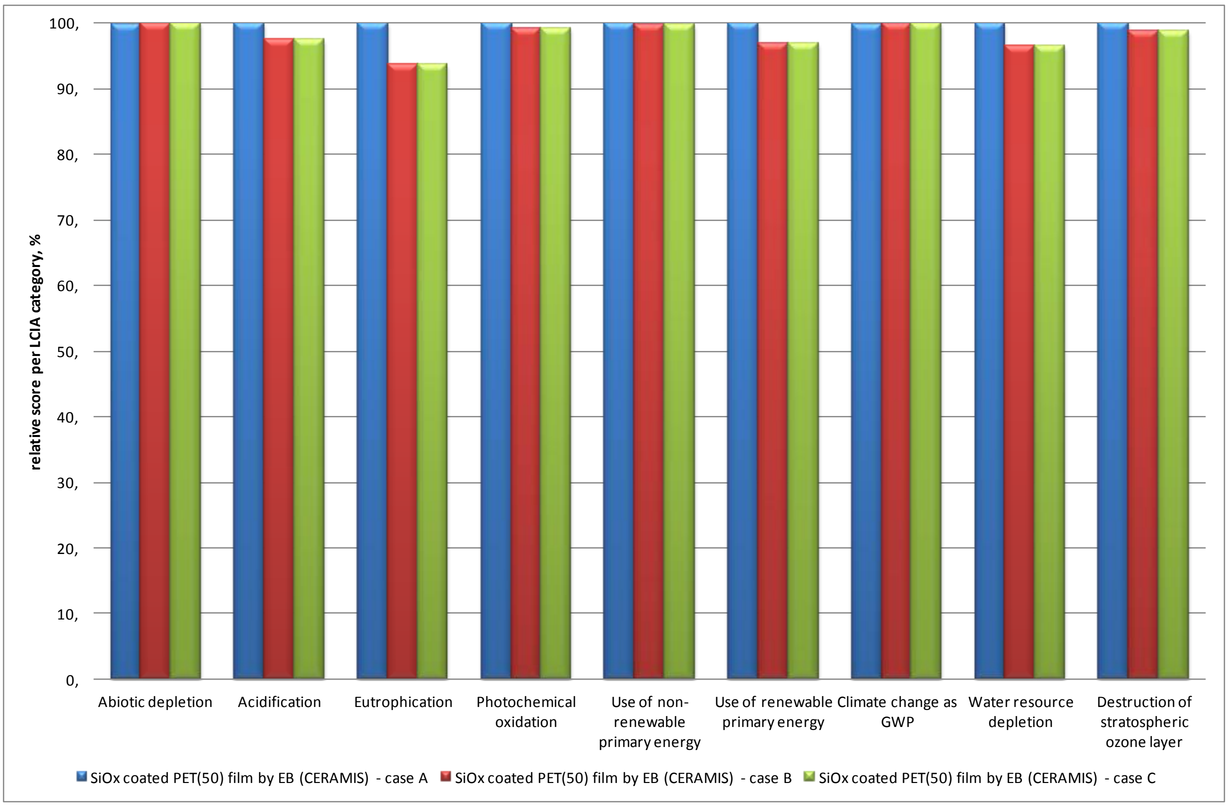

Figure 52. Compared production of 1000 m^2 SiOx coated PET film (case A *vs* case B *vs* case C)

7.4.4 Opaque vs Transparent barrier laminate

Finally, the comparison of the environmental profiles of the two novel barrier laminates developed in the NanoInsulate project has been performed. The comparison is made on a "1000 sq.m of laminate film" basis. For the comparison, in both cases, metal or inorganic material not deposited onto the film substrate is assumed to be lost (assimilated as disposal in landfill for environmental modelling).

The graphical results in Figure 53 show that the production of 1000 m^2 of transparent barrier laminate (equiv. 195.3 kg) causes higher environmental impacts than the production of the same amount of opaque barrier laminate (equiv. 86.4 kg). The reason behind those results is fundamentally the larger mass of PET used in the transparent laminate (50 μm film *vs* 23 μm film in the opaque structure). Differences are smaller in the *Photochemical oxidation* category, as a result of the emission of solvents in the wet layer coating of ORMOCER® lacquer: value of their associated POCP impact is similar to the value of that indicator for face-to-face lamination process in transparent barrier film.

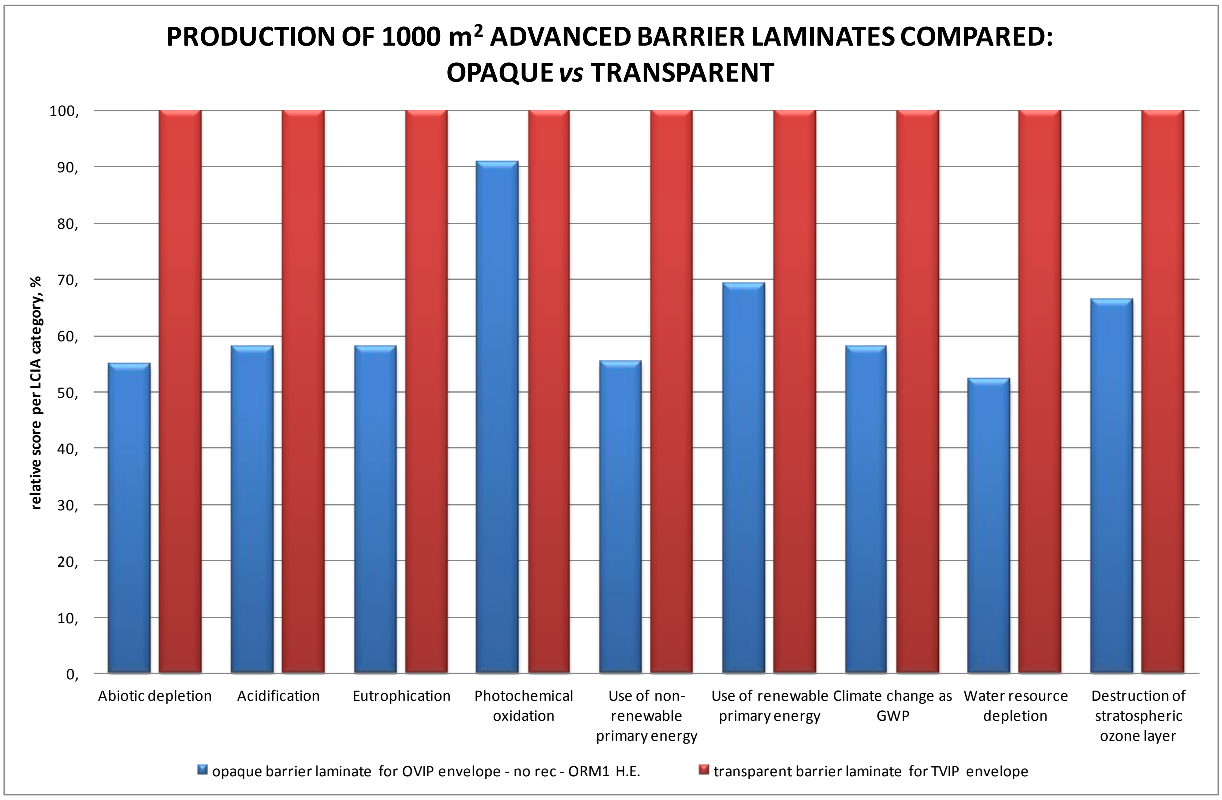

Figure 53. Compared production of 1000 m^2 of opaque barrier laminate PET(23)/Al/AlOx/ORM1/AlOx/Al//HDPE(50) and 1000 m^2 of transparent barrier laminate PET(50)/SiOx// SiOx/PET(50)//HDPE(50)

8 Appendices

PRODUCTION STAGE- *EcoInvent Database v2.2*	
Material	Aluminium sheet, primary prod., prod. mix, aluminium semi-finished sheet product RER S
	Glass fibre, at plant/RER S
	Methylene diphenyl diisocyanate, at plant/RER S
	Polyols, at plant/RER S
	Catalyst (confidential)
	Solvent (confidential)
	Methyl ethyl ketone, at plant/RER S
	Ethanol from ethylene, at plant/RER S
	Water, ultrapure, at plant/GLO S
	Water, deionised, at plant/CH S
	Polyethylene, HDPE, granulate, at plant/RER S
	Aluminium, primary, at plant/RER S
	Aluminium, secondary, from new scrap, at plant/RER S
	Oxygen, liquid, at plant/RER S
	Hydrogen, liquid, at plant/RER S
	Carbon dioxide liquid, at plant/RER S
	Quicklime, milled, packed, at plant/CH S
	Polyurethane, rigid foam, at plant/RER S
	Ethyl acetate, at plant/RER S
	2-butanol, at plant/RER S
	Aluminium hydroxide, at plant/RER S
	Methanol, at regional storage/CH S
	Silicon tetrahydride, at plant/RER S
	Sodium hydroxide, 50% in H2O, production mix, at plant/RER S
	Methyl ethyl ketone, at plant/RER S
	Silicone product, at plant/RER S
	Epoxy resin, liquid, at plant/RER S
	Silicon tetrachloride, at plant/DE S
	Silicon carbide, at plant/RER S
	Polyethylene terephthalate, granulate, amorphous, at plant/RER S
	Packaging film, LDPE, at plant/RER S
	Silica sand, at plant/DE S
	Tetrachlorosilane, at plant/GLO S
	Ammonia, liquid, at regional storehouse/RER S
	Hydrochloric acid, 30% in H2O, at plant/RER S
Transport	Transport, lorry >16t, fleet average/RER S
	Transport, freight, rail/RER S

Energy	Natural gas, burned in industrial furnace >100kW/RER S
	Natural gas, burned in industrial furnace low-NOx >100kW/RER S
	Electricity, medium voltage, production UCTE, at grid/UCTE S
	Heavy fuel oil, burned in industrial furnace 1MW, non-modulating/RER S
Processing	Extrusion, plastic film/RER S
	Sheet rolling, aluminium/RER S
	Process steam from natural gas, heat plant, consumption mix, at plant, MJ EU-27 S
	Fleece production, polyethylene terephthalate/RER S
Emissions to the air	Hot air
	Methyl ethyl ketone
	Particulates, < 2.5 um
	Nitrogen oxides
	Chlorine
	Chloride
	VOC, volatile organic compounds
	Oxygen
	Carbon dioxide
	Ethanol
	Water
	Methanol
	2-Butanol
	Acetoacetic ester
Inputs	Air
Disposal	Disposal, inert material, 0% water, to sanitary landfill/CH S
	Disposal, solvents mixture, 16.5% water, to hazardous waste incineration/CH S
	Disposal, paint, 0% water, to municipal incineration/CH S
	Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH S
	Disposal, hazardous waste, 25% water, to hazardous waste incineration/CH S
	Disposal, polyurethane, 0.2% water, to municipal incineration/CH U
	Disposal, polyethylene terephtalate, 0.2% water, to municipal incineration/CH S

CONSTRUCTION STAGE- *EcoInvent Database v2.2*	
Materials	EUR-flat pallet/RER S
	Packaging film, LDPE, at plant/RER S
	Corrugated board boxes, technology mix, prod. mix, 16,6 % primary fibre, 83,4 % recycled fibre EU-25 S
Transport	Transport, lorry >16t, fleet average/RER S
Disposal (Packaging)	Disposal, wood untreated, 20% water, to municipal incineration/CH S
	Disposal, polyethylene, 0.4% water, to municipal incineration/CH S
	Disposal, packaging cardboard, 19.6% water, to municipal incineration/CH S
	Disposal, expanded polystyrene, 5% water, to municipal incineration/CH S
	DummyWasteTreatment

USE STAGE- *EcoInvent Database v2.2 & ELCD*	
Energy	Heat, at air-water heat pump 10kW/RER S
	Heat, from resid. heating systems from NG, consumption mix, at consumer, temperature of 55°C EU-27 S
	Heat, from resid. heating systems from LFO, consumption mix, at consumer, temperature of 55°C EU-27 S

EOL STAGE- *EcoInvent Database v2.2*	
Disposal	Disposal, inert material, 0% water, to sanitary landfill/CH S
	Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH S
	Disposal, polyurethane, 0.2% water, to municipal incineration/CH U
	Disposal, polyethylene terephtalate, 0.2% water, to municipal incineration/CH S
	Transport, lorry >16t, fleet average/RER S
	Electricity, medium voltage, production UCTE, at grid/UCTE S