CODE 128

LIFE CYCLE ASSESSMENT OF INNOVATIVE ECO-CONSTRUCTION SYSTEM: INTERLOCKING MODULAR INSULATION PANELS (IMIP)

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ABSTRACT

The IMIP project is about taking action to achieve the triple bottom line: economic, environmental, and social, both in the life cycle of the materials and processes and in the service life of the building systems developed in the project.

Four panels have been designed to implement a new industrialised and green building system using bio-based materials to improve energy efficiency, assembly, disassembly, reuse and reducing demolition costs and waste materials.

The objective of this paper is to assess the environmental impact of the panels and to compare them to conventional constructive systems.

According to the analysis, the panels have great potential in terms of energy efficiency, circularity, cost, and environmental impact. As they are made from natural bio-based materials and their design is based on assembly and disassembly, the panels sequester CO2 and show excellent sustainability, circularity, and reusability results. The disassembly and recycling capacity of IMIP products are critical to the results of the manufacturing stage, as they can be considered a substitute in further production.

This assessment identifies the main strengths of the proposed panels in terms of sustainability compared to usual market competitors.

KEYWORDS: Life cycle assessment; Bio-based materials; Circularity; Sustainable construction; Prefabricated construction.

1. INTRODUCTION

Interlocking modular insulation panels (IMIP) were developed in the IMIP project titled Innovative Eco-Construction System Based on Interlocking Modular Insulation Wood & Cork-Based Panels. The panels were designed using substandard wood and Oriented Strand Board (OSB) for Cross Laminated Timber (CLT) and natural cork to evaluate low-performance wood and to integrate construction systems with low environmental impact, high energy efficiency, reusable and recyclable [1].

The present paper aims to determine the environmental impact through a Life Cycle Assessment (LCA) for four different IMIP panels due to various indicators for providing manufacturers and all agents interested in implementing the IMIP panels with technical documentation of their sustainable values. In addition, the LCA will be followed by an assessment of the environmental impact of the panels by comparing them to conventional constructive systems.

2. DEVELOPMENT

2.1. Product specification

The materials used in the IMIP panels are the following:

- CLT: maritime pine (*pinus pinaster*, PEFC certified) with a 12 ± 2 % moisture content.
- Some CLT layers: OSB-3 according to EN 13986 wood-based panels for use in construction.
- Glueing: a bicomponent (A+B) polyurethane (PUR) adhesive following EN 15425 [2].
- Insulating material: loose cork and cork panels are used according to EN 14304 [3] specifications.

More than 50 types of IMIP panels were developed, sorted into four types [1]. However, four panels (Figure 1) have been selected under study for this paper.

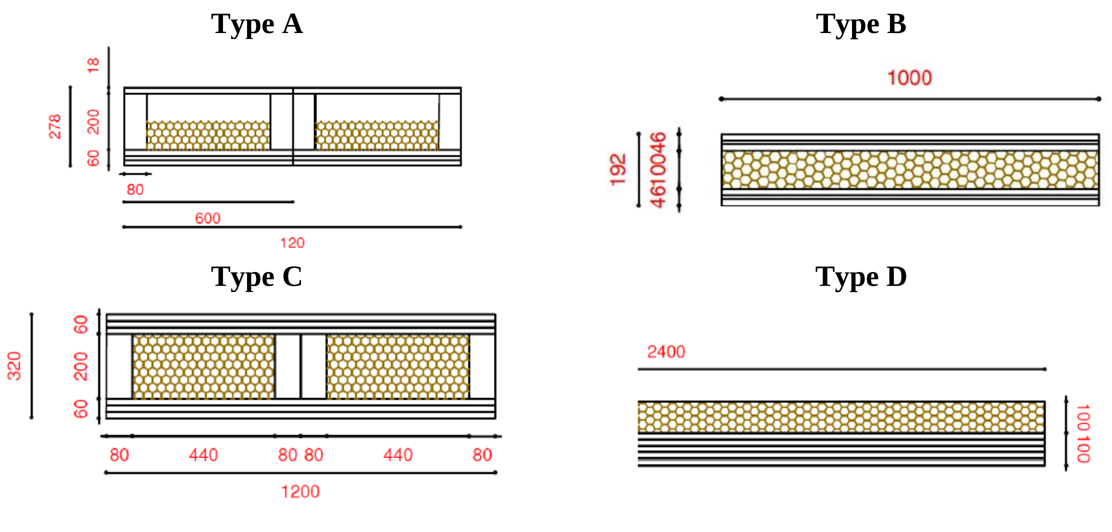

Figure 1: IMIP type details.

The panels present the following characteristics:

- Type A (for roofs) is made of CLT of 60 mm (3 layers of 20 mm) + ribs of 80 x 200 mm + OSB of 18 mm, designed as a roof element with flexural loads.

- Type B (for sandwich roofs or partitions) is made of CLT of 45 mm (2 external layers of 14 mm + inner OSB layer of 17 mm) + 100 mm cork insulation + CLT of 45 mm, designed for small spans.

- Type C (for slabs/floors) is made of CLT of 60 mm (3 layers of 20 mm) + ribs of 80 x 200 mm + CLT of 60 mm, designed as a slab element with flexural loads.

- Type D (for façades/walls) is made of CLT of 100 mm (5 layers of 20 mm) + 100 mm cork insulation, designed as a wall element under compression and wind loads.

For the packaging, the products will be protected with various polyethene (PE) foil and, on customer request, with edge protection systems such as cardboard to replace PE.

The service life of the IMIP panels, since they are made of CLT, on proper conservation, has no limit established [4]; thus, they are expected to equal the building service life. However, IMIP manufacturers set the lifespan for LCA calculations at 50 years.

IMIP panels are designed for the possibility of disassembly and further recycling at the end of life (EOL) [5]; thus, this will be the scenario calculated for stage D in the LCA. If this is impossible, they must be used as energy valorisation or biodegraded as composting material.

2.2. Product specification for comparative scenarios

To ease the understanding of the results, a comparison between IMIP products and a standard constructive layer configuration has been proposed according to TABULA archetypes [6]. Three different constructive designs have been chosen to be compared with IMIP products: Brick wall (Table 1) - IMIP D; Concrete floor - IMIP C; Tile roof - IMIP A. However, in this paper, only the first case will be detailed.

Table 1: Conventional construction elements layers for a brick wall.

Layer	**Density (Kg/m^3)**	**Thickness (m)**	**Total (kg/m^2)**	**Ecoinvent Process**
Façade brick	1.43E+03	0.0650	93.25	Clay brick {GLO}| market for | APOS, U
Plaster	7.00E+02	0.0090	6.30	Cement mortar {RoW}| market for cement mortar | APOS, U
Cavity insulation	3.15E+01	0.1200	3.78	Polystyrene foam slab {GLO}| market for | APOS, U
Interior cavity wall	8.12E+02	0.2000	162.40	Clay brick {GLO}| market for | APOS, U

2.3. LCA Calculation rules

The functional unit for IMIP panels (Table 2) is comparable to CLT panels already tested and standardized in the market. The most common functional unit will be one cubic metre (m^3) according to PCR 2012:01 - Construction products and construction services version 2.2, Sub-PCR-E Wood and wood-based products for use in construction (EN 16485) [7].

Table 2: IMIP panels functional unit details.

Name	**Value**	**Unit**
Declared unit	1.00	m^3
Type A gross density	277.18	kg/m^3
Type B gross density	431.14	kg/m^3
Type C area density	259.94	kg/m^3
Type D area density	353.25	kg/m^3

The LCA system boundary is from cradle to grave; it addresses the life cycle phases A1, A2, A3, A4, A5, B1, B2, B3, B4, B5, B6, B7, C1, C2, C3, C4 and D, following EN 15804 (Figure 2) [8].

PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				BENEFITS BEYOND SYSTEM BOUNDARIES
Raw material supply	Transport	Manufacturing	Transport from gate to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction demolition	Transport	Waste processing	Disposal	Reuse, recovery, recycling, potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Figure 2: Life cycle stages covered in the LCA.

Since no pollution emissions or associated operative expenditures (energy) occur in the use of IMIP panels, B1, B2, B6 and B7 are set to 0 (zero) and B3, B4 and B5 are declared as not relevant (MNR). The LCA has been done using SimaPro 9.4.0.3 LCA software [9], and the EN 15804+A2 2020 [8] impact assessment method has been applied. All the relevant background data records for the manufacture and disposal were taken from the Ecoinvent 3.9.1 cut-off database [10]. When primary data is unavailable, secondary data provided by Environmental Product Declarations (EPDs) and well-established databases are used. The analysed impact categories for the different methods are reported below (Table 3). However, material, waste, and energy indicators can also be considered.

Table 3: LCA selected indicators, categories and assessment methods.

Impact category	Unit	Parameter	Assessment method
Climate change (total) Climate change (fossil) Climate change (biogenic) Climate change (land use and land use change) Climate change (CO_2 uptake)	kg CO_2 eq kg CO_2 eq kg CO_2 eq kg CO_2 eq kg CO_2 eq	GWP_t GWP_f GWP_b GWP_{luluc} GWP_{uptake}	IPCC 2021 GWP100 (incl. CO2 uptake) v1.01 [11]
Ozone layer depletion (ODP steady state) Acidification potential (accumulated exceedance) Eutrophication Human toxicity Photochemical oxidation	kg CFC-11 eq kg SO_2 eq kg PO_4^{3-} eq kg 1,4-DB eq kg C_2H_4 eq	ODP AP EP HT PO	CML 2 baseline 2000 v2.05, The Netherlands, 1997 [12]
Depletion of abiotic resources - elements Depletion of abiotic resources - fossil fuels	kg Sb eq MJ	ADPE ADPF	EPD (2018) v1.04 [13]
Water use deprivation index - weighted water consumption	m^3	WDI	Berger et al 2014 (Water Scarcity) v1.01 [14]

Demo buildings were constructed in Portugal, France and Spain within the IMIP project. The LCA results are referred to the production and installation in those buildings. Therefore, allocations and assumptions will require adequacy in different applications. Data collection, along with the calculation and results interpretation, may need to be performed again.

2.4. Estimates and assumptions

Some assumptions have been considered for the present LCA. Since no specific data is available, the same energy requirement is assumed for dismantling and assembly; this is the worst-case scenario. The transport distances to the recycling plant are considered to be, on average, 50 km. Transport distance between ancillary materials suppliers is assumed to be, on average, 400 km, as well as the installation average distance.

The manufacturing begins with considering all the necessary raw materials for production, including all preliminary chains and the CO2 sequestration of the raw materials (growth of wood in the forest). The CO2 storage is balanced and calculated according to the product nature in kg per kg of CO2 removed from the atmosphere, where pinus pinaster C16-18 capture 1.68 kg/kg, OSB 1.66 kg/kg and for cork 5.67 kg/kg according to the Valencia Building Institute environmental indicators database (TURIA) [15].

2.5. LCA: Scenarios and additional data

The product suppliers provided the following technical information (Table 4).

Table 4: Specifications for stage.

Transport for manufacturing (A2)		
Vehicle type	-	freight, lorry 16-32 metric tons, EURO4
Transport distance	400	km
Capacity utilisation	70	%
Average gross density products	330	kg/m^3
Transport to installation (A4)		
Vehicle type	-	freight, lorry 16-32 metric tons, EURO4
Transport distance	200	km
Capacity utilisation	70	%
Average gross density products	330	kg/m^3
Installation in a building (A5)		
Auxiliary material brackets and screws	0.37	kg
Water consumption	0	m^3
Other resources	0	kg
Electricity consumption power: drills, power screwdrivers	0.1	kWh
Other energy carriers. Diesel for cranes and lifts	100	MJ
Operational energy and water requirements (B1-B7)		
Water consumption	0	m^3
Electricity consumption	0	kWh
Other energy carriers	0	MJ
Equipment output	0	kW
End of service life (C)		
Landfill	0	kg
Transport distance	200	km
Electricity consumption power: drills, power screwdrivers	0.1	kWh
Other energy carriers. Diesel for cranes and lifts	100	MJ
Benefits and loads beyond the system boundaries (D)		
Collected separately waste (screws)	2.58	kg
Collected separately waste (mix)	0	kg
Reuse	0	kg
Recycling material (screws)	2.58	kg
Recycling material (wood)	264	kg

For transport, installation, operational and end-of-life stages of the different IMIP products, average and mean assumptions have been made for all IMIP types.

For the end-of-life stage, it has been considered that it will be necessary to carry out the assembly of the structure in reverse order to the assembly, since IMIP panels are not joined together using permanent joints, but rather perfectly removable joints.

For stage D, considerations from the original project have been followed. IMIP panels will be recycled to make IMIP panels, assuming that at least 90 % can be recovered from the building site, and just 80 % from the original product will substitute for the production of a new panel. Thus, 80 % of the environmental benefit of replacing new raw materials has been considered.

3. RESULTS AND DISCUSSION

3.1. LCA Results

The results of the LCA for each of the IMIP panels are shown in the tables below:

Table 5: Environmental impact 1m^3 IMIP Type A.

Parameter (Unit)	**A1-A3**	**A4**	**A5**	**B1-B7**	**C1**	**C2**	**C3-C4**	**D**
GWP_t (kg CO_2 eq)	-190.70	10.83	9.79	0.0	9.05	10.84	0.0	-14.05
GWP_f (kg CO_2 eq)	38.30	10.80	9.78	0.0	9.04	10.80	0.0	-13.40
GWP_b (kg CO_2 eq)	0.95	0.09	0.03	0.0	0.02	0.09	0.0	-0.62
GWP_{luluc} (kg CO_2 eq)	0.05	0.00	0.00	0.0	0.00	0.00	0.0	-0.03
$GWP_{uptakem}$ (kg CO_2 eq)	-230.0	0.00	0.00	0.0	-0.01	-0.05	0.0	0.00
ODP (kg CFC-11eq)	6.12E-6	1.98E-6	1.59E-6	0.0	1.56E-6	1.98E-6	0.0	-1.74E-6
AP (kg SO_2 eq)	0.16	0.04	0.07	0.0	0.07	0.04	0.0	-0.06
EP (kg PO_4^{3-} eq)	0.04	0.01	0.01	0.0	0.01	0.01	0.0	-0.02
HT (kg 1,4-DB eq)	19.40	4.11	1.99	0.0	1.05	4.11	0.0	-8.96
PO (kg C_2H_4 eq)	0.01	0.04	0.01	0.0	0.00	0.00	0.0	-0.01
ADPE (kg Sb eq)	2.32E-4	3.61E-5	7.77E-5	0.0	4.17E-6	3.61E-5	0.0	0.00
ADPF (MJ)	610.00	162.00	131.00	0.0	124.00	162.00	0.0	-229.00
WDI (m^3)	0.25	0.03	0.01	0.0	6.42E-3	0.03	0.0	-0.15

Table 6: Environmental impact 1m^3 IMIP Type B.

Parameter (Unit)	**A1-A3**	**A4**	**A5**	**B1-B7**	**C1**	**C2**	**C3-C4**	**D**
GWP_t (kg CO_2 eq)	-459.37	14.14	10.31	0.0	9.05	14.14	0.0	-113.58
GWP_f (kg CO_2 eq)	128.00	14.10	10.30	0.0	9.04	14.1	0.0	-79.7
GWP_b (kg CO_2 eq)	42.40	0.11	0.04	0.0	0.02	0.11	0.0	-33.7
GWP_{luluc} (kg CO_2 eq)	0.23	5.5E-3	2.0E-3	0.0	9.00E-4	5.50E-3	0.0	-0.18
$GWP_{uptakem}$ (kg CO_2 eq)	-630.00	-0.07	-0.03	0.0	-0.01	-0.07	0.0	0.00
ODP (kg CFC-11eq)	1.75E-5	2.57E-6	1.61E-6	0.0	1.55E-6	2.57E-6	0.0	-9.89E-6
AP (kg SO_2 eq)	0.57	0.05	0.07	0.0	0.06	0.05	0.0	-0.37
EP (kg PO_4^{3-} eq)	0.22	0.01	0.01	0.0	0.01	0.01	0.0	-0.16
HT (kg 1,4-DB eq)	119.00	7.15	8.34	0.0	6.13	7.15	0.0	-84.00
PO (kg C_2H_4 eq)	0.06	0.00	0.00	0.0	0.00	0.03	0.0	-0.26
ADPE (kg Sb eq)	0.00	4.71E-5	1.04E-5	0.0	4.17E-6	4.71E-5	0.0	-7.50E-4
ADPF (MJ)	2.06E3	211.00	136.00	0.0	0.20	0.66	0.0	-66.40
WDI (m^3)	1.26	0.04	0.01	0.0	6.4E-3	0.04	0.0	-0.94

Table 7: Environmental impact 1m^3 IMIP Type C.

Parameter (Unit)	**A1-A3**	**A4**	**A5**	**B1-B7**	**C1**	**C2**	**C3-C4**	**D**
GWP_t (kg CO_2 eq)	-354.60	8.54	9.68	0.0	9.05	8.50	0.0	-20.44
GWP_f (kg CO_2 eq)	41.20	8.51	9.67	0.0	9.04	8.47	0.0	-19.6
GWP_b (kg CO_2 eq)	1.12	0.07	0.03	0.0	0.02	0.07	0.0	-0.78
GWP_{luluc} (kg CO_2 eq)	0.08	3.33E-3	3.21E-3	0.0	9.56E-4	3.32E-3	0.0	-0.06
$GWP_{uptakem}$ (kg CO_2 eq)	-397.00	-0.04	-0.02	0.0	-0.01	-0.04	0.0	0.00
ODP (kg CFC-11eq)	7.39E-6	1.55E-6	1.58E-6	0.0	1.55E-6	1.55E-6	0.0	-3.46E-6
AP (kg SO_2 eq)	0.17	0.03	0.07	0.0	0.06	0.03	0.0	-0.09
EP (kg PO_4^{3-} eq)	0.05	7.49E-3	0.01	0.0	0.01	7.46E-3	0.0	-0.03

HT (kg 1,4-DB eq)	32.10	4.32	7.22	0.0	6.13	4.31	0.0	18.80
PO (kg C_2H_4 eq)	0.01	1.07E-3	1.69E-3	0.0	1.44E-3	1.07E-3	0.0	-0.01
ADPE (kg Sb eq)	2.88E-4	2.85E-5	17.25E-6	0.0	4.17E-6	2.85E-5	0.0	-1.86E-4
ADPF (MJ)	670.00	128.00	130.00	0.0	124.00	127.00	0.0	-335.00
WDI (m^3)	0.32	0.02	0.01	0.0	6.42E-3	0.02	0.0	-0.21

Table 8: Environmental impact 1m^3 IMIP Type D.

Parameter (Unit)	**A1-A3**	**A4**	**A5**	**B1-B7**	**C1**	**C2**	**C3-C4**	**D**
GWP_t (kg CO_2 eq)	-453.39	11.63	9.56	0.0	9.05	11.63	0.0	-103.17
GWP_f (kg CO_2 eq)	111.00	11.60	9.55	0.0	9.04	11.60	0.0	-70.80
GWP_b (kg CO_2 eq)	40.40	0.09	0.03	0.0	0.02	0.09	0.0	-32.20
GWP_{luluc} (kg CO_2 eq)	0.21	4.52E-3	1.39E-3	0.0	9.56E-4	4.52E-3	0.0	-0.17
$GWP_{uptakem}$ (kg CO_2 eq)	-605.00	-0.06	-0.02	0.0	-0.01	-0.06	0.0	0.00
ODP (kg CFC-11eq)	1.48E-5	2.11E-6	1.58E-6	0.0	1.55E-6	2.11E-6	0.0	-8.48E-6
AP (kg SO_2 eq)	0.50	0.04	0.07	0.0	0.07	0.04	0.0	-3.34E-1
EP (kg PO_4^{3-} eq)	0.20	0.01	0.01	0.0	0.01	0.01	0.0	-0.14
HT (kg 1,4-DB eq)	106.00	5.87	7.02	0.0	6.13	5.87	0.0	-75.20
PO (kg C_2H_4 eq)	0.05	1.45E-3	1.65E-3	0.0	1.44E-3	1.45E-3	0.0	-0.04
ADPE (kg Sb eq)	9.10E-4	3.86E-5	6.67E-6	0.0	4.17E-6	3.86E-5	0.0	-6.67E-4
ADPF (MJ)	1.79E3	173.00	129.00	0.0	124.00	173.00	0.0	-1.16E3
WDI (m^3)	1.12	0.03	0.01	0.0	0.00	0.03	0.0	-0.83

The excellent GWP stage results are due to the CO_2 uptake effect of the materials from which the panels are made. In addition, the high recyclability of IMIP panels at the end of their life has resulted in increased performance during stage D.

3.2. Comparative LCA results

The results of the comparison between the IMIP panel type D and a traditional brick wall are shown in the following figures:

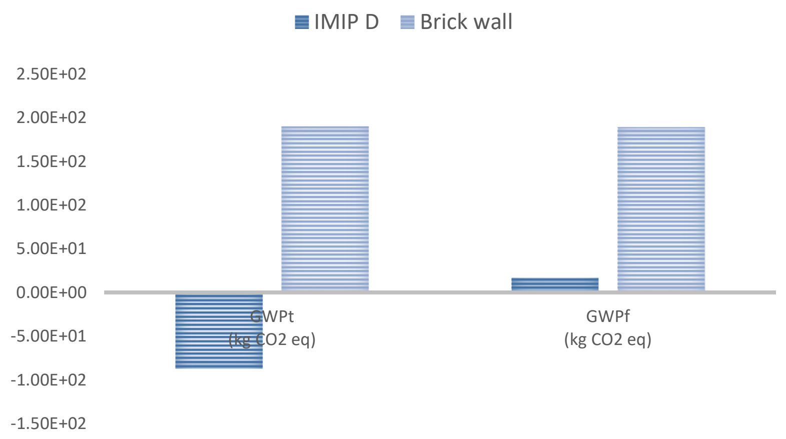

Figure 3: Comparison between IMIP D (façade) and Brick wall. WLC indicators.

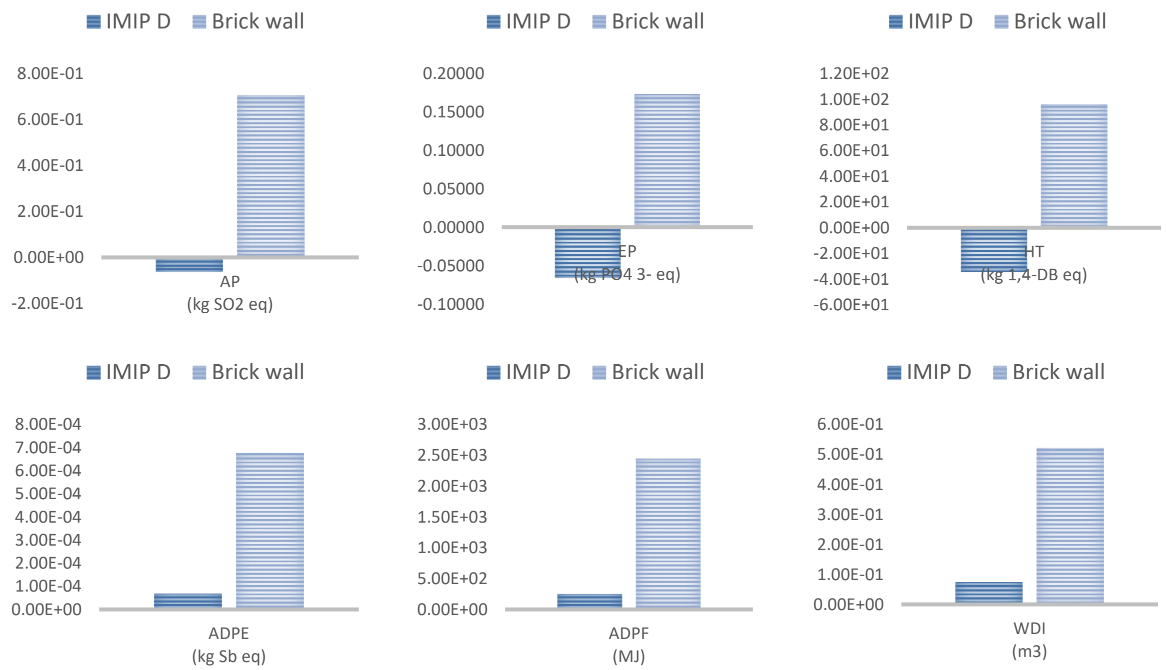

Figure 4: Comparison between IMIP D (façade) and Brick wall. Other indicators.

The IMIP panel type D has lower environmental indicators than the traditional brick wall. These results were similar for the other IMIP panel types and equivalent traditional constructive solutions.

4. CONCLUSIONS

This assessment spots the main strengths in terms of the sustainability of the proposed panels against common market competitors. A comparative LCA between IMIP products and conventional constructive systems enables the identification of priorities and potential improvements.

The conclusions of the assessment are:

- IMIP panels have a lower impact than the proposed conventional constructive systems in the categories assessed.

- The CO_2 uptake effect of the IMIP ancillary materials is vital for the manufacturing stage GWP results.

- The ability to disassemble and recycle IMIP products is critical to the results of the manufacturing stage in all impact categories, as it counts as a substitution for further production. The potential benefits of substituting fossil fuels by recycling the product at the end of its life cycle are considered in stage D.

Further information and details can be consulted in the Deliverable D4.3.1 Life Cycle Analysis of interlocking panels, developed in the project IMIP SOE3/P3/E0963 Innovative Eco-Construction System Based on Interlocking Modular Insulation Wood & Cork-Based Panels.

The E-LCA methodology applied according to ISO 14040/14044 standard sets a proper structure for future research, such as LCC or S-LCA, to complete a triple perspective assessment.

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