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Impact of air barriers application in LCA and LCC of naturally ventilated dwellings in mild climate regions

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ABSTRACT

Assessing singular elements that constitute the air barrier of a building envelope is quite unfeasible in Life Cycle Assessment (LCA). The study of these solutions through this particular scope is often overlooked. Two major aspects contribute to it: the complexity of the relationships between elements and the reduced embodied impact of these materials in the overall construction or retrofitting works. This work uses LCA and Life Cycle Costing (LCC) to study the viability of applying two envelope air barrier solutions in dwellings with excessive air change rates and equipped with different heating systems. The application of air barrier solutions resulted in average energy consumption savings in urban terrain, almost half of those in rural terrain during the heating season. Environmental performance and life cycle costs revealed mechanically (MECH) fastened air barriers to outperform fluid (FLUID) applied ones. The median annualized cost of adopting a FLUID solution was almost four times that of a MECH solution. Dwellings equipped with electric radiators ranked first in the shortest average Energy Payback Period (EPP) and the highest average Reference Service Life (RSL) savings. With the current analysis, the adoption of MECH solutions is recommended, independently of the heating system the dwelling is equipped with.

1. Introduction

The Architecture, Engineering and Construction (AEC) industry has some of the most challenging sustainability issues [1]. Environmentally, the sector is one of the most impactful regarding energy consumption and carbon emissions [2]. Economically, buildings are assets with high initial and operational costs and long life cycles [3], and socially, as humans spend most of their time inside buildings, the numerous challenges have deep implications in societies [4].

Among several reasons for which its structure and inefficiencies can be highlighted [5], the sector has one of the most substantial potentials for reducing greenhouse gas emissions (GHG) and cutting energy consumption [6].

Principles of sustainable construction encompass reusing and recycling resources, reducing their consumption, protecting natural systems, and eliminating toxic materials from the life cycle [7]. Life cycle assessment (LCA) is a major tool driving decisions and policies [8].

In the initial approach of the Energy Performance of Building Directive (EPBD) [9], priority was on energy efficiency measures in the form of design or retrofit packages pointing to cost-optimality through the life cycle of reference buildings [10,11]. In the current version of the EPBD [12], there is a shift to clean energy adoption, deployment of renewables, and general decarbonization of the building stock [13]. This trend requires the nearly Zero Energy Buildings (nZEB) and ZEB to focus significantly on carbon targets, not solely on energy ones [14–16].

Embodied carbon and energy refer to the CO_2 emissions produced and the primary energy required, respectively, during the resource extraction, transportation, fabrication, assembly, disassembly and end-of-life disposal of a particular product [17]. Operational carbon and energy refer to the resources spent on building usage, such as heating, cooling, and powering.

Throughout the literature, between embodied and operational, one finds average values of GHG emissions, over 50 %, and energy

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consumption, around 80 %, associated with the latter [18]. Low-energy buildings face a shifting paradigm [19,20]. As the operational phase gets less impactful, the percent contribuition of the embodied energy increases [21–23]. Increasing insulation levels and adopting new technologies on active systems are two examples of the trend of rising embodied and declining operational impacts. Proportions can go as high as 40 % of embodied energy impact and as low as 60 % of operational energy impact [24,25], for considered lifespans of 50 years.

However, even in low-energy buildings, the operational energy still contributes the most to the total. The air change rate (ACH) strategy of a building has a significant impact in the operational phase as the annual related heating energy loss represents around 35 % of the delivered energy for space conditioning [26–29]. It is dependent on ventilation effectiveness, which is closely related to and sensitive to the envelope airtightness performance [30–32]. Designing or retrofitting of the latter often overlooks the first, which translates into disruptions and underperformance of the ventilation strategy as a whole [33–36]. Southern European countries, with mostly mild climates, experience this reality frequently, such as Greece, Italy, Portugal, and Spain. Of these, only Spain instated whole envelope airtightness requirements by the end of 2020, showing that the existing envelopes encounter similar challenges for retrofitting works.

Achieving high levels of airtightness often relies on air barrier systems [37] dependent on air barrier materials, components and accessories [38–41]. Mechanically wrapped air barrier materials include polyethene fibre wraps or gypsum plastering. Windows and doors are examples of air barrier components. Air barrier accessories refer to tapes and sealants, elements that maintain the airtightness performance in the penetrations and joints of air barrier materials and the joints between materials and components. Their performance relies on durability, compatibility and constructability as they are often complex regarding proper installation [42–45]. Constructability issues are mostly absent when the barrier is a fluid-applied polymer membrane. This system adapts better than its mechanical alternatives to complex envelope geometries and is less prone to human fault during application. However, the chemical composition of such a membrane highly influences its movement accommodation factors and the need for primers for proper substrate adhesion [46–49].

Partially due to the complexity of these relationships [50–52], partially due to a reduced embodied impact of these materials in the overall construction or retrofitting works, the study of airtightness solutions regarding life cycle assessment is often overlooked. Usually, when reporting airtightness and air infiltration improvements, they come as a by-product of the consideration of works not primarily intended to target the issue [53]. When directly considered, the reductions in air change rates generally result from window replacement [54].

Moreover, Environmental Product Declarations (EPDs) on complete air barrier solutions are scarce compared to the current availability of EPDs in individual elements of an air barrier [55]. Assessing singular elements that constitute the air barrier is quite unfeasible in an LCA approach. The available ones often do not comprise the same LCA information modules in the system boundaryand list of environmental parameters, creating difficulties in correctly summing their impacts. Also, the common unavailability of data regarding use stage modules results in the Reference Service Life (RSL) going unreported in an EPD, further hindering a comprehensive analisis of this stage.

Additionally, quantifying singular elements such as point envelope penetrations or envelope elements perimeters is increasingly prone to misjudgement and bias compared to evaluating surface elements such as the envelope area. Therefore, considering whole envelope airtightness solutions seems to be a more plausible path.

The present research's objective is to assess the life cycle impacts and costs of applying two different envelope air barrier solutions to naturally ventilated dwellings already equipped with different heating systems, which have excessive heat losses due to ventilation. It aims to evaluate:

- The energy saving potentials during the operational phase by identifying the energy performance variations from a default scenario to one with an envelope air barrier;
- The environmental and economic viability of applying air barriers to the envelope of these dwellings by assessing the embodied energy payback periods and quantifying life cycle costs of such works.

The equipment of the heating system may be physical in the case of retrofitting works or, in the case of new designs, be already planned regardless of the air barrier solution installation.

2. Methodology

2.1. Research strategy

The developed research follows a clear flux of events. Fig. 1 portrays a flowchart of the methodology followed. It aims to ease the reader's comprehension, improve the structuring and encapsulation of topics, and promote reproducibility.

The methodology addresses four levels: (1) the sourcing of the case study dataset, (2) considered heating systems and air barrier solutions, (3) LCA and LCC considerations, and (4) heating loads calculation and research assumptions. Each of the following subsections will address these topics in detail.

Detailing the heating systems occurs simultaneously with the exposition of life cycle cost methods and primary energy considerations. This way, it eases the comprehension of equations flow and their respective variables.

2.2. Case study dataset

The case study dataset derives from a previous work [56], which outputted a large dataset on dwelling characteristics, their respective air change rates (ACHs) time series and labels. These labels represent dwellings with low, adequate, and high ACHs, according to defined lower ($0.4\ h^{-1}$) and upper ($0.7\ h^{-1}$) limits. The group of dwellings with high ACHs applied to the present research, as they experience a significant amount of time above the defined upper limit.

From that work [56], the roof slope (RS), the side ratio (SR), and the number of vertical exposed surfaces (ES) all proved to have residual relative importance in explaining the variability of ACHs. The terrain was the categorical feature with the most relative importance. Because of these findings and for visualization purposes, only the dwellings with a 20° RS, a 2:1 SR, four ES, two floors (NF), and three vertical extraction ducts (ND) undergo evaluation in this research. The dataset for analysis comprises 298 unique dwellings: 171 in rural terrain and 127 in urban terrain. The importance of wind speed at the building site was the major reason for dividing the analysis according to the two types of terrain. Table 1 informs on the centrality and variability of these dwellings' features.

The average dwelling in rural terrain has a volume of 339.7 m^3 and an envelope area of 248.1 m^2, which translates into an average air permeability of 13.3 $m^3/(h{\cdot}m^2)$ at 50 Pa. In urban terrain, the average dwelling has a volume of 305.1 m^3 and an envelope area of 231.6 m^2, resulting in an average air permeability of 14.1 $m^3/(h{\cdot}m^2)$ at 50 Pa.

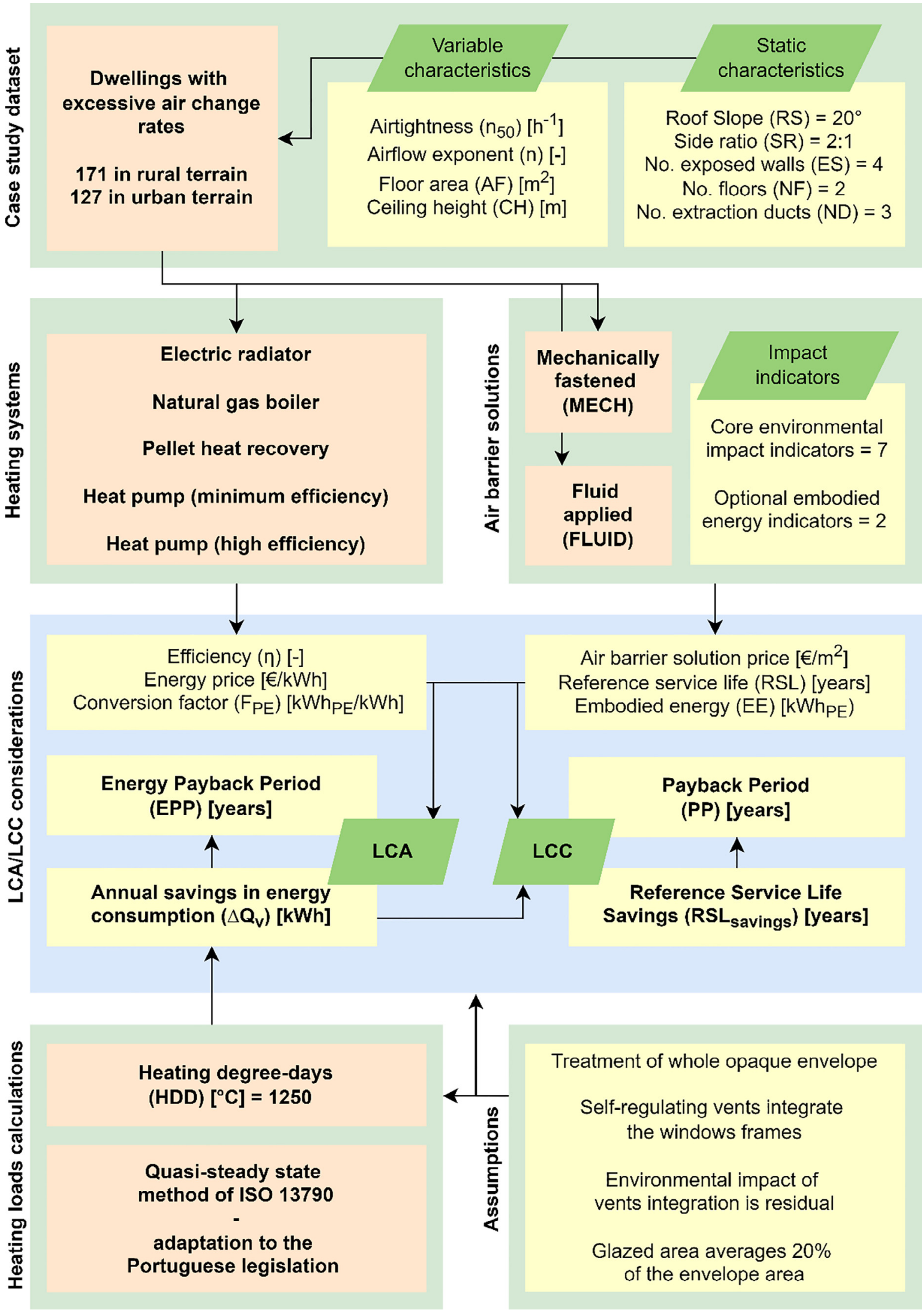


Fig. 1. Flowchart of the proposed methodology.

Table 1
Descriptive statistics of the case study's dwellings with a 20° RS, 2:1 SR, 4 ES, 2 NF, and 3 ND, by terrain, rural and urban. P(ACH condition) stands for the percentage of time the ACH complies with the stated condition.

Feature	Metric	Rural (N = 171)	Urban (N = 127)
ACH [h^{-1}]	Mean	1.11	0.85
	Std. dev.	0.39	0.25
P(ACH < 0.4 h^{-1}) [%]	Mean	2.61	1.76
	Std. dev.	4.64	2.88
P(0.4 h^{-1} < ACH < 0.7 h^{-1}) [%]	Mean	25.60	38.78
	Std. dev.	16.21	25.19
P(ACH > 0.7 h^{-1}) [%]	Mean	71.79	59.45
	Std. dev.	19.05	26.97
Airtightness (n_{50}) [h^{-1}]	Mean	9.08	9.96
	Std. dev.	3.64	3.82
Airflow exponent (n) [-]	Mean	0.59	0.59
	Std. dev.	0.04	0.04
Floor area (AF) [m^2]	Mean	129.18	116.46
	Std. dev.	62.87	59.80
Ceiling height (CH) [m]	Mean	2.63	2.62
	Std. dev.	0.28	0.25

2.3. Air barrier solutions and dwellings type

While research reports significant disparities in materials' airtightness performance in a controlled environment [40], one must assume that commercial products and systems are completely airtight when properly installed. Therefore, the main goal is not to compare solutions by their ability to perform in conferring airtightness, taken as similar, but by their environmental and cost performance as a function of a dwelling airtightness level and installed heating system. With this rationale, two external air barrier systems, with their own EPDs, were chosen for analysis: a mechanically fastened (MECH) [57] and a fluid applied (FLUID) [58].

These solutions already account for the estimated number of separate elements needed to perform and the detailing between the system and other components, such as windows, and technical penetrations, such as electrical and plumbing systems, since they include self-adhered flashings and tapes. They share system boundary modules, production and installation phases, and end-of-life transport. Their impacts are reported in the functional unit of one square meter (m^2), leading to a straightforward comparison of environmental performance [59]. A functional unit is a quantified product description that serves as a basis of reference for the subsequent impact assessment calculations [60].

The scope of the airtightness solutions is closely associated with dwelling construction types. Dwellings of heavyweight construction are mostly susceptible to point penetrations, such as pipes and cables, and elements perimeters, such as windows and doors. The opaque envelope is mostly homogeneous in these, providing one or more highly airtight layers by default.

By comparison, most lightweight dwelling construction types experience an increase in the contribution of the opaque envelope to the whole envelope leakage. This is mostly justified by the higher partitioning of envelope elements, e.g., Structural Insulated Panels (SIPs) or wood frames, to comply with geometry requirements. Because of it, most of the buildings of this last construction type require purpose-provided air barriers as a necessary component of an airtight envelope solution.

Thus, while the chosen air barrier solutions provide detailing of the opaque envelope with point penetrations and elements perimeters, i.e. there is a benefit for heavyweight constructions as well. They are more suitable for lightweight constructions, which experience a higher payoff. Additionally, the potentially occurring moisture condensation in the envelope inner layers has far less serious consequences in heavyweight constructions compared to lightweight constructions. Hence, the present research is most appropriately applied to this latter construction type.

2.4. Environmental indicators

The environmental indicators were extracted from the two used EPDs [57,58] (Table 2). They include: abiotic depletion potential for both fossil (ADPF) and non-fossil resources (ADPE); global warming potential (GWP); depletion potential of the stratospheric ozone layer (ODP); formation potential of tropospheric ozone photochemical oxidants (POCP); acidification potential of land and water (AP); and eutrophication potential (EP). These indicators are assessed using the characterization factors of CML [61]. Two additional indicators related to energy consumption were extracted from the EPDs: non-renewable primary energy (NRPE) and total primary energy (TPE), obtained through the Cumulative Energy Demand (CED) single-issue method [62].

2.5. Life cycle cost methods and primary energy considerations

Life cycle cost (LCC) methods enable the effective evaluation of investment options, considering the impact of all costs instead of initial expenses alone, and planning the management of buildings and infrastructures during their lifetime [13].

As the EPDs of the solutions do not indicate a Reference Service Life (RSL), their lifespan is treated as a constituent of the envelope and similar to insulation materials. The lifespan considered was 40 years, and it is a compromise between:

- the stated 30 years calculation period, by the European Commission [63], for residential buildings, on establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements;
- the used lifespans in the literature, 50 years for envelope components [6465], and more specifically, 40 years for air barrier elements [66];
- the 40 years indicated life span of major replaceable components in international standards such as ISO 15686–1:2011 [67].

There are no maintenance costs to be included in the calculation of global costs, as they are elements of the envelope non-accessible after installation. Therefore, a dwelling RSL savings is simply the

Table 2
Life cycle assessment indicators considered for the comparison of air barrier solutions by the functional unit (m^2).

Parameter	Unit	Mechanically fastened (MECH) [57]	Fluid applied (FLUID) [58]
ADPE	kg Sb eq.	2.64E−07	1.61E−05
ADPF	MJ	1.17E + 01	7.21E + 01
GWP	kg CO_2 eq.	5.38E−01	3.83E + 00
ODP	kg CFC-11 eq.	1.24E−06	3.62E−07
POCP	kg C_2H_4 eq.	2.90E−04	8.15E−03
AP	kg SO_2 eq.	1.45E−03	1.07E−02
EP	kg PO_4^{-3} eq.	1.44E−04	1.36E−03
NRPE	MJ	1.24E + 01	7.60E + 01
TPE	MJ	1.27E + 01	8.00E + 01

difference in operational costs between a scenario of absence, and a scenario of application of one of the proposed airtightness solutions, through its RSL (Eqs. (1) and (2)). For each year after, the annual savings in operational costs adjust by a discount factor (Eq. (3)). A discount factor is a weighting term to convert future values into net present values (NPV) [11].

The CYPE software was applied to generate construction prices, by early 2021 in Portugal, and quantify the initial investment by using similar solutions to the ones considered in the present research [68]. The MECH solution was considered a vapor barrier with an air permeability of 0.03 $m^3/(h{\cdot}m^2)$ at 50 Pa, at 7.68 €/m^2 (VAT included). The FLUID solution adopted the compound price of a spray-applied liquid polyurethane-based waterproofing coating with an air permeability of 0.0003 $m^3/(h{\cdot}m^2)$ at 50 Pa, at 20.51 €/m^2 (VAT included). The prices of the solutions already account for the installation labor. Eq. (4) displays the formula for the payback period (PP). The PP is when, the financial savings from a certain improvement scenario equal its initial investment [69]. A positive PP indicates that the financial savings exceed the initial cost before the end of the RSL.

$$RSL_{savings} = \sum_{i=1}^{RSL} \Delta C_{a,i} \cdot R_{d,i} - C_0 \tag{1}$$

$$\Delta C_{a,i} = \frac{\Delta Q_{v,i}}{\eta_k} \cdot P_s \tag{2}$$

$$R_{d,i} = \left(\frac{1}{1+\frac{r}{100}}\right)^i \tag{3}$$

$$PP = j\ for C_0 \leqslant \sum_{i=1}^{j} \Delta C_{a,i} \cdot R_{d,i} \tag{4}$$

$RSL_{savings}$ reference service life savings (€).
$\Delta C_{a,i}$ difference in operational costs between a scenario of absence or application in the year i (€).
$R_{d,i}$ discount factor in the year i (-).
C_0 initial investment in applying the airtightness solution (€).
$\Delta Q_{v,i}$ difference in heat losses between a scenario of absence or application in the year i (kWh).
η_k nominal efficiency of the heating system k (-).
P_s energy price by source s (€/kWh).
r discount rate in year i (%).
PP payback period (year).

Table 3 compiles the considered heating systems, their efficiencies, respective energy sources, prices, and conversion factors from final to primary energy.

The selected four heating system types are the most common in the Portuguese built stock [73]. National technical documents [71] provided the efficiencies (η) of the natural gas boiler, pellet heat recovery, and heat pump for residential buildings. A heating system efficiency translates the ratio between the total energy output and the total energy input. The minimum requirements applied for all the heating systems.For the sake of a top-performing heating system, the research considered an additional heat pump with a higher efficiency.

Energy costs on electricity and natural gas refer to Portuguese energy prices (VAT included) for household consumers available at Eurostat [70] in the second half of 2020. For biomass as pellets, the used value refers to the value in Bioenergy Europe [72] for 2018, at 0.27 €/kg. As pellets' Low Heating Value (LHV) is 18.84 MJ/kg [74], which equals 5.23 kWh/kg, their price conversion equals 0.0516 €/kWh. The discount rate (r) in energy prices is 3 %, in line with European Commission directives [75].

The heating system efficiencies (η) and the primary energy factors (F_{PE}) from final energy to primary energy apply in calculating the primary energy needs (Eq. (5)). These factors account for energy used for transportation, processing, losses, etc. They are sourced from additional Portuguese legislation [76] and are in fair agreement with the factors obtained using the CED v1.09 method [62] in SimaPro with data from the Ecoinvent database [77]. The latter sum up to 2.72 kWh_{PE}/kWh for 1 kWh of electricity, 1.21 kWh_{PE}/kWh for 1 m^3 of natural gas, and 0.96 kWh_{PE}/kWh for 1 kg of wood chips that make up pellets.

Eq. (6) gives the Energy Payback Period (EPP). Like PP, the EPP is the time, in years, that the primary energy savings from a before to after intervention scenario equals or overcomes the embodied energy of that same intervention.

$$\Delta PE_a = \frac{\Delta Q_v}{\eta_k} \cdot F_{PE} \tag{5}$$

$$EPP = \frac{EE_0}{\Delta PE_a} \tag{6}$$

F_{PE} conversion factor between final energy and primary energy for energy source s (kWh_{PE}/kWh).
ΔPE_a annual difference in primary energy needs between a scenario of absence or application (kWh_{PE}).
EPP energy payback period (year).
EE_0 embodied energy of applying an airtightness solution (kWh_{PE}).

2.6. Heating loads and assumptions

Being heat transfers by ACHs the scope of this research, and windows opening a prevailing strategy in the cooling season [78], one considers only heat losses through ACHs in the heating season. A value of 1250 °C heating degree-days (HDD) applies to the assessment, corresponding to the Portuguese Porto metropolitan area, which is in line with the region considered in the simulations of the ACHs time series of the case study dwellings. Eqs. (7) to (9) show the calculations required to obtain the heat losses through air change rates during the heating season. They correspond to the adaptation to the Portuguese legislation [79] of the quasi-steady state method of ISO 13,790 [80].

$$\Delta Q_v = 0.024 \cdot HDD \cdot (H_{v,before} - H_{v,after}) \tag{7}$$

Table 3
Considered heating systems and efficiencies, their energy sources and respective prices.

Heating system	Heating systemefficiency (η)	Energy source	Energy price [€/kWh]	F_{PE} [kWh_{PE}/kWh]
Electric radiator	1.0	Electricity	0.2133 [70]	2.5
Natural gas boiler	0.90 [71]	Natural gas	0.0783 [70]	1.0
Pellet heat recovery	0.75 [71]	Biomass	0.0516 [72]	1.0
Heat pump (min. efficiency)	3.00 [71]	Electricity	0.2133 [70]	2.5
Heat pump (high efficiency)	5.00	Electricity	0.2133 [70]	2.5

$$H_{v,before} = 0.34ACH_{before}A_fC_h \tag{8}$$

$$H_{v,after} = 0.34ACH_{after}A_fC_h \tag{9}$$

HDD heating degree days (°C).
$H_{v,before}$ coefficient of heat transfer during the heating season in the absence scenario (W/°C).
$H_{v,after}$ coefficient for heat transfer during the heating season in the application scenario (W/°C).
ACH air change rate (h^{-1}).
A_f floor area (m^2).
C_h ceiling height (m).

One assumes the treatment of the whole opaque envelope area. Self-regulating vents integrate the window frames of the main housing divisions to offset the reduction in ACH from the absence of air infiltration through the building envelope. Since the vents are self-regulating, one assumes that, with the proper dimensioning, average ACHs values become similar to the average of the dwellings with adequate ACHs in the study from which the dataset is sourced [56], 0.55 h^{-1} and 0.65 h^{-1} for urban and rural locations. This assumption applies in assessing energy performance.

The potential environmental impact of these vents, the embodied energy, and the initial investment are assumed to be residual compared to a window without the vents. Such assumption relies on the elements often integrating across window frame depth and their composition being similar to the frame for functional and aesthetic reasons. This hypothesis is true in design scenarios, as windows installation takes place anyway, and retrofit scenarios where window replacement often occurs without airtightness being the main focus. According to a study of reference buildings in the Portuguese built stock, the glazed area averages 20 % of the envelope area [81].

3. Results and discussion

3.1. Energy performance

In subsection 2.5, one admitted that the maintenance cost of an air barrier implementation would be null since there is no access to it after installation. Therefore, only the expenditure with energy consumption applies to annual costs. Fig. 2 presents several percentiles of the annual savings in energy consumption between the scenarios of absence and application of an air barrier solution. The mean in an urban environment is 1460 kWh, slightly below 40 % of that in a rural terrain, 867 kWh. The standard deviations stand at 1401 kWh and 810 kWh, respectively. As the distributions approach higher percentiles, the differences are emphasized.

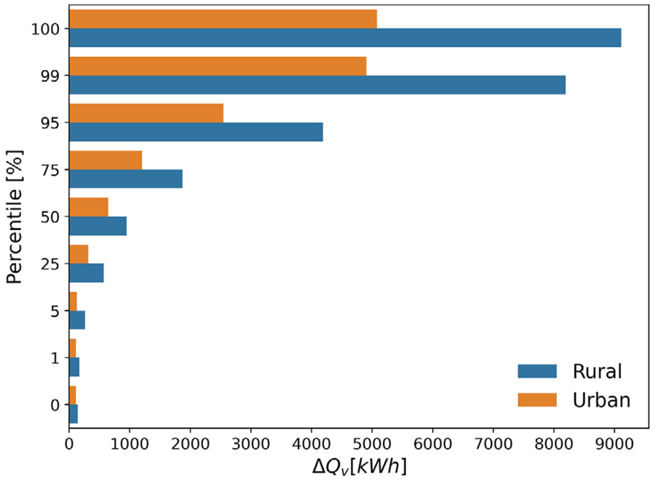


Fig. 2. Percentiles of annual savings in energy consumption between absence and application scenarios for the dwellings of the case study dataset.

While these reductions in energy consumption are a positive outcome, a comprehensive outlook on the economic viability of these applications is only achieved by identifying which dwellings with which heating systems have positive PP. When so, one quantifies the savings through the RSL..

Additionally, one must assess the Energy Payback Period (EPP). It allows identifying if the saved primary energy in heating the indoor environment compensates for the embodied energy of each air barrier solution by the end of the RSL.

3.2. Environmental performance

From the analysis of Table 2, only ODP presents lower impacts by square meter with FLUID instead of MECH. For all the other environmental indicators, the FLUID impacts significantly exceed MECH's.

The number of years the reduced primary energy from heating the dwellings take to equalize the embodied energy of the application, the EPP, present very different outcomes depending on the airtightness of the dwelling, the heating system, and the solution applied to the envelope (Fig. 3). Table 4 further informs EPP means and standard deviations for the considered air barrier solutions, terrains, and heating systems.

Treating a dwelling envelope with the FLUID solution confers an EPP 6.32 higher than the MECH solution when comparing within the same terrain and heating system. On average, for the same heating system and air barrier solution, the EPP of a dwelling in an urban location is 1.63 higher than the EPP of a dwelling in a rural terrain.

For the MECH solution, independently of the heating system and terrain, all the dwellings justify its implementation regarding primary energy, as the EPP never surpasses the respective RSL. For the FLUID air barrier, in rural terrain, only a portion of the dwellings equipped with a high efficiency heat pump does not have a positive EPP, being 6.4 %. In urban terrain, this percentage increases and is joined by a small percentage of dwellings equipped with minimum efficiency heat pumps and natural gas boiler, 18.1 %, 5.5 %, and 1.6 %, respectively.

3.3. Life cycle costs results

Addressing the embodied energy payback does not provide the complete picture. One needs to appraise each dwelling's savings through the RSL to assess the economic viability. Examining the dwellings with a positive and negative PP through their RSL savings by the heating system, airtightness solution, and airtightness performance (n_{50}) provides further understanding. Table 5 presents these data.

While the great majority of the dwellings with electric radiators experience a positive PP, with the MECH solution, this percentage drops to 19.1 % in the ones equipped with high efficiency heat pumps. The natural gas boiler, the minimum efficiency heat pump, and the pellet heat recovery stove are in between by descending PP. The order of PP by heating system is unchanged in the FLUID solution, but the percentages drop drastically, ranging from 45.3 % to 1.0 % of dwellings with a positive PP.

With MECH, in the groups with positive PP, the average RSL savings range from 5438 € to 1123 €. With FLUID, for the negative PP groups, the RSL savings range from −2437 € to −3853 €, showing the greater financial burden of this airtightness solution than MECH.

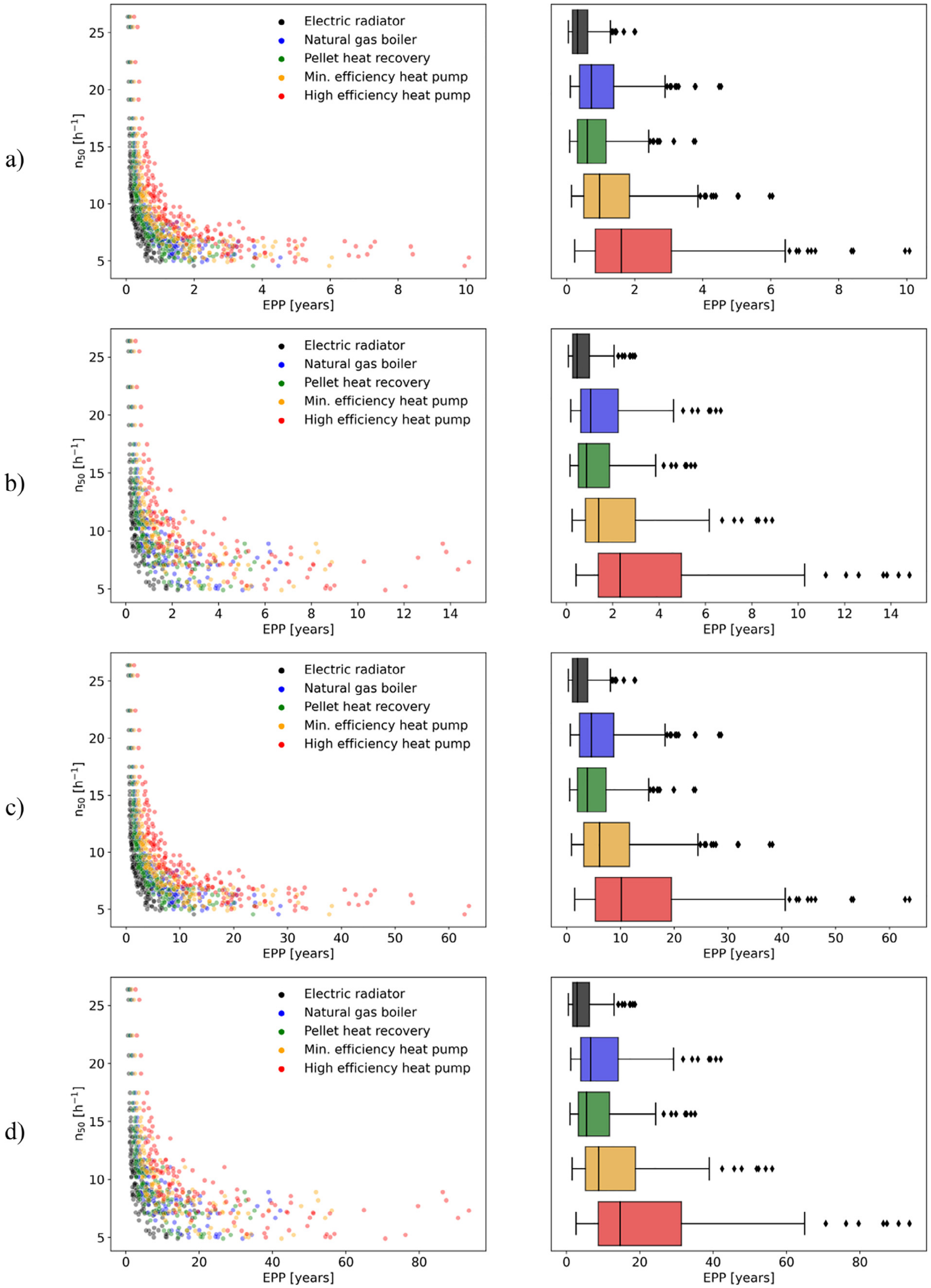


Fig. 3. Energy Payback Period (EPP) as a function of the airtightness performance (n_{50}) of the considered dwellings, by terrain, air barrier solution, and heating system in both scatter plots (left column) and boxplots (right column): a) rural terrain – MECH solution; b) urban terrain – MECH solution; c) rural terrain – FLUID solution; d) urban terrain – FLUID solution.

Table 4
EPP mean and standard deviation by air barrier solution, terrain, and heating system.

EPP [years] Air barrier solution	Terrain		Electric radiator	Natural gas boiler	Pellet heat recovery	Min. efficiency heat pump	High efficiency heat pump
MECH	Rural	Mean	0.46	1.03	0.86	1.37	2.29
		Std. dev.	0.39	0.88	0.73	1.17	1.95
	Urban	Mean	0.75	1.68	1.40	2.24	3.73
		Std. dev.	0.66	1.48	1.23	1.97	3.29
FLUID	Rural	Mean	2.89	6.50	5.42	8.67	14.45
		Std. dev.	2.46	5.53	4.61	7.38	12.29
	Urban	Mean	4.71	10.61	8.84	14.14	23.57
		Std. dev.	4.16	9.35	7.79	12.47	20.79

Table 5
Mean and standard deviations for the variables of interest of the dwellings with positive and negative PP, by heating system and airtightness solution.

	Pos. PP [%]		n_{50} [h^{-1}]	PP [years]	RSL savings [€]	Neg. PP [%]		n_{50} [h^{-1}]	RSL savings [€]
Electrical radiator	80.2	Mean	10.2	11.0	5438	19.8	Mean	6.5	−569
MECH		Std. dev.	3.8	8.3	6192		Std. dev.	1.2	400
FLUID	45.3	Mean	12.0	18.2	5385	54.7	Mean	7.3	−2437
		Std. dev.	3.9	9.1	6327		std	1.6	1449
Natural gas boiler	49.7	Mean	11.8	17.9	2161	50.3	Mean	7.2	−902
MECH		Std. dev.	3.9	9.4	2567		Std. dev.	1.6	526
FLUID	11.1	Mean	16.4	25.8	2301	88.9	Mean	8.6	−3124
		Std. dev.	4.8	8.2	2856		Std. dev.	2.5	1592
Pellet heat recovery	39.3	Mean	12.5	19.5	1730	60.7	Mean	7.5	−960
MECH		Std. dev.	4.0	9.0	2048		Std. dev.	1.7	552
FLUID	5.0	Mean	18.7	26.1	2242	95.0	Mean	9.0	−3326
		Std. dev.	5.0	8.7	2468		Std. dev.	3.0	1592
Min. eff. heat pump	40.9	Mean	12.3	19.4	1775	59.1	Mean	7.5	−955
MECH		Std. dev.	4.0	9.2	2112		Std. dev.	1.7	546
FLUID	5.7	Mean	18.3	26.2	2228	94.3	Mean	8.9	−3295
		Std. dev.	4.8	8.5	2521		Std. dev.	2.9	1594
High eff. heat pump	19.1	Mean	14.5	23.2	1123	80.9	Mean	8.3	−1076
MECH		std	4.5	8.2	1335		Std. dev.	2.3	600
FLUID	1.0	Mean	24.8	27.7	1670	99.0	Mean	9.3	−3853
		Std. dev.	2.1	7.6	1446		Std. dev.	3.4	1482

The lowest average n_{50} in the dwellings with positive PP is 10.2 h^{-1}, in the MECH solution and 12.0 h^{-1}, in the FLUID solution. Still, they experience substantial variability, as the standard deviation ranges from 3.8 to 4.5 h^{-1} in MECH and from 2.1 to 5.0 h^{-1} in FLUID, respectively.

To assess this relationship, one addresses the annualized savings through the RSL as a function of the airtightness performance (n_{50}). Since natural gas boiler, pellet heat recovery, and minimum efficiency heat pump have similar percentages of dwellings with positive PP, only the minimum efficiency heat pump is assessed (Fig. 4).

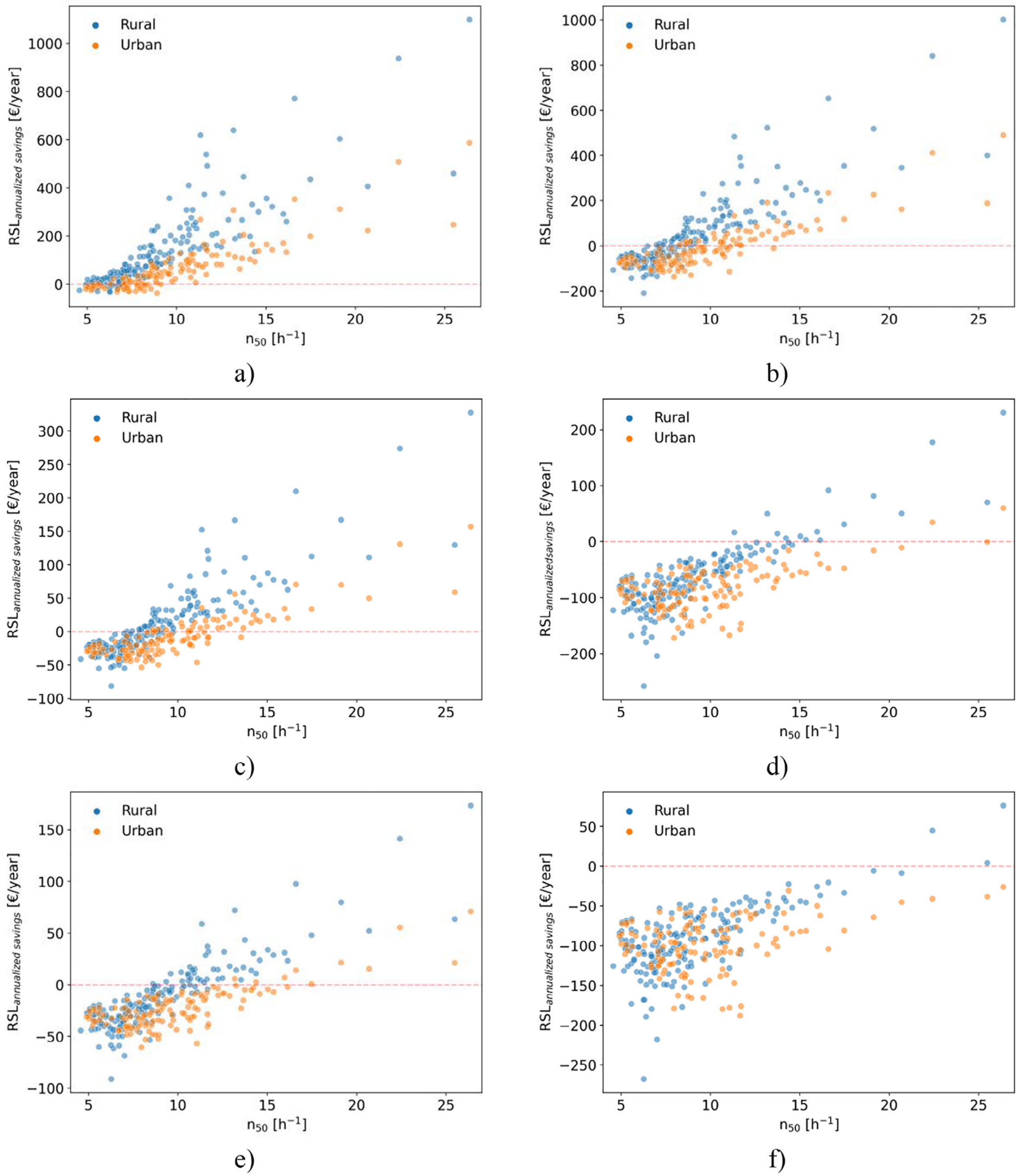
These results portray the information with a higher degree of interpretability. For MECH, in a rural location, all dwellings have positive RSL annualized savings with an n_{50} over 6.9 h^{-1} when equipped with electric radiators, over 9.7 h^{-1} with minimum efficiency heat pump, and over 11.7 h^{-1} with high efficiency heat pump. With the FLUID solution, these n_{50} need to be over 8.9 h^{-1}, 14.6 h^{-1}, and 20.7 h^{-1}, respectively.

The lower bound n_{50} values increase in an urban location. For MECH, they are 9.1 h^{-1}, 13.5 h^{-1}, and 16.1 h^{-1}, and for FLUID, they reach 13.5 h^{-1}, 25.5 h^{-1}, and 26.4 h^{-1}, for the same order of heating systems.

3.4. Ranked heating systems

Overall, for the research case study's scope, for dwellings equipped with electric radiators, adopting the MECH solution almost always justifies the financial investment, especially in rural locations, as even for those with negative RSL savings, they are quite low. The opposite occurs with a high efficiency heat pump, especially in urban locations. For all the other dwellings, the relationship between airtightness performance and the heating system will condition the RSL savings to be positive or negative. As a more expensive solution, FLUID experiences even greater costs. The greater majority of the dwellings compute negative RSL savings. The exception is in dwellings equipped with electric radiators as a heating system, where the results are quite mixed.

Table 6 indicates the heating systems ranked by EPP and RSL savings from applying an airtightness solution. The first ranked has the shortest average EPP and the highest average RSL savings. While scoring second in average EPP, the pellet heat recovery scores fourth in RSL savings, meaning that despite being environmentally superior, it comes with an aggravated financial burden compared to the natural gas boiler and the minimum efficiency heat pump.



a)

b)

c)

d)

e)

f)

Fig. 4. RSL annualized savings, by terrain, as a function of airtightness performance (n_{50}): a) electric radiator – MECH; b) electric radiator – FLUID; c) min. efficiency heat pump – MECH; d) min. efficiency heat pump – FLUID; e) high efficiency heat pump – MECH; f) high efficiency heat pump – FLUID.

Table 6
Ranked heating systems by shortest average EPP and highest average RSL savings.

Rank	EPP [years]	RSL savings [€]
1	Electric radiator	Electric radiator
2	Pellet heat recovery	Natural gas boiler
3	Natural gas boiler	Min. efficiency heat pump
4	Min. efficiency heat pump	Pellet heat recovery
5	High efficiency heat pump	High efficiency heat pump

4. Conclusions

The developed research explored the life cycle impacts of applying air barrier solutions in a set of naturally ventilated dwellings with excessive heat losses by air change rates. The life cycle assessment contributed to picturing and contextualizing the impacts of including air barrier solutions. While expectedly, the benefits of installing an air barrier system are larger in less airtight dwellings equipped with heating systems that are more expensive to operate and this research aimed to quantify these benefits.

Despite a more thorough study falling out of the scope of the developed work, since the focus is on LCA aspects, the results have an inherently causal relationship with heating systems efficiency and the wind speeds at the building site. However, this aspect does not undermine or devalue the achieved results, from which some main points are made:

- For a MECH solution, independently of the heating system and terrain, all the dwellings justify its implementation regarding primary energy, as the EPP never surpasses the respective RSL. For the FLUID air barrier, in rural terrain, only a portion of the dwellings equipped with a high efficiency heat pump does not have a positive EPP;
- The FLUID solution conferred an EPP 6.32 higher than a MECH solution, for dwellings with same terrain and heating system. On average, the EPP of a dwelling in an urban location was 1.63 higher than the EPP of a dwelling in a rural location;
- The dwellings with positive PP range from 80.2 % to 19.1 % if equipped with electric radiators or high efficiency heat pumps. The mean PPs range from 11.0 and 23.2 years. The natural gas boiler, the minimum efficiency heat pump, and the pellet heat recovery stove are in between by descending PP. The order of PP by heating system is unchanged in the FLUID solution, but the percentages drop drastically;

With the current analysis, and for the restricted scope, assumptions, and acceptance criteria of the used case study, the adoption of mechanically fastened air barrier solutions is recommended in southern Europe with its mild heating season, especially in dwellings equipped with electric radiators.

Still, a FLUID solution has several technical advantages compared to a MECH one. It more easily adapts to complex envelope geometries and provides more efficient adhesion and detailing connections between envelope components and respective penetrations.

Overall, assessing the feasibility of these solutions can point to potential environmental and economic net positive paths, increasing awareness and encouraging adoption by the AEC industry. Results on the present research show a mixed outcome depending mainly on the existing heating system and its energy source, pointing to the easier accomplishment of environmental net gains than economic ones.

It is relevant to note that the data related to air barrier solutions, both regarding environmental aspects, i.e. the used EPDs, and financial ones, i.e. the material and labor cost of the installation of the solutions, greatly impacts the outputted results. Changes to these variables could dramatically modify the relative burden of one solution to the other. On top of these, considering an RSL of 30 or 50 years, pointed out as a suitable range in subsection 2.5, would make the air barrier systems decreasingly feasible and increasingly feasible, respectively, compared with the adopted RSL of 40 years.

The methodology of this work has a high degree of reproducibility, further aided by the presented structured flux of research, potentiating future works. Future works in LCA and LCC scopes should favour: the use of different envelope airtightness solutions; the tackling of assumptions regarding the air change rate performance of applying self-regulating vents; the study of the air barrier application in different climate conditions; the adaptation from a methodology predominantly focused on lightweight construction to one focused on heavyweight construction. This last future work is highly challenging because of the difficulty in objectively or even statistically quantifying airtightness solutions in this type of constructions.

Data availability

The data that has been used is confidential.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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