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Energy and emergy based cost–benefit evaluation of building envelopes relative to geographical location and climate

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ABSTRACT

This paper presents an environmental evaluation of building envelopes, made of three different technologies: a traditional air-cavity wall, a plus-insulated wall (with an external cork covering), and a ventilated wall (with external brick panels fixed on extruded frames). An environmental accounting method, namely Emergy Evaluation (EE), was performed for assessing environmental resource use (energy and material flows), both directly and indirectly, for the construction of a façade (1000 m^2). Then, energy use during the building lifetime was assessed as a constant inflow to the building depending on the thermal skills of building envelopes, besides thermal efficiency of air-conditioning system. In particular, this energy inflow is needed for maintaining constant indoor climate conditions (18 °C) and has to balance heat dissipation through envelopes (heat loss in winter and heat gain in summer). Outcomes were compared with an Energy Analysis (EA) based on an embodied energy accounting. Finally, costs for manufacturing walls (with enhanced performance) and benefits (energy saving) were compared in a unique balance, through both EA and EE. Moreover, outcomes were obtained for three scenarios corresponding to three geographic locations (Berlin in northern Europe, Barcelona on the Mediterranean coast and Palermo in the south of Italy). Results highlighted that performances of building envelopes depend on technologies relative to external climate conditions. Different environmental accounting methods, such as EE and EA, provided outcomes with some difference that are not contradictory to each other but complementary.

1. Introduction

Recent statistics highlighted the high environmental concern of the building industry, especially relative to the problems of non-renewable resource exploitation and environmental unsustainability due to the construction of new buildings. About 30–40% of total energy consumption in western countries is assigned to building. About 50% of these refer to the energy consumption for indoor air conditioning (heating and cooling) [3]. Statistics are available in the E.C. Green Paper [12] and, some discussion about energy demand split by sectors for the European Union was presented, among many others, in Refs. [2,19,8]. This data usually concerns energy demand while material flows are rarely considered. Thus, methods for monitoring both energy and material flows of the building industry are strongly required in order to make choices for future urban planning and management.

Buildings are expected to maintain a constant comfortable and healthy indoor climate with respect to variable external climate conditions. This requires high energetic performances of building envelopes, besides an additional use of energy inputs for heating and cooling. Related studies concerning building envelopes and energy demand relative to climate were, among others: [29,17,14,28,15,16,7].

A characteristic of a sustainable building includes a high thermal efficiency, especially through a careful design of the building envelope and a limited use of active air-conditioning systems during the building's lifespan. Moreover, a building design should consider its context, since building envelopes exchange thermal energy with the external environment and therefore depend on outdoor climate conditions, such as temperature, air humidity, atmospheric pressure, solar irradiation, precipitations, and winds. In other words, a building is not only a box with mechanical equipment for heating and cooling, but an integrated structure able to spontaneously adapt itself to a variable external climate.

Technology and material choices of building envelopes have different environmental impacts. New building technologies for energy saving, namely *environmental-free*, *bio-architecture* or *eco-building*, call for new comprehensive methods for monitoring their direct and indirect effects on the environment and for evaluating their sustainability. How many resources are used and which

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impacts are due to these new eco-technologies? How much is their environmental cost with respect to benefits? Environmental accounting methods can provide additional information for evaluating building materials and technologies, even considering different scenarios, in order to make choices and screen for the best procedures.

2. Methods

This paper presents an *emergy evaluation* (EE) – emergy is spelled with an "m" – of building envelopes according to the calculation introduced by Howard Odum [20–22]. A few concepts and definitions are as follows.

- EE uses the "energy systems language", based on the thermodynamics of open systems, to measure the environmental resources used for a given process or product.
- EE can be performed for different processes and products. It assesses both the work of humans and nature in terms of energy and material inflows to a given process or product by transforming energy and mass quantities (Joules and kilo) into equivalent quantities of one form of energy, the solar energy (unit: solar emergy joule – sej).
- Based on this unit, emergy is defined as the quantity of solar energy that was used, directly or indirectly, to obtain a final product or service.
- A unit emergy value (UEV), namely *transformity* or *specific emergy* (unit: sej/J or sej/g, respectively), can be used to "convert" a given product into emergy. Mass quantities (g) or energy quantities (Joule) multiplied by UEV give an emergy content (sej).
- The UEV represents the position that a given transformation process (and its product) occupies in the hierarchical network of the earth's biosphere.

Emergy units are therefore a measure based on the concept of energy hierarchy in nature. In a formation–production process of a given product, it quantifies both the anthropic inputs (e.g. in the case of a raw material, the work made by humans for mining or quarrying) and the natural inputs (e.g. the sedimentary cycle that was necessary in the long run to provide a raw material). Thus emergy can be conceived as a measure of environmental resources or, in other words, of the natural capital corresponding to a given product.

Moreover, an Energy Analysis (EA), based on an Embodied Energy analysis, was also used to assess the energy demand due to building construction and use. In the case of buildings, it is defined as the energy used during all stages of the life cycle of the building, including the energy use for extracting raw materials and producing building materials [3]. Thus EA accounts for the energetic inputs to these processes. Previous works about embodied energy of buildings, among many others, are Refs. [1,10,11,3,27,13].

2.1. Previous works: emergy evaluation of buildings

The list in Table 1 presents embodied energy values and unit emergy values (specific emergy) of building materials. Materials in the list were ordered according to their specific emergy. With respect to the embodied energy that considers the energy used from the extraction to the production of a final grade material, the calculation of specific emergy includes the energy (such as fossil fuels) and material use, and accounts for the work made by nature in the long run to provide a certain quantity of fossil fuels and raw materials (sedimentary cycle).

Table 1
Previous calculated embodied energy and specific emergy values of building materials

Item	Embodied energy (MJ/kg)	References (energy)	Specific emergy (10^{12} sej/kg)	References (emergy)
Copper	71.6	[27]	104	[4]
Paint	60.2	[27]	25.5	[6]
Aluminium	191	[13]	21.3	[6]
PVC	70	[27]	9.86	[6]
Polystyrene	94.4	[27]	8.85	[6]
Steel	32	[13]	6.94	[6]
Brick	2.7	[27]	3.68	[23]
Mortar	0.1	[27]	3.31	[5]
Plaster	7.8	[13]	3.29	[18]
Cement	3.7	[27]	3.04	[26]
Ornamental stone	18.9	[3]	2.44	[23]
Wood (deal) – cork	10.8	[27]	2.4	[22]
Concrete	1.2	[13]	1.81	[26]
Limestone	0.1	[27]	1.68	[22]
Glass	6.8	[27]	1.42	[24]

In previous works, an emergy based calculation was performed for evaluating building manufacturing [25], particularly, the construction of a contemporary building with common characteristics. Quantity of materials and other flows (such as land, energy, and human labour) in the building process were assessed. In Table 2 there are quantities of materials per built m^3 and the corresponding quantity of embodied energy (given in MJ) and emergy (given in sej). In particular, emergy values highlighted that certain materials have higher impacts than others in terms of environmental resource use because of their high UEV (as shown in Table 1) and high quantity used.

EE of building manufacturing, maintenance and use provided the following outcomes [25].

- Emergy for building manufacturing was about $1.07^{\circ}\times 10^{15}$ sej per m^3. This represents an emergy stock that persists over time during the entire building lifespan. Considering 50 years, this value corresponds to an emergy inflow of $21.47^{\circ}\times 10^{12}$ sej/yr.
- The emergy inflow for building maintenance was about $15.30^{\circ}\times 10^{12}$ sej/yr per m^3. This represents an energy and material inflow that is necessary to replace the entropic degradation of the built stock and to maintain its content constant in time.
- The emergy flow for building use (mainly due to electricity and natural gas consumption) was about $6.76^{\circ}\times 10^{12}$ sej/yr per m^3. This energy demand depends on the technology used for the

Table 2
Composition of a built cubic meter and energy-emergy per m^3 (elaboration from Ref. [25])

Materials	g/m^3	Energy (MJ/m^3)	Energy (%)	Emergy (10^{12} sej/m^3)	Emergy (%)
Concrete	263,665	316.40	21.70	477	44.65
Brick	75,759	204.55	14.03	279	26.07
Mortar	21,239	2.12	0.15	70.3	6.57
Steel	7898	252.74	17.33	55.1	5.15
Plaster	11,383	88.79	6.09	37.5	3.51
Gres	7521	142.15	9.75	36.1	3.38
Paint	1138	68.51	4.70	29.1	2.72
Ornamental stone	10,871	205.46	14.09	26.5	2.48
Copper	89	6.37	0.44	9.2	0.86
Polystyrene and HDPE	1025	96.76	6.64	9.08	0.85
PVC	579	40.53	2.78	5.71	0.53
Aluminium	149	28.46	1.95	3.17	0.30
Wood (fir)	486	5.25	0.36	1.17	0.11
Glass	20	0.14	0.01	0.028	0.003
Other flows	–	–		–	2.82
Total emergy per m^3		**1458**	100	**1070**	100

building envelope and other active equipments for lighting, heating, and cooling.

In a comprehensive balance, emergy inflow to building manufacturing, maintenance, and use was $43.52^{\circ}\times 10^{12}$ sej/yr per m^3. Emergy inflow due to building manufacturing corresponds to 49% (considering a building lifetime of 50 years), while maintenance is 35% (maintenance needs material use as well) and building use is 15%. In other words, the choice of building materials, the energy for their production and assembly in the building yard, and their duration have to be taken into account, besides the energy consumption (electricity, fuel) during the building lifespan.

2.2. Case study: energy analysis and emergy evaluation of building envelopes

The present study developed an EA and an EE of three different technologies for building envelopes. In particular, these methods were applied to a 1000 m^2 continuous wall. A compared analysis considered the following three case studies: (1) a traditional air-cavity wall; (2) a plus-insulated wall (a cavity wall with an external cork covering added); (3) a ventilated wall (with external brick panels fixed on an extruded frame). Fig. 1 shows the composition of three walls under study.

As shown in Fig. 1, (a) the air-cavity wall (30 cm thick) is made of external plaster (1 cm), external brick wall (12 cm air-brick), air-cavity (4 cm) and polymeric insulation (6 cm), internal brick wall (12 cm air-brick), interior plaster (0.4 cm). (b) The plus-insulated wall was assembled as a traditional air-cavity wall with an external cork cover added. Cork panels have a density of 145 kg/m^3 (8 cm thick), fixed through an iron net plunged in an external plaster (2 cm thick). (c) A ventilated wall corresponds to an air-cavity wall combined with an added polymeric insulation (8 cm thick), a PVC film and an external cover of brick panels (1.7 cm thick – 6 kg/m^2 density) fixed on an extruded frame (aluminium – 0.66 kg/m^2 density – with a steel support – 2.48 kg/m^2 density). An open air-cavity (that is not hermetic because brick panels are close to each other, not hermetically settled) increases thermal resistance and, during summer, an air stream starts moving inside, following a vertical convection, and helps heat dissipation (in summer, when temperature is more than 21 °C, some narrow slits are opened at the top and the bottom of the wall, to let air move).

Both EA and EE were conducted separately for two main processes: (A) the construction of the building envelope (an initial energy–emergy investment for enhancing thermal performances); (B) the building use (considering the heat dissipation through the envelope and the energy–emergy demand for cooling and heating). Since a building envelope with enhanced performances required a higher initial investment but a lower energy demand during the building lifespan, environmental costs (energy–emergy for manufacturing) were compared to environmental costs/benefits (energy demand/energy saving for heating and cooling). Furthermore, EA and EE of building envelopes were performed relative to three different scenarios corresponding to three geographical locations with specific climate conditions: Berlin (cold weather), Barcelona (Mediterranean temperate weather), Palermo (warm weather). In other words, this study aims to evaluate how much natural capital is used for manufacturing three different layered walls (costs) and how much is the gain (benefits) in time, in terms of energy saving for heating (natural gas) and cooling (electricity).

Since technical skills, such as insulation and ventilation, change energetic performances of a building envelope, a Thermal Analysis (TA) was conducted on each of the three different layered walls. Heat dissipation through the wall (1000 m^2) was assessed assuming that the indoor temperature was constantly 18 °C, and outdoor climate condition was variable and relative to geographical location. Energy dissipation due to thermal conduction and convection (heat loss in winter and heat gain in summer through the wall) was considered to be totally replaced by an energy input for heating in winter and cooling in summer, in terms of natural gas and electricity consumption, respectively.

3. Results #1: energy analysis and emergy evaluation of environmental costs for the construction of a building envelope

EA and EE were here applied for assessing energy and material inflows to the manufacturing process of building envelopes.

The energy–emergy amount for the construction of the wall represents the environmental cost that was necessary, as an initial investment, to provide it. A plus-insulated wall and a ventilated wall have a higher cost than a traditional air-cavity wall. This difference is the energy-emergy added investment to obtain a higher performance and a lower energy demand during the

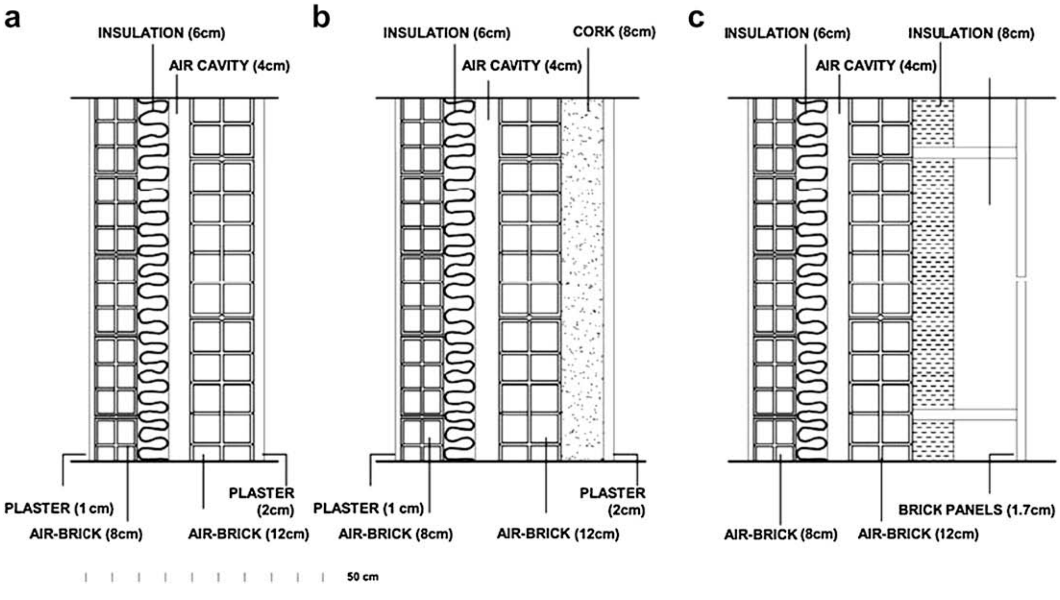

Fig. 1. (a) Traditional air-cavity wall; (b) plus-insulated wall; and (c) ventilated wall.

building use. The higher environmental cost of a plus-insulated wall and a ventilated wall with respect to a traditional air-cavity wall was here assessed.

EA of the construction of a traditional air-cavity wall, a plus-insulated wall and a ventilated wall was presented in Table 3. Items are given in mass and energy quantity. Energy was assessed according to the embodied energy values reported in Table 1.

EE was presented in Table 4. Items are given in mass and emergy quantity. Emergy was assessed according to the specific emergy values reported in Table 1.

The total energy for manufacturing a traditional air-cavity wall was 6.46×10^5 MJ. The total emergy was 5.65×10^{17} sej. A high percentage of the total emergy is due to brick works. This depends on the huge mass-quantity used and on the high UEV of raw materials, such as lateritious, due to the sedimentary cycle and to the fossil fuels consumption (high temperature production process).

In a previous work [25], the emergy for the construction of a 10,000 m^3 building was 1.07×10^{19} sej, and the building envelope was approximately 9.45×10^{17} sej, about 9% of the total. According to this more detailed analysis, the construction of four facades (air-cavity walls), equivalent to a total of 2200 m^2 corresponding approximately to a volume of 10,000 m^3 (100 m × 10 m × 10 m), was 1.24×10^{18} sej. This enhances the importance of the building envelope that would be about 12% of the emergy inflow for the construction of the entire building.

The total energy for the construction of a plus-insulated wall was 8.70×10^{15} MJ. The additional energy investment, relative to a traditional air-cavity wall, is about 2.24×10^5 MJ, corresponding to 34%. The total emergy was 6.17×10^{17} sej. The additional emergy investment is about 5.27×10^{16} sej, corresponding to 9%.

Cork is an environmental-free building material because of its renewability (if its production is well managed). Furthermore, the specific emergy of cork (2.40×10^9 sej/g) is much lower than the unit emergy value of a polymeric insulation (8.85×10^9 sej/g) because it is a natural material and does not need a high temperature production process with fossil fuels. Nevertheless, cork has a higher density (145 kg/m^3) than polymeric insulation (30 kg/m^3) and an emergy evaluation would present similar outcomes for a wall with a cork external covering (2.79×10^{16} as shown in the table) and a wall with a polymeric cover (that would be 2.12×10^{16}). The difference is that cork corresponds to a renewable flow and polymeric insulation to a non-renewable one. The Environmental Loading Ratio (the ratio of non-renewable and renewable emergy) would highlight that cork is more sustainable than polystyrene (the wall with a cork cover has an ELR = 21, while it is close to infinite in the case of polystyrene). If we assume that the initial emergy investment only includes non-renewable resources, the emergy for manufacturing a plus-insulated wall with cork would be 5.90×10^{17} sej.

Table 3
Energy Analysis of the construction of three buildings envelopes

Item	Raw data (kg)	Trad. Air-cavity		Plus-insulated		Ventilated	
		MJ	%	MJ	%	MJ	%
Brick (air-brick)	50,400	136,080	21.06	136,080	15.64	136,080	15.62
Insulation	1800	169,920	26.30	169,920	19.53	169,920	19.50
Brick (air-brick)	84,000	226,800	35.10	226,800	26.07	226,800	26.03
Cork	11,600			125,280	14.40		
Settled iron net	3081			98,596	11.33		
Mortar	2000	200	0.03	300	0.03	200	0.02
External plaster	14,500	113,100	17.51	113,100	13.00		
Insulation	2400					226,560	26.00
PVC	138					9660	1.11
Aluminum	2484					0	0.00
Steel	659					21,101	2.42
Brick panels	30,000					81,000	9.30
Total		**646,100**		**870,076**		**871,321**	

Table 4
Emergy Evaluation of the construction of three buildings envelopes

Item	Raw data (kg)	Trad. air-cavity		Plus-insulated		Ventilated	
		sej × 10^{15}	%	sej × 10^{15}	%	sej × 10^{15}	%
Brick (air-brick)	50,400	185.43	32.83	185.43	30.03	185.43	26.20
Insulation	1800	15.94	2.82	15.94	2.58	15.94	2.25
Brick (air-brick)	84,000	309.05	54.72	309.05	50.05	309.05	43.67
Cork	11,600			27.87	4.51		
Settled iron net	3081			21.48	3.48		
Mortar	2000	6.62	1.17	9.93	1.61	6.62	0.94
External plaster	14,500	47.75	8.45	47.75	7.73		
Insulation	2400					21.25	3.00
PVC	138					1.36	0.19
Aluminium	2484					53.00	7.49
Steel	659					4.60	0.65
Brick panels	30,000					110.38	15.60
Total		**564.79**		**617.44**		**707.62**	

The total energy for the construction of a ventilated wall was 8.71×10^5 MJ. The additional energy investment, relative to a traditional air-cavity wall, was about 2.25×10^5 MJ, corresponding to 35%. The total emergy was 7.08×10^{17} sej. The additional emergy investment was about 1.43×10^{17} sej, corresponding to 20%.

EE provided different results for the plus-insulated and the ventilated wall with respect to the traditional air-cavity wall. This difference is due to the high UEV assigned to materials such as aluminium and brick. EE accounts for the use of non-renewable resources such as minerals, extracted materials and fossil fuels. On the other hand, EA assigned a high value to the insulation due to the energy for the production and transport of polystyrene.

4. Results #2: energy analysis and emergy evaluation of environmental benefits due to building use

EA and EE focused on building use considering the energetic performance of three building envelopes, assuming that the wall was faultlessly manufactured, homogeneous and without thermal bridges.

4.1. Thermal analysis: heat dissipation through building envelopes

Heat loss and heat gain in the building depend on the difference between indoor and outdoor temperatures in cold and warm months, respectively. It is clear that heat transfer has two directions: towards the outside during winter and towards the inside during summer.

A Thermal Analysis (TA) was performed for three scenarios corresponding to three geographic locations with a given temperature, humidity, atmospheric pressure and solar irradiation (the latter refers to the daily solar energy on a vertical wall facing south). These parameters were considered for estimating the effective external temperature in terms of daily average values (see Appendix 1).

Power of heat dissipation (Q) was calculated independently from the heat transfer direction (from or to the outside) as in the following equation:

$$Q = k \times \Delta T \times A \quad (1)$$

where k is the transmittance given in W/m^2K, ΔT is the difference between indoor and outdoor temperatures, and A is the wall surface.

Transmittance k was assessed as follows:

$$k = \frac{1}{1/\alpha_i + \sum_i R_i + 1/\alpha_e} \tag{2}$$

where R_i (given in m^2K/W) is the Thermal resistance of materials in a layered wall, α_i is the coefficient of internal Convective Resistance, α_e is external Convective Resistance. In this case study, these values were $\alpha_i = 7.7$, $\alpha_e = 25$.

Thermal resistance of each material in the layered wall was assessed as follows:

$$R_i = \frac{d_i}{\lambda_i} \tag{3}$$

where d_i is thickness of each layer, and λ_i is the specific coefficient of Thermal Conductivity of each material, given in W/mK.

Values of resistance R and transmittance k were presented in Table 5.

Thermal resistance of a traditional air-cavity wall is $R = 2.34$ m^2K/W and total Transmittance is $k = 0.40$ W/m^2K. For a plus-insulated wall, these values are $R = 4.35$ m^2K/W and $k = 0.22$ W/m^2K, that corresponds to a thermal efficiency 44% higher than a traditional wall. In the case of a ventilated wall, since the external brick panels are not hermetically close to each other and the external air-cavity makes the effect of a wool covering, we considered the thermal resistance of the air layer inside a non-airtight and non-ventilated cavity and we did not added that of brick panels. For a ventilated wall, $R = 4.61$ m^2K/W and $k = 0.21$ W/m^2K, that corresponds to a thermal efficiency 47% higher than a traditional wall.

Focussing on the action of air-motion in the ventilated wall, the dissipated energy through the vertical air convection inside the air-cavity was expected to partially avoid the heat gain through the building envelope during summer. Although passive ventilation usually has uncertain effects, because it can depend on very localized environmental conditions such as shadows or temperature of the ground (e.g. sidewalk), we measured heat dissipation considering that certain parameters, such as direct solar irradiation, strongly influence its functioning. Ciampi et al. [9] presented a calculation of heat loss due to passive ventilation in ventilated walls considering a set of case studies with different technical skills. Their outcomes for a ventilated wall, that is very similar to our case study (with a 12 cm ventilated air-cavity and external brick panels), highlighted that ventilation helps heat dissipation and its contribution can be calculated relative to the intensity of solar irradiation on the external face. In particular, the authors plotted on a diagram a curve that shows the relation between solar irradiation (given in W/m^2), and the percentage of energy saving due to ventilation, relative to the total heat gain (for example, according to them, energy saving due to passive ventilation is 41% when solar irradiation is about 350 W/m^2 and it is 30% when solar irradiation is about 200 W/m^2). Therefore, based on the estimation by Ciampi and co-authors, we considered the specific contribution of passive ventilation relative to the mean solar power in daylight hours on a vertical wall facing south in months with temperature $T_e > 21$ °C. In these cases, with open air duct, we did not consider the thermal resistance of air in the cavity but its capacity of absorbing and dissipating a heat flux. Eq. (1) for assessing the net heat flux to the inside including the contribution of passive ventilation (Q_V) changed into

$$Q_V = k \times \Delta T \times A - Q \times \frac{Q - Q_V}{Q} \tag{4}$$

where Q is the total heat flux to the inside with closed air duct (W/m^2) as defined above (Eq. (1)) and $Q - Q_V/Q$ is the portion of heat loss due to ventilation relative to the total heat flux (Q), whose value was estimated on the basis of solar irradiation according to the outcomes of Ciampi et al. [9].

Table 5
Thermal resistance and transmittance of three building envelopes

Materials	d (m)	Coeff. (W/mK)	Trad. air-cavity R		Plus-insulated R		Ventilated R	
			km^2/W	%	km^2/W	%	km^2/W	%
Internal plaster	0.010	0.87	**0.01**	0.49	**0.01**	0.26	**0.01**	0.25
Brick (air-brick)	0.080	0.39	**0.21**	8.76	**0.21**	4.71	**0.21**	4.45
Insulation	0.060	0.035	**1.71**	73.81	**1.71**	39.37	**1.71**	37.16
Air-cavity	0.040	0.25	**0.16**	6.83	**0.16**	3.67	**0.16**	3.47
Brick (air-brick)	0.120	0.50	**0.24**	10.25	**0.24**	5.51	**0.24**	5.20
External plaster	0.010	0.87	**0.01**	0.49	–		–	
Cork	0.080	0.04	–		**2.00**	45.94	–	
External plaster	0.020	0.87	–		**0.02**	0.53	–	
Insulation	0.080	0.04	–		–		**2.00**	43.35
Air-cavity (non-airtight and non-ventilated)	0.120	0.50	–		–		**0.24**	5.20
Brick panels	0.017	0.40	–		–		**0.04**	0.92
R (total)			**2.34**		**4.35**		**4.61**	
k (total)			**0.40**		**0.22**		**0.21**	

Based on TA, the three building envelopes showed different thermal performances. In Table 6, the power of heat dissipation through a 1000 m^2 wall during cold and warm months is reported. These values include the contribution of passive ventilation in a ventilated wall during warm months. Values are negative or positive relative to the direction of heat flux through the wall (heat loss in cold months and heat gain in warm months).

4.2. *Energy Analysis and Emergy Evaluation of air conditioning in buildings*

EA was performed based on results from TA. On one hand, the heat loss in winter was considered to be replaced by a heat production, provided by a heating system, and, on the other hand, the heat gain in summer, replaced by a heat absorption, provided by an electric cooling system. In other words, we assessed the portion of energy demand by the air-conditioning systems that is expected to replace the energy dissipation through the wall. Operating hours of the heating and cooling equipment were estimated based on monthly Day Degrees. Heating and cooling Day Degrees (DD_h and DD_c, respectively) were calculated separately. DD were considered as the sum of gradients between the environmental indoor temperature (18 °C) and the daily outdoor mean temperature. Operating hours (h_d) were given in hours/day and were considered dynamically as follows: $DD_h > 500$, $h_d = 20$ h/d; $500 > DD_h > 400$, $h_d = 18$ h/d; $400 > DD_h > 300$, $h_d = 16$ h/d; $300 > DD_h > 250$, $h_d = 14$ h/d; $250 > DD_h > 200$, $h_d = 12$ h/d; $200 > DD_h > 150$, $h_d = 10$ h/d; $150 > DD_h > 100$, $h_d = 8$ h/d; $100 > DD_h > 50$, $h_d = 6$ h/d; $50 > DD_h > 30$, $h_d = 4$ h/d; $DD_h < 30$, $h_d = 0$ h/d; $DD_c < 50$, $h_d = 0$ h/d; $50 < DD_c < 100$, $h_d = 4$ h/d; $100 < DD_c < 150$, $h_d = 6$ h/d; $150 < DD_c < 200$, $h_d = 8$ h/d; $200 < DD_c < 250$, $h_d = 10$ h/d; $250 < DD_c < 300$, $h_d = 12$ h/d; $300 < DD_c < 350$, $h_d = 14$ h/d; $350 < DD_c < 400$, $h_d = 16$ h/d; $DD_c > 400$, $h_d = 18$ h/d.

The energy that is used to recover the energy dissipation (E) through the wall was assessed as follows:

$$E = Q \times D_m \times h_d \times \varepsilon \times 3600 \tag{5}$$

where Q is Q_V in the case of a ventilated wall, D_m is the number of days per month, h_d is the number of working hours per day of an air-conditioning equipment that is proportioned on the bases of DD as shown above, ε is the efficiency of the air-conditioning system

Table 6
Thermal Analysis: power of heat loss and heat gain through three building envelopes (1000 m^2 wall) in Berlin, Barcelona and Palermo – unit: W

	Berlin			Barcelona			Palermo		
	Air-cav. (W)	Plus-ins. (W)	Ventilated (W)	Air-cav. (W)	Plus-ins. (W)	Ventilated (W)	Air-cav. (W)	Plus-ins. (W)	Ventilated (W)
Jan	9203	5111	4834	3361	1867	1765	1641	911	862
Feb	6486	3602	3406	2118	1176	1112	923	513	485
Mar	4021	2233	2112	619	344	325	−217	−120	−114
Apr	1634	907	858	−581	−323	−305	−1918	−1065	−867
May	595	330	312	−1703	−946	−774	−3898	−2165	−1788
Jun	−2470	−1372	−1156	−3742	−2078	−1789	−5224	−2901	−2304
Jul	−4025	−2235	−1893	−4947	−2747	−2300	−5185	−2880	−2356
Aug	−1112	−618	−479	−3426	−1902	−1603	−5621	−3122	−2511
Sep	−1219	−677	−539	−2925	−1625	−1346	−2751	−1528	−1204
Oct	1268	704	666	−2223	−1234	−1021	−2650	−1472	−1180
Nov	2584	1435	1357	−169	−94	−89	−1449	−805	−629
Dec	5230	2904	2747	2731	1517	1434	139	77	73
Winter	3877	2153	2037	2207	1226	1159	901	500	473
Summer	−2206	−1225	−1017	−2733	−1518	−1275	−3213	−1784	−1439

(heating and cooling systems were considered to have a 85% and 37% efficiency, respectively).

Results from EA show different extensive quantities in different geographical locations. In Berlin, the total heat dissipation (here conceived as energy use) is distributed 71% in winter and 29% in summer. In Barcelona it is 15% and 85%, respectively. In Palermo it is 2% and 98%. In general, EA shows that annual heat dissipation is lower in Barcelona (with a temperate climate) and higher in Berlin (about 11% more than Barcelona, especially due to cold temperatures in winter) and in Palermo (about 58% more than Barcelona, especially due to hot temperatures in summer).

In Table 7, results from EA are shown. Values represent the energy use that replaces the energy dissipation through the wall during a year. These flows persist for the building's entire lifetime.

Values in Table 7 were plotted in the diagrams in Fig. 2. In the diagrams, energy use to replace energy dissipation through a traditional air-cavity wall (*black + grey + white area*) is compared to a plus-insulated wall (*grey + white area*) and a ventilated wall (*white area*). The diagrams also show the energy saving by using a plus-insulated wall (*black area*) and a ventilated wall (*grey + black area*) with respect to a traditional wall. Negative values in the diagrams refer to warm months.

In the EE the energy use was assessed through EA and transformed into equivalent solar energy joules through the UEV of natural gas (6.72×10^4 sej/J) and electricity (2.07×10^5 sej/J) that are needed to feed a heating and cooling system, respectively. UEVs were available in the literature cited [25] and represent the solar energy that was used, directly or indirectly, for providing a unit (Joule) of product, such as natural gas and electricity. In particular, the latter was assessed considering an integrated electric production process that mostly includes thermoelectric production (fossil fuels) and accounts for the resource use due to the infrastructure network of electric production and distribution.

In Table 8, results from EE are shown. Values represent the emergy inflows to the building during a year.

Based on the thermal efficiency of air-conditioning equipment (especially considering that electric cooling systems have a lower efficiency than heating systems and also that the global warming makes temperatures progressively increase in Europe) results from EA highlighted the critical problem of energy demand during the warm season (this is important thinking, for example, that an over-consumption of electricity, on September the 28th 2003, caused a blackout in the all Italian country).

EE also assigns a higher UEV to electricity than natural gas, thus results from EE stress outcomes and show that in Berlin, the emergy inflow is 44% in winter and 56% in summer (according to EE, even in northern Europe summer is more relevant than winter). In Barcelona it is 6% and 94%, respectively. In Palermo it is 1% and 99%.

Results from EE show that the annual energy consumption, relative to building envelopes, if expressed in terms of environmental resource appropriation (according to the theory of emergy), is lower in Berlin and higher in Barcelona (about 54% more than Berlin) and in Palermo (about 168% more than Berlin). Emergy takes

Table 7
Energy Analysis: calculation of energy use corresponding to the energy dissipation per month through three building envelopes (1000 m^2 wall) in Berlin, Barcelona and Palermo – unit: MJ

Energy	Berlin			Barcelona			Palermo		
	Air-cav. (MJ)	Plus-ins. (MJ)	Ventilated (MJ)	Air-cav. (MJ)	Plus-ins. (MJ)	Ventilated (MJ)	Air-cav. (MJ)	Plus-ins. (MJ)	Ventilated (MJ)
Jan	24,166	13,421	12,693	6178	3431	3245	1723	957	905
Feb	13,844	7688	7271	2009	1116	1055	657	365	345
Mar	8447	4691	4437	325	181	171	0	0	0
Apr	1661	922	872	0	0	0	3551	1972	1605
May	312	173	164	3258	1809	1481	17,401	9664	7980
Jun	6098	3387	2853	13,857	7695	6625	25,792	14,324	11,376
Jul	17965	9977	8449	25,238	14,016	11,736	29,761	16,528	13,522
Aug	1419	788	611	13,107	7279	6135	32,261	17,916	14,409
Sep	1504	835	666	9027	5013	4152	8488	4714	3715
Oct	999	555	525	5670	3149	2605	8450	4693	3763
Nov	3283	1823	1725	0	0	0	2684	1490	1165
Dec	12,359	6864	6491	4303	2390	2260	0	0	0
Winter	65,072	36,138	34,177	12815	7117	6731	2380	1322	1250
Summer	26,987	14,987	12,579	70,157	38,962	32,733	128,388	71,300	57,534
Total	**92,059**	**51,125**	**46,756**	**82,972**	**46,078**	**39,464**	**130,768**	**72,622**	**58,784**

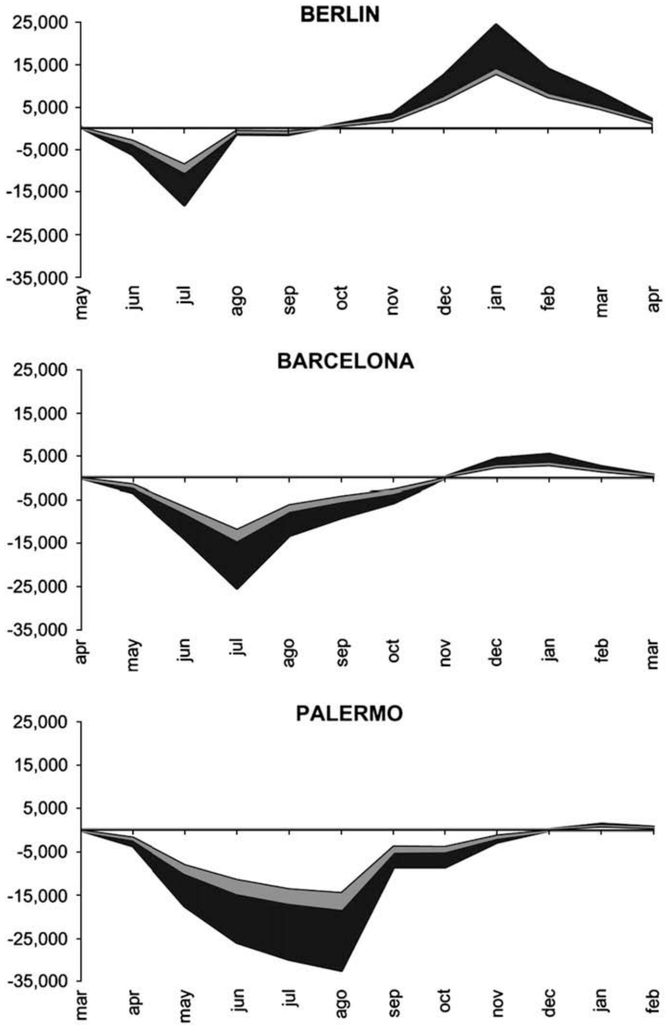

Fig. 2. Energy dissipation (MJ) through a traditional air-cavity wall (white + grey + black area) during a year and energy saving due to a plus-insulated wall (black area) and a ventilated wall (black + grey area), in three locations.

into account energy and material inflows and the work of nature to make these available.

5. Discussion: energy and emergy based cost–benefits' evaluation

Here, the energy–emergy cost for manufacturing building envelopes and the energy–emergy benefits, in terms of energy saving, were compared to each other. In Table 9, outcomes were presented in terms of energy–emergy payback time, that is the time interval needed to recover the initial higher investment of a plus-insulated and ventilated wall with respect to a traditional air-cavity wall. How much time does it take to recover the higher energy-emergy investment through energy saving?

A plus-insulated wall and a ventilated wall have a higher cost than a traditional air-cavity wall. In terms of energy investment, this difference corresponds to about 224,000 and 225,000 MJ, respectively. In terms of emergy, this is 5.27×10^{16} and 1.43×10^{17} sej. Benefits due to enhanced performance are variable, depending on external climate conditions.

Results from EA show that both a plus-insulated and a ventilated wall have higher performances in Berlin and Palermo, with extreme climate conditions, than in Barcelona, with a temperate clime. According to this accounting method, any improvement to the thermal efficiency to building envelopes is more efficient in cold and warm locations (such as Berlin and Palermo) than in Barcelona, with a temperate weather.

EE stretched results from EA considering that, in terms of emergy, enhanced envelopes play a relevant role in places with temperate and warm climate (such as Barcelona and Palermo). Since EE quantifies direct and indirect environmental resource use (including energy and raw materials) and assigns a higher UEV to electricity than natural gas, outcomes show that good environmental effects of building envelopes can be easier achieved in Barcelona and Palermo with respect to Berlin.

This highlights the importance of improving passive technologies for energy saving through building envelopes in southern European countries (even reloading traditional low-tech architecture and materials that seem to be forgotten), where building technologies have not been developed enough in recent years (these technologies have been mostly developed and used in northern European countries with good results).

Payback time relative to energy and emergy values were also assessed in order to provide a synthetic information about the use of a plus-insulated and a ventilated wall. According to EA, since the energy investment for a plus-insulated and a ventilated wall is almost the same, both the cases have a good efficiency in terms of energy. The initial energy investment is replaced in 5–6 years if located in Berlin and Barcelona, while energy payback time is about 3–4 years in Palermo.

EE assigned high UEV to building materials and, in this optic, payback time are longer, from a maximum of 29 years to a minimum of 4 years. In terms of emergy, the initial investment of a plus-insulated wall with a cork insulation is replaced in less than 12 years in Berlin, less than 8 years in Barcelona, and about 4 years in Palermo. The evaluation of the investment for manufacturing a ventilated wall has different outcomes. Emergy payback time was estimated of about 28 years in Berlin, less than 18 years in Barcelona, and less than 10 years in Palermo. Due to the use of lateritious and aluminium in ventilated walls, according to EE, a plus-insulated wall has lower environmental impacts, in terms of resource appropriation, than a ventilated wall. This highlights the importance of developing renewable environmental-free materials and material recycling for building manufacturing instead of non-renewable. However, it is also important to consider that building lifetime should be longer as possible and materials (even non-renewable) and technologies should be projected in order to be

Table 8

Emergy Evaluation: calculation of emergy use in terms of natural gas in warm months and electricity in cold months corresponding to the energy dissipation through three building envelopes (1000 m^2 wall) in Berlin, Barcelona and Palermo – unit: sej

Emergy	Berlin			Barcelona			Palermo		
	Air-cav. sej × 10^{12}	Plus-ins. sej × 10^{12}	Ventilated sej × 10^{12}	Air-cav. sej × 10^{12}	Plus-ins. sej × 10^{12}	Ventilated sej × 10^{12}	Air-cav. sej × 10^{12}	Plus-ins. sej × 10^{12}	Ventilated sej × 10^{12}
Winter	4373	2428	2297	861	478	452	160	89	84
Summer	5586	3102	2604	14,523	8065	6776	26,576	14,759	11,910
Total	**9959**	**5531**	**4900**	**15,384**	**8543**	**7228**	**26,736**	**14,848**	**11,994**

Table 9
Emergy benefits of a plus-insulated and a ventilated wall relative to a traditional air-cavity wall: energy and emergy based payback time to recover the initial investment

		Unit	Plus-insulated	Ventilated
Energy investment		MJ	223,976	225,221
Emergy investment		sej	$52,659 \times 10^{12}$	$142,836 \times 10^{12}$
Berlin				
Energy saving		MJ/yr	40,934	45,303
	Energy payback time		5 y 6 m	5 y
Emergy saving		sej/yr	4428×10^{12}	5059×10^{12}
	Emergy payback time		11 y 11 m	28 y 3 m
Barcelona				
Energy saving		MJ/yr	36,894	43,508
	Energy payback time		6 y 1 m	5 y 2 m
Emergy saving		sej/yr	6840×10^{12}	8156×10^{12}
	Emergy payback time		7 y 8 m	17 y 6 m
Palermo				
Energy saving		MJ/yr	58,146	71,984
	Energy payback time		3 y 10 m	3 y 2 m
Emergy saving		sej/yr	$11,888 \times 10^{12}$	$14,743 \times 10^{12}$
	Emergy payback time		4 y 5 m	9 y 8 m

used in the long run and recycled. In this perspective, there is a high convenience in building ventilated walls especially places of southern Europe, such as Palermo.

6. Conclusion

Building envelopes have different energetic performances relative to technology and general climate conditions. An Energy Analysis (EA) and an Emergy Evaluation (EE) were performed in order to assess environmental costs and benefits of building envelopes. Results were provided for three scenarios corresponding to three geographical locations: Berlin (cold), Barcelona (temperate), and Palermo (warm). The environmental cost for manufacturing building envelopes and benefits due to energy saving were compared. In particular, a plus-insulated wall and a ventilated wall were compared to a traditional air-cavity wall in order to evaluate their costs and their performances. Time for recovering the initial higher investment in order to have net benefits was then calculated as a synthetic outcome.

Plus-insulated and ventilated walls have a higher manufacturing cost than a traditional air-cavity wall because they need more energy and materials. This difference was assessed through EA in terms of embodied energy and correspond to a 34% and 35% added energy investment, respectively. Through an EE, the additional use of environmental resources (both energy and materials) was 9% and 15% more than a traditional wall.

The energy dissipation during the building lifetime was assessed through a Thermal Analysis (TA) by considering heat transfer through the wall. This is mostly due to conduction. The passive ventilation inside the external air-cavity of a ventilated wall (in months with a mean temperature of more than 21 °C) was also taken into account, and was found to have a positive effect relative to the intensity of solar irradiation. Moreover, when ventilation is avoided, the external air-cavity, behind brick panels, works like a wool covering and enhances thermal resistance. Therefore, according to TA, plus-insulated and ventilated walls have a higher thermal efficiency than a traditional air-cavity wall corresponding to an improvement of about 44% and 54%, respectively. Results based on daily values were dynamically assessed and their evolution through the 12 months of the year was presented in tables and diagrams.

Through EA and EE, environmental benefits due to the energy saving in both the cases of a plus-insulated and ventilated wall were assessed. In the case of EA, results showed that enhanced envelopes for energy saving, such as a plus-insulated wall and a ventilated wall, can achieve better results in locations with extreme weather conditions such as Berlin and Palermo. EE stressed these results and assigned a more relevant role, in terms of environmental resource use, to regions with warm weather, such as Palermo, and with temperate weather, such as Barcelona. This is especially due to the fact that procedures for cooling generally have a higher environmental impact than heating, since the electric equipment of air-conditioning has a lower thermal efficiency and the unit emergy value of electricity is higher than natural gas, considering that the European electric production mainly depends on fossil fuels (thermoelectricity is about 80%). This highlights the need of developing new technologies for building envelopes that respond much more to specific climate conditions, especially in the south where these technologies have not yet developed and have been scarcely applied. This is true especially considering the environmental problem of greenhouse gas emissions and the risk of electric blackouts for over-consumption during summer (mainly due to air-conditioning), while proposals for assembling new thermoelectric power stations for satisfying the increased demand should be avoided.

Ventilated walls have a high environmental efficiency in the southern region of Palermo. A plus-insulated wall also has good environmental performances, especially considering that the external covering is made of cork. Natural materials, such as cork, represent an emergy input as well as other building materials, such as polystyrene, but their use should be considered to have a lower impact in terms of resource exploitation, if their production is renewable and well managed.

However, building envelopes should be designed for enhancing energetic performances relative to local climate conditions, and a careful research on building envelopes should be developed and applied in southern regions of Europe. This is also in accordance with the ideal of an architecture able to mirror local identities, relative to geographical location, including culture, landscape and climate.

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Appendix 1. Calculation of the effective external temperature

In the following Table 10, mean daily values of the recorded temperature, relative humidity, atmospheric pressure and solar irradiation (daily amount of solar energy on a vertical wall facing south) in Berlin (cold), Barcelona (temperate) and Palermo (warm) were presented with a final estimation of the effective external temperature.

The difference between indoor and outdoor temperature ΔT was assessed considering that

$$\Delta T = T_e - T_i \tag{6}$$

where T_i is the indoor temperature, assumed to be always constant at 18 °C, and T_e is the variable outdoor temperature. In particular, the latter was calculated based on mean daily values of recorded temperature (T), relative humidity (H_{rel}), atmospheric pressure (P_{atm}) and solar irradiation (SI).

We calculated the effective external temperature T_e as in the following equation:

Table 10
Recorded temperature, relative humidity, atmospheric pressure and solar irradiation (on a vertical wall facing south) in Berlin, Barcelona and Palermo with estimated values of effective external temperature

	Berlin					Barcelona					Palermo				
	T (°C)	H_{rel}	P_{atm} (hPa)	Solar irr. south (kWh/m^2)	T_e (°C)	T (°C)	H_{rel}	P_{atm} (hPa)	Solar irr. south (kWh/m^2)	T_e (°C)	T (°C)	H_{rel}	P_{atm} (hPa)	Solar irr. south (kWh/m^2)	T_e (°C)
Jan	−6.2	86	1026	1.40	**−5.1**	7.6	76	1018	2.95	**9.6**	11.6	76	1016	3.46	**13.9**
Feb	0.3	82	1010	2.02	**1.7**	10.575	73	1013	3.26	**12.7**	13.225	75	1016	3.91	**15.7**
Mar	6.15	78	1014	2.47	**7.9**	14.225	74	1013	3.11	**16.4**	16	73	1013	3.90	**18.5**
Apr	11.9	73	1012	2.85	**13.9**	17.3	72	1015	2.78	**19.5**	20.2	74	1011	3.42	**22.8**
May	14.5	65	1010	2.86	**16.5**	20.0	73	1018	2.52	**22.3**	25.0	76	1013	2.95	**27.8**
June	21.9	69	1019	2.63	**24.2**	24.9	72	1016	2.47	**27.4**	28.3	73	1016	2.76	**31.1**
July	25.6	68	1018	2.75	**28.1**	27.7	71	1016	2.68	**30.4**	28.1	74	1014	2.94	**31.0**
Aug	18.6	68	1011	2.90	**20.8**	24.0	73	1014	2.80	**26.6**	28.9	76	1014	3.48	**32.1**
Sept	18.7	78	1015	2.60	**21.1**	22.7	74	1013	3.10	**25.3**	22.0	75	1011	3.93	**24.9**
Oct	12.9	83	1009	2.10	**14.8**	21.0	76	1015	3.24	**23.6**	21.7	77	1017	4.03	**24.7**
Nov	9.9	88	1017	1.40	**11.5**	16.2	71	1018	3.03	**18.4**	19.1	71	1016	3.48	**21.6**
Dec	3.6	87	1029	1.17	**4.9**	9.2	73	1029	2.88	**11.1**	15.4	73	1027	3.09	**17.7**

$$T_e = T + 2.52 \times H_{abs} + \frac{\alpha_w \times SI}{\alpha_e} \quad (7)$$

where H_{abs} is the absolute humidity, α_w is a coefficient of absorption of white and bright colours corresponding to 0.2, α_w is the coefficient of external convective resistance corresponding to 25 W/m^{2}K, and SI is the mean daily solar power given in W/m^2. Absolute humidity H_{abs} was assessed (if more than 273 K) as follows:

$$H_{abs} = 0.622\left(\frac{H_{rel} \times p_{vs}}{p_{atm}}\right) \quad (8)$$

where H_{rel} is the relative humidity (quantity of water relative to the maximum quantity per air volume), p_{vs} is pressure of saturated vapour and p_{atm} is the atmospheric pressure. Furthermore

$$\frac{p_{vs}}{p_{atm}} = \frac{1}{H_s} \quad (9)$$

where H_s is the Specific Humidity and pressure of saturated vapour corresponds to $P_{vs} = 6.1\,e^{0.037T_e}$.

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