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Quantifying Thermal Bridge Effects and Assessing Retrofit Solutions in a Greek Residential Building

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Abstract

Material and component performances are blunt instruments for appraising the thermal performance of structures. A certain amount of consumed energy is attributable to the interaction of building fabric components, where thermal bridges occur. This paper analyses the thermal bridging effect and provides a number of modelled, cost-effective retrofit approaches in Greek single family houses, in order to address thermal bridges and improve the building's energy performance. The impact of thermal bridging on the overall annual heating load was estimated at 13%. The investigated retrofit solutions achieved a decrease of the annual heating energy requirement of 4-10%. The sunspace achieved the highest energy reduction of 10%, offering 'free' solar heating at a reasonable payback period.

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Keywords: Thermal bridges; Heat loss; Building thermal simulation; TRNSYS; THERM; Retrofit.; Cost-Benefit Analysis.

1. Introduction

The 1970s energy crises forced the building community to investigate and implement strategies to minimise the buildings' energy losses. At a national level, European countries established legislative actions to face the explosion in oil prices by decreasing the energy demand of buildings. However, thermal bridging effect was never broadly considered until 1995 when the European ISO 10211-1:1995[1] provided an acceptable way of calculating the heat flows through the building fabric due to thermal bridging and setting surface temperature limitations[1].

Thermal bridges or coldbridges are described in different studies as localised areas of the building fabric, with significantly lower thermal insulation protection, where the thermal barrier of the building envelope is interrupted

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and substantial heat flows occur[2,3].

Thermal bridging effects are created where two materials with noticeably different thermal conductivity are used in combination on the building fabric and when there are discontinuities in the uniform thermal insulation layer (due to structural or geometrical requirements or defects)[4]. Thermal bridges can be classified into two types: the linear and point ones[2]. Linear bridges have a uniform cross-section along one dimension. They are characterized by a linear thermal transmittance (ψ-value or psi value W/m*K) and are always calculated as they significantly affect the thermal performance of the envelope[2]. The linear transmittance or the ψ-value expresses the effect of all the linear thermal bridges of a building envelope.

Table 1 summarises results from studies that investigated the contribution of thermal bridges to the total building heat losses in different locations and climates. Around 1984, in Washington DC, Fang *et al.* studied the impact of thermal bridges on the energy demand of three office buildings using in situ thermography and laboratory based estimations and found that could account for up to 21% of the building's heat losses[3]. In Germany, a study for two family houses, with insulated bricks, triple, low emissivity glazing and insulation on the roof and slabs, revealed that approximately 11 kWh/m^2 per year could be saved[5].

Lahmidi & Leguillon also concur that 15% is the primary energy reduction for a concrete family house in Paris when using thermal breaks and insulation on floor and ceiling[6]. In a case study building in Northern France (Trappes) Gao *et al.* investigated the contribution of thermal bridges (up to14% of the total heat losses) for a single zone building by using a simplified model in TRNSYS[7].

In Czech Republic, a study for an existing 70's brick residential building with wooden windows indicates that the relative influence of thermal bridges on the total heat loss balance is 7%, while this could reach 17% when an insulation layer is added[8]. On the other hand, a Polish research calculated the thermal bridge contribution on the energy consumption of a typical two storey house at only 6%(All cited in[9]). Two cases with different levels of thermal bridging correction for a terraced and a semi-detached house were examined in an Italian study and calculated 25% and 18% reduction of the primary energy for the terraced and semi-detached house respectively[2].

Table 1. The thermal bridges relative influence on the total heat losses of various building types. Literature review summarized.

Source	Building type	Location	Climate*	Th. br. as % of heat losses	Method**
3	Office	Washington	Cfb	21%	Tr.
5	Family houses 'high thermal performance'	Germany	Cfb	15%	M
6	Family house	Paris	Cfb	15%	M
7	Single zone building	Trappes, France	Cfb	14%	Tr.
8	70's residential house, uninsulated	Czech Republic	Cfb	7%	SS
8	70's residential house, insulated	Czech Republic	Cfb	15%	SS
9	Two storey house	Poland	Cfb	6%	SS
2	Terraced house	Italy	Csa	25% (winter)	Tr./SS
2	Semi-detached house	Italy	Csa	18% (winter)	Tr./SS
10	Detached, 2-storey house	Greece	Csa	16% (winter)	Tr.

*Climate C:Temperate ($-3<T_{min}<18$), f: fully humid, b: Warm summer (T<22= and T>10 at least 4 months), s: Dry summer, a: Hot summer ($T_{max}>22$) Climate data taken from [11]. **Method: Tr.=Transient simulation; SS=Steady state calculation; M=Measured.

In Greece, 40% of the residential building stock was constructed between 1980 and 2010, during the validity period of the Regulation of Thermal Insulation[12]. However, the majority of them do not comply with the regulation[12]. An insulating layer on the load bearing parts has been introduced only in the last few years of the 30 year timescale[12]. The double wall construction which includes an insulation layer was and continues to be a common practice. Familiar features of the residential buildings in the Mediterranean region, such as cantilevers, overhangs, semi-open spaces, ground floor open parking spaces (pilotis) and flat roofs, mostly address the climatic and social need for immediate access to the outdoors. Typically partially insulated, they are responsible for substantial unwanted thermal flows[10,13]. In the 'Mediterranean research area', Theodosiou and Papadopoulos investigated the effect of thermal bridges for a multi-family building in Thessaloniki, Northern Greece, for 4 characteristic insulation configuration scenarios, using TRNSYS and energy data typical for the region and found it to be 16% of the heating demand[10].

The aim of the present paper is to investigate the impact of thermal bridges on the energy performance of a typical Mediterranean single family house in Thessaloniki, Greece, and explore cost effective solutions to improve the building's energy performance and address the thermal bridge effects.

2. Case study building

The selected case study building is a typical, semi-detached, three-storey, single family house with parking spaces on the ground floor and a flat roof, located in Thessaloniki, in a Northern part of Greece. The climate of Thessaloniki, according to Köppen - Geinger is classified as warm temperate with dry and hot summers (Csa)[11]. The city has similar climate with other Mediterranean cities located on the Western and South coasts of Italy, the South coast of France and Eastern Spain (Catalonia).

The structure consists of an uninsulated, in-situ cast, load baring reinforced concrete frame with brick masonry cavity infill (two layers of hollow clay bricks with glass fibre insulation in the middle). There is one apartment on each of the two living floors with a similar layout and a floor area of 92 m^2 each; however the third floor has an additional South facing balcony and a protecting overhang (Fig. 1). Semi-open spaces present on the South façade are a common characteristic of residential buildings in the area.

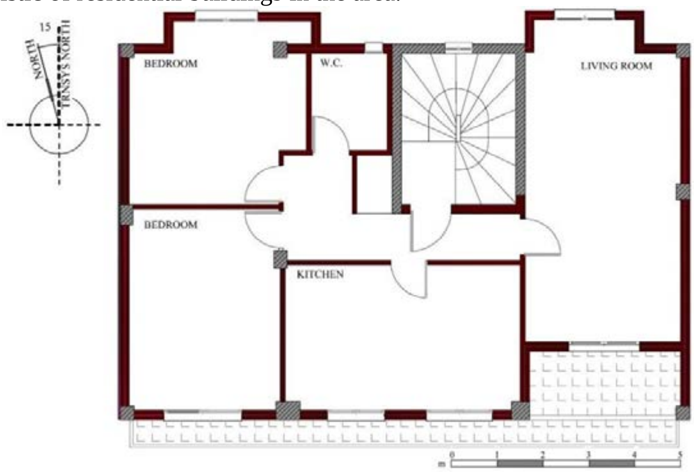

Fig. 1. Floor plan of the case study building Brick masonry walls are indicated in red and load baring frame in grey.

The building is heated by a central oil-fired boiler with a typical efficiency of 85% with hydronic radiators, according to the national building typology[13]. The cooling system is comprised of air-to-air heat pumps with an average performance coefficient of 2.7, typical for the regional climate[10,14].

The electricity tariff, obtained from [15] and is £0.14/kWh (0.18€/kWh)[16]. An average fuel price of £0.80/lt (1.01€/lt) is based on data published weekly for the second half of 2014 by the Hellenic ministry of Development[17].

2.1. Building envelope thermal properties

The properties of the materials, specifically the thermal conductivities, density and specific capacity, were acquired from CIBSE Guide A[18], while BS ISO 10077-1 was used to estimate the U values of the windows according to their materials and geometry[19]. The Table 2 below summarises the results of the thermal transmittance calculation for each section.

Table 2. U-value for each section illustrated, including sheltered,(already) refurbished sections by the users and proposed renovated sections.

	U W/(m^2*K)
Reinforced concrete in touch with air /sheltered (East)/previously refurbished (West) /renovated	2.452 /3.146 /0.851 /0.311
External wall in touch with air /sheltered (East)/previously refurbished (West) /renovated	0.522 /0.548 /0.370 /0.311
Sheltered floor (over unheated space)	1.936
Flat roof initially /previously refurbished	1.729 / 0.311
Windows (average used)	2.83

3. Methodology

3.1. Thermal bridge calculation

The European ISO 10211 presents the methodology to calculate heat losses through thermal bridges[20]. The linear thermal transmittance of thermal bridges, ψ (W/(m*K)), is prerequisite for this, and several calculation options exist. First, numerical calculations (±5% accuracy) and second thermal bridge atlases which have been created using finite element software and (±20% accuracy)[2,21].

The validation of cold bridges was carried out by using two-dimensional models to represent those points identified in the building. Each of the details was designed and introduced into THERM 7.3 and the layers were set to be same as the existing construction materials. The output of the calculation in THERM is the Ufactor (W/m^2*K) which is the thermal transmittance of the model with the thermal bridges. The thermal coupling coefficient L_{2D} of a junction that contains a linear thermal bridge is the heat flow rate from the internal to the external environment expressed in W/m*K and it is calculated by multiplying the Ufactor by the length of the junction. The linear thermal transmittance (ψ value) of the thermal bridge is the remaining heat flow from the hottest to the coldest side of a thermal bridge element calculated by subtracting the one-dimensional heat flow through the flanking elements from the thermal coupling coefficient, L_{2D} (W/m*K)[22–26]. Certain conventions and simplifications were undertaken to model the junctions were windows exist, according to [19,22].

3.2. Dynamic simulation

A simplified model of the house has been used and the thermal bridges (THERM processed results) have been simulated in TRNSYS[27] as equivalent building elements that have the same properties, albeit assumed that they perform an one-dimensional heat flow[7].

In the simulation, the two heated floors of the case study building were modelled as a simplified single zone, because heating and cooling operate at the same temperature set point. The house's axis (x axis), perpendicular to the main façade, is rotated 15° clockwise from true North. This has been included in the TRNSYS model. The simplified model of the house formed a rectangular plan of 12.50 m x 13.15 m (without internal partitions) with a total height of 6.10 m.

With regards to thermal bridging, there is a gap of knowledge on how to simulate these three-dimensional heat transfer envelope components. Gao *et al.* developed a TRNSYS low order model to balance the difference between those simplifications and the three-dimensional real heat transfer through thermal bridges[7]. Carpenter proposed the equivalent wall method for thermal bridging instead of a three-dimensional modelling and noted a perfect correlation between the two models[28]The calculated thermal bridges were distributed to each orientation and then equivalent brick walls similar with the existing ones were created (same area but different thermal performance). Thus, instead of a calculated U value (W/m^2*K) of a wall, an equivalent U' value (W/m^2*K) was used. The U' value assignment was undertaken by equally decreasing the thickness of each of the brick wall layers. The linear thermal bridges heat losses of other elements were all included here. Thus, the advantageous high thermal mass of the reinforced concrete which is found at columns, beams and slabs is retained. Hence, by following the methodology described above; the 'Current' (House 1) model is created, which has the thermal transmittances depicted on Table 3 below. By applying all the initial U values calculated House 2 ('Coldbridge_free') model derived.

Table 3. Thermal transmittance of building elements that were set for ‘Current’ (House 1) and ‘Coldbridge_free’ (House 2) TRNSYS models (both inputs are same for House 1, 2 unless differently stated)

		(W/m^2K)	South	West	North	East	Floor	Roof
Opaque	Reinforced concrete	$U_{rf.}$	3.15	0.85	3.15	2.45	1.94	0.31
	Brick wall	$U'_{brick\ wall}$ (House 1)	1.97	0.82	1.33	1.09	-	-
	Brick wall	$U_{w\ brick\ wall}$ (House 2)	0.55	0.37	0.55	0.52	-	-
Transparent	windows	$U_{open.}$	2.83	-	2.83	-	-	-

The set point of the heating system equals to 15°C all day long during the heating season (October to April). During weekdays, the heating set point increases to 23°C from 6:00-8:00 in the morning and from 18:00-22:00 in the afternoon. For weekends, heating is set to 23°C from 10:00 to 22:00.

The set point temperature for the operation of the A/C system was equal to 23°C when the ambient temperature is higher than 27°C and from 14:00 to 21:00, while natural ventilation is applied during nights, from June to August. The application period of night ventilation was from 22:00 to 6:00, while the cooling is off during unoccupancy (during the midday until 14:00).

4. Proposed solutions

Four (4) retrofit solutions were examined and classified from a less intervening, inexpensive fabric upgrade, up to geometrical, invasive interventions, such as balcony demolition or sunspace inclusion.

In the first retrofit solution called ‘House 3: ThB_insulation’, detailed care is being applied to balconies and around window edges. Thus, the upper and lower corner of the protruding balcony slab with the wall are both being insulated at the distance of 0.45 x 0.45 (m x m) (Fig. 2 (a)). The specific application distance would also cover the uninsulated vertical concrete beams and decrease the heat flow through them. The selected insulating material is 5 cm of extruded polystyrene (XPS) with a thermal resistance of λ=0.027 W/(m*K)[18].

The second intervention named ‘House 4: Ext_insulation’ involves the insulation of the North façade (Fig. 2 (b)). The external insulation is common practice in Greece in recent years, especially after the implementation of EPBD. The case study house has already been retrofitted by adding external insulation on the West façade, thus the same practice is now applied on the North façade and the same materials are being used.

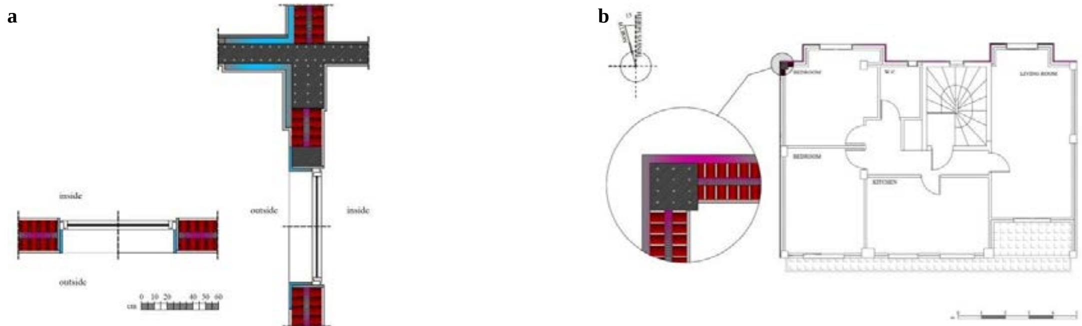

Fig. 2. (a) Balcony and window edge intervention, jambs on the left balcony and lintel insulation on the right; (b) North façade intervention, close view of the corner intercept with the previously refurbished West façade

For the ‘House 5: Demolition’ model, the South façade of House 1 (‘Current’) is externally insulated and the balcony is being demolished (Fig. 3 (a)). This geometrically intervening solution ‘ideally’ rejects a great percentage of thermal bridging and offset balcony coldbridge; an extreme type of thermal by-pass for a vast number of Mediterranean constructions.

The proposal of ‘House 6: Sunspace’ includes the introduction of South solar greenhouses, in touch with the conditioned internal area and enclosing both the semi-open space on the 2nd floor and the balcony (which is attached to the 3rd floor and includes a semi-open space) (Fig. 3 (b)). The glazing promotes the solar gains, while overheating protection is achieved by setting openable glazing to keep the natural ventilation during summer period.

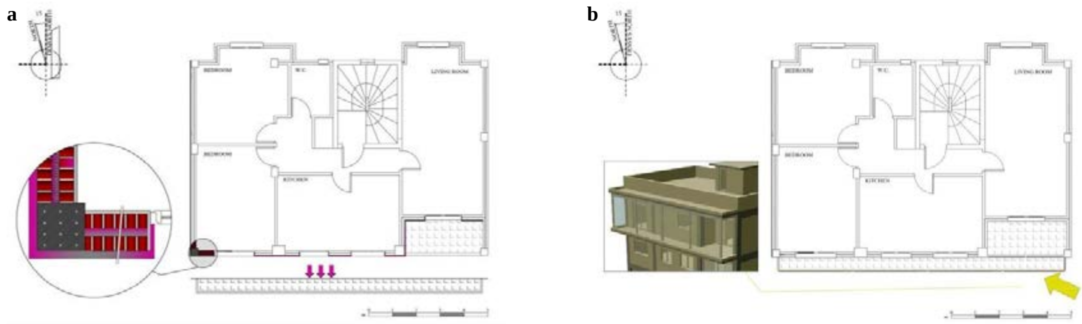

Fig. 3. (a) The South façade intervention, showing the dismissed balcony part and a close view of the corner intercept with the previously refurbished West façade; (b) Illustration of the proposed solution on the 3rd floor

The economic feasibility analysis was undertaken by using the global cost calculation method. For this study, an average inflation i=2%, and nominal interest rate D=4% for the construction sector was taken. The annual energy bill earnings will be scaled to a real discount rate of d= 2%. All the prices are today's prices and 1 euro (€) equals to £0.791 (average 2014 currencies). The expenditures for the renovation solutions were collected by manufacture companies and include materials; labour, machinery, costs for scaffold and supplementary costs.

5. Results and discussion

Overall almost one fifth of the total fabric heat losses are attributed to thermal bridges, while their contribution on the final heating reaches 13%. Minimising thermal bridges represents an almost 12% decrease in the annual energy bills. The annual heating and cooling requirement of each of the simulated models (House 1-6) are presented in Fig. 4 (a). The heating load could potentially drop by 13% when a notional model without thermal bridges is considered (House 2) (163 kWh/m^2 to 142 kWh/m^2). Among the 4 proposed solutions the 'Sunspace' (House 6) has the lowest annual heating demand by addressing thermal bridging. On the contrary, the North wall includes corners and a bigger brick wall area compared with the South façade which, as presented in Fig. 4 (b), leads to higher average U-value for the 'Ext_insulation' model (House 4) compared to the 'Demolition' (House 5), thus increased heat losses.

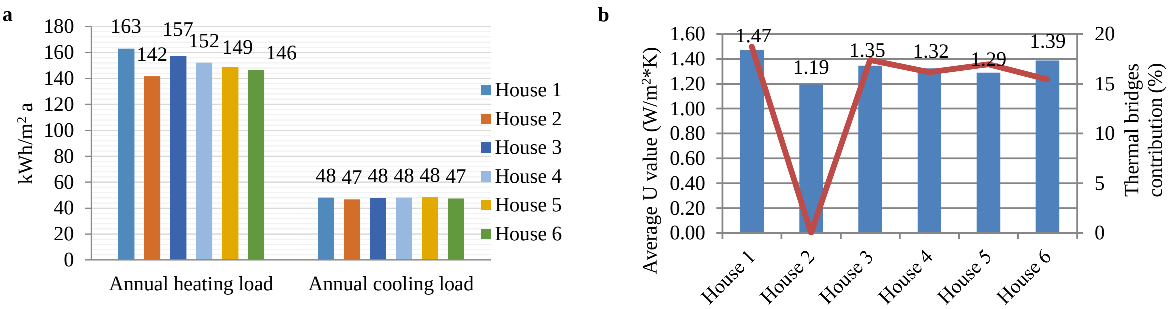

Fig. 4. (a) Annual heating and cooling loads for all the models (kWh/m^2 per annum); (b)Average U value (thermal bridges included) of the all the models (House 1-6) and percentage of thermal bridges on the total heat loss through the fabric elements. (House 1: Current, House 2: Coldbridge_free, House 3: ThB_insulation, House 4: Ext_insulation, House 5: Demolition, House 6: Sunspace)

The treatment of those 'black spots' on the buildings' fabric by suggesting retrofit proposals and introducing improved house models, resulted to a reduction of the annual energy expenses. These savings are presented in Fig. 5 (a) in comparison with the energy requirement of the final user (in kWh/m^2). At the extreme left in the graph, House 2 is positioned, illustrating the potential earnings that could be achieved; however it is a non-applicable (N.A.), unrealistic solution. The total investment costs and net energy earnings are illustrated below (Fig. 5), showing an ascending trend between House 3-6 with the 'Sunspace' (House 6) being the most expensive solution reaching £3,800 (approximately 4,800€), about 120% of an annual energy bill of the house (£3,200 (approximately 4,050€)).

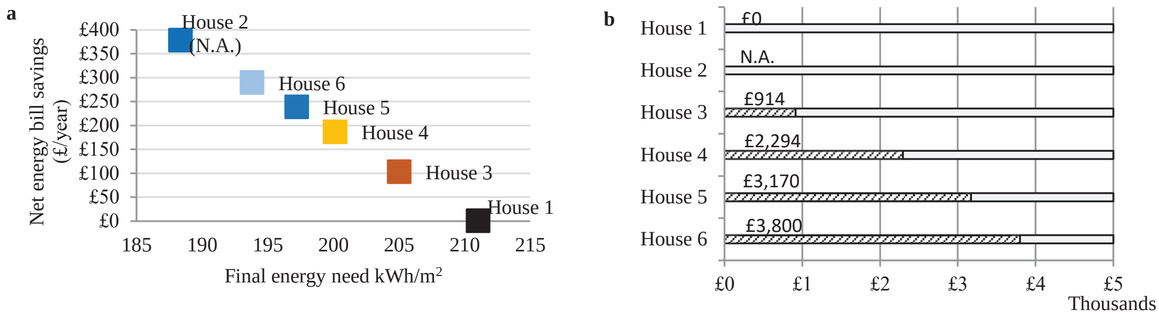

Fig. 5. (a) Net energy savings per year for each of the solutions; (b) Total cost of intervention for each of the solutions. (House 1: Current, House 2: Coldbridge_free non-applicable, House 3: ThB_insulation, House 4: Ext_insulation, House 5: Demolition, House 6: Sunspace)

The cumulative net present value on the first 20 years after the proposed renovations is presented in Fig. 6 (a), against the final energy per unit of heating floor area. The values for the current House 1 account only the annual energy bills for cooling electricity and heating oil. The prices were scaled to exclude the inflation. Houses 3-6 include the annualised depreciated costs for energy bills, the discounted earnings and the initial investment costs. The 'Sunspace' (House 6) is a sensible solution, combining the lowest possible cumulative cost balance and the smallest annual energy consumption among the solutions.

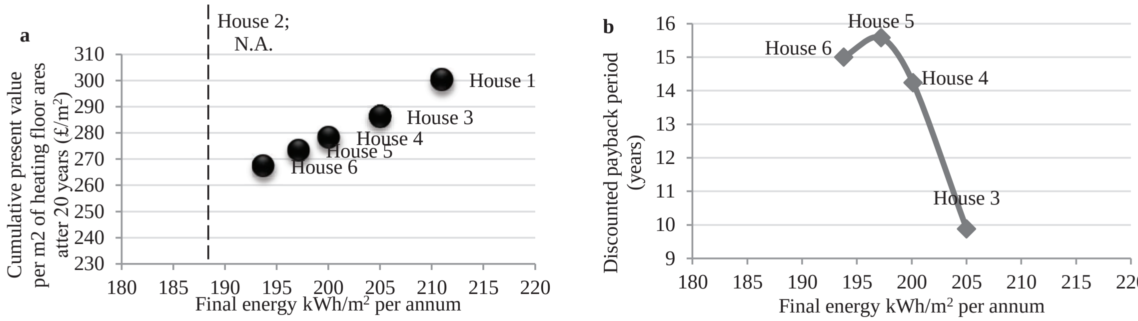

Fig. 6. (a) Cumulative present value of the overall investment and energy costs over a 20-year timeframe; (b) Discounted payback period (House 1: Current, House 2: Coldbridge_free, House 3:ThB_insulation, House 4:Ext_insulation, House 5: Demolition, House 6: Sunspace)

Papadopoulos *et al.*[29] propose that a building renovation investment needs to pay back of less than one third of the remaining lifetime of the structure. The case study here was built in 1980, thus a 15 year discounted payback period (DPP) would be acceptable for this study. The DDP of the solutions against the final energy load in kWh/m^2 are plotted on Fig. 6 (b). Overall, Houses 4-6 all have a payback period close to the acceptable 15-year timeframe.

6. Conclusion

In Greece, the on-going economic crisis has severely affected the construction sector and brought forward the need to improve the energy efficiency of the existing buildings. Based on this study, the impact of thermal bridging on the overall heating load of a single family building was estimated to be an annual average of 13%. However, their impact on the cooling load is negligible in Mediterranean regions. The investigated retrofit solutions achieved a decrease of the annual heating energy requirement of 4-10%. The sunspace constitutes an appealing solution, achieving the highest energy reduction of 10%, offering 'free' solar heating with a reasonable payback period.

Under the increasing awareness for climate change, energy security and growing unpredictable energy prices the importance of energy upgrades and conservation will grow albeit there is need for cost and feasibility evaluations. Therefore, there is need for further research on multiple case studies, assessment of the environmental impact of proposals and monitoring of users' satisfaction. Governmental initiatives to incentivise the incorporation of well validated results could inform new guidelines for prioritising solutions for energy conservation.

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