Assessing the Potential of Affordable Passivhaus Tenement Housing in Urban Glasgow

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ABSTRACT: There is a need to develop attractive alternatives to suburban living in order to cater for the increasing number of small households in cities. This paper examines the potential and suitability of tenement housing constructed to the Passivhaus Standard from pre-fabricated cross-laminated timber. There is a lack of in-depth understanding of the performance of both massive timber and the Passivhaus Standard in the context of Glasgow. The present work tested the affordability, construction feasibility and environmental performance of a hypothetical Passivhaus Tenement prototype in the context of local climatic, economic and legislative conditions. The prototype is based on the Scottish Building Standards and the Passivhaus Institute guidelines. The Passive House Planning Package (PHPP) and the Standard Assessment Procedure (SAP) were used to test Passivhaus compliance in a number of urban configurations and to compare the prototype's energy demands to the following options with identical external dimensions: 1) original tenement, 2) refurbished tenement 3) Scottish Building Standards compliant tenement. The challenges and possibilities of upgrading existing tenements to the Passivhaus standard were assessed. An insight is provided into the potential for adopting the Passivhaus Tenement as an affordable housing model.
Keywords: Passivhaus, affordable, tenement, timber, Glasgow

INTRODUCTION

A close-knit pattern of vertical flatted tenements has been a common feature of Scottish urban life for centuries [22]. Unique ownership laws have enabled the tenement to flourish as housing for various socio-economic groups. The tenement is a 3-4 storey block with a variety of one- and two-room flats at each landing (Fig.1). Tenement streets have a high dwelling/acre ratio and form lively communities. Areas of Glasgow that are in particular need of affordable housing feature traditional tenements [18, 14]. The city's Development Plan acknowledges the benefits of densification [12], and the proportion of small households in the city is projected to increase. Studies show that energy efficiency decreases with the decrease in household size [7]. This work proposes and tests a Passivhaus Tenement prototype as a possible solution to fill the gaps in existing neighbourhoods that lack sustainable density. It would use cross-laminated timber (CLT) construction that could be produced locally. There is also a need to upgrade energy performance in existing tenements and such a scenario was also tested.

The main driving force for sustainability in Scottish housing is the Sullivan Report, which recommended energy improvements on 2007 standards: (1) 30% by 2010; 60% by 2013; Net zero carbon by 2016; and total life zero carbon domestic standard by 2030 [25]. Section 7 of the Building Standards encourages sustainability by rewarding improvements over standard performance as well as the use of low and zero carbon generating technology [26].

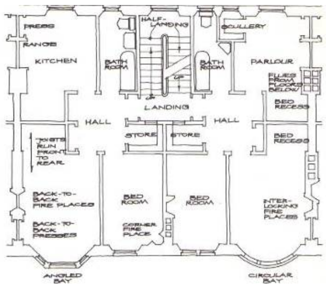

Figure 1: Plan of a typical tenement [11]

The EcoHomes Standard is currently applied to large-scale residential developments in Scotland [12]. A new strategy is currently being developed to tackle energy efficiency in both new and existing housing in Scotland. A 'Zero Carbon' home - compulsory from 2016, must also meet the Fabric Energy Efficiency Standard (FEES). FEES sets a limit for energy demand for space heating and cooling at 39kWh/m2/a for flats and terraced houses; and 46 kWh/m^2/a for detached and semi-detached houses [32]. A way to exceed these requirements and come close to meeting the 'Carbon Compliance' of the 'Zero Carbon' definition is to opt for the Passivhaus Standard (PH) [28]. A Passivhaus-certified building is required to achieve:

- Specific Heating Demand ≤ 15kWh/m^2/a
- (or) Specific Heating Load ≤ 10 W/m^2
- Specific Cooling Demand ≤ 15 kWh/m^2/a
- Specific Primary Energy Demand ≤ 120 kWh/m^2/a
- Air tightness ≤ 0.6 ach @ 50pascals (n_{50})

A way to achieve this is to use the Passivhaus guideline targets for U-values; thermal bridging; and whole house mechanical ventilation with heat recovery (MVHR). The Passive House Planning Package (PHPP) software should be used to verify the predicted performance at all stages [8, 23]. Only upon final certification can a building claim the Passivhaus Standard. An Area to Surface (A/V) ratio of 0.7 or less is considered favourable for Passivhaus [19]. That of the existing tenement blocks is 0.38 and 0.49 if one considers the common close as external – giving a considerable advantage over single-family houses.

Adoption of the Passivhaus Standard in the UK has been slow, and there is lack of a developed market and suitable local products. The standard is not recognised as an alternative route to compliance with UK's Building Regulations, and it is up to the industry to transform the market. There is also lack of in-depth understanding of its performance in the context of the tenement typology. The present work tested the affordability, construction feasibility, and environmental performance of a hypothetical Passivhaus Tenement in the context of local climatic, economic, and legislative conditions.

THE PROPOSED PASSIVHAUS TENEMENT

Timber frame dominates housing construction in Scotland [10], but pre-fabricated kits are also available. Cross-laminated timber (CLT) is proposed for the Passivhaus Tenement. It comes in panels with softwood plank layers stacked on top of each other at right angles and glued together under pressure. CLT panels have good thermal properties (λ = 0.13 W/mK); and walls, floors and roofs can be pre-fabricated, reducing the whole-life costs and time on site [30]. Pre-fabrication makes thermal bridge-free and air-tight construction easier to achieve compared to conventional tenements. Based on 300m^3 of cross-laminated timber calculated for the proposed Passivhaus Tenement, it can potentially store 70 tonnes of locked-in carbon in its structure [17].

A notable precedent of the proposed Passivhaus Tenement is a certified scheme at Mühlweg Street, Austria [33]. It has 70 affordable flats within four cross-laminated timber 4-storey blocks – total 6,750 m^2 at 1,065 EUR/m^2. This cost was achieved largely through economies of scale and numerous subsidies from product manufacturers. The project uses a centralised mechanical ventilation system with heat recovery located in the attic, and the same is proposed for the Passivhaus Tenement prototype. The adoption of both Passivhaus and solid timber construction in UK has been slow. The only identified project that combines the two is an up-market development in London (Nash Terrace, 4orm architects, 2010).

ENERGY AND CO_2 PERFORMANCE OF THE PASSIVHAUS TENEMENT

To put the proposed prototype in context, four scenarios were modelled to assess their specific annual heating demand and their Dwelling CO_2 Emission Rate (DER): Original tenement (1), Refurbished tenement (2), Building Standards tenement from cross-laminated timber (CLT) (3), and Passivhaus Tenement (4). The modelling was done using two software packages - the 'Passive House Planning Package' (PHPP), and UK 'Government's Standard Assessment Procedure for Energy Rating of Dwellings' (SAP) [15]. SAP is a mandatory Building Standards compliance assessment tool for all new buildings. Version 'FSAP 2009' [27] was used to perform SAP calculations and to determine 'Ene 1' and 'Ene 2' Credits for the EcoHomes standard. Unlike PHPP, where the whole tenement was modelled, an area-weighted figure was obtained from separate flat simulations. It is worth noting that flats cannot achieve Passivhaus certification separately [9]. External dimensions (Fig.2) were kept constant leaving internal floor areas and ceiling heights to vary based on their construction. In PHPP, the exterior dimensions of the thermal envelope are always used and the treated floor area required in calculations excludes all walls [8]. In SAP, internal dimensions of walls are used and the floor area includes the footprint of partitions [15]. The common close of the tenement is not considered in SAP calculations. In PHPP simulation, it can only be omitted when it falls outside of the thermal envelope. The calculations for the proposed Passivhaus Tenement omitted the stairwell.

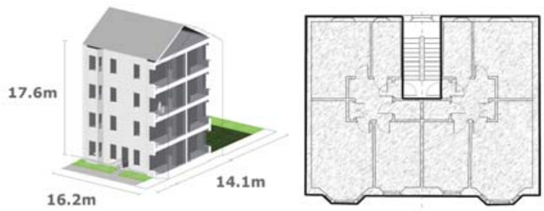

Figure 2: 3D View and floor plan of a typical tenement with the external dimensions of the envelope modelled in this study

The prototype was based on a typical pre-1919 stone walled tenement (Fig.1) with external wall thickness of 600mm [5] and the plan scaled up to conform. As the unheated common stairwell was omitted from the thermal envelope (Fig.2), the walls and doors facing the close were considered semi-external, with a corresponding reduction factor used in calculating their U-values [15]. Further adjustments were made to the overall floor and exterior wall areas to exclude the close before supplying the figures to both SAP and PHPP. Wall build-ups were modelled in 'Dynamic Thermal Property Calculator' [1] to provide specific kappa-values for input into SAP. Taken as a whole, the values were a little above the average thermal mass parameter. In PHPP, default values for 'high' (Scenarios 1, 2) and 'medium' (Scenarios 3, 4) were used. An allowance for thermal bridging in SAP was based on the total exposed surface area. In PHPP, lengths of geometric thermal bridges were kept constant, with the coefficient changing according to scenario.

To cover the worst-case scenario, a free-standing tenement was modelled, and in the SAP simulations 'heavy' overshadowing was selected. In PHPP a row of tenements was placed in front of all windows at the minimum allowed distance of 18m [13]. Since 60% of glazing in traditional tenements is located at the front, north-facing orientation was chosen for it. The best-case scenario was also modelled for comparison. Individual tenements were assumed to have gas boilers for space heating and a communal solar hot water system supplemented by individual gas boilers.

Scenarios 1, 2: Original and Refurbished Tenements
U-values for external walls were based on in-situ measurements, 1.1 W/m^2K [2]. The U-value for the close wall, 0.76 W/m^2K, is an average of the values by Baker [2], subjected to the reduction factor as described previously. U-values of the roof, floor and windows were taken as 1.6, 0.6 and 4.8 W/m^2K [5]. Due to the lack of data on the typical air-tightness of the original tenement, a value of 10 $m^3/h*m^2$ at 50 Pa was assumed. For Scenario 2, the original tenement was improved to take it closer to Package 1 of the Building Standards, without too much disturbance to the fabric. Windows were double-glazed and the air permeability was lowered to 7. Loft insulation helped to achieve 0.13 W/m^2K and the roof was fitted with 35m^2 of evacuated tube collectors.

Scenario 3: Building Standards + CLT
The 'whole dwelling approach' to energy use was adopted in the Building Standards to allow greater design flexibility. It focuses on the calculated CO_2 emissions (Dwelling Emission Rate, DER) not exceeding the target carbon emissions (Target Emission Rate, TER) for a 'notional dwelling' [5]. A simplified approach which avoids the mandatory SAP calculations is to design the building to one of the 'packages' defined in clause 6.1.2. 'Package 1' was used for this study. It specifies U-values, air permeability of 7 m^3/m^2h, y-value of 0.08 W/m^2K and glazing solar energy transmittance of 0.63. The thermal conductivity of insulation was set at 0.035 W/mK. Achieving the target U-values with 96mm of CLT reduces the thickness of external walls to 315mm. However, as the common stairwell was outside the thermal envelope, the walls of the close had to be treated as fire-rated, acoustically-isolated semi-external walls, increasing their thickness, but still saving 26 m^2 of total floor area compared with the original tenement. Simulation results showed that the simplified approach would not cover the worst-case scenario. Without modifying the thickness of insulation, compliance with the Building Standards and a 2% reduction of Dwelling Emission Rate/Target Emission Rate could be achieved by increasing the g-value to 0.72, improving the air permeability to 5 m^3/m^2h (minimum before mechanical ventilation is required) [26] and almost eliminating thermal bridging (Fig.3).

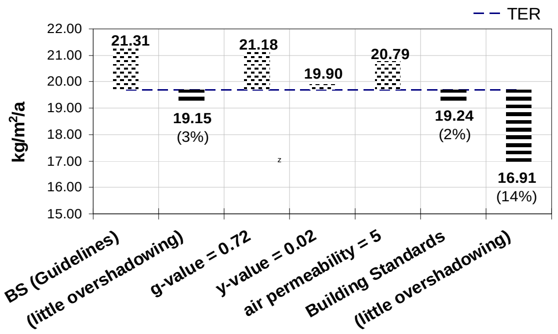

Figure 3: Achieving Building Standards compliance in worst and best case scenarios: DER, TER and % Reduction

Scenario 4: Building Standards + CLT + Passivhaus
The guidelines for the Passivhaus Standard were used. Passive House Planning Package modelling for an occupancy of 16 people showed that this does not yield a working PH in the worst case scenario, unless the tenement is adjacent to at least one other (Table 1).

Table 1: Effect of terracing on PH compliance of a tenement designed to guideline specifications. (A = PH Tenement (Guidelines); B = Adjacent to 1; C = Terrace).

	A	B	C
Specific Space Heating Demand ($kWh/m^2/a$)	25	22	18
Heating Load (W/m^2)	11	10	9
Specific Primary Energy Demand* ($kWh/m^2/a$)	81	77	73

To ensure suitable performance in all configurations, either the efficiency of MVHR had to be raised to the best practice standard of 85% [6], or air-tightness had to be improved to 0.3ac/h. A combination of improvements (Table 2) to the baseline specification for the Passivhaus prototype ensured workability at the maximum allowed U-values. External walls became 370mm thick, saving 4m^2 compared to the original construction within identical external dimensions. Passivhaus demands the addition of MVHR, and no extra space would be required, as the vertical riser for centralised distribution could be positioned in the storage cupboard. The thickness of the floors, however, had to be increased to house air ducts, which reduced the total treated volume.

Table 2: Development of Passivhaus-compliant prototype using Passive House Planning Package (A = PH Tenement (Guidelines); B = Higher g-value (0.68); C = Better MVHR Efficiency (85%); D = Lower Specific Fan Power (1); E = Better air-tightness (0.3); F = Passivhaus)

	A	B	C	D	E	F
Specific Space Heating Demand (kWh/m²/a)	25	24	23	25	23	20
Heating Load (W/m²)	11	11	10	11	10	9
Specific Primary Energy Demand* (kWh/m²/a)	81	80	78	79	79	73

** includes Domestic Hot Water, Heating, Cooling, Auxiliary and Household Electricity. It expresses energy in primary units, depending on fuel type used.*

RESULTS AND DISCUSSION

Compliance Check

To check the performance of the four scenarios against the Building Regulations, their Dwelling Emission Rate (DER) was compared with the Target Emission Rate (TER) based on values taken from the Standard Assessment Procedure (SAP). As expected, the results show that the first two scenarios are far from reaching the benchmark while the Passivhaus Tenement exceeds it (Fig. 4). The DER taken from SAP was then evaluated against comparable CO_2 emissions estimated by Passive House Planning Package (taken from the 'PE Value' worksheet). SAP underestimates the benefits of high insulation, air-tightness and efficiency of MVHR systems [24], which could explain the shift in value domination in the last scenario (Fig. 5).

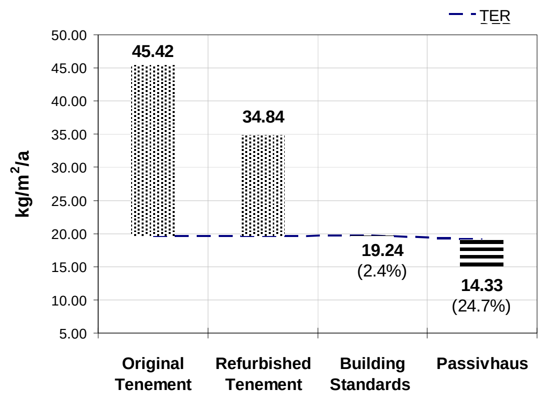

Figure 4: Dwelling Emission Rate (DER), Target Emission Rate (TER) and % Reduction

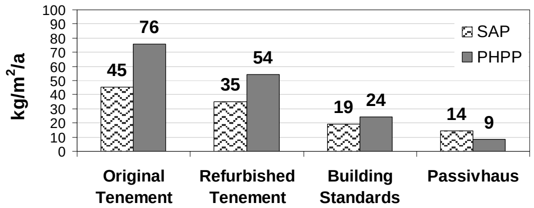

Figure 5: Total CO_2 Emissions Equivalent (no household applications) – SAP (DER) & PHPP results

While the Building Standards tenement could get 9 EcoHomes credits for 'Ene 1' category, Passivhaus could obtain at least 11 [4]. EcoHomes category 'Ene 2' credits are assigned for low heat loss parameters, and Passivhaus would have also gained more credits (Fig. 6).

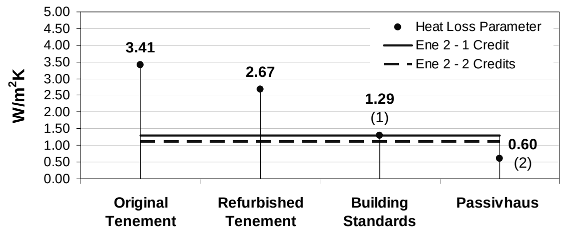

Figure 6: Heat Loss Parameter and EcoHomes Ene 2 Credits (based on SAP calculations)

Specific Annual Heating Demand

Due to inherent differences in the approach to internal heat gains calculations, results from PHPP tend to be higher than SAP results [31], which was confirmed in this study (Fig.7).

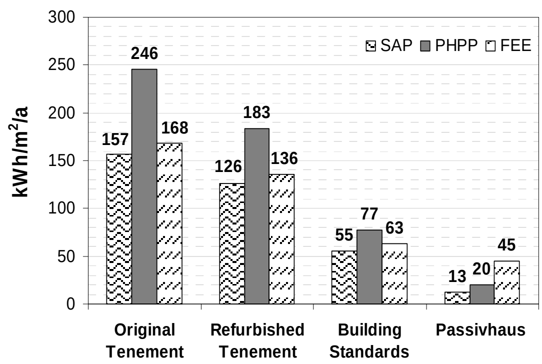

Figure 7: Specific Annual Space Heating Demand and Fabric Energy Efficiency – SAP and PHPP results

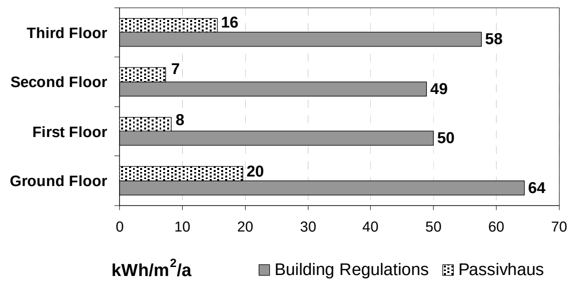

Figure 8: Specific Annual Space Heating Demand Variations (per flat type, as modelled in SAP) (Author)

Although the worst case scenario falls short of the 39 kWh/m²/a set by the Fabric Energy Efficiency Standard, a detached north-facing Passivhaus Tenement would meet it without overshadowing. The typical tenement has 4 flat types and their specific annual space heating demand varies greatly (Fig. 8). This is especially noticeable in the Passivhaus, where the demand of mid-floor flats is less than a half of that of ground or top floor flats, which is offset by the centralised MVHR, which spreads heating across the flats. Fig. 9 shows the estimated increase in the associated electricity usage.

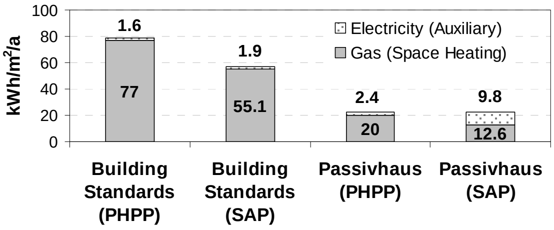

Figure 9: Specific Annual Space Heating and Auxiliary Electricity Demand (comparison of SAP and PHPP)

Having ensured that the prototype works in the worst-case scenario, the orientation was changed and street width was increased to test the effect of improved solar exposure. The results (Table 3) show significant benefits of solar gains for south-facing Passivhaus tenements.

Table 3: Difference in specific annual heating demand (kWh/m²/a) depending on orientation and street width (PHPP results). ● =18m and ☼=100m.

	Original Tenement		Refurbished Tenement		Bldg Stds Tenement		Passivhaus Tenement	
	●	☼	●	☼	●	☼	●	☼
North	246	241	183	179	77	73	20	19
South	246	240	182	178	77	72	19	15
West	246	244	183	181	77	75	20	18
East	246	244	183	181	78	75	20	18

Effect of Urban Configurations

The Passivhaus Tenement was modelled adjacent to one and two other tenements, achieving savings of 3 and 7 kWh/m²/a respectively (Table 4), assuming no heat loss through party walls. Table 4 also shows the effects of the partially exposed party walls when the tenements are located on a hill. A half a storey (2.2 m) change in level was assumed between adjacent tenements.

Table 4: Effect of terracing and hillside terracing on the performance of Passivhaus Tenement (PHPP results) (A = PH Tenement; B =Adjacent to 1; C =Terrace; D =Adjacent to 1 lower; E =Adjacent to 1 higher; F =Hillside Terrace

	A	B	C	D	E	F
Specific Space Heating Demand (kWh/m²/a)	20	17	13	17	17	14
Heating Load (W/m²)	9	8	7	8	8	7
Specific Primary Energy Demand (kWh/m²/a)	73	69	65	69	69	65

Overall, the results show that the clustering of small households in Passivhaus Tenements would deliver significant savings. To improve the performance of the prototype, the pitch of the roof could be changed to optimise the efficiency of solar thermal collectors. Treating the close walls as external and achieving the necessary U-values without applying any reduction factors would deliver further energy savings. Common barriers to achieving low carbon targets in Europe include the lack of locally available standard solutions, skills and knowledge [20]. A demonstration Passivhaus Tenement in Glasgow could address this gap and could serve as a practical testing lab, becoming an open-source prototype that stakeholders could share, directing savings on the design fees to specifying better components. It could also be a vehicle to disseminate the skills required in the market, particularly the training of builders to improve their workmanship for better air-tightness and low thermal bridging.

In Germany, Passivhaus construction costs around 3% to 8% extra compared to typical alternatives [3]. In the previous decade the figures reported in Germany and Austria were 10-15% [16]. One of the first Passivhaus projects in the UK was 14% more expensive than a house built to the 2010 Building Regulations [21]. This was a one-off project which did not benefit from the economies of scale. Among the additions required to bring a cross-laminated timber tenement from the Building Standards level to Passivhaus are 1300m² of 50mm thick insulation and a MVHR system. An assumed 5% increase on the base construction cost of £1400/m² (derived from UK case studies of CLT construction [29]), yields a rate of £1470/m². Social housing associations own a significant proportion of tenements in Glasgow and it is government subsidies that determine their budgets. Glasgow City Council allocates an estimated £700/m² to housing associations, which only covers half of the predicted Passivhaus Tenement cost. This suggests that such associations would find it difficult to build Passivhaus Tenements if costs remain high, unless they are really successful at developing their assets.

CONCLUSION

A tenement constructed to minimum Passivhaus specifications exceeds the Building Standards but is not able to meet the criteria required for Passivhaus certification in the worst-case orientation and overshadowing scenario. Best practice improvements ensure that it not only meets Passivhaus-criteria, but also gains a minimum of eleven credits for EcoHomes Ene 1 and two for Ene 2. By exceeding the target emission rate (TER) of the 2011 Building Standards by at least 24%, the proposed Passivhaus Tenement is in good position to achieve the 60% reduction required from 2013 and the Fabric Energy Efficiency Standard compulsory from 2016. Even though the heating demand varies between flats, a centralised mechanical ventilation with heat recovery would help to redistribute solar gains. If we prioritise lifecycle costs over capital costs, then the Passivhaus Tenement from cross-laminated timber is a valid prototype. Affordability would be achieved by low operational costs and by the performance of its components only slightly exceeding the minimum recommended specification. However, until the market develops to offer the specified construction at much lower prices, the likelihood of widespread adoption of Passivhaus Tenements will remain low.

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