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Squaring the Circle

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Abstract. Research into building-physics in the UK over the last 15 years has demonstrated the significant constraints to the extent to which the energy efficiency of historic buildings can sensibly be improved. While some of these include risk to character and heritage significance, others are linked to moisture movement, mould growth and the comfort of building fabric and users. In parallel with this research and project work, the UK has signed the Paris Accord and committed to delivering zero-carbon by 2050. Although there may be alternative sources of energy, such as hydrogen, to deliver the decarbonisation of industry and transport it seems unlikely that these will make a significant contribution to the decarbonisation of building energy use. In these circumstances electricity will be the sole zero-carbon energy supply for the heating, ventilation and lighting of all existing and new buildings. This dependence suggests that any supply-side limitations on the energy available will inform or impose a requirement for improved performance and thus on the scale and nature of retrofit measures required to each building. This paper establishes potential energy allowances for existing residential buildings from the published future energy supply scenarios and cross references these with the existing metrics for retrofit and with the available post-occupancy performance data on completed retrofit projects for historic residential buildings. This analysis provides an indication of the nature and extent of the level of retrofit that will be required to existing buildings in order for the UK to deliver on its zero-carbon commitment and suggests the kind of approach and methodology that should be adopted for retrofit in order to avoid the fabric risks identified above.

Keywords – Energy efficiency; demand reduction; energy supply; performance metrics; retrofit

1. Introduction

Research and practice into the retrofit of historic buildings has largely focussed on the identification of building physics risks and the development of strategies to mitigate both these and the risks to character and significance, while maximising improved thermal efficiency of heritage assets.

The work of our studio has sought to reduce the energy demand of historic buildings in a way that is both respectful of character and prudent about the risk of moisture build-up and mould growth. Our research published and presented to the 2016 EECHB Conference [1], highlighted the significance of the use of vapour permeable insulations and the critical importance of adequate ventilation in addressing the moisture movement within solid wall constructions. The implementation of building work on the project presented in this paper followed 4 years of careful monitoring and modelling and the conditions within the fabric of the completed project are still being carefully monitored.

This paper responds to the concerns within the heritage sector, and those involved in practical research to date, that uncalibrated responses to a, perceived or political, imperative to retrofit existing, historic buildings will lead to damage to the fabric and historic value. For example, an approach that seeks to simply maximise the thermal efficiency in order to deliver Enerphit or other published standards as a target *per se*, might lead to the unthinking use of too much insulation and of vapour-tight constructions. Rather than an integrated approach to retrofit, that views thermal and moisture movement together with the use of ventilation systems, there is a risk that adoption of an elemental approach to retrofit risks will cause damage to historic fabric.

Conversely, there are concerns that an overcautious approach to retrofit risks under-delivering on improved performance and the need to re-retrofit projects in the future when it is clear that this is necessary.

In order to provide some context for these, necessarily balanced, judgements about how much improvement is needed to existing buildings to make these sustainable, this paper explores the energy supply side of the equation and, by identifying estimated 'allowances' for the zero-carbon energy use which will be available to existing and new buildings by 2050, paper suggests appropriate standards of performance in use.

Setting energy allowances for completed projects can inform the establishment of design targets that can take account of the key factors, such as the performance gap and comfort taking, that affect the ability of delivered projects to perform as designed, and in order to address the concerns discussed above, the building physics research required to obviate the risks to fabric and historic value while delivering zero-carbon.

This paper aims to Square the Circle by establishing a top-down calibration, and reinforcement, of retrofit standards that have emerged - bottom-up - through project-based research and practice.

2. Methodology

2.1. The capacity of the UK Grid Energy Supply

For last 3-years, the UK National Grid has published annual plans for the transition to zero-carbon electricity, and other power, supplies in 2050. The latest Future Energy Scenarios (FES) [2] report identifies a number of scenarios for the future of the UK energy supply and for the safe and reliable delivery of low carbon energy to consumers to meet net zero. For each of four scenarios the National Grid have identified energy budgets for residential buildings. The four scenarios are:

2.1.1. Steady Progression.

Representing the slowest credible route to decarbonisation, this scenario is based on minimum levels of behaviour change and adoption of energy efficiency measures. It yields the highest total end-user energy demand, envisaging continued high levels of natural gas usage for domestic heating and industry. This scenario fails to deliver zero-carbon by 2050

2.1.2. System Transformation.

This scenario is based on significant supply-side flexibility to offset a low level of behaviour change and energy efficiency improvement to buildings (predicting over 65% of homes using hydrogen for heating). It envisages a widespread use of hydrogen for home heating, with hydrogen produced in UK through methane reformation and with large requirement for natural gas with Carbon Capture and Storage (CCS).

2.1.3. Consumer Transformation.

In contrast to System Transformation, this scenario is based on high demand-side flexibility and willingness of consumers to change behaviours with significant implementation of energy efficiency measures and the adoption of electrified heating with heat pumps and thermal storage.

2.1.4. Leading the Way.

This scenario is based on elements of the other scenarios and represents the fastest credible route to decarbonisation. It envisages significant lifestyle change with a combination of hydrogen and electricity used in heating. 40% of homes would have heat pumps and thermal storage. Hydrogen being produced in UK with electrolysis from dedicated offshore wind.

2.2. Notes on metrics.

This paper has adopted the Passivhaus standard of kWh/m^2.per annum (kWh/[m^{2}a]) as a measurement of energy use and basis for establishing future building allowances. Although this is widely accepted as a simple, measurable figure that is open to very little misinterpretation or misuse, it does embody a basic inequity by effectively favouring larger dwellings (or those not heated or cooled for continuous - annual or diurnal -use) while penalising small, compact and more continuously occupied and serviced buildings. We have considered adoption of other metrics related to occupancy level, compactness factor, or a blend of all of these, to arrive at a measure that is more equitable (to smaller, well-designed or retrofitted projects) but, on the basis of the near-universal acceptance of the kWh/m^2.a metric, have adopted this as a starting point for, what may be more nuanced and useful, future studies.

2.3. Notes on choice of building stock used in this study

This paper uses the UK housing stock as a model for analysis of supply-side study of retrofit energy allowances. The English Housing Survey (2019-20 version) [3] records that 29%, of the housing stock in the UK comprises pre-1919 houses of solid-wall construction. Of these 8.4m houses, more than 7m have heritage features, some have been designated as listed buildings and many lie within, and define the character of, Conservation Areas.

By contrast, the particularities of age, use, and character of each of the 400,000 listed buildings in the UK make any modelling of energy use demand reduction too complex for the scope of this exercise.

2.4. Note on peak and average energy usage.

The following calculations are based on annual energy supply and demand levels. It is acknowledged that, within these annualised figures, there will be diurnal and seasonal variations in both supply and demand. There is insufficient space here for a more detailed study of these variations or of the effect of these variations on the need for increased peak power supply capacity or power balancing.

2.5. Derivation of an energy budget for existing buildings.

For the purposes of this exercise, only the Consumer Transformation and Leading the Way scenarios will be studied. The other two scenarios being discounted on the basis that:

- Steady Progression does not deliver zero-carbon by 2050
- System Transformation is heavily dependent on the use of hydrogen to heat homes. The technologies for amenity-scale production of hydrogen and for CCS do not currently exist in a viable form and the cost, programme and disruption of upgrading or replacing the current gas infrastructure, at every level from national distribution to connections within each home, is thought to be unrealistic. It seems more probable that the supply of hydrogen for use in industry, for transport, and in limited use in electricity generation will be more economically deliverable.

Table 1. The FES energy allowances given for residential buildings by scenario:

FES Scenario	Energy allowance for residential buildings (TWh)[a]	Notes
Consumer Transformation	177	predominantly electrical but with elements of gas and bioresource for off-grid properties
Leading the Way	186	predominantly electrical but with elements of hydrogen and bioresource for off-grid properties.

[a] 1 TWh = 1Wx10^{12} or 1,000,000,000 kWh

2.6. Formula for derivation of energy allowances for existing buildings

A simple formula has been adopted in order to arrive at energy allowances for existing dwellings in 2050- from the FES figures.

$$E^e = \frac{T - E^N}{A^e}$$

Where:

E^e Energy available to existing buildings - (kWh/[m²a])

T Total energy for residential buildings (kWh) under different FES scenarios

E^N Energy required for new residential buildings to be built between 2020 and 2050

A^e Floor area of existing residential buildings (m^2)

The English Housing Survey [3] identifies the average existing house size in the UK as $88m^2$

The values for the latter two terms are derived:

$$E^N \quad N^n \times Av^n \times E^n$$

Where:

N^n Number of new houses to be built in UK between 2020 and 2050

The UK Government has made a high-level commitment to building 300,000 new houses per year. This is close to delivered performance over the last 20 years and equates to 1% simple growth per year.

Av^n Average area of a new house (m^2)

The English Housing Survey [3] identifies the average new house in the UK as 68 m^2

Eurostat Statistics [4] confirm that new housing in the UK is built to lower space standards than anywhere else in northern Europe

E^n Energy performance of a new house (kWh/[m^2a])

This paper adopts an assumption that all new houses will be built to Passivhaus Standards [4]

This assumption is supported by the findings of the Green Construction Board publication Building Mission 2030 [5] which recommended adoption of comparable levels of energy use in order to halve energy consumption in new housing by 2030 and illustrated this with a range of compliant case studies.

N.B. Many new houses in the UK deliver only the energy performance levels set by the current Approved Document L of the Building Regulations [6] which sets default standards for the Conservation of Fuel and Power, and almost all new housing under construction will require a degree of retrofit in order to meet the target allowances.

$$A^e \quad N^e \times Av^e$$

Where:

N^e Number of existing residences in UK

The English Housing Survey (2020 version) [3] records 29,100,000 existing houses

Av^e Average existing house area (m^2)

The application of this formula to the alternate FES scenarios produces the following energy allowances.

Table 2. Energy allowances for Homes in two FES Scenarios

FES Scenario	Energy allowance for existing buildings (kWh/[m^2a])
Consumer Transformation	60
Leading the Way	64

2.7. Comparison of Energy Allowances with existing metrics

The table below shows a comparison of the energy allowances calculated above, with the performance standards required by the Passivhaus Institute for Enerphit and PHI Low Energy Building Standard [4].

Table 3. Comparison of Energy Allowances for Homes in two FES Scenarios with Passivhaus standards for new build and retrofit of existing buildings

FES Scenario	Heating/Cooling Demand (kWh/[m^{2}a])	Energy allowance for existing buildings (kWh/[m^{2}a])[b]
Consumer Transformation		60
Leading the Way		64
Passivhaus Standards		
New Build	15	60
Enerphit	20-30[a]	60
PHI Low Energy Building Standard	30	75

[a] The UK straddles Cold as well as Cool and Warm Temperate climatic zones creating a range of allowances for heating and cooling demand

[b] The allowances and Passivhaus standards quoted above all exclude the impact of, or qualifications arising from, provision of on-site renewable generation.

3. Energy performance of completed retrofit projects

3.1. Availability of performance data

The principal constraint on any current assessment of the capacity of retrofit projects - of moderate ambition and householder-funded - to meet the energy allowances under the FES scenarios, is the lack of available performance data for completed projects.

This constraint has affected all efforts to quantify the benefits and rewards of retrofit to all existing, and particularly to heritage properties. In the work lying behind the Sixth Carbon Budget recently published by The Committee on Climate Change [7], the team at University College London (UCL) [8] recognize that their advice was based on very small sample sizes and widespread assumptions. UCL adopted a metric of (£/TCO_2 saved) to compare the carbon saved by retrofit with that saved, for example, by a switch to hydrogen as a fuel for housing. The assumptions used for proposed fabric performance improvements were also adjusted to allow for broad assumptions about the Performance Gap (between 7-50% (28% assumed) and behavioral factors like Comfort Taking (<33%) or other Behavioural Factors (+10%). Due to the large factors of uncertainty and the metric used this data has not been convertible or useful for this paper.

Similarly, the current work on Decarbonising the Public Sector [9], that has been commissioned by the Department of Business, Energy and Industrial Strategy, has adopted a metric of (£/TCO_2 saved over the 'lifetime' of each measure or intervention). The added complexity of assessing the lifetime of fabric and systems measures makes this dataset very difficult to convert to meaningful use in the current paper.

In the absence of published data, this study has relied on the post-occupancy monitoring undertaken by built-environment professionals. This has proved immensely difficult to obtain during the current pandemic. Of the 70 case-studies originally offered, only 6 have been forthcoming. Whilst this sample is statistically insignificant, it does suggest the outcomes that might be expected of a wider study and the capacity of normal levels of intervention, that are able to gain Listed Building or Conservation Area consent, to deliver improvements in performance that meet predicted energy allowances.

3.2. Summary of data available

The data summarised here is set out in more detail in Appendix A - with details of original condition of property and the retrofit measures involved (constructions and systems).

Table 4. Post Occupancy energy performance of retrofit projects

Project Number	**1**	**2**	**3**	**4**	**5**	**6**
Property Type	Semi-detached house	C19th stone and rendered brick college building	Mid Terrace, 3 storeys plus loft.	Mid Terrace cross wall property.	Mid terrace 3 storey	End of terrace 3 storey
Age	1926	1822	1860	1960s	1890	1890
Protection / Listing	Conservation Area	Grade 1	Conservation area	None	Conservation area	Conservation area
Net Internal Floor Area m^2	68 extended to 137	5340	100 extended to 120	96 extended to 108	140	190 extended to 200
Measures Completed						
Fabric	75mm phenolic foam insulation + render over-cladding to walls with Velfac triple glazed windows. 400mm mineral fibre quilt to roof	72mm wood fibre insulation to walls on lime parging a/t lining. Slimline d/g units to windows. 300 mm insulation to roof	IWI glasswool insulation with insulated cavity. U-value approx 0.2 W/m2K. 100mm XPS floor insulation Roof rebuild with 150mm PIR insulation to achieve U 0.15 W/m2K.	Front and rear walls insulated frame to achieve U value 0.12 W/m2K. 80mm EPS insulation over concrete slab on ground. 150mm PIR to roof as part of roof extension work.	Wood fibre and aerogel internal wall insulation on main house to U values 0.3-.0.5. 300mm blown cellulose and airtight loft hatched to main roof. Suspended floors insulated.	50mm diathonite insulation plaster, new windows with vacuum glazing, super insulated new mansard roof.
Systems	16kW PV array on roof MVHR ASHP supplying DHW and heating with extg radiators and pipework	MVHR to all rooms. Extg gas boilers providing DHW and heating to new u/floor heating system	Itho MVHR and ductwork fitted. Air tightness 1.1 ach.	Paul 200 MVHR providing high air quality and 85% heat recovery. Air tightness 0.7 ach.	Aereco MEV (no HR). To Provide air quality with minimal losses. Air tightness 3.0ach	Paul MVHR. Air tightness 1.3 ach. ASHP for UFH and DHW.
Outstanding to be done	Upgrade d/g windows. EV+V2G connector to act as a house battery	Roof mounted PV array and GSHP borehole array to courtyard	Potential to change gas boiler to heating pump when boiler reaches end of life	Potential to change gas boiler to heating pump when boiler replaced	Potential to switch from gas boiler to ashp. Potential for PV array approx 2 kWpe	Potential to add PV 2-3 kWpe
Post-Occupancy Energy Usage: kWh/[m2a]						
Before Works	213	200[a]	estimated 300	estimated 200	estimated 300	estimated 300
After Works	**59**	**23**[b] **(space heating)**	**66** **(space heating 28)**	**63** **(space heating 23)**	**90** **(space heating 45)**	**50** (est) **Initial readings are closer to 35. due to ASHP)**

[a] Estimated from interpolation of incomplete energy metering

[b].Estimated - to be confirmed by ongoing monitoring

4. Discussion

A number of issues arise from the above findings

The assumption that all new houses in the UK will be built to Passivhaus Standards relies on a degree of political will and acceptance by the UK construction industry and housing market. Failure to deliver new housing to this standard will not only reduce the energy available to existing housing but increase the number of houses (by then existing) that will need to be retrofitted to these tighter allowances.

Table 3 demonstrates that the allowances derived the adjusted grid capacity for the two FES scenarios - 60 and 64 kWh/[m^2a] - lie between the standards required by Enerphit and PHI Low Energy Building Standard at c.60 and 75kWh/[m^2a] respectively. Perhaps confirming the relevance of these standards.

It is worth noting that the performance data in Table 4 is limited in timescale - often for no more than one year's energy usage - so should carry a caveat with regard to the influence of variation in the length and severity of heating seasons.

The delivered performance of the completed projects falls within a range of between 59-90 with 3 of the 6 projects falling within the target allowances of between 60 and 64 kWh/[m2a]. The project that falls significantly outside this target performance being the retrofit of a late C19th house in which the existing gas boiler has been retained - until the end of its lifetime - at which point this will be replaced with an ASHP).

5. Conclusions

The outcomes above suggest that the range of retrofit measures commonly undertaken to existing, and specifically historic, houses are capable of delivering the reduced levels of energy demand that align with the anticipated grid capacity under the FES Scenarios considered while adopting a careful approach to building physics and moisture risk.

The levels of energy demand reduction recorded have all been delivered in projects that have incorporated ventilation systems with heat recovery as well as fabric improvements to insulation and airtightness within an integrated package of measures to deliver both energy and carbon saving targets and fabric and occupancy comfort. Any adoption of targets such as the energy allowances derived above, will necessitate that the retrofit of existing buildings be considered in this holistic and careful manner and on a case-by-case basis.

The close relationship of the performance of these completed projects to the extant Passivhaus metrics for retrofit suggests that these metrics are relevant and that it would be appropriate to adopt the Enerphit and PHI Low Energy Building Standards as a yardstick not only for all retrofit projects but as a tool for policymakers in assessing the alternative routes to zero-carbon, future Carbon Budgets, Future Energy Scenarios, and initiatives to Decarbonise the Public Sector.

The tiny size of this sample - even allowing for the constraints imposed by the pandemic - and the broader lack of available data on the performance of retrofit, suggests that extensive post-occupancy monitoring of energy usage in retrofit project - grant-aided if necessary - is required to sensibly inform future policy and funding initiatives.

6. European Energy Scenarios

This study has outlined the future energy context in which existing and historic buildings in the UK will be heated/cooled and occupied in 2050. This would not have been possible without the publication of the FES by the National Grid.

Comparable energy scenarios have been published most member EU states as follows. It would be very interesting to explore how the outcomes of the above analysis is affected by the different political choices, power sources and building stocks across the EU:

- Belgium: http://www.elia.be/~/media/files/Elia/AboutElia/Studies/20171114_ELIA_4584_AdequacyScenario.pdf
- France: https://www.rte-france.com/fr/article/bilan-previsionnel
- Ireland: http://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid-Tomorrows-Energy-Scenarios-Report-2017.pdf
- Denmark. Germany, Northern Ireland, Italy, Netherlands, Poland, Spain, Sweden: https://tyndp.entsoe.eu/tyndp2018/

7. References

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[3] English Housing Survey. Homes 2011. Ministry of Housing, Communities and Local Government (MHCLG). ISBN: 978-1-4098-3922-4. https://www.gov.uk/government/collections/english-housing-survey.

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[10] Eurostat Statistics Explained: Housing Statistics https://ec.europa.eu/eurostat/statistics-explained/index.php/Housing_statistics

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