Heriot-Watt University

Reducing CO2 emissions through refurbishment of UK housing

Peacock, Andrew; Banfill, Phillip Frank Gower; Turan, Seyhan; Jenkins, David P; Ahadzi, Marcus; Bowles, Graeme; Kane, David; Newborough, Marcus; Eames, Philip; Singh, Harjit; Jackson, Timothy; Berry, Alison

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Andrew Peacock
The Energy Academy
Heriot Watt University
Edinburgh, EH14 4AS
Tel: + 44 (0)131 451 4329
Fax: +44 (0)131 451 3132
a.d.peacock@hw.ac.uk

P.F.G Banfill*, S. Turan*, D. Jenkins*, M. Ahadzi*, G. Bowles*, D. Kane[#], M. Newborough[¥], P.C. Eames[§], H. Singh[§], T. Jackson [Ψ], A. Berry [Ψ]

* - School of the Built Environment, Heriot Watt University
[#] - School of Engineering and Physical Sciences
[¥] - ITM Power
[§] - University of Warwick
[Ψ] –University of Surrey

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Abstract

Recent research by the Tyndall Centre in the UK has suggested that a 70% reduction in CO_2 emissions will be required by 2030 to mitigate the worst impacts of global climate change. In the UK, approximately 30% of CO_2 emissions are attributable to domestic buildings. Of the UK housing stock that will be present in 2030, 80% will have been constructed before 2005. Consequently, refurbishment of existing housing is likely to strongly influence whether these emissions reduction targets are met. This paper catalogues interim research outcomes from a research project (TARBASE) whose aim is to identify technological pathways for delivering a 50% reduction in CO_2 emissions of existing UK buildings by 2030. This investigation describes the approach as applied to the domestic sector. The approach taken was to describe a series of domestic building variants, chosen due to their prominence in the stock as a whole and also by their ability when taken together to describe the range of construction methods found in UK housing. Technological interventions, grouped by building fabric, ventilation, appliances and on-site micro-generation (of both heat and power) as applied to the building variants were investigated. Their applicability was determined with respect to energy and CO_2 emission savings. The interdependence of the technological interventions was evaluated allowing a series of intervention sets to be depicted for each variant.

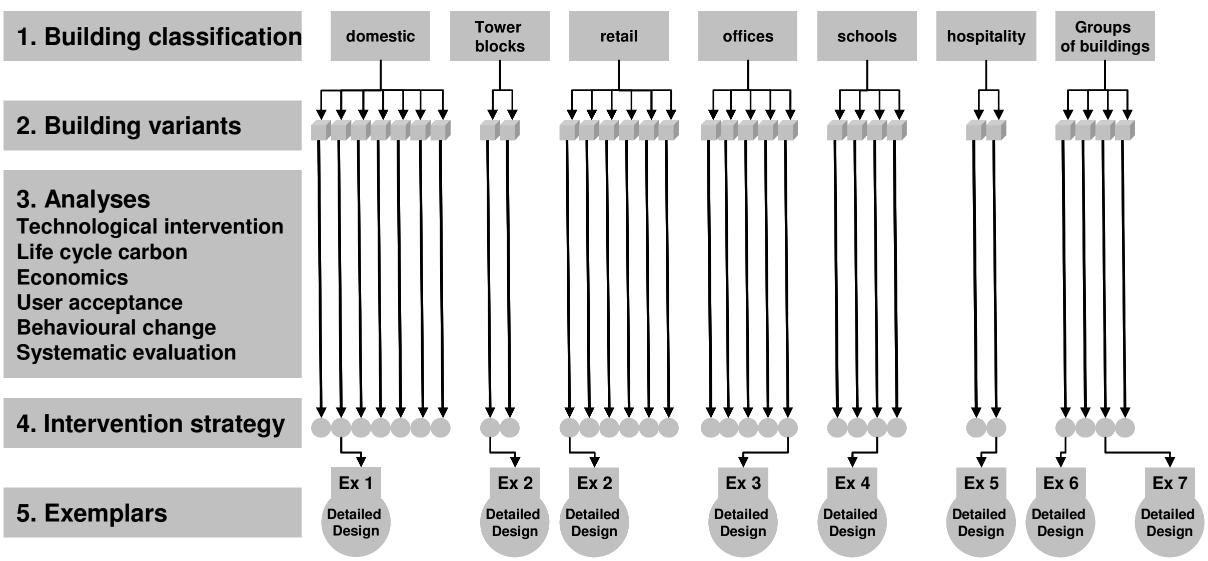
Introduction

Recent research by the Tyndall Centre in the UK has suggested that a 70% reduction in CO_2 emissions will be required by 2030 to mitigate the worst impacts of global climate change [1]. In the UK, approximately 30% of CO_2 emissions are attributable to domestic buildings [2]. Of the UK housing stock that will be present in 2030, 80% will have been constructed before 2005. Consequently, refurbishment of existing housing is likely to strongly influence whether these emissions reduction targets are met. The aim of the TARBASE project is to deliver technological solutions which will allow a radical, visible, step change input to policies and programmes designed to reduce the carbon footprint of the existing UK building stock. Developing technological interventions to reduce the energy consumption of existing buildings is a well researched pathway and the findings have been incorporated into the legislative process both in the UK and abroad. Given the weight of knowledge in this field, the results, in terms of take up of technologies has been disappointing and energy consumption so that energy consumption and CO_2 emissions attributable to existing buildings have continued to grow. There are numerous reasons why this has occurred but one possible cause may however lie in the character and quality of the data itself. The Sustainable Construction Task Group [3] suggested that one of the reasons for this market failure was that the costs and benefits of refurbishment options are often complex to determine. Following an assessment of the available data on refurbishment interventions for reducing carbon emissions they concluded that, while there is a wealth of guidance and literature regarding technological intervention strategies for reducing carbon emissions in existing buildings, the data is disparate, too specific or not specific enough. TARBASE aims to contribute to the bridging of these gaps by developing a methodology for assessing technological intervention strategies which attempts to (Figure 1):

- Characterise energy flows for specific buildings, the choice of which is informed by a thorough understanding of the data describing the existing stock. It is not incumbent upon Tarbase to select buildings that could be described as average. The aim is to choose buildings that are prominent in the stock from the perspective of CO_2 emissions and that the buildings when taken as a whole reflect variables that are fundamental in describing the wealth of buildings found in each classification. In the domestic sector for instance, a prominent characteristic that has been considered is age and therefore type of construction.
- Produce an assessment vehicle that will develop intervention strategies for these buildings that will provide an understanding of their suitability from the perspective of CO_2 savings, engineering veracity, externalities (climate and electricity), embodied energy, economics and user acceptance.

An overview of work carried out to date on the Domestic Building Classification is reported here.

Figure 1: TARBASE Project flowchart



Scope of this Paper

This paper is concerned with the assessment of technological interventions as deployed to a series of domestic building variants and their effect on energy consumption and CO_2 emissions. The results do not provide an exhaustive list of the interventions considered. For instance, biomass boilers, solar thermal hot water and space heating, air and ground source heat pumps and electricity storage systems are being investigated but the results are not available at time of press. Similarly, the cost, embodied energy, user acceptance and behavioural aspects pf energy consumption are also in the process of being developed.

TARBASE Domestic Variants

In the UK domestic sector, where the predominant energy use is space heating, the importance of construction method is paramount in determining baseline energy data and consequent strategies for mitigating CO_2 emissions.

The predominant constructions used in UK housing are a) masonry cavity wall, b) timber frame, c) solid wall and d) factory construction. These types of construction appear in the list of typical constructions being considered for inclusion in the UK approach to implementing the European Energy Performance of Building Directive [4].

A domestic stock model has been developed [5] that attributes CO_2 emissions to dwellings based on a number of factors, some of them dwelling based (for instance construction details) and some of them household based (for instance electricity consumption linked to household size). This stock model was interrogated and the domestic sector disaggregated by age and type of dwelling to produce 73 different variations of dwelling constructed up to 1996. CO_2 emissions arising from total energy consumption were attributed to these variants, the top 23 being shown in the Pareto diagram in Figure 2. The black bars refer to the selected Tarbase variants which are indicative of dwellings to which 28% of the total UK domestic sector CO_2 emissions can be attributed. Thus they can be viewed as being prominent in the stock while affording consideration of different constructions and occupancy characteristics. Additionally, three detached dwellings of identical physical size, occupancy type and level have been selected that vary according to their age and type of construction. These include a variant that ostensibly complies with the most recent revision of the UK Building Regulations (Variant 6). This allows the influence of building standard on the intervention set finally chosen to achieve the targeted reduction in CO_2 emissions to be investigated.

Figure 2: Tarbase Domestic sector variants (pre 1996) – CO2 emission attribution

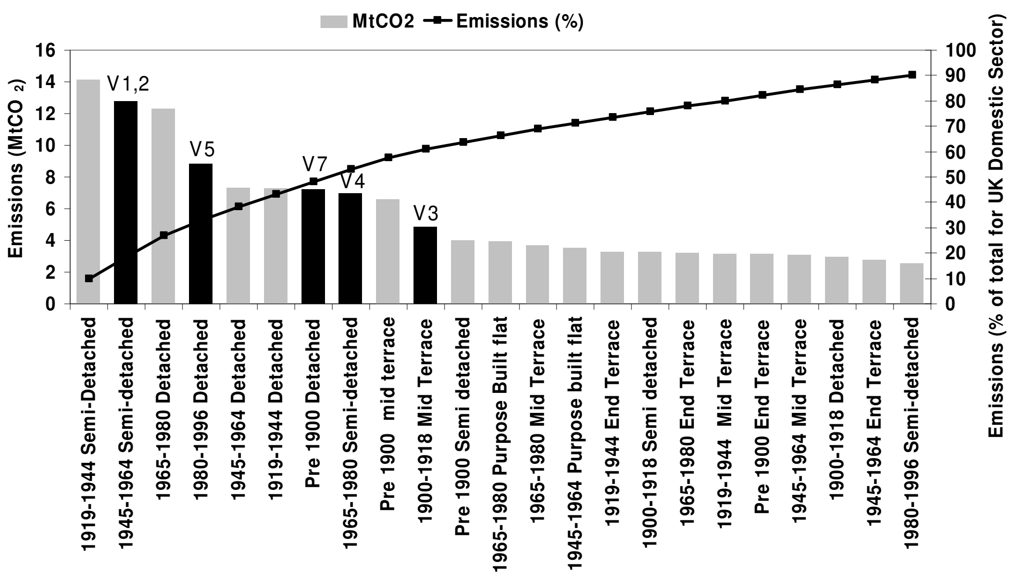


Table 1: Principal construction details and age of TARBASE Domestic variants

Variant 1	1945-1964 Semi-detached Masonry cavity wall – 50mm cavity - Filled
Variant 2	1945-1964 Semi-detached Masonry cavity wall – 50mm cavity - Clear
Variant 3	1900-1918 mid-terrace Solid wall construction
Variant 4	1980-1996 Semi-detached Masonry construction – 75mm – partial fill
Variant 5	1980-1996 Detached Timber frame – compliant to 1992 UK Building Regulations
Variant 6	2002 Detached Masonry cavity wall – compliant to 2002 UK Building Regulations
Variant 7	Pre 1900 Detached Solid Wall construction

Characterising Energy Demand of the Domestic Variants

The space heating requirements of the variants were estimated using a bespoke steady state heating model based on CIBSE Guide A [6], SAP (Standard Assessment Procedure) [7] and Thermal bridge calculation methods [8]. The gross heat loss coefficient estimated using this model, disaggregated by building element is shown in Figure 3 for each variant. The exhibited variation is due to variances in the ratio of floor area to external wall area, thermal bridging, infiltration level and insulating capacity of the building fabric. For instance, the proportion of heat loss attributable to the external wall was greater than 40% for the stone built dwellings (Variants 3 and 6) but fell to less then 20% in the Variants where high levels of external wall insulation were assumed e.g. Variants 1 and 5.

These heat loss coefficients were used in combination with an assumed thermal comfort requirement for each variant based on the occupant description, an estimated contribution of internal and solar gains, a discrete climate file for each variant and hot water requirement based on occupant level [9] to produce an estimation of the annual thermal requirement, q. The annual electrical demand of the variants was estimated by translating assumed occupancy level and economic activity to ownership and usage of a range of 45 different electrical appliances [10, 11]. The building variants annual thermal and electrical demand varied from 5.7 – 23.2 MWh and 2.8-5.4MWh respectively (Table 2) with their CO_2 emissions ranging from 2600kgCO_2 pa in Variant 4 to 7000kgCO_2 pa in Variant 7 (Figure 4).

Figure 3: Heat loss co-efficients for the TARBASE Domestic Variants

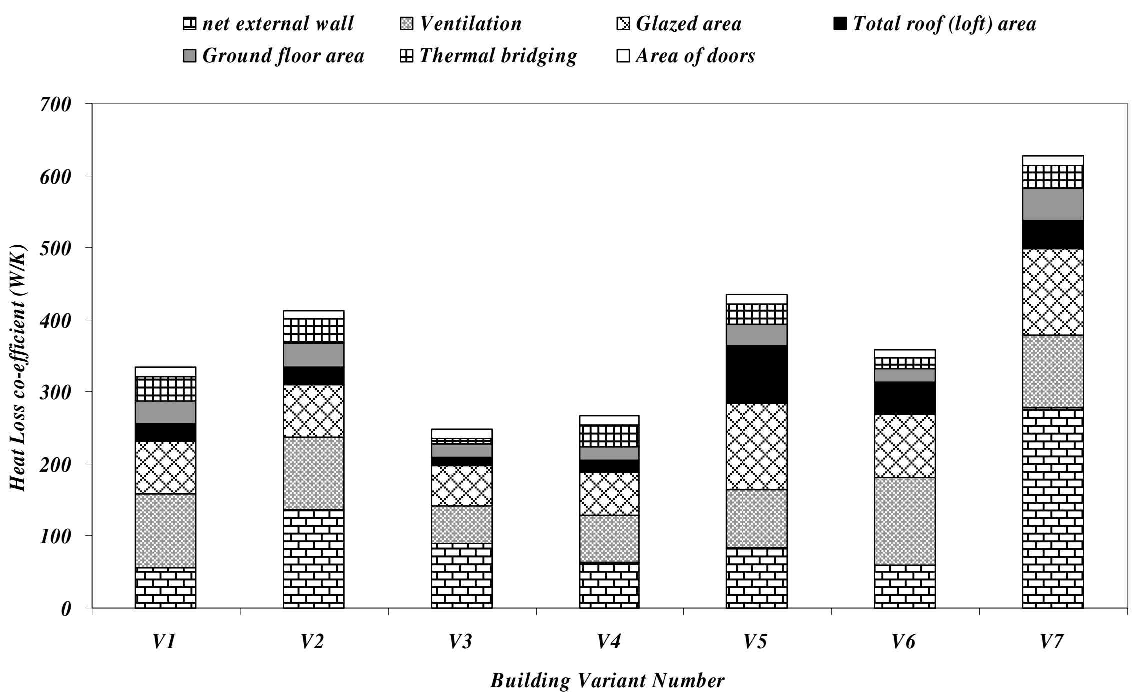
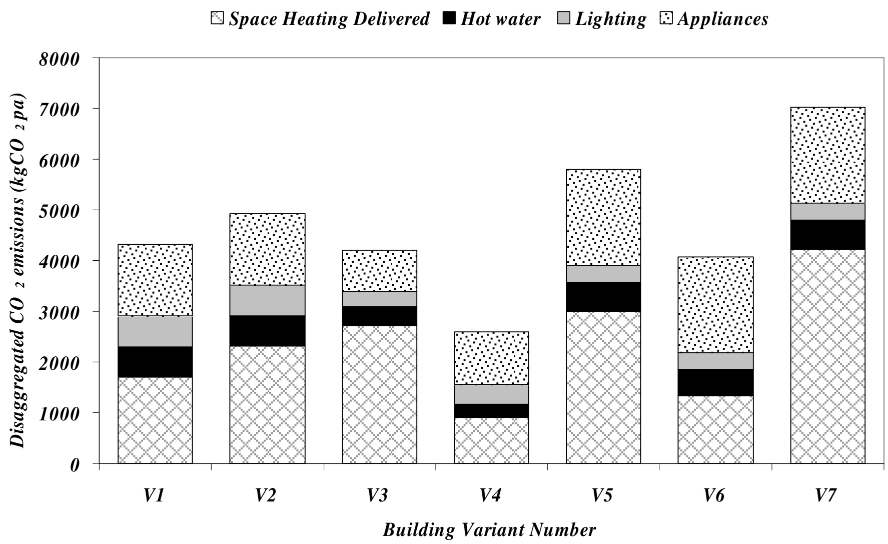


Table 2: Thermal and electrical demand of the TARBASE Variants

Variant Number	q (kWh pa)	e (kWh pa)
1	10100	4760
2	13250	4760
3	14050	2830
4	5700	3080
5	16800	5420
6	8400	5420
7	23300	5420

Figure 4: Disaggregated CO2 emissions of the TARBASE Domestic variants



Technological Interventions

The characterisation of technological interventions that can be made to the variants has been considered in the categories building fabric, ventilation, end use equipment and energy production and storage. This methodology has been applied to all domestic variants but is discussed in detail here for only Variant 1 and 7.

Building Fabric

Walls

In the two variants selected for detailed consideration, the contribution of heat loss through the external wall to the baseline CO_2 emissions attributable has been estimated at 9 and 27% for Variants 1 and 7 respectively. Clearly, in Variant 7, the ability of the CO_2 emission reduction target to be met through technological intervention is predicated to a large extent on modifications being made that reduce the heat loss co-efficient of the external wall. This presents some architectural and cultural problems in the UK where the architectural vernacular of many towns and cities is encapsulated in its stone built dwellings and buildings. With dwellings, it is feasible that external wall insulation can be applied to the back i.e. the non-public face. The proportion of wall at the rear of a dwelling is likely to be in the region of 40% but maybe as high as 60% in Victorian terraces for instance. External wall insulation in the form of Polyurethane board is typically applied on timber battens weather proofed via cement or lime rendering. Application of external wall insulation to 40% of the available external wall area was adopted as a technological intervention to external walls and would reduce the composite u-value of the external wall from 1.6 to 1.1W/m^2.K in Variant 7 and from 0.5 to 0.4W/m^2.K in Variant 1.

Glazing

The u-value assumed for the glazings in both dwellings was 2.75W/m$^{2.}$K, constituting a standard UK double glazed unit as installed prior to 2000. Heat loss through glazing contributed 11.3 and 11.7% of the CO_2 emissions attributable to Variants 1 and 7 respectively. There is a potential for space heating energy being saved on application of more advanced glazing systems. Triple glazings with a window U-value (frame) of 1.6 W/m$^{2.}$K are available in the market place and application of this glazing type has been assumed here as a technological intervention. Triple-glazed windows have three glazing layers with low-emissivity; one or two, with argon or krypton gas fill between glazings. Advanced glazing systems are being developed to enter the market place over the next decade. These include vacuum glazing which comprises an evacuated gap between two glass sheets. Double vacuum glazing is commercially available. The vacuum in the gap area can be of the magnitude of <0.1 Pa and eliminates the gaseous conduction and convection thus resulting in a low heat loss coefficient. As the vacuum gap between the two glass panes is very small the total thickness of the vacuum glazing system also is reduced compared to a conventional gas filled glazing. Significant advances have been achieved since 1998 when [12] a double evacuated glazing with a window U-value of 0.9 $W/m^2.K$ was reported. Fang et. al. [13] reported a double vacuum glazing encased in a multimaterial insulating frame with a minimum window U-value of 0.82 $W/m^2.K$. Shultz et al. [14] reported manufacturing a prototype double vacuum glazing with an average window U-value of 0.72. A triple vaccum glazing with stainless steel support pillars and four low-emittance coatings (Є=0.03) can achieve a predicted mid-pane U-value of 0.2 $W/m^{2.}K$ [15]. Triple vacuum glazing will provide a significant potential for application in low-energy buildings and may well be available in the medium term.

Roofs

In 2001, over 50% of UK dwellings had loft insulation to a depth of > 100mm [16]. The TARBASE domestic variants assumed loft insulation of 100mm. Heat loss through the roof of the dwelling contributed 3.7 and 3.2% of the CO_2 emissions attributable to Variants 1 and 7 respectively. Increasing loft insulation to a depth of 250mm would reduce the roof u-value from 0.45 to $0.1W/m^{2.}K$ in each dwelling.

Infiltration

Infiltration levels in domestic dwellings shows a clear relationship with construction type with, for instance, timber frame dwellings typically having significantly lower levels than masonry constructions [17]. For the two constructions considered here in detail, the assumed infiltration levels were 0.57 and 0.75 air change rates per hour under average weather conditions [17]. It has been reported that the infiltration level of an existing dwelling can be reduced by as much as 70% as a consequence of for instance; (a) draughtstriping all external doors, (b) draughtstriping the loft hatch, (c) point joints between door frames and the surrounding wall with sealant, (d) blocking up unused chimneys, (e) seal around service pipes cables where they enter the dwelling or pass through the ceiling into the loft space, (f) seal suspended timber ground floors and (g) by the fitting of new glazings. As a consequence the heat loss co-efficient attributable to infiltration can be reduced from 72 to 25W/K in Variant 1 and from 66 to 20W/K in Variant 7.

Ventilation

The minimum ventilation rate required to maintain adequate indoor air quality has been specified in the UK building regulations since 2005. The rate is linked to the number of bedrooms (and by association the occupancy) in the dwelling and is 0.3ach for the two building variants considered in detail here [18]. The definition of minimum ventilation rate and subsequent control of ventilation in a dwelling is a fundamental strand of building legislation aimed at reducing built environment CO_2 emissions. There is considerable variation internationally with for instance, minimum ventilation rate in 0.5ach in Japan, 0.54ach in the Netherlands and 0.35ach in America. Maintenance of adequate indoor air quality is required for human health, and recent research has indicated that control of indoor levels of humidity is the dominant factor, requiring minimum levels of 0.8ach, far in excess of that defined if CO_2 concentrations in indoor air are used as the criterion of indoor air quality. This ventilation level would have the effect of increasing CO_2 emissions for the dwelling by 9 and 11% for Variant 1 and 7 respectively. Ensuring delivery of ventilation at these levels is likely to be obtained only by some form of mechanical or hybrid ventilation system. If coupled to a heat recovery system, the energy penalty associated with the revised ventilation requirement would be offset. A mechanical ventilation (MV) usually combines supply and extract ventilation in one system. Fresh air is distributed throughout the dwelling with air being extracted from kitchen, bathrooms and WCs. A heat exchanger is employed to recover heat energy from the exhaust air and to preheat the incoming fresh air. A variety of heat exchangers such as heat wheel (both, sensible and enthalpy type), plate type, coil type and heat pipe may be employed to recover heat from the exhaust air. A sensible heat exchanger was specified for the TARBASE variants as it has an essentially constant effectiveness over a wide range of outdoor temperature. To avoid overheating of incoming air, outlet temperature of a sensible heat wheel exchanger can be controlled using a temperature sensor connected to a bypass or wheel speed control module. A heat wheel exchanger is reported to have a maximum effectiveness of 85% (19).

End use Equipment

Lighting

The lighting technology used in calculating the baseline emissions had a combination of GLS, Halogen and CFL. The US Department of Energy's Next Generation Lighting Initiative in collaboration with the Optoelectronics Industry Development Association [20], have produced Technology Roadmaps for solid state lighting technology with target luminous efficacies of 200 lm/W by 2025. In the UK, MTProg have estimated that system efficacies (including ballast factor) of 150lm/W [21]. TARBASE have used the latter figure in estimating the effect of solid state lighting on the emissions attributable to the domestic variants. The reduction in lighting energy consumption is estimated at being 92% and 78% for Variants 1 and 7 respectively.

Refrigeration

Two market ready technologies are being developed that are likely to have a significant effect on the energy consumption of domestic refrigeration; (a) Vacuum insulation panels and (b) Free piston Stirling cycles. Vacuum insulation panels (VIP) have been used in the past with convention refrigeration casing where the panels are encapsulated in Polyurethane (PU) foam [22]. Adoption of this technology would reduce energy consumption of a current 'A' rated fridge freezer by approximately 19%. An alternative method is to redesign the cabinet itself to effectively make incorporation of VIP and elimination of thermal bridging the design goal. This approach produces a thin walled hermetic barrier with modified internal atmosphere and an insert consisting of VIP that in effect recasts the refrigeration casing into a VIP itself. Adoption of this technological route is estimated to reduce energy consumption by approximately 52%. The adoption of Free piston Stirling cycle compressors increases the COP of a single temperature refrigeration cycle from typically 1.4 to 3.0, the effect being to reduce energy consumption on its own by 39%. If the two technologies are adopted in tandem, any issues associated with temperature lift attributable to the Stirling cycle compressor are likely to be assuaged and cumulative energy reduction is estimated at being 71%.

Cooking

The end-user has a substantial impact on the energy consumption of cooking appliances in domestic dwellings. Ultimately, while technological interventions may be suggested in this area, it may prove likely that an improved and potentially more assured course of action is to understand more comprehensively how to alter occupant cooking behaviour. Technological improvements have been suggested for electric ovens (which are assumed to be present in all domestic variants). These all concentrate an improving the thermal isolation of the oven cabinet, resulting in an estimated energy reduction of approximately 80% [23].

Laundry

An 'A' rated washing machine with mean energy consumption was assumed for each variant with the number of cycles linked to the occupancy [24]. The water volume used has fallen substantially in the last decade. 'A' rated models that use 10litres during the hot water cycles are in the market place and these were adopted as a technological intervention. In addition, the average wash temperature is falling as a consequence of changes in clothing fabric and washing powder. It has been assumed that the wash temperature will fall further from 44°C to 40°C. These two interventions will reduce the energy consumption of domestic washing machines by 33% in each variant.

Consumer Electronics

There has been substantial growth in consumer electronics in the last two decades, and this pace of change is forecasted to continue through the period to 2030. It is difficult to quantify how this might translate into energy consumption since at the same time as ownership of the services provided increases (for instance broadband internet and home cinema) the technology and method of service provision is also changing rapidly. As a consequence, the energy consumption attributable to this sector is assumed to remain constant at 2005 levels and different levels of overall growth in energy consumption in this sector will be used as a sensitivity analysis to test the robustness of the different intervention sets ascribed to each of the variants.

Energy Production

Micro-Combined Heat and Power (µCHP)

A number of µCHP system types are entering the market place including systems based on Stirling engines, internal combustion engines, PEM fuel cells and solid oxide fuel cell systems [25]. The full load electrical efficiencies that encompass these technologies range from approximately 10-20% for Stirling engine systems to 45%-55% for Solid oxide fuel cell systems. The electrical outputs of systems intended for the UK domestic sector lie in the range 0.75 – 5 kW, with 3.68kW being the limit for single phase connections [26]. Estimating the CO_2 emissions savings attributable to these systems is highly dependant on the temporal precision of the power and thermal demand data used [29 – Hawkes and Leach]. TARBASE has employed a dataset for 9 dwelling where thermal and power demand were recorded on a 1 minute time base for a full calendar year. Operational constraints, applicable control options and balance of plant conditions were assumed for each prime mover technology [27, 28].

Figure 5 shows the CO_2 emission savings potential of µCHP systems responsive enough to be controlled under a heat led operating strategy. The CO_2 savings of the µCHP systems increased with electrical efficiency, ζ_e. When ζ_e is low, the thermal power output, P_{ot}, of the system is high for a given electrical output, P_{oe}. The control methodology seeks to limit the production of thermal surplus from the µCHP system. Consequently, increasing the maximum P_{ot} of a µCHP system increases the likelihood that its run time will be curtailed. For instance, a prime mover of P_{oe} = 1kW and ζ_e = 10% in a dwelling with an annual thermal demand of 17.6 MWh was predicted to operate for approximately 32% of the year producing a saving of 197 $kgCO_2$, whereas a system of P_{oe} = 1kW and ζ_e = 30% would operate for 41% of the year producing a saving of 542 $kgCO_2$. The CO_2 savings attributable to µCHP systems is predicated on the production of electricity of lower carbon intensity than the network electricity it displaces. Increasing the electrical output of the prime mover would therefore be expected to increase CO_2 savings. However, when ζ_e = 10%, the effect of increasing P_{oe} is to reduce CO_2 savings. The carbon benefit of increased electrical production is inhibited by the impaired ability of the heat output of the µCHP system to match the thermal demand of the dwelling. Consider two systems; the first where P_{oe} = 1kW, ζ_e =10% and P_{ot} = 5.1kW and the second where P_{oe} = 3kW, ζ_e =10% and P_{ot} = 21.0kW (the greatest thermal output of the systems considered here). For the dwelling with an annual thermal demand of 17.6MWh (Figure 5b), the annual CO_2 savings of the first system were estimated as 197$kgCO_2$ whereas those of the second system fell to 46$kgCO_2$. At high electrical output, the P_{ot} values are still comparatively low (for instance a 3kW prime mover of 30% electrical efficiency has a thermal output of 5.7kW). Consequently, the effect of increasing P_{oe} when ζe is high will be to increase CO_2 savings.

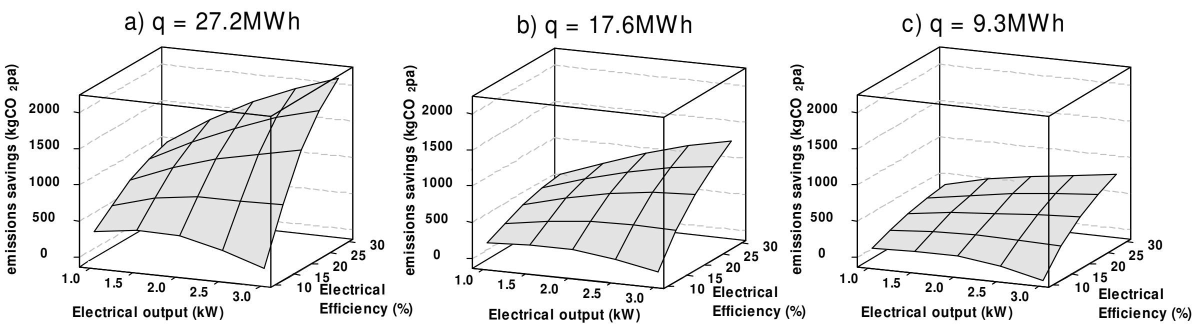


Figure 5: CO_2 savings attributable to µCHP systems with heat led control for dwellings with different heat demand

Using the 9 dwelling dataset it was possible to derive algorithms that allowed CO_2 emissions to be predicted based on the heat demand of the dwelling and prime mover electrical output and efficiency. These algorithms were then applied to the TARBASE domestic variants. Crucially this allowed the inter dependence between µCHP performance and energy demand of the dwelling to be investigated. The ability of µCHP system to reduce CO_2 emissions in dwellings is predicated on its heat demand, with both the overall run time and the time at which the prime mover is operating at full rated output falling with heat demand. The CO_2 savings attributable to µCHP systems and their availability to the electricity network as dispersed generation will therefore be adversely affected by the implementation of heat-saving interventions. For instance, the effects of heat saving fixes on the CO_2 savings of a 1.5kW 15% electrically efficient µCHP system using heat led control were estimated for variants 1 and 7 (figure 6). The savings are compared to those for the original boiler when the same fixes were applied. Additional heat saving measures narrows the CO_2 savings attributable to the µCHP system to the point where in Variant 1, the CHP system savings are now marginal compared to the original 78% efficient boiler when roof, glazing, infiltration and ventilation measures have been applied. For Variant 7, which has a substantially higher heat demand, the savings attributable are reduced from 14% to 6% as a consequence of the heat saving measures shown.

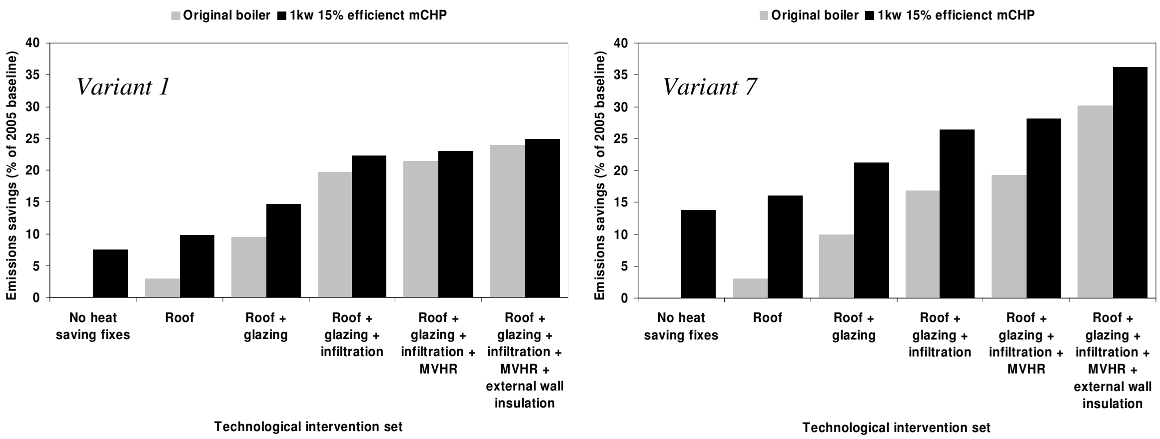


Figure 6: Effect of reduction in thermal requirement on the CO_2 savings attributable to a 1kW, 15% electrically efficient μCHP prime mover when compared to a 78% efficient conventional boiler in the selected building variants

Micro-wind

Considerable economic activity is to be seen in the UK small wind turbine industry with efforts being made to develop the urban environment market through (a) rooftop installations and (b) Vertical Axis Wind Turbines (VAWT's). Present methods for estimating potential yields utilises a database of annual mean wind speed based on a 1 km grid of the UK. These wind speeds do not take account of urban surface roughness and as a consequence yields are typically over estimated by as much as a factor of 7. More accurate yield estimation is not possible at the moment, with local site conditions likely to have a more exacting effect than geographical conditions. TARBASE have monitored the wind speed in two locations on the Heriot Watt University campus over a full calendar year with a temporal precision of 10 minutes. The two sites had mean annual wind speed of 2.0 and 4.8m/s respectively. This wind speed data was applied to the power curves given by the commercial organisations for their wind turbines to estimate the yields available (Figure 7). The results highlight the extremely site specific nature of this technology. The distance between the two wind sites was less than 0.5km and as a consequence, using conventional yield assessment both sites would have generated the same estimated electrical output. Yield estimation varied from between 80 and 570kWh for the year for the 0.4kW turbine to between 500 and 4900kWh for the 2.5kW turbine.

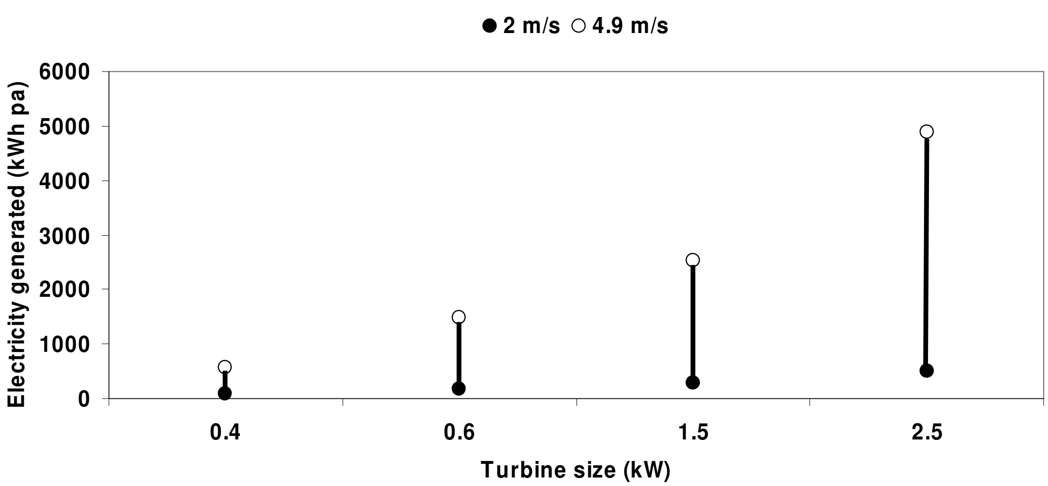


Figure 7: Electricity generation yield for 4 different micro-wind turbines at using two wind speed datasets with annual mean wind speeds of 2.0m/s and 4.9m/s respectively

Solar-PV

Flat plate PV panels, PV roof tiles, thin film systems, PV integrated louvers and glazings are options that may be suitable for domestic applications. Currently flat plate PV panels employing mono or poly crystalline silicon technology with confirmed module peak efficiencies of 22.3% and 15.3% respectively with at least a 20 year life time, are the most implemented. Table 3 presents selected technical specifications of some commercially available PV systems.

Table 3: Technical and economic comparison of presently available different PV systems

System option with supplier	Technology	Peak power density (m^2/kWp)	Module efficiency at STC (%)	Weight /module area (kg/m^2)
PV tiles (Solar Century- Sunslate)	Mono or poly crystalline	11.4	12	36
Flat plate panel (Solarwatts Ltd.- Sharp ND-L3E6E)	Poly crystalline	11	12.4	14.1
Flat plate panel (Wind and Sun Ltd.- BP 7170)	Mono crystalline	9	13.5	12.3
Flat plate panel (BP 485)	Mono crystalline	9.9	12.3	11.9

PV roof tile packages that are currently available are generally limited to applications where complete replacement of an existing roof is required thus allowing a proportion of the PV costs to be offset. Mono silicon thin film PV systems with module efficiency of 8.2% and multijunction thin film PV systems achieving an efficiency of 13.4% are available and are expected to achieve a significant market share of total PV production in near future. PV glazings and PV integrated louvre shading systems are also options for the future. Concentrator PV systems using multijunction solar cells with a confirmed module efficiency of 40% under concentration are available for commercial power generation (minimum 20-25 kW). In the medium to long term such systems may be developed suitable for adoption in domestic situations with specifications of 1-5 kW. Research programmes to develop the high concentration PV systems technology are ongoing in Europe and elsewhere. It is expected that the cost of PV systems will significantly reduce in the medium term bringing them within reach of domestic consumers. The system investigated for the TARBASE domestic variants was a mono-crystalline Flat panel PV module (BP 785, 85 Watt per module) with a system efficiency of 14%.

Using the CIBSE Test Reference Year Climate file for Edinburgh, the yield is estimated for a 1.5kWp system assuming orientation ± 20° of south with no overshading (Figure 8). The annual yield shows characteristic peak in the summer months. The system generated on average of 6kWh per day during the summer months compared to 2kWh during the winter. The same system was modelled for 5 cities in the UK showing variation between Cardiff (the highest yield - 1740kWh pa) and Edinburgh (the lowest yield 1470kWh pa).

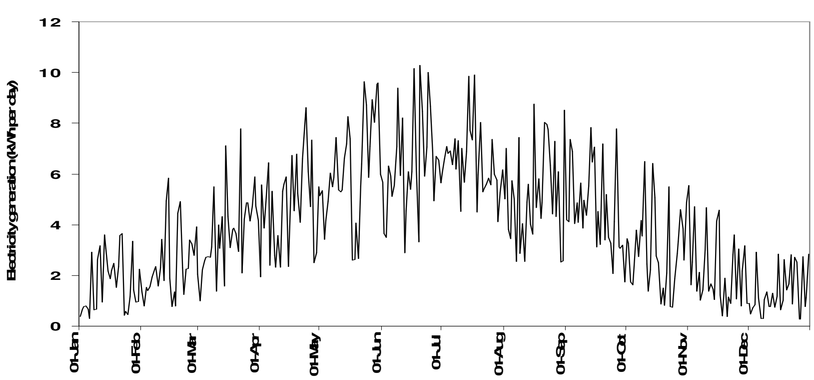


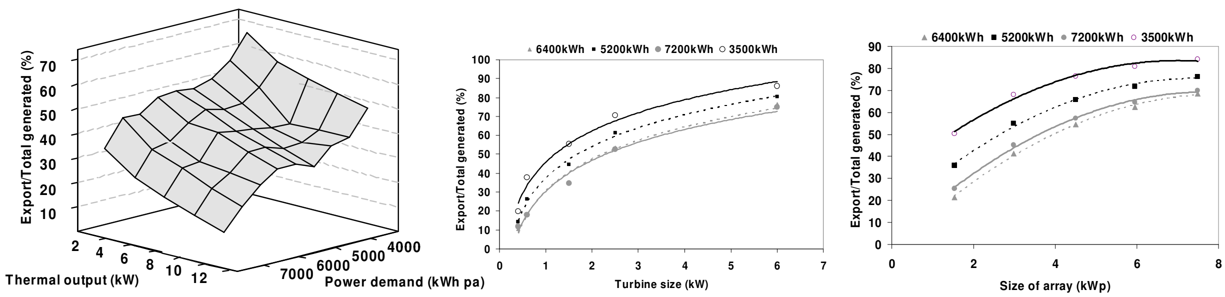
Figure 8: Estimated annual yield for domestic PV array of 1.5kWp (BP 785 – system efficiency of 14%) in Edinburgh with no overshading orientated ±20° of south

Micro-Generation Supply:Demand Matching

A substantive issue concerning the deployment of micro-generation technologies in dwellings is the proportion of electricity that is generated that will be used within the home compared to that exported to the electricity network. The proportion of electricity that is exported is substantial and becomes more so as system sizes increase (Figure 9). Micro-CHP system display a loose relationship between the power demand of the dwelling and the proportion of electricity that is exported for a given prime mover size, although the relationship is confounded by the degree to which the timing of heat and power demand is dislocated. With micro-wind and solar-PV, no such relation ship is found. The figures for CO_2 savings quoted here assume that (a) this electricity will be used elsewhere, (b) that it will incur negligible losses and (c) that electricity generated will displace an equivalent amount of network electricity. It is unlikely that this idealised position will actually be realised and the extent to which the full generation yield will contribute to lowering of CO_2 emissions will be a function of the response of the electricity network, with this relationship becoming more critical as micro-generation penetrations increase.

Figure 9: Electricity generated by micro-generation technologies exported from the dwelling

a) Micro-CHP *b) Micro-wind* *c) Solar-PV*



Gas Condensing Boiler

The average domestic gas boiler efficiency in the UK in 2001 was 78%. This value was assumed in estimating the baseline energy and emission data for the TARBASE domestic variants. Gas condensing boilers are currently in the marketplace with a seasonal efficiency of 93% and this was adopted as a technological intervention.

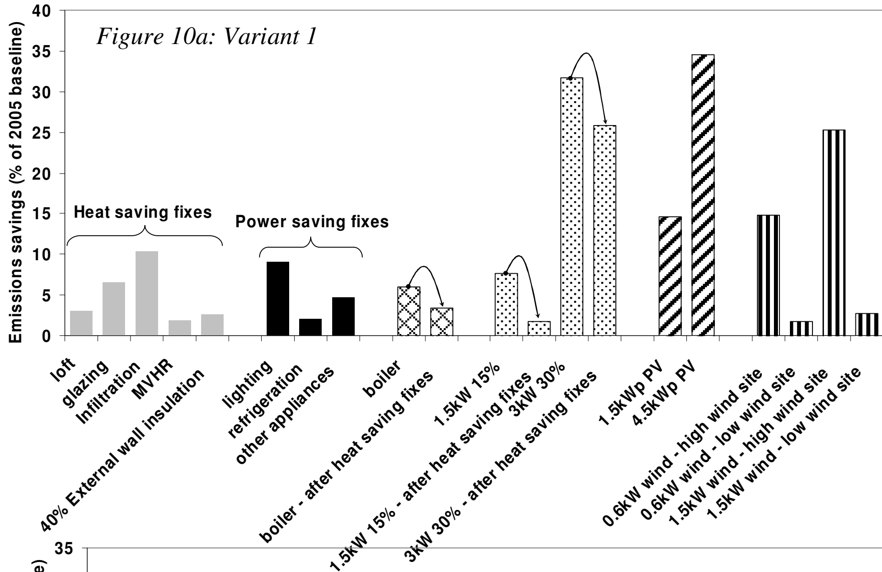
Technological Intervention Sets

Individual Comparison of technological interventions

The effect of the single intervention technologies described in the preceding sections on the 2005 baseline CO_2 emissions attributable to variants 1 and Variant 7 are shown below (Figures 10a and 10b). The heat saving fixes represent current known technology, for instance vacuum glazings are not considered. Demand side fixes save between 2 and 11% of 2005 baseline CO_2 emissions in both variants with infiltration reduction and external wall insulation providing the highest reductions in variant 1 and 7 respectively. The 1.5kW, 15% electrically efficient µCHP system produces only a marginal increase in savings when compared to a 93% efficient boiler with the margin being eradicated if deployment is accompanied by adoption of heat saving fixes. Higher output (and therefore efficiency) systems are likely to be required if margins of improvements over more conventional energy supply arrangements are to be sustained. The Solar-PV system yields (both shown here for Edinburgh) are estimated to produce reductions of 35 and 24% in Variants 1 and 7 for system sizes of 4.5kWp. The risks associated with deployment of micro-wind in urban environments make estimation of effect difficult but it is likely to lie between the two values – with dense urban site likely to tend towards the lower value i.e. below or equivalent to the technological improvement possible in domestic refrigeration equipment.

Grouped Intervention Sets

Figure 11 suggests that it is likely that groups of interventions will have to be deployed in UK domestic dwellings in order to achieve the target emissions reductions. Reductions of the scale sought are not effected by any single intervention. The individual technological interventions were grouped together to form sets, taking account of the interdependencies that exist between for instance power saving fixes and incidental gains and, as discussed in a previous section the effect of heat saving fixes on the performance of both boilers and µCHP systems. Only the high wind yield site was considered as the emissions saves in low wind sites is negligible. On their own, the demand side interventions result in a substantial reduction in CO_2 emissions, as might be expected for the variants studied with savings of approximately 40% estimated for both variants. For Variant 1, only the 4.5kWp PV set and the 2.5kW turbine set achieve the 70% target. Variant 7 had significantly higher initial CO_2 emissions due to its solid wall construction. This confounds the ability of the interventions sets shown here to effect a 70% reduction in emissions. Future 'best' technologies may be required with dwellings of this type to effect the desired reduction in emissions.



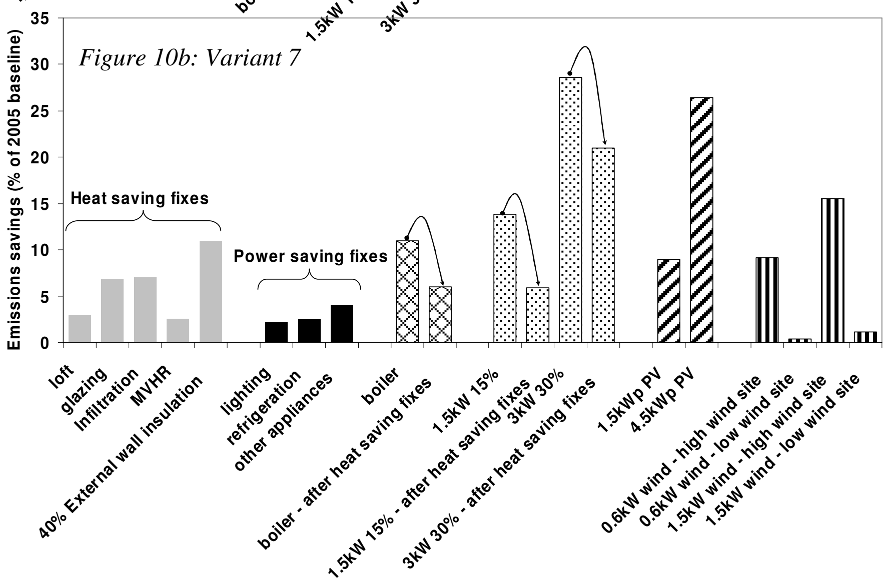


Figure 10: CO2 reduction potential for a range of technological interventions applied to TARBASE Domestic Variants 1 and 7

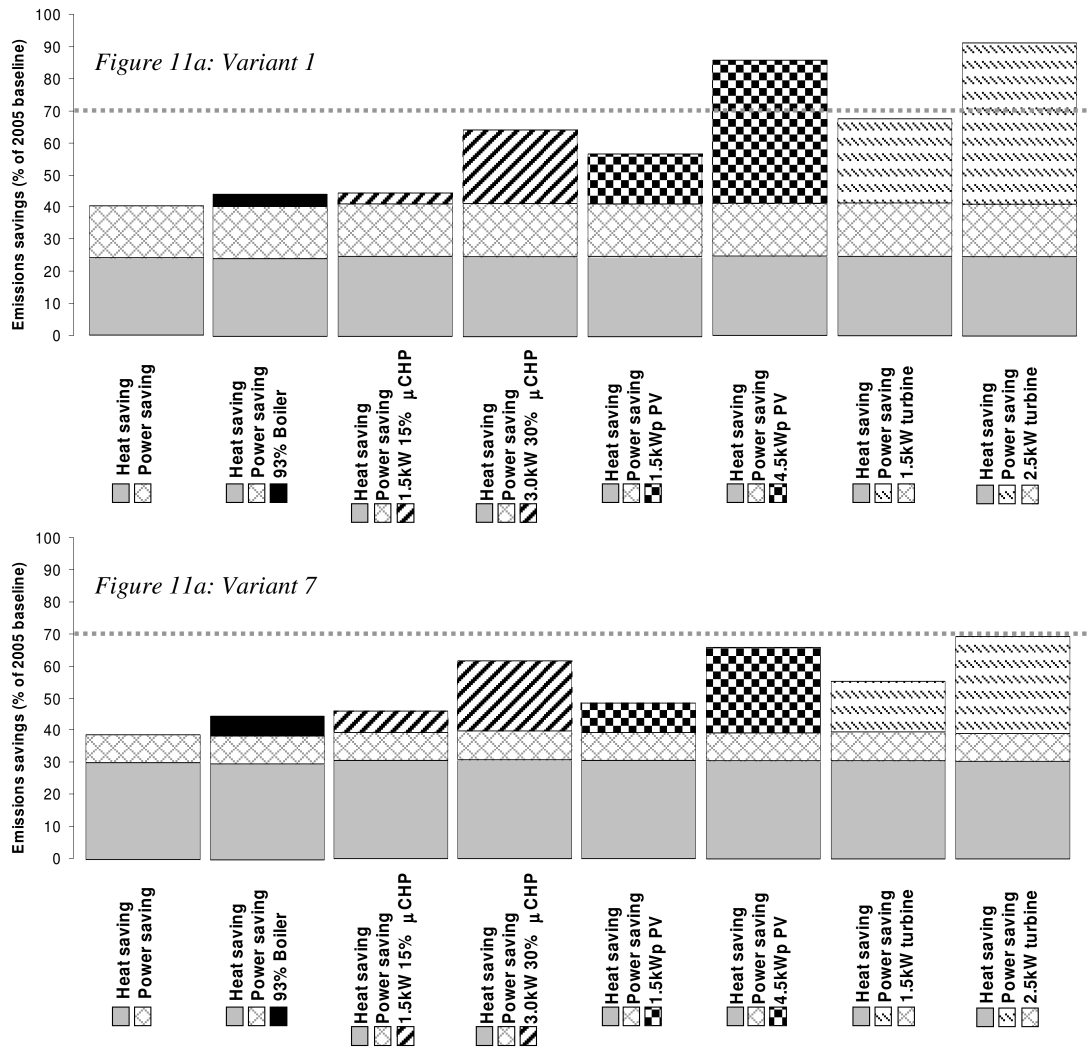


Figure 11: Grouped Intervention sets for TARBASE domestic Variants 1&7

Conclusions

The emissions reduction targets required to address the climate change agenda are only likely to be met through a combination of demand and supply side interventions. Many of the demand side interventions involve mature technologies, with estimations of CO_2 benefit being relatively robust for a given set of circumstances. The CO_2 benefits attributable to the supply side solutions, i.e. micro-generation of electricity are more complex to determine as they rely on the reaction of the electricity network. The capacity of on-site electrical generation (PV, µCHP or wind where applicable) required to achieve a 70% reduction in the building variants studies is such that substantial flows of electricity will be exported from the dwelling to the network. In addition to implications for CO_2 accounting, this will also have a significant impact on the economics of micro-generation with a differential tariff between imported and exported electricity likely to be employed.

Identifying technological solutions for achieving a 70% reduction in UK domestic dwellings is complex. A substantial number of assumptions have to be made regarding for instance construction, occupancy and occupant behaviour in order to define baseline criteria with the technological interventions themselves in certain circumstances being interdependent. The figures presented here can be considered as initial estimations based on a single set of assumptions. Further domestic sector work is being conducted by the TARBASE research group to understand more explicitly the robustness of the estimations made. Sensitivity analyses will involve factors such as thermal comfort, consumer electronics growth, climate change and carbon intensity of network electricity.

Embodied energy and cost metrics are being developed to aid in the identification of intervention sets that appear to be best suited to specific building variants. In addition, the interaction between the building occupants/owners and the interventions is being investigated to understand both acceptability and also changes in behavioural literacy that are implied by their deployment.

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