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Energy and environmental appraisal of domestic laundering appliances

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At a time when UK and Scottish governments are aiming for zero-carbon housing, there are two key issues for domestic laundering: passive indoor drying, affecting heating use and the indoor environment (addressed elsewhere); and energy and environmental impacts of appliances. Relevant findings are reported on the 2008–2011 study 'Environmental Assessment of Domestic Laundering', drawing on monitored data from 22 case studies out of 100 dwellings surveyed in Glasgow. Differing consumer traits and habits, combined with variable technical performance, provide quantitative and qualitative evidence of a wide estimated annual consumption range. Actual usage and energy consumption averaged less than UK predictions; and values did not necessarily correspond with manufacturers' energy ratings. In a wider discussion, case study median and mean extrapolations of electricity consumed by laundering (105 and 174 kWh/person-year) prove significant relative to the proportion of what could be available to a dwelling achieving the German Passivhaus standard. The potential for heat recovery from 'grey' water is posited along with other options for mitigating power consumed by appliances. Renewable technology to offset consumption in shared facilities is discussed as a means of easing the performance of individual homes. The foregoing aspects are among key conclusions directed at housing occupiers, providers, national and local governments, and industry.

Keywords: appliances, consumer habits, domestic laundering, energy consumption, housing, indoor air quality, inhabitant behaviour, plug loads

A l'heure où les gouvernements du Royaume-Uni et de l'Ecosse se donnent pour objectif des logements zéro carbone, il existe deux problèmes concernant le lavage domestique: le séchage passif en intérieur, qui affecte l'utilisation du chauffage et l'environnement intérieur (traité par ailleurs) et les incidences énergétiques et environnementales des appareils électroménagers. Il est fait état de résultats pertinents de l'étude 2008–2011 « Evaluation Environnementale du Lavage Domestique », qui s'appuie sur les données de surveillance issues de 22 études de cas sur 100 logements étudiés. Les différences dans les traits et les habitudes de consommation, associées aux variations des performances techniques, fournissent des éléments quantitatifs et qualitatifs probants indiquant une plage de consommation annuelle estimée étendue. L'utilisation et la consommation d'énergie effectives étaient inférieures en moyenne aux prévisions pour le Royaume-Uni; et les valeurs ne correspondaient pas nécessairement aux classements énergétiques des fabricants. Il ressort d'une discussion plus large que la médiane des études de cas et les extrapolations moyennes de l'électricité consommée par le lavage (105 et 174 kWh/personne-an) s'avèrent significatives quant à la part dont pourrait disposer un logement atteignant la norme allemande Passivhaus. Les possibilités de récupération de chaleur à

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partir des eaux « grises » sont avancées ainsi que d'autres options de réduction de l'énergie consommée par les appareils électroménagers. Il est discuté des technologies renouvelables permettant de compenser la consommation dans des installations partagées comme étant un moyen de réduire les performances attendues de chaque logement. Les aspects qui précèdent figurent parmi les principales conclusions qui s'adressent aux occupants des logements, aux fournisseurs de logements, aux administrations nationales et locales, et à l'industrie.

Mots clés: appareils électroménagers, habitudes de consommation, lavage domestique, consommation énergétique, logement, qualité de l'air intérieur, comportement des habitants, charges des prises de courant

Introduction

The overall research aim of the study entitled 'Environmental Assessment of Domestic Laundering' (EADL) was to investigate the energy use (how significant a proportion of consumption) and other potentially detrimental environmental impacts, and to develop recommendations to address and improve both aspects. The social rented sector in Glasgow is used as the main vehicle for the study for two reasons. Firstly, it targets the greatest need and risk in terms of low income relative to laundering loads, also corresponding with high intensity of occupation over daily and weekly cycles; both representative of post-industrial UK urbanism rather than suburbia. Secondly, it was thought to offer relatively easy access for survey purposes via housing associations, with a history of involvement by the research team. However, identifying the required number of volunteers from this sector proved harder than anticipated, and the scope of the survey was widened to include a proportion of privately rented or home-owned properties. This also helped to improve the demographic spread both for the 100 households initially surveyed, and the 22 households selected from these as case studies for more detailed monitoring. Nevertheless, out of 100, the breakdown of 88 flats or maisonettes suggests the dominance of the social sector, with only 12 terraced, semi-detached or detached dwellings. In the set of 22 case studies, there are only two houses (semi-detached and terraced), the remainder flats or maisonettes; but, as in the total cohort, some of these are also privately rented or owned. In terms of relevance and transferability of the findings to all sectors, the study is, as stated above, confined to a specific post-industrial city, Glasgow, and some differences relative to the whole of the UK are to be expected. In this regard, a significant parallel comparator or benchmark for EADL in Glasgow was the Department for Environment, Food and Rural Affairs' (DEFRA) Market Transformation Programme, which includes domestic laundering across the UK, with key inputs and reference, policy and technology scenarios summarized in four papers (DEFRA, 2010a, 2010b, 2010c, 2010d). The first of these in turn cites an earlier academic UK study (Fawcett *et al.*, 2000).

Between the latter study in 2000 and the present a number of papers have been published that have either direct or indirect relevance to domestic laundering appliances. For example, Wood and Newborough (2003), whilst focusing on cooking in a UK field study of 44 dwellings, related the fact that price is often the determinant of purchase, rather than energy efficiency; that users' perceptions of ranking consumption of appliances is frequently misguided, thus influencing operational behaviour; and that, for example, a tumble-dryer costs 11.4 times as much as a washing machine per hour of running time, adapted from Dobson and Griffin (1992). Rode *et al.* (2004) examined the programming patterns of domestic appliances, compared with 'direct manipulation', and found an average of nearly 30 appliance types in dwellings with an average number of appliances of 34.2; amongst which washing machines ranked easiest to set up as a 'repeated task' and washer-dryers had the potential to set up ahead of time. Chappells and Shove (2005, p. 32) demonstrated 'that comfort is a highly negotiable socio-cultural construct', an argument that might equally be applied to usage of appliances. Wall and Crosbie (2009) went on to examine the reduction of domestic lighting demand from a 'socio-technical perspective' with a sample of 18 UK dwellings investigated in spring 2007; and although respective lighting and appliance control patterns tend to vary, decision culture may be shared (*e.g.* not switching fully off). Richardson *et al.* (2010) described a 'high resolution energy demand model', *e.g.* pointing out the variability of washing machines over their cycle, using information obtained from a leading manufacturer; this work was more recently cited by Blight and Coley (2011). Thus, apart from this and DEFRA's predictive work relative to laundering appliances, there is an evident research gap concerning practice which the Glasgow study seeks to fill; this in the wider context of the 'Sullivan Report' (Sullivan, 2007) in Scotland and the commitment to 'zero carbon' housing by the UK government (Department for Communities and Local Government (DCLG), 2006).

The summarized research objectives embedded within the aims of EADL and in the above context[1] were:

- *Objective 1*
  To evaluate all significant environmental impacts of domestic laundering in varied house types with a

view to identifying: (1) overall energy use and CO_2 emissions resulting from the means used; (2) particularly for drying, the balance between energy efficiency and good air quality; and (3) adverse indoor environmental problems such as condensation risk and associated health impacts; this to be facilitated by means of a two-stage survey of representative dwellings, using an 'interview–observe–measure' methodology to devise key scenarios for controlled laboratory experiments and simulation studies (Objectives 2 and 3 below).

- *Objective 2*
  To measure and improve knowledge of transient, moisture-related properties of relevant materials, surface finishes, furniture, etc. associated with social housing (low-income groups relate to the prevalence of a certain type of furnishings) and to carry out laboratory experiments based on MEARU scenarios – to provide high-quality data for ESP-r model validation (Strachan, 2008).

- *Objective 3*
  To generate a theoretical framework enhancing the capabilities of ESP-r dynamically to model transient moisture transport; to develop a procedure for undertaking parametric tests to cover the large number of factors that influence health and comfort risks; and to extract the important performance metrics for the design variables studied, based on scenarios derived from Objective 1 and material tests of Objective 2. This will include heating and ventilating regimes relative to passive indoor drying (PID) methods in differently planned and constructed house types.

- *Objective 4*
  Dissemination to influence housing procurement, including statutory standards and best practice (with a new Design Guide) in order to address the shortcomings and risks identified in Objectives 1–3 above.

The focus of this paper lies within parts (1) and (2) of Objective 1 – the extent to which appliances are owned and used. This includes, for example, the potential moisture and energy hazards attributable to venting types of tumble-dryers, but not energy and environmental effects of PID (Porteous, 2011, pp. 232–235; Menon and Porteous, 2012; Porteous *et al.*, 2012). Other interactive examples relating to appliance usage are methods of drying potentially influencing the amount of ironing; and both initially driven by the frequency and amount of washing. An underlying agenda apropos the entire study for Objective 1 was to generate realistic scenarios for advanced modelling in Objective 3 (where one parameter at a time can be systematically changed in order to test the significance of laundering scenarios); this having also identified issues of moisture related to laundering that affected a moisture-buffering investigation of materials in Objective 2. The three domestic laundering appliances played their part in this wider environmental analysis, *e.g.* tumble-dryers adding to relative humidity (RH) and space heating loads, as identified in the Results section below.

Method

The method adopted to meet the first objective of the study, as the 'front end' in tackling the overall socio-technological aim, sought to relate relevant measurable data to users' habits, traits and motivations – the latter qualitative aspects axiomatically instrumental in the found conditions of the former quantifiable set, as in any environmental issue related to life in the home. This strategy was executed in two parts: (1) a survey of 100 households, with a questionnaire conducted face to face, plus relevant photographs, 'snapshot' environmental measurements and observational notes by the surveyor; and (2) the monitoring of 22 volunteer households from the initial sample of 100, including logging relevant data for two weeks, air sampling and analysis, and diary-keeping by the householder following a 'script'.

This in turn brings in the influence of demography – the age of children having particular relevance – as well as other traits such as the predominant type or material of clothing, bedding and so forth, as well as hygiene or appearance standards. Such aspects in turn relate to status and income (*e.g.* employed, retired, student, in receipt of benefits and/or tax credits). However, this kind of information was only acquired by default, as a policy decision was taken to avoid such socially sensitive enquiry; relevant questions simply relating to the number and age of adults and children, and typical hours of occupation during weekdays and weekends.

The set of 100 households embraced both demographic and architectural variety, with an 'interview–observe–measure' survey process carried out in differing weather conditions over a calendar year. This consisted mainly of a comprehensive questionnaire, with face-to-face responses subject to observational checking and additional research by the investigator (*e.g.* manufacturers' data for appliances), and spot measurements of key indoor environmental conditions. These were CO_2, temperature and RH, recorded with an Eltek (Cambridge, UK) GENII Telemetry Transmitter GD-47; the second two enabling calculation of vapour pressure to indicate the absolute moisture level; and all such 'snapshot' daytime values comparators for continuous logging of the same variables in the 22 case studies selected from the 100 initially surveyed. The questionnaire had over 600 items, some contextual and some directly related to laundering activity. In each of these categories there were objective, quantitative questions, some of which were 'hard', *e.g.* the type of heating control, or power rating of laundering appliance, and some 'soft', *e.g.* estimates of expenditure on heating, or the use of heating to assist indoor drying. Each category also included subjective, qualitative questions. Examples included reasons for using various methods of drying; those who owned tumble-dryers were asked if they also used alternative methods, and, if so, why; this question was further refined relative to reasons for use of PID devices in addition to tumble-dryers. Those who did not own one were asked why not, with three options offered. Respondents were also asked whether they would use a communal laundry if there were one nearby, and open comments were invited regarding the use of such a facility, etc.

Continuous data collection in the 22 volunteer case studies was carried out over a two-week period – the same environmental variables, plus direct measurement of power consumption by appliances where possible (most commonly the washing machines). Again the Eltek GENII Telemetry Transmitters GD-47 logged environmental data, while power by appliances was measured by means of GC-62 Pulse inputs connected to an ammeter clamp and plug socket; both recording at 1- or 10-min intervals into a GENII Rx250AL Receiver/Logger. The householder augmented these quantitative data with a prescribed diary of laundering activity and other relevant traits, habits or comments. Hence, as for the complete set of 100, there was an appropriate combination of data with the aim of gaining behavioural insights relative to energy consumption. In some instances relevant habits were undeclared, but evident from the objective information, *e.g.* CO_2 often tracking moisture, and therefore the presence of occupants, and migration of air evident at times. In broad terms, the methodology for the 22 case studies, in the context of the larger survey sample, posits that close scrutiny of the particular has the merit of increased understanding of the general.

Air samples, which were collected in each main space in each of the 22 case studies, might only have been relevant in the context of this paper for isolated instances (*e.g.* tumble-dryers vented into habitable spaces). Accordingly, the relevance of the spore analysis is not pursued here.

The staged approach adopted with respect to electricity consumption by appliances was as follows:

- all appliances – washing machines, tumble-dryers and irons – were photographed showing model name/number at time of survey so that this information could be cross-checked subsequently with manufacturers, and this information in turn was cross-checked against answers given in the questionnaire (*e.g.* washing machines hot or cold feed; dryers vented or condensing)
- in cases where use was made of communal laundering facilities within housing schemes, equivalent information was gathered as far as possible
- additional data were obtained from the 22 case studies drawn from the survey sample of 100

  (1) Where possible, appliances were directly measured during the monitoring period as described (normally two weeks' duration, but some for one week due to a short recording timestep at logging set-up; and noting that the majority of washing machines were measured in this way, but not many of a smaller number of tumble-dryers and no irons). (2) Where washing machines or tumble-dryers were not logged directly, values for typical energy consumption were obtained via manufacturers. (3) A controlled test was carried out on a set of three differently power-rated steam irons; this test was used as the basis for estimating consumption. (4) Householders were asked to keep diaries of all laundering activities, and this information was cross-checked with measured readings and with the spread-sheet data from the initial survey, as well as used to facilitate estimates of energy use from manufacturers' data and experimental data per (2) and (3). With respect to (1)–(3), the Eltek system[2] allowed direct transmission of all data by modem, including the other environmental parameters and greatly assisting the logistics of the monitoring process, acknowledging the overlap between initial surveys and monitoring.

Energy consumption by appliances was then examined comparatively in a number of different ways – per cycle, per person, per hour of running time – and key measures extrapolated to estimate annual consumption. These data were then compared with government data as appropriate. Although such extrapolation is conjectural and to an extent subject to seasonal variability, the justification lies in the spread of case studies over four seasons and in the naturally repetitive routine of the three domestic laundering activities of washing, drying and ironing.

Associations between CO_2 as the indicator of indoor air quality (IAQ) and moisture levels were also checked over daily cycles for all 22 case studies, in particular during periods when tumble-dryers were used, this in order to identify where these appliances are likely to have been influencing humidity increase rather than the occupants (*e.g.* due to inappropriate venting). In other words, the method accounts for usage factors that may impact beyond electricity consumption to thermal energy loads, comfort and associated environmental quality. This is relevant to the following commentary on the results.

Results: commentary on appliance use

Summary of laundering habits and key data from survey of 100 homes

Tables 1 and 2 highlight key indicative findings from the initial surveys and questionnaires. Broadly, there is high ownership and use of washing machines and steam irons, but not of tumble-dryers. There is also proportionately little opportunity or take-up of communal or commercial facilities, although these seem popular where used.

For tumble-dryers, all 18 respondents who had their own stand-alone appliances also used other forms of drying – six also using both passive outdoor drying (POD) and PID; three also using only POD, and the remaining nine only PID. The opportunity for POD was also underexploited, with 50 declared facilities (half of the survey sample), but only 36 declared uses – nine, as stated, also using a tumble-dryer, with only one exclusive use of POD and 26 a combination of POD and PID. There were 24 stated disadvantages for POD – 13 related to weather, eight to lack of adequate security or getting mixed up with neighbours' clothing, and three to lack of space. The reasons given for both low ownership and partial use of machine drying was predominantly the consumption and cost of energy used, although lack of suitability for certain materials and increasing the need for ironing was also noted in some cases. More than twice as many of the dryers were C-rated for energy as A-rated, with B-ratings one-third of this subset, and over 60% of the simple vented type.

Table 1 Washing and drying habits relating to appliances in a set of 100 homes surveyed

Scenario	Number	Number	Number	Number	Number	Number
Own washing machine in home (out of 100)	94					
Own washing machine in home plus hand-wash		37 out of 94				
Use commercial laundrette (out of 100)			3			
Use commercial laundrette plus hand-wash				2 out of 3		
Use communal laundry plus hand-wash (out of 100)					3	
Detergents – use biological (out of 94)	49					
Detergents – use non-biological (out of 94)		30				
Detergents – use either (out of 94)			15			
Use fabric softener – yes (out of 94)	52					
Use fabric softener – no (out of 94)		42				
Hand-wash location – kitchen (out of 50)	17					
Hand-wash location – bathroom (out of 50)		32				
Hand-wash location – utility (out of 50)			1			
Use spinner after hand-wash – yes (out of 48)				11		
Use spinner after hand-wash – no (out of 48)					37	
TD location – kitchen (out of 18)	16					
TD location – other (out of 18)		2				
Reason for non-use TD – no space (out of 100)			17			
Reason for non-use TD – too dear to buy (out of 100)				3		
Reason for non-use TD – too dear to run (out of 100)					62	
Those who use TD and other methods (out of 18)						18
Those who use TD and other methods – too dear to run and economise (out of 18)						14
Those who use TD and other methods – not suitable for cloth/material (out of 18)						4

Note: TD, tumble-dryer.

Table 2 Summary data relating to appliances in a set of 100 homes surveyed

Washing Machines

Number	**Manufactuer** (kWh/cycle)[c]	**Energy** Rating (A–D)	**Fastest spin** (frequency)	**Load** (full/half)	**Temperature** (number: °C)	**Cycle** (minutes)
94 (6 wash-dryers)[a]	1.08 mean (0.85–2.05)	57 A 27 B 8 C 2 D	38 never 28 occ[d] 33 all	89 full 5 half	37: 30 52: 40 4: 60 1: 80	54: <60 40: 60–120 +

Tumble Dryers

Number	**Manufacturer** (kWh/cycle)	**Energy** Rating (A–C)	**Type** (vent/cond)	**Load** (kg)	**Temperature** (highest used)	**Cycle Time** (minutes)
18 individual (6 wash-dryers)[b]	3.76 mean (3.25–4.48)	4 A (22%), 6 B (33%), 8 C (45%)	11 vent. (61%), 7 cond. (39%)	8 @ 3–5 kg, 10 > 6 kg	2: never 7: occasionally 9: always	3: < 60 12: 30–60 3: 60–120

Steam Irons

Number	**Manufacturer** (kW output)	**Where?**[e] (L, Br, K, H)	**Iron damp?**[f] (yes/no)	**Amount** [g] (all, $^{1}/2$, $<^{1}/2$)
99–100 used	1.75 mean (1.2–2.4)	56 L, 20 Br, 18 K, 6 H	42 yes, 57 no	26 all 51 $^{1}/2$

Notes: [a] Six washer-dryers included in 94 users of washing machines in homes.
[b] Data for drying for washer-dryers are not included – not comparable with any of 22 case studies.
[c] Manufacturer = available industry estimates for specific models, including from http://www.sust-it.net/.
[d] occ = Occasional use of the fastest spin.
[e] One hundred returns.
[f] Ninety-nine returns out of a total of 100 surveyed.
[g] Approximate amount of washing ironed. Ninety-nine returns out of a total of 100 surveyed.

For the 94% with washing machines, more than twice as many had A-energy ratings as B, with a small minority less than that. In other words, models of washing machines were generally of a higher order of efficiency compared with tumble-dryers. The most frequent wash temperature stated averaged 37°C, with more than one-third at 30°C and more than half at 40°C. Regarding use of the highest temperature setting, two-thirds stated 'never', one-quarter 'occasionally' and a small balance 'always'. Over one-third stated that they always used the fastest spin setting, one-quarter occasionally and two-fifths never. Over two-thirds averaged fewer than four loads weekly, over one-quarter more than four loads and a small number more than ten loads; and most stated that they washed full loads compared with half-loads. Exactly half (50) also hand-washed, nearly all in addition to machine washing, and there was a tendency for those who hand-washed in kitchens also to spin dry, whereas few of the majority who hand-washed in bathrooms did so – location and materiality probably linked.

Most respondents stated that they ironed regularly – more than one-quarter of respondents ironed all of their washing, and more than half did approximately half of it. Over four-fifths also ironed material before fully dry, with implications for IAQ in terms of added moisture and chemicals; with approximately half of the sample using biological detergents and half using fabric softeners.

Some of these indicators are likely to relate to the demography of the sample. Of the 100 households, 72 were adult only, with a maximum of four occupants. The overall average for adults in the set of 100 was 1.73/household – 1.61 in the 72 all-adult situations and 2.07 in the 28 homes with 46 children below the age of 18 years; in turn averaging 1.64 in the subset of 28, 0.44 for the set of 100, and the most densely populated home having five children with ages ranging from one to 12 years and both parents. The average adult age in the total sample was 55 years (minimum of 23 years and maximum of 90 years); while there were only six children aged from 16 to 18 years. The average number of all occupants for each of the 100 dwellings was 2.2, which can be compared with 2.33 for the UK – 61 858 000 persons in 2009 divided by 26 533 000 households (DEFRA, 2010e).

To add more detail to the above, in particular energy consumption by washing machines and tumble-dryers, it is necessary to bring in the 22 case studies drawn from those initially surveyed. Although these represent a statistically small sample, it was 120% greater than that originally proposed, and data acquisition and analysis constituted an upper limit relative to the resources and time approved for the study. The sample also matched the total cohort reasonably well demographically with 1.95 adults per dwelling, 0.44 children and 2.41 total occupants per household. The UK household average of 2.33 in 2009 between respective values for the set of 100 and that of 22 also gives comfort in terms of the relevance of findings in this small sample compared with the national benchmark of DEFRA's energy predictions for what is almost a universal domestic activity.

Washing machine ownership and usage

A very small proportion, 6%, of the total sample interviewed (100) used communal washing machines – three using facilities within their housing block or estate and three using a laundrette outside the estate. One of those using communal facilities within the housing block was included among the 22 case studies, but this household also made use of an individual appliance within the home. Ninety-three of the 94 washing machines or washer-dryers were located in the kitchen, and none in a utility room, as advocated in a Second World War housing design guide (The Scottish Housing Advisory Committee, 1944). In many of the dwellings, including the 22 case studies drawn from the main sample, kitchens were planned directly off living rooms. A slightly smaller percentage, 91% (20 out of 22) of the case studies, owned a washing machine or washer-dryer. Of these, over half (11 out of 20) did some hand-washing and one other washed entirely by hand – a proportion similar to the complete set of 100.

Apart from the issue of moisture migration from various 'wet' kitchen activities, the issue of noise is particularly pertinent for the rapid spin cycles of washing machines. This factor and demography may well influence the timing of washes recorded for the 22 case studies – with mornings found to predominate at approximately 32%, followed by afternoons and evenings at 22% each, then late evening to overnight at 14% and early morning at 10%. In this regard, one respondent explained that she timed washes to coincide with the off-peak tariff, while more generally timing was indicative of family routines. Of these four categories, washes during the evenings are likely to be most acoustically irritating, *e.g.* when watching television in an adjacent living room. With the increasing advent of open living-kitchens the issue of location of washing machines is becoming more pressing, with utility rooms, bathrooms or cloakrooms possible alternatives. The use of washing machines also involves wastewater, with the potential for heat recovery to be addressed below. But it does not involve a significant issue of moisture output or migration unless vented dryers are combined with washing machines, or unless a completed cycle is left in the drum with the door ajar for a period before drying commences.

Within the set of 22 case studies, only one household had a washer-dryer and since there was no mention in the diary of using its drying cycles, and the measured consumption was in accordance with other washing machines, this appliance was regarded as a washing machine only for the purpose of this study. A UK figure calculated for total consumption by domestic washing machines of 4.68 TWh in 2007 (DEFRA, 2008a) translates to 180 kWh/household, given 26.011 million households in the same year (DEFRA, 2010e); and to 77 kWh/person annually, given a population of 60.973 million. These 2007 estimates correspond to 2.34 persons per household compared with 2.41 in the set of 22 Glasgow case studies. The UK-wide figure of 180 kWh/household compares with an arithmetic mean of 166 kWh/household for 20 Glasgow households (out of 22 case studies, one hand-washed exclusively, and there were no reliable data for another). When averaged per person in these households, Glasgow's annual figure was 67 kWh. These two indicators are respectively 8% and 12% less than DEFRA's UK values. Given a maximum to minimum factorial range of nearly 15.0/person and 17.0/household in a small set, statistical outliers will tend to compromise the validity of arithmetic means. The geometric means should be more representative, and these are significantly lower at 53.3 kWh/person (with a median between 50 and 58 kWh/person) and 121.4 kWh/household (with a median between 120 and 126 kWh/household).

Expressed as estimates of annual CO_2 emissions for the same 20 out of 22 with data for using washing machines, the arithmetic means are approximately 36 kg/person and 89 kg/household; and the geometric means are 29 kg/person and 65 kg/household.[3]

Setting aside the issue of sample size, with the relatively narrow period of monitoring and its extrapolation, there are a number of factors that provide a rationale to explain the trend of differences between the Glasgow sample and the UK estimates. In general terms, it is possible that a number of low users in the Glasgow sample have unreasonably biased the averages downwards. More significantly, it is possible that the various methodological assumptions made in the UK case have led to an overestimate. For example, there is a proportional assumption between the typical number of washes at 40°C (68%), 60°C (30%) and 90°C (2%), which indicates a mean of 47°C. Averages given for both the complete set of 100 and for the 22 case studies were approximately 10 K lower; the mean for 121 cycles 36.5°C (where occupants' diaries stated temperature setting: two cycles at 25°C, 54 at 30°C, 56 at 40°C, four at 50°C, and five at 60°C).

Another key UK assumption is 274 cycles/year or 5.27 cycles/household weekly (DEFRA, 2008a). This compares with 3.4 cycles per week or 35.5% less for the average Glasgow household in the set of 20. Translating to weekly cycles per person, the UK figure is 2.26 compared with 1.46 found in Glasgow, a similar reduction of 35%. In the second regard, 75% of the Glasgow sample is below the UK weekly average of 2.26 cycles/person, starting from 1.25 down to as little as 0.25; with a geometric mean of 1.13 cycles/person weekly for the set of 20. The other factor to bear in mind is that these 20 Glasgow case studies included one-quarter with children, averaging two in each of these households. The lower numbers of wash cycles together with the lower temperatures provide a logical basis to explain the disparity between respective estimates. It also tends to support the validity of the small Glasgow sample in its post-industrial urban context; moreover, in a particular year after the major international financial crisis of 2008, which could justify careful budgeting.

Another comparator relating to the temperature of washes, load size and appliance efficiency is the energy consumed per cycle. The DEFRA documentation states that at 40°C and using a 2 kg load, the average consumption would be 0.63 kWh. In the Glasgow series of case studies, with a tendency to lower temperatures but fuller loads (according to diaries kept by users), the arithmetic mean consumption per cycle is 0.75 kWh with a geometric mean of 0.71 kWh; here directly measured in all but one case where a laundrette was used, and with a factorial range from highest to lowest of over 4.0. A related measure used for the Glasgow case studies was energy consumed per hour of running time. The arithmetic mean is then 0.59 kWh with a geometric mean of 0.54 kWh. In this last measure the factorial range increases somewhat to 5.0. The lowest of the 'hot-fill' set was B-rated at 0.21 kWh compared with the highest B-rated 'cold-fill' at 1.05 kWh – both at 30°C. In the highest case, a significant 28% of the gross consumption was in stand-by mode, providing a specific explanation for the high hourly rate. This may be compared with only 8% stand-by for the lowest 'hot-fill' case. Further, of the small number with 'hot-fill' ('cold-fill' now being the UK market norm), the arithmetic mean energy consumption per hour of running time reduces to 0.35 kWh. Indeed this appears to be a better indicator of performance than energy ratings, with 12 A-rated appliances averaging 0.56 kWh/h of running and five B-rated appliances marginally less at 0.55 kWh.

Figure 1 indicates the power used for a typical cycle in one cold-fill, A-rated case study (two elderly adults in a terraced house) – 0.803 kWh over a cycle of 1.82 h for a full load at 40°C, or 0.44 kWh/h of running time. Diaries provided additional qualitative detail with respect to choice and length of some cycles – *e.g.* a respondent who reset after an initial short spin to get a full spin having used a 30°C programme setting for specific items; another who used a 'kids rinse' setting at 60°C that lasted approximately 2.5 h.

Given the above information and line of reasoning, comparison of the Glasgow consumption by washing machines, extrapolated for a full year, with the equivalents estimated for other appliances in the UK is of interest. For example, the Glasgow 166 kWh annual arithmetic mean calculated for washing machines per household compares with UK estimates of 175 kWh

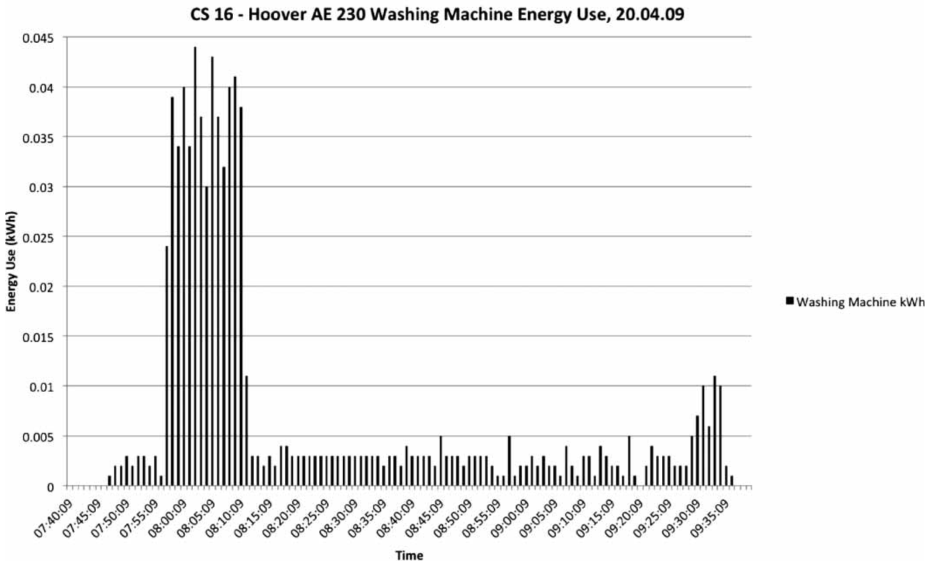

Figure 1 Monitored data: electrical consumption of a washing machine

for an upright freezer, 157 kWh for a fridge and 186 kWh for a fridge-freezer (DEFRA, 2010f); these figures are for the 'best available technology', and noting that Wood and Newborough (2003) give 500 kWh for a fridge-freezer compared with DEFRA's 309 kWh typical consumption in 2009. Comparison with an A-rated dishwasher of medium capacity (nine place-settings) used at an average rate of once for each day of the year at 0.81 kWh/cycle gives a greater contrast at 296 kWh (DEFRA, 2008b); and a 12-place-setting A-rated dishwasher, also averaging one cycle daily at 1.06 kWh, would use 387 kWh, close to the value of 400 kWh given by Wood and Newborough (2003). This can be compared with manual washing, estimated as 1.6 kWh for an equivalent amount of daily dishwashing of a 12 place-setting, which extrapolates to 584 kWh annually (DEFRA, 2008c) – a similar value to that estimated for a D-rated dishwasher with a 12-setting load. In broad terms, dish washing is clearly more energy intensive than clothes washing, but of course washing is only one part of the laundering energy burden.

Tumble-dryer ownership and usage

Approaching one-third (31 of the 100 surveyed households) used a tumble-dryer, 24 with individual appliances within the home (18 stand-alone – 11 vented and seven condensing; and six washer-dryers) and seven using a communal facility (four in a commercial laundrette and three in a communal facility, normally included in the rent). This compares with 45% of the 22 case studies, or ten dryers of which seven were within the home and three were communal or commercial, two of these claiming this as their sole method of drying. Five of the seven in the home were of the vented type, and only two being condenser dryers, and only two used their dryers as the sole method during monitoring (noting again that all 18 out of 100 with stand-alone dryers stated they dried by other means at times). Similarly to the survey returns for the full set, the diaries of the 22 case studies made it clear that economics was a major concern in terms of drying options, with issues such as unsuitability for certain materials and increased need for ironing secondary concerns.

These indications of use and ownership are significantly lower than those calculated for the UK as a whole:

> owned by around 42% households with each tumble-dryer using an average of 354 kWh per year.
>
> (DEFRA, 2008d)

Also this 2007 percentage is predicted to rise to some 44% ownership between 2009 and 2010 when the Glasgow monitoring took place. Moreover, although the figure for consumption closely matches that extrapolated from measuring one of the few Glasgow case studies that used a tumble-dryer exclusively, the number of wash-loads for this household was well below average at 0.5 washes/person weekly. Correspondingly, the DEFRA figure of 354 kWh annually reflects partial use of the tumble-dryer for drying, but quite large amounts of washing in the first instance. The information given is that 148 uses per year, or fewer than three per week, were assumed for those owning a tumble-dryer and that this is 60% of the number of times a washing machine is used in these households. This implies an assumption of 247 washing cycles or 4.75 weekly. Glasgow case studies using their own tumble-dryers averaged 5.1 wash cycles weekly (allowing hand-washes in one instance; and with one user having 13 wash cycles) and 60% of this would amount to 3.06 drying cycles weekly or 159 annually – 7.5% more than the DEFRA assumption. On a pro rata basis one might expect the Glasgow dryer consumption to average some 380 kWh, which is close to the arithmetic mean figure of 377 kWh estimated for the seven case studies using their own machines; as is the median of 390 kWh, with the geometric mean lower at 299 kWh. Comparable figures per person in a household were a mean of 141 kWh for the seven owners of tumble-dryers and 207 kWh when those using communal or commercial dryers are included. Therefore it is evident from the Glasgow case studies that consumption where tumble-dryers are used bears comparison with the DEFRA prediction, even though ownership is significantly lower; and that a small sample indicated a wide range reflecting specific habits or circumstances (varying by a factor of 4.0 computed per person in a household).

Estimated arithmetic means of annual CO_2 emissions for the same seven out of 22 using stand-alone tumble-dryers are approximately 76 kg/person and 203 kg/household; and the geometric means are 68 kg/person and 161 kg/household.

Where cycles were measured in a particular case study (CS 3) of two adults and a young child, not only is a tendency to part-dry in short cycles on a relatively frequent basis evident, but also that vented dryers can result in a rise in humidity in the host room, the kitchen in this instance. This might be due to back-ventilation via a window opened for the flexible vent pipe, and some migration to other spaces within the home is also evident. Ambient humidity during the periods in question was often quite high, with RH over 80% and temperatures from 10 to 15°C. The CO_2 readings in most cases indicate that the presence of occupants is not a factor in humidity increases, and the open window is also bound to add to the heating load during times when the home is heated – the second half of October into the beginning of November for

CS 3. Since the remainder of the drying is carried out passively, normally in the living room, and windows are liberally opened according to the householder's diary, the addition to the heating burden due to laundering will be considerable. Table 3 summarizes key data with regard to tumble-drying in the kitchen, noting that humidity rises tend to prevail even if the drying cycle is quite brief, and that the air quality is always good – comfortably below the 1000 ppm threshold – while the temperature is also reasonably high. Table 3 also shows that the energy use over 19 cycles totalling 14 h 40 min is 15.89 kWh, which gives an average per cycle of 0.836 kWh and an average per hour of running time of 1.08 kWh.

Another case study, CS 5 for which measured consumption was not possible, used the tumble-dryer for the entire drying process, with 24.5 kWh estimated over two weeks based on the manufacturer's information. Again the host room is the kitchen but in this case the rises in humidity are more significant – four times up by over 20%, twice over 25% and once over 30%. At the same time, the CO$_2$ levels, apart from one occasion, tend to be even lower than those for CS 3, supporting the diary statements that windows were left almost permanently open during monitoring. On three occasions the temperature also increases appreciably, but all cycles correspond to some rise in temperature. Table 4 summarizes these data. A realistic explanation is that the tumble-dryer is vented directly into the kitchen. The temperature increase along with humidity would then depend on the rate of ventilation during the drying cycle. However, the ambient conditions were not particularly moist at times when these rises in indoor RH occurred, *e.g.* on 17 October, when RH increased internally by 25%, the ambient temperature averaged 5.85°C and RH was 77% (VP = 0.7 kPa); and on 20 October, when RH increased internally by 32%, the ambient temperature averaged 8.4°C and RH was 67% (VP = 0.73 kPa). On the other hand, on 15 October, when RH increased internally by a smaller amount, 20%, the ambient temperature averaged 16.0°C and RH was 70% (VP = 1.29 kPa). It is possible that this usage occurs because the householder is under the mistaken impression that the dryer is a condensing type.

Table 3 Energy and environmental data relating to tumble-dryer cycles for CS 3

Date	Energy (kWh)	Duration (min)	RH (%)[a]	VP (kPa)[b]	Temperature (°C)[c]	CO$_2$ (ppm)[d]
19 October 2009	0.805	40	58.2–59.7	1.33–1.37	19.6–19.5	818–748
19 October 2009	1.311	90	57.0–61.6	1.30–1.44	19.6–20.0	782–666
20 October 2009	0.599	20	49.0–49.6	1.03–1.05	18.3–18.4	736–717
21 October 2009	1.078	40	58.8–64.6	1.30–1.47	19.1–19.6	615–633
21 October 2009	0.643	30	64.2–62.9	1.46–1.43	19.6–19.5	630–612
21 October 2009	0.856	60	60.0–62.9	1.36–1.44	19.5–19.7	609–640
21 October 2009	0.410	20	62.0–60.9	1.42–1.42	19.7–20.0	609–623
23 October 2009	0.435	30	54.9–57.8	1.35–1.37	20.8–20.2	672–667
25 October 2009	0.873	50	60.4–65.3	1.43–1.56	20.2–20.4	802–746
28 October 2009	0.481	20	62.9–65.3	1.49–1.53	20.2–20.0	666–649
29 October 2009	0.611	40	58.7–61.3	1.41–1.48	20.5–20.5	835–980
29 October 2009	0.749	30	58.1–63.4	1.47–1.54	21.3–20.6	868–733
30 October 2009	0.601	30	57.1–59.3	1.39–1.44	20.7–20.6	627–613
31 October 2009	0.568	40	59.6–62.3	1.57–1.64	21.9–22.0	889–843
1 November 2009	0.724	40	58.4–60.8	1.36–1.47	19.9–20.6	619–680
1 November 2009	0.692	40	56.7–59.7	1.31–1.42	19.8–20.3	622–712
2 November 2009	2.013	130	53.4–59.4	1.22–1.40	19.7–20.1	678–850
2 November 2009	1.508	80	57.6–61.3	1.35–1.50	20.0–20.7	714–701
2 November 2009	0.934	50	59.8–62.5	1.47–1.54	20.8–20.9	758–765
Total period	15.891	880				

Notes: [a] RH range from the start to a maximum during cycle, or to a minimum if a fall is applicable.
[b] VP range from the start to the maximum during cycle, or to a minimum if a fall is applicable.
[c] Temperature range from the start to the maximum/minimum RH point.
[d] Carbon dioxide range from the start to the maximum/minimum RH point.

Table 4 Energy and environmental data relating to tumble-dryer cycles for CS 5

Date	Load (full/half)	Start time (24 h)	RH (%)[a]	VP (kPa)[b]	Temperature (°C)[c]	CO_2 (ppm)[d]
15 October 2009	Full	19.00	67.8–88.7	1.42–2.06	18.2–19.6	420–480
16 October 2009	Full	20.30	53.3–78.6	1.05–1.60	17.3–17.8	481–492
17 October 2009	Full	10.30	42.9–65.5	0.97–1.47	19.5–19.4	670–1038
20 October 2009	Full	23.25	56.0–88.9	1.26–2.38	19.4–22.2	787–560
23 October 2009	Full	17.25	64.5–85.8	1.36–2.37	18.3–22.7	464–534
24 October 2009	Half	08.07	65.5–91.9	1.22–1.83	16.4–17.4	444–683
24 October 2009	Half	12.00	59.9–83.3	1.54–2.40	21.5–23.4	558–544

Notes: [a]RH range from the start to the maximum during 1 h from the start time in the diary.
[b]VP range from the start to the maximum during 1 h from the start time in the diary.
[c]Temperature range from the start to the maximum RH point.
[d]Carbon dioxide range from the start to the maximum RH point.

This is not the case, but that is what is stated in the questionnaire response.

CS 5 again indicates that moisture has migrated to the living room, *e.g.* on 15 October the living room rises from 65.7% to 86.0%. However, on other occasions, the intervening door appears to have been closed. Another flat, CS 6, where high moisture prevailed throughout indoors in an autumnal monitoring period, presented a more complex picture with respect to tumble-drying. This was the sole means used during monitoring in this household of two parents and a young child. The host room for the appliance on this occasion was a bedroom and out of three drying cycles measured over two weeks, only one displayed a significant rise in humidity. However, again this does fit with the explanation of the window, left ajar to accommodate the flexible hose from the dryer, and back-venting occurring only when there is positive wind pressure on it. Table 5 summarizes the data, noting the contrast in duration and consumption compared with the partial drying cycles of CS 3. Here the mean energy consumed per cycle is 4.62 kWh and 3.08 kWh/h of running time. This is also the case study that when extrapolated closes matches the DEFRA figure.

Monitoring of all three of the above case studies took place in autumn. Since all also involved window opening as part of the drying context, the ambient conditions may have played a negative role in the consequent internal level of humidity in some instances, *i.e.* back-venting from tumbler exhaust would mix with already moist ambient air. For example, the mean ambient RH in Glasgow on 30 October was 88% and the mild temperature stable with a mean of 13.7°C and the maximum of approximately 15.0°C and minimum of 13.0°C. Another household, CS 11 with three adults, which used a vented tumble-dryer in early summer as the main method and more frequently than CS 6 also had no regular association with a rise in humidity in the host room. CS 11, again similar to CS 6, tended towards higher CO_2 levels than the first two examples, indicating that occupancy may have helped to mask any humidity effects attributable to the dryer. Table 6 summarizes the key data once again. Note that for the second cycle the high RH of 82.4% is a 10-min spike at the start, sandwiched between 64.5% and 64.8% in the 10-min periods on either side. It is conceivable that the flexible outlet hose was not directed out of the kitchen window during this brief period. Ventilation is reliant on occasionally open windows as

Table 5 Energy and environmental data relating to tumble-dryer cycles for CS 6

Date	Energy (kWh)	Duration (min)	RH (%)[a]	VP (kPa)[b]	Temperature (°C)[c]	CO_2 (ppm)[d]
20 October 2009	5.951	110	65.5–73.5	1.18–1.41	15.8–16.8	1259–698
1 November 2009	5.320	100	77.5–78.1	1.56–1.70	17.6–18.9	988–621
3 November 2009	2.590	60	75.8–68.4	1.37–1.35	15.9–17.3	1407–1256
Total period	13.861	270				

Notes: [a]RH range from the start to the maximum during cycle, or to a minimum if a fall is applicable.
[b]VP range from the start to the maximum during cycle, or to a minimum if a fall is applicable.
[c]Temperature range from the start to the maximum/minimum RH point.
[d]Carbon dioxide range from the start to the maximum/minimum RH point.

Table 6 Energy and environmental data relating to tumble-dryer cycles for CS 11

Date	Load(full/half)	Duration (min)	RH (%)[a]	VP (kPa)[b]	Temperature (°C)[c]	CO_2 (ppm)[d]
29 May 2009	Full	110	68.9–74.1	2.33–1.74	21.8–21.4	1486–1589
03 June 2009	Half	50	82.4–61.8	1.56–1.70	23.1–23.0	825–1002
06 June 2009	Half	50	67.3–60.2	1.61–1.48	20.4–20.8	840–1034
06 June 2009	Half	40	60.6–64.0	1.46–1.54	20.5–20.5	1132–972
09 June 2009	Half	45	60.1–63.2	1.39–1.47	19.7–19.9	837–840
Total period		295				

Notes: [a]RH range from the start to the maximum during cycle, or to a minimum if a fall is applicable.
[b]VP range from the start to the maximum during cycle, or to a minimum if a fall is applicable.
[c]Temperature range from the start to the maximum/minimum RH point.
[d]Carbon dioxide range from the start to the maximum/minimum RH point.

Table 7 Window opening on washdays from 29 May to 12 June 2009 for CS 11

Date	Living	Bedroom 1	Bedroom 2	Bedroom 3	Kitchen	Bathroom
29 May	Nil	30 min	Nil	Nil	Nil	20 min
3 June	Nil	1 h	30 min	30 min	30 min	1 h
6 June	Nil	1 h	10 min	30 min	30 min	20 min
9 June	Nil	1 h	30 min	20 min	30 min	30 min

Table 8 Energy and environmental data relating to tumble-dryer cycles for CS 12

Date	Energy (kWh)	Duration (min)	RH (%)[a]	VP (kPa)[b]	Temperature (°C)[c]	CO_2 (ppm)[d]
25 May 2009	1.100	50	57.7–62.6	1.19–1.32	18.2–18.3	566–591
29 May 2009	0.470	20	65.4–67.8	1.35–1.37	17.9–17.9	590–587
31 May 2009	0.270	20	43.8–44.6	1.23–1.25	23.5–23.0	503–501
Total period	1.840	90				

Notes: [a]RH range from the start to the maximum during cycle, or to a minimum if a fall is applicable.
[b]VP range from the start to the maximum during cycle, or to a minimum if a fall is applicable.
[c]Temperature range from the start to the maximum/minimum RH point.
[d]Carbon dioxide range from the start to the maximum/minimum RH point.

shown in Table 7, and CO_2 levels bear this out, with higher values compared with some of the autumn households that were operating heating systems.

Another early summer case study, CS 12, whose sole occupant used a tumble-dryer sparingly in a bedroom (this to complete drying of hand-washed items that had been partially passively dried), yielded similar indeterminate results to those of CS 11. The main difference is that CO_2 values are significantly lower. This in turn accords with a rather better ventilated or less intensively occupied regime compared with CS 11, resulting in rather lower levels of humidity (Table 8).

Finally, in this set of individual tumble-drying cases where habits of occupants can result in raised internal humidity levels as well as increased heating consumption, a comparison is made with two homes using a condenser dryer, initially CS 8. This was a household of two adults monitored during the autumn at a similar time to CS 3, 5 and 6. Although the first full load and third half load both correspond with a rise in humidity, they also have rises in CO_2, indicating that occupants may have raised humidity. The data for the second and fourth cycles suggest that when CO_2 is stable, *i.e.* occupancy is not an influence for change, the condenser type of dryer does not influence humidity in the same way as

Table 9 Energy and environmental data relating to tumble-dryer cycles for CS 8

Date	Load	Start time (24 h)	RH (%)[a]	VP (kPa)[b]	Temperature (°C)[c]	CO_2 (ppm)[d]
17 October 2009	Full	17.00	60.8–68.5	1.16–1.35	16.8–17.3	710–1177
17 October 2009	Half	20.30	69.5–69.9	1.41–1.42	17.7–17.8	934–897
17 October 2009	Half	22.50	68.1–73.8	1.39–1.55	17.8–18.2	670–1038
24 October 2009	Full?	20.30	76.9–76.5	1.53–1.49	17.4–17.1	776–755

Notes: [a]RH range from the start to the maximum or minimum during 1 h from the start time in the diary.
[b]VP range from the start to the maximum or minimum during 1 h from the start time in the diary.
[c]Temperature range from the start to the maximum or minimum RH point.
[d]Carbon dioxide range from the start to the maximum or minimum RH point.

the vented type (Table 9). Not having to open windows in order to cope with a flexible hose is logically a significant factor in this regard.

The second home with a condenser dryer, CS 4, had two drying cycles during the monitoring period and in this instance there was a slight fall in humidity on both occasions, 71.2–70.9% and 64.3–62.2%, while temperatures remained steady and CO_2 levels also dropped slightly.

Steam iron ownership and usage

Of the 100 households surveyed, 99 stated they used the steam function on their iron and one did not. Fifty-six ironed in their living room, 20 in a bedroom, 18 in their kitchen and six in the hall (total of 100). Twenty-six said they ironed all their washing, 51 approximately half and 22 less than half (total of 99). Asked whether they would iron before items were fully dry, 42 said ‘yes’ and 57 ‘no’ (total of 99). Nineteen out of 42 (45%) also used a fabric softener, *i.e.* 19% of the total claiming to iron. Not only does this last aspect have a bearing on the amount of moisture released during ironing, but it may also have significance relative to the release of acetaldehyde (Steinemann *et al.*, 2011). This is recognized as carcinogenic and water-soluble volatile organic compounds (VOCs) such as aldehydes will also increase in concentration with moisture; *e.g.* formaldehyde concentrations in the air have been found to be ‘directly proportional to the relative humidity at a given temperature’ (Arundel *et al.*, 1986, p. 357). However, such potential significance is inevitably qualified. Even though the climate in West Scotland bears comparison with the Pacific seaboard of the United States and Canada, where this research was carried out, home-laundering culture is different, as are the characteristics of housing. Nevertheless, given the importance now attached to IAQ and associated health hazards, the American work indicates that there is a case for similar future investigations in the UK.

In the smaller sample of 22 case studies, a slightly smaller proportion, 38% (eight out of 21), ironed before their washing was fully dry, but of these a larger proportion, 62.5% (five out of eight), used a fabric softener – 24% or nearly one-quarter of those ironing; and four out of those five said they ironed all their washing. Again, there is a two-fold concern – added humidity where already over-moist, and release of chemical irritants.

Similar proportions of those in respective cohorts (100 initially surveyed and 22 case studies), where use of tumble-dryers dominated, said they ironed all their washing: 29%. This was also of the same order as those without tumble-dryers, 27% and 28.5%, respectively. However, when estimated quantitatively in terms of energy, tumble-dryers corresponded with greater ironing consumption. Since there was a large range of irons owned and consumption could not be directly measured, it was necessary to establish hourly consumption as a function of the iron’s power rating. Hence a controlled test was carried out. This established a shallow curve for consumption per half hour of ironing, which enabled quantification based on known power ratings and information in householders’ diaries.

The arithmetic mean estimates for energy used by ironing thus determined for 19 out of 22 households were 12.5 kWh/person annually and 25 kWh/household; with respective geometric means of 9.9 kWh/person and 21.0 kWh/household. The former were 39% more per person and 31% more per household for those using tumble-dryers compared with the entire set. Respective increases were similar for geometric means, but rose significantly when comparing tumble-dryers with non-tumble-dryers – 67% and 58%, as shown in Table 10.

Estimated as annual CO_2 emissions for the same 19 out of 22, the arithmetic means are approximately 7 kg/person and 14 kg/household; and the geometric means approximately 5 kg/person and 11 kg/household.

Figure 2 and Table 11 summarize data for an initial practice for the controlled ironing test, followed by

Table 10 Ironing consumption relative to drying method

Sample	Households (*n*)	Average	kWh/p-year	Percentage increase	kWh/h-year	Percentage increase
TD set	8	Arithmetic	17.4	39	32.9	31%
All set	19	Arithmetic	12.5 (100%)		25.1 (100%)	
TD set	8	Geometric	13.2	35	27.2	31%
All set	19	Geometric	9.9 (100%)		20.8 (100%)	
TD set	8	Geometric	13.2	67	27.2	58%
Non-TD set	11	Geometric	7.9 (100%)		17.2 (100%)	

Note: kWh/p-year = annual consumption per person; kWh/h-year = annual consumption per household.

three ironing sessions, each with different irons, but the same number of fully dry garments – two pairs denim jeans, three shirts, one pair of shorts and two t-shirts. The maximum power output for respective models was 1.2, 1.45 and 2.0 kW. RH, temperature and CO_2 concentration of the room over the duration of the ironing were logged with the monitor placed at a height of 1.0 m and not in the path of any direct solar radiation. The true electrical draw of each appliance was recorded at 1-minute logging and 3-second measurement intervals. Irons were used on maximum heat for the majority of the experiment, but in each instance turned down to medium heat for last two items (two t-shirts). The results show that consumption does not increase proportionally to maximum power output. Respective iron 1 (1.2 kW), 2 (1.45 kW) and 3 (2.0 kW) consumptions translated to 30 minutes in all cases were 0.233, 0.267 and 0.280 kWh; this implying a flattening curve as the power increases. The first test ironing was undertaken to check equipment and to create the 'control' start condition for the clothing. Prior to each ironing phase, the dry garments were mixed, placed in a laundry basket and compressed, by body weight, to ensure that a random and even creasing was maintained as best as possible throughout the process – it was essential to endeavour to maintain a parity of the volume and complexity of ironing which was required at each phase.

After the last phase of ironing the room was left for 30 minutes with the door closed to allow the decay of parameters to be monitored under these conditions; and was then left with the door open for comparison. It was noted that the initial test phase was longer than the three trials and resulted in the largest rise in vapour pressure – 0.274 kPa in 39 minutes. The first two ironing cycles each resulted in another 0.145 kPa increase in 22 and 21 minutes, respectively, and the third only a further 0.076 kPa rise in 15 minutes. Although decreasing times spent from minimum to maximum are clearly relevant,

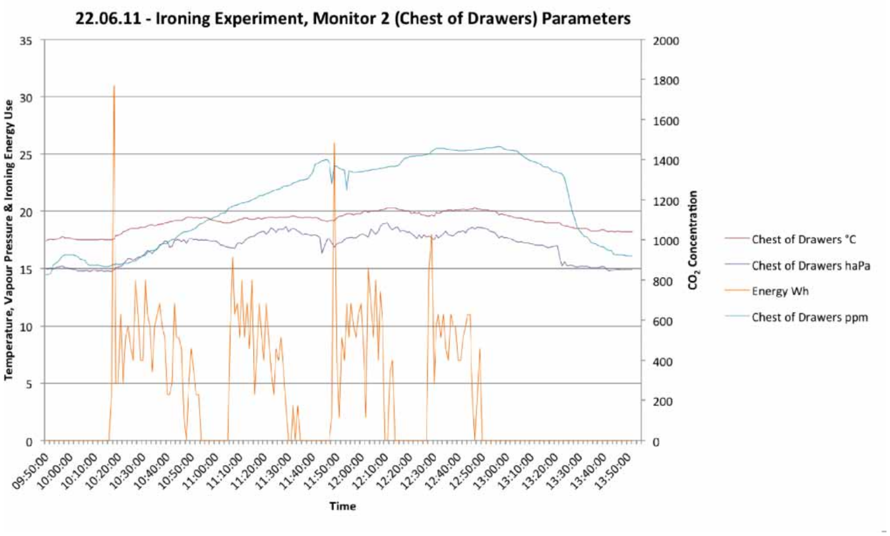

Figure 2 Monitored data: steam ironing experiment from the 'chest of drawers' position. Room volume = 41.3 m^3 (a tenement bedroom, with reasonable volumetric equivalence to a modern living room). The experiment was conducted in a bedroom with the door closed for the duration. The door was briefly opened at 10.57, 11.45 and 12.50 hours. The room trickle vent was open throughout the duration of monitoring.

Table 11 Energy-use results

Iron number	Ironing duration (min)	Total energy use (kWh)	Equivalent energy/h
01	29	0.225	0.465
02	26	0.231	0.533
03	21	0.196	0.560

this does not proportionally account for all of the respective reductions. For example, direct proportionality relative to time for the third ironing session would have given a rise of 0.105 kPa, whereas the actual rise of 0.076 kPa is only 72% of this. It is possible that variable air flow via the trickle vent accounted for some of the diminishing impact, but it is more likely to be due to a delayed timescale in terms of absorbent materials accumulating some of the water vapour from the iron and ironer, *e.g.* bedding.

Having already established that approximately two-fifths of households tend to iron before material is fully dry, the above results using dry clothing represent a 'best case' scenario. Although energy consumed is relevant, it is the interactive nature of a practice with respect to one appliance affecting practice with another that seems likely to have the most significant environmental consequences. For example, any release of VOCs from fabric softeners in the wash cycle is likely to be concentrated if partial drying cycles are followed by steam-ironing sessions; in the same way that tumble-drying vented through open windows can add to heating demand and raise humidity. By contrast, use of a community or commercial laundrette for all three functions removes all such environmental hazards from the home environment.

Discussion: a need for a change in ways and means?

Extending the agenda

The above results for the use of the three laundering appliances reflect differing domestic routines, involving personal traits and habits, with a common denominator of hygiene, but with scope for significant lifestyle differences – whether a daily set of both working clothes and leisure clothes; clothes for sporting activities; frequent teenage changes or infrequent, dependent on gender, etc. Averages given above for each appliance, based on the numbers using them out of 22 case studies, when treated as a set reflect the relatively low use of tumble-dryers – 174 kWh and 94 kg CO_2 annual estimated arithmetic mean per person; and respectively 105 kWh and 56 kg CO_2 for the median and 108 kWh and 58 kg CO_2 for the geometric means. Since the proportion using tumble-dryers falls further for the 100 households initially surveyed, it may be inferred that these averages would be lower. However, without defining their context in the domestic energy firmament, these quantities do not indicate whether they can fit easily within an overall energy-efficient framework, commensurate with governmental aspirations and targets.

Hence, the research questions embedded within the stated objectives relevant to the topic of this paper, having been met as described in the commentary on results above, have wider implications. Two key ones are the relationship of the energy consumption by domestic laundering appliances to the prevailing whole-house energy-efficiency standards, and what changes to best practice are needed or desirable. The first issue locates Scotland and the UK in a European Union context, and the second involves governmental instruments, housing providers, industry and consumers.

Electricity consumed by laundering appliances in a Passivhaus context

It has been established above that the Glasgow study, accounting for both ownership and usage, indicates a tendency to consume less electricity for laundering appliances than values predicted for the UK as a whole – estimated as 4.3% of the total energy consumption (DEFRA, 2008e). Notwithstanding current wavering of the UK government's 2006 decision to include all electrical consumption from appliances in its definition of 'zero carbon' (DCLG, 2006; Porteous and Menon, 2008a) and Scotland's adherence to regulated energy use (Sullivan, 2007), there is an inexorable drive to ratchet up thermal standards in European Union countries. Given the increasing presence of the German Passivhaus standard in this context, it is of interest to relate the average Glasgow consumption by laundering appliances to that which might be available in a typical Passivhaus scenario. Accordingly three 'what if?' scenarios are examined in terms of values for laundering appliances:

- *Scenario A*: a mean where space heating is 91% efficient, water heating 85% efficient and 40% met by solar thermal
- *Scenario B*: a median where space heating is 91% efficient and water heating as Scenario A
- *Scenario C*: a mean where space heating is 85% efficient, water heating 80% efficient and there is no solar thermal

The scenarios are examined both in terms of floor area of 65 m^2, which is representative of the Glasgow study, and 90 m^2, which is representative for the UK as a whole (see below). If the Passivhaus space heating maximum of 15 kWh/m^2 is first divided by 0.91 (the efficiency of a gas condensing 'combi' boiler) to give

16.5 kWh/m^2 delivered, and then the result is divided by a 'primary to delivered' coefficient of 0.90, the 'demand' limit rises to 18.3 kWh/m^2. If the assumed delivered hot water for 2.41 persons (the mean found in the Glasgow case studies) at 85% efficiency is 2300 kWh, with 40% met by solar thermal collection, and dividing the balance by 65 m^2, this gives 21.23 kWh/m^2; in turn dividing this by a 'primary to delivered' gas coefficient of 0.90, the primary hot water by fossil fuel comes to 23.6 kWh/m^2. The primary energy total for space heating and hot water is therefore approximately 42 kWh/m^2. Subtracted from the Passivhaus limit of 120 kWh/m^2 for total primary consumption, this leaves 78 kWh/m^2. To allow a margin for fans, pumps and efficiency loss, the balance is reduced to 76 kWh/m^2, which in the UK indicates approximately 28 kWh/m^2 available for use in the home. Taking Scenario A, the mean laundering consumption of 174 kWh/p-year (annual consumption per person) divided by 0.365 primary electrical efficiency (DEFRA, 2011, pp. 14, 17)[4] gives 477 kWh/p-year; and this multiplied by 2.41 persons = 1149 kWh/year; thence divided by 65 m^2 = 17.7 kWh/m^2; which is 23.3% of the 76 kWh/m^2 Passivhaus balance for lighting and appliances, now reduced to 58.3 kWh/m^2, or approximately 21 kWh/m^2 delivered for lighting and other appliances.

Repeating for Scenario B, with a median average of 105 kWh/p-year, the primary value for laundering drops to 10.7 kWh/m^2, which decreases the proportionate share of total lighting and appliances to 14% of the 76 kWh/m^2 allowance. This leaves approximately 24 kWh/m^2 for lighting and other appliances.

However, although 65 m^2 was representative for the Glasgow case studies, Boardman *et al.* (2005), citing work published by the Office of the Deputy Prime Minister (ODPM) (2003), indicates higher UK floor areas, *e.g.* 88 m^2 for a two-person household and 93 m^2 for a three-person household. The UK average number of occupants per household is given as 2.33 in 2009, when most of the Glasgow monitoring occurred, and 2.31 in 2012 (DEFRA, 2010e).

Interpolating from the ODPM figures, this gives an approximate area of 90 m^2 for 2009–2012. Applying this area to the Glasgow laundering averages would lower the total/m^2 for heating and hot water and so increase the balance available for power. Additionally, one must bear in mind that the lower values estimated for washing and tumble-drying in Glasgow compared with the official UK predictions, as noted above, will tend to favour the specific part of this balance left for lighting and other appliances.

Repeating the calculation for Scenario A at 90 m^2, the Passivhaus estimate for hot water and space heating reduces to 35.34 kWh/m^2, leaving 82.66 kWh/m^2 for all power needs other than fans and pumps. The laundering power use, as found in the Glasgow case studies, now reduces to 12.8 kWh/m^2, 15.4% of 82.66 kWh/m^2, with a residual of 69.9 kWh/m^2 primary energy for all other power. This translates to approximately 25.5 kWh/m^2 at point of use (69.9 × 0.365).

Similarly Scenario B would be modified downwards using the UK average of 90 m^2 floor area for 2.31–2.33 persons per household. In terms of Scenario C, it also seems likely from recent monitoring studies – *e.g.* at Elm Tree Mews (Bell *et al.*, 2010) – that actual boiler efficiencies for A-rated condensing boilers will be lower for heating – approximately 85%, not over 90%; and hot water may be subject to the vagaries of intermittency and distance from boiler to supply point; noting that the 2006 Standard Assessment Procedure (SAP) rating for a condensing gas boiler was 85% for heating and 83% for hot water (2006). If one pragmatically assumes an 85% heating efficiency and an 80% hot water efficiency, and then omit a solar thermal system, for a floor area of 65 m^2, the primary electricity available for lighting and appliances other than for laundering is approximately 43.7 kWh/m^2, and 58.9 kWh/m^2 for 90 m^2. In terms of useful electricity available to the consumer, this translates respectively to 16.0 and 21.5 kWh/m^2.

In order to pursue this 'what if?' line of enquiry further, the estimated Glasgow values for laundering appliances will be used alongside UK averages for other appliances expressed firstly for a floor area of 65 m^2 and secondly for 90 m^2:

- lighting ('earliest best practice' (EBP)) 4.6; 3.32 kWh/m^2 (DEFRA, 2008f)
- fridge ('best available technologies' 2008) 2.4; 1.73 kWh/m^2 (DEFRA, 2010f)
- upright freezer ('best available technologies' 2008) 2.7; 1.95 kWh/m^2 (DEFRA, 2010f)
- dishwasher (A-rated, nine-place-setting capacity) 4.6; 3.32 kWh/m^2 (DEFRA, 2008b)
- personal computers and laptops 2.65; 1.91 kWh/m^2 (DEFRA, 2010g)
- televisions 4.6; 3.32 kWh/m^2 (Chobanova *et al.*, 2009)[5]
- electric kettles 1.9; 1.37 kWh/m^2
- hobs 3.3; 2.28 kWh/m^2; ovens 1.5; 1.08 kWh/m^2
- microwave 1.4; 1.01 kWh/m^2 (DEFRA, 2008g)

The respective totals for appliances other than those for laundering and miscellaneous items are 29.65 and 21.29 kWh/m^2.

This cumulative process based on available data reveals a significant underlying problem for Scenarios A–C for a 65 m^2 floor area, but suggest that Scenario A and 90 m^2 should be feasible within the Passivhaus standard, providing the relatively low values for laundering appliances in Glasgow prevail. Although the analysis omits miscellaneous electrical items such as electric toasters common in most homes, the balance of 25.5 kWh/m^2 gives some leeway relative to 21.3 kWh/m^2; this assuming maximum efficiency ratings and EBP. Scenario C at 90 m^2 is borderline in this regard – see the summarized data in Table 12.

What this means is that unless the primary to useful delivered grid efficiency in the UK improves significantly, Passivhaus standards will be hard to achieve, especially when or where house areas are small. Even if all appliances, including those relating to laundering activity in the home, move to maximum achievable efficiency and consumers become more frugal in their use of such commodities, in the normal constrained 'social' and competitive private housing sectors, low- and zero-carbon standards will remain illusory. It is clear that primary energy generation must improve its efficiency as well as reducing greenhouse gas emissions. This would have to be in tandem with industry achieving targets such as EBP, housing providers achieving much higher standards than at present (*i.e.* reducing space heating and water heating demand), and consumers reducing their consumption, when at present the trend is increasing – one may assume ironically reflecting the success of the free market in a period when the threat of climate change suggests constraint.

Potential to improve efficiency of appliances: better than EBP, etc.

The Glasgow study has indicated that market penetration of the most efficient up-to-date models is relatively slow, especially in the case of tumble-dryers. This meant that although the estimate of average use by stand-alone appliances per household was comparable with the DEFRA estimate, the lower level of ownership in a sample of 100 dwellings implied considerably lower consumption than predicted for the UK as a whole. Of the three appliances used in the home, tumble-dryers nevertheless represent the greatest challenge – in terms of energy consumption by the appliance itself, added energy consumption due to venting practice and in raised humidity in the latter case. Ironing also tends to be more frequently used by those who tumble-dry as well as also involving ironing before the material is fully dry. The process of tumble-drying consumes and rejects considerable amounts of thermal energy, with air as the medium to be heated, as do washing machines to a lesser degree with water as the medium. There are also issues with option of either passive outdoor drying (POD) or passive indoor drying (PID), and specific environmental and health concerns with regard to the latter that will be explored in depth relative to this study elsewhere. The industry move to cold-fill washing machines inevitably results in greater primary energy consumption than if water is heated by a fuel other than electricity with a much greater primary to delivered efficiency. If manufacturers were to revert to hot-fill, both primary energy and CO$_2$ emissions could be saved. Ironing consumes a significantly smaller amount of energy, but is also associated with other potential environmental hazards.

The other aspect that has emerged from the commentary on findings in this paper is the environmentally interactive roles played by the three laundering

Table 12 Testing the viability of the Passivhaus standard relative to laundering data

Scenario	hw + sh (PE) (kWh/m^2)[a]	Net el'y (PE) (kWh/m^2)[b]	Laundry (PE) (kWh/m^2)[c]	Balance (PE) (kWh/m^2)[d]	Balance (UE) (kWh/m^2)[e]	UK cf. (UE) (kWh/m^2)[f]
(A) 65 m^2	42.0	76.0	17.7	58.3	21.3	29.65
(A) 90 m^2	35.3	82.7	12.8	69.9	25.5	21.29
(B) 65 m^2	42.0	76.0	10.7	65.3	23.8	29.65
(C) 65 m^2	61.4	56.6	17.7	38.9	14.2	21.29
(C) 90 m^2	44.3	73.7	12.8	60.9	22.2	21.29

Notes: [a] hw + sh (PE) = hot water plus space heating (Primary Energy).
[b] Net el'y (PE) = net electric power available having deducted fans/pumps (Primary Energy).
[c] Laundry (PE) = power estimated for laundering appliances in Glasgow (Primary Energy).
[d] Balance (PE) = balance electric power available for lighting plus appliances (Primary Energy).
[e] Balance (UE) = balance electric power available for lighting plus appliances (Used Energy).
[f] UK cf. (PE) = UK comparator (official estimates) for lighting plus appliances (Used Energy).

appliances taken together with consumer choices. Examples include whether hand-washed items are spun or not spun being apparently dependent on where the hand-wash occurs; the use of tumble-drying relative to the need for ironing; the type of tumble-dryer relative to additional space heating loads; rationing of tumble-drying and augmenting by PID, together with type of detergent and additive such as fabric softener affecting IAQ as well as convenience, aesthetic ambience, etc.

Ideally, if all three processes occur outside the home in a communal facility, not only are all the hazards displaced to another location, but also the scale of the operation offers greater scope for energy economy and heat recovery (Menon *et al.*, 2010). For example, if such a facility were located on the ground floor of a tower block, as in two of the Glasgow case studies (one a full laundry, the other dryers only), potential exists for some of the heat from a combined heat and power (CHP) system to be used as hot air for tumble-drying. One of the housing associations concerned previously commissioned a detailed ‘options appraisal’, which included the possibility of installing CHP serving such tower blocks in order to convert from electrical storage to ‘wet’ central heating (Porteous and Menon, 2008b). This infrastructure is now nearing completion. If such systems are matched to electrical demand, the tendency is to have more heat than required for water heating and space heating, especially as such buildings are simultaneously thermally upgraded. Therefore, directing some of the heat to an adjacent laundry has a virtuous logic, especially in months without a space-heating load. In addition, some of the heat could be stored in a calorifier as a hot water supply for washing machines, while the CHP can meet all the electrical demand for laundering on site. Another housing association, which currently has a communal tumble-drying facility built into its rental structure, is also considering ways in which to upgrade the towers thermally, including CHP. Such tower blocks also offer scope for substantial photovoltaic (PV) arrays (Porteous and Menon, 2010), which potentially offer an income to housing associations via the ‘feed in tariff’ (FIT), depending on suitable governmental support. However, although electricity generated could be used to offset consumption by laundering appliances, it might be better directed to other needs such as communal lighting.

Another area that is a concern in terms of sustainable environmental practice is the use of water in general and the scope for recycling or reusing ‘grey’ water in particular. Average annual water use per household based on the population density in Glasgow is likely to be approximately 120 000 litres per dwelling (150 l/person daily); and washing clothing and other fabric represents some 12% of total domestic use indoors at an estimated 50 l/cycle or approximately 21% of ‘grey’ water from all key washing activities – clothes/bedding, dishes and personal hygiene (Environment Agency, 2011). Therefore, the opportunities for saving energy and carbon emissions from this alone, recycling for flushing toilets, for example, are inherently limited.

If one takes a Scottish CO_2 emissions value of 0.17 g/l for supply and 0.81 g/l for waste (Scottish Water, 2011), one could potentially save approximately 1.0 g/l by grey water recycling to flush toilets – possibly a net saving of 0.9 g/l, allowing for emissions arising from this process. But since a typical household might use from 30 000 to 40 000 litres for flushing annually, the annual CO_2 saving potential is only of the order of 27–36 kg/house; with a proportion attributable to domestic laundering. In summary, even though the saving on water use, rather than CO_2, would be valuable, with remote harvesting and delivery of rainwater to urban dwellings expensive, capturing it on site is simpler than utilizing grey water for this purpose.

However, in tandem with other domestic ‘grey’ water there is potential for contributing to thermal demand via a water-source heat pump. For example, all of it could be passed through a holding tank of 0.3 m^3/house (*e.g.* 1.2 × 0.5 × 0.5 m) allowing for a daily throughput of ‘grey’ water of 70% of a net capacity of 270 litres or approximately 185 litres (Environment Agency, 2011). If the mean temperature in the tank is 20°C, and this is reduced by 15 K to 5°C by a heat pump of 2.5 COP, the tank could yield approximately 12 kWh daily (0.001163 kWh × 270 litres × 15 K × 2.5 = 11.8 kWh, where 1.163 Wh raises 1 litre water by 1 K). Even a temperature difference of 7 K would yield 5.5 kWh on a daily basis. Since hot water demand for this size of household is likely to be in the range 5.0–5.5 kWh/day, such a system should be viable, with additional benefits for larger systems for groups of houses. To fund 5.5 kWh/day from solar PV net over a year, with a COP of 2.5, implies approximately 10 m^2 PV averaging 80 kWh/m^2; and a solar thermal array in tandem with a heat pump and PV of 10 m^2 could also facilitate tackling space heating demand renewably.

In order to establish the viability of such a system, a live demonstration project would be required. Three technical key risks would be: (1) inadequate average outflow temperature for all grey water to fund a suitable temperature difference as indicated in the ballpark estimate above: (2) a COP significantly less than 2.5; and (3) too low a supply of grey water on a daily cyclical basis. A fourth risk would be that the initial cost of the holding tank and associated extra plumbing would not compare favourably with equivalent costs of other ambient sources for a heat pump. Successful technological advances to further lower typical wash temperatures could also tend to compromise heat recovery from the combination of household sources.

Future policy direction

The previous two subsections both employ rudimentary calculations in support of change, or 'that which mutates', juxtaposed with continuity, or 'that which persists', the 1953 phrases of architect, product designer and artist Max Bill (Steele, 1953/2010, p. 71). In this regard, both highlight a common denominator – the issue of whether households and wider communities of interest are best served by individual appliances within the home or shared services. Similar to the electrical loads imposed by the appliances themselves, the issue of water conservation and heat recovery from water might be more advantageously located in communal facilities close to the home. This implies a shift in culture by housing providers and their funders, as well as by users. Crucial for the latter is not only the issue of convenience, but also one of autonomy. But if the social map is metaphorically considered, people are accustomed to being only autonomous in certain regards. From this point of view, reinvigorating a community facility, which has worked well in the past in cities like Glasgow, and still does in other cities and towns, seems a reasonable proposition.

Furthermore, sharing of laundering services would be of significant benefit in rendering Passivhaus standards realizable. As shown in the 'what if?' analysis, this will be difficult to achieve for small dwellings unless some appliances are removed from the home. Since convenience, leisure and communications appliance culture seems unlikely to diminish significantly, and despite the efforts of DEFRA's Market Transformation Programme to make such electrical usage more efficient, displacement of home laundering to a communal facility would be very helpful. The evidence clearly shows that there would also be concomitant benefits in terms of reducing thermal loads for space heating as well as reduction of indoor humidity; the latter also likely to a have beneficial effect on health.

Conclusions

The Glasgow study indicates that for two key laundering appliances, washing machines and tumbler dryers, consumption is less than governmental estimates of UK averages. This may have partly reflected the social dimensions of the group surveyed, *i.e.* relative poverty. For example, this aspect manifested itself more in low ownership than in part use of tumble-dryers as well as the relatively low average washing frequency – 35.5% lower than UK estimates (cf. Sunikka-Blank and Galvin, 2012). On the other hand, the move away from 'hot-fill' washing machines mitigates against further energy reductions, especially if the fuel for hot-fill has a significantly lower primary energy value than electricity.

A further problem for tumble-dryers in particular is that market penetration of the newest and most energy-efficient models is slow. A propensity toward older vented models in the Glasgow study also led to ancillary environmental issues: open windows to permit venting raised space heating demand and levels of humidity. Tumble-drying also tended to increase the quantity of ironing, and there was an additional trend to iron partly dried washing. This also invokes the issue of IAQ in terms of the release of potentially hazardous VOCs associated with fabric softeners, in turn influenced in concentration by moisture (both aspects raised by work on the western seaboard of North America), implying a need for similarly focused research in the UK. There is also some scope for recovering heat from 'grey' wastewater from washing machines in association with that from other domestic functions and appliances. This is proposed via a water-source heat pump, suggesting a demonstration project to establish efficacy; while mitigation of CO_2 emissions by reuse or recycling of the water would be marginal.

The typical floor area in the Glasgow sample was less than the UK average relative to the average number of persons per household. Again, this reflects the type of social housing that dominated the sample, *i.e.* generally constructed close to minimum area standards. A key consequence is that standards such as Passivhaus overall primary energy limit of 120 kWh/m^2 are harder to achieve. This will present a considerable future challenge for manufacturers of appliances, including those for laundering, and also indicates a need for Scotland and the UK to improve its generating efficiency and curb grid losses.

For housing providers and their instruments of finance, the study indicates potential for increasing the provision of communal laundry facilities. By exploiting an economy of scale and displacing the use of individual energy-consuming appliances from the home environment, the delivery of energy-efficient standards would be more achievable as noted above. This tactic also opens opportunities for innovative reduction of energy and environmental impact, *e.g.* some heat generated from combined heat and power (CHP) could be used for drying. At a smaller scale, communal drying facilities alone could benefit from solar thermal or solar photovoltaic arrays in association with heat pumps.

In summary, laundering appliances represent a significant component of the increasing portfolio of electrical appliances in a context where, despite performance improvement, consumption continues to rise. In addition, two of the laundering appliances, tumble-dryers and irons, are currently tending to increase demand for space heating and compromise air quality.

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Endnotes

[1] The Mackintosh Environmental Architecture Research Unit (MEARU) within the Mackintosh School of Architecture, The Glasgow School of Art, conducted Objective 1 of the study and led the project – EADL. Another research unit, Research into Indoor Climate and Health (RICH), at Glasgow Caledonian University, covered Objective 2. A third research unit, Energy Systems Research Unit (ESRU), University of Strathclyde, Glasgow, undertook work on Objective 3 in liaison with RICH. MEARU is leading Objective 4 as an ongoing component in association with RICH and ESRU.

[2] Eltek, Cambridge, UK.

[3] Coefficients to derive CO_2 emissions from electricity used at the point of delivery inherently reflect shifts in political and economic energy policy alongside market volatility. Key future variables are the extent of nuclear generation, coal generation with carbon capture, onshore and offshore wind generation, other renewable sources such as wave and tidal power, ‘fracking’ as a new fossil fuel source, gas generation, etc. All of these have their adherents and opponents. Therefore, although the UK trend for the coefficient appears to be numerically downwards, a relatively cautious approach has been adopted; namely to retain the DEFRA/DECC coefficient of 0.537 at the ‘birth’ of EADL in 2007 (Department of Energy and Climate Change (2011), *2011 Guidelines to DEFRA/DECC’s GHG Conversion Factors for Company Reporting*, Annex 3, p. 13). This also recognizes the uncertainty of differing values emanating from the same source, e.g., the above document gives 0.524 for 2008 and 0.482 for 2009; whereas DECC in 2010 has a value of 0.517 for March 2010 specifically applied to housing (Department of Energy and Climate Change (2010), *SAP 2009, the Government Standard Assessment Procedure for Energy Rating of Dwellings*, BRE, Version 9.90, Table 12, 199).

[4] Table 3 gives 334 351 GWh generated in 2009, with grid losses of 7.5%, indicating a net value of 309 274.7 GWh; and when divided by the value given in Table 9 for all energy used in generation by all methods in 2009 of 846 736 GWh, it gives a coefficient of 0.365.

[5] The 65 and 90 m^2 floor area estimates for consumption by televisions is found by interpolating values given for Western Europe of 39.6 TWh in 2005 to 103.6 TWh in 2030 to 52.4 TWh in 2010; and assuming 174.91×10^6 households = 300.0 kWh/household, then divided by 65 m^2 = 4.6 kWh/m^2.