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Utilising Time of Use Surveys to Predict Domestic Hot Water Consumption and Heat Demand Profiles of Residential Building Stocks

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Authors' contributions

This work was carried out in collaboration between all authors. Author ON developed the model, conducted the simulations, performed the results analysis, wrote and revised the manuscript. Authors SO, D. Flynn and D. Finn provided valuable suggestions and input for the model development, the results analysis and reviewed the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Aims: The prediction of water consumption patterns is a challenge, especially when water metering is not available at scale. The use of time-of-use survey (TUS) data offers an alternative to metering in order to track the general patterns of water consumption across large and representative groups of end-users. The paper focuses on the prediction of analytical domestic hot water (DHW) demand profiles for detailed building archetype models, using an occupant focused approach based on TUS data. The paper illustrates and discusses the resulting capability of dwelling archetypes to capture variations in heat demand and energy usage for water heating on a national scale and at high time resolution.

Methodology: Five dwelling types are considered over different construction periods, representative of the majority of the Irish residential stock, which is used here as a case study. They are modelled at room level using EnergyPlus and converted into archetype models. A bottom-up approach is utilised to develop the required operational data at high space and time resolution. That methodology applies Markov Chain Monte Carlo techniques to TUS activity data to develop activity-specific profiles for occupancy and domestic equipment electricity use. It is extended to DHW demand profiles by combining the probability distributions for particular TUS activities with average daily DHW consumptions, depending on the household size, day type and season.

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Results: The archetype models capture variations in DHW consumption, heat demand and energy usage for DHW heating, on a national scale and a fifteen-minute basis. Moreover, they are found to be 90% accurate with the Irish standard dwelling energy assessment procedure in estimating the annual energy requirements for DHW heating.
Conclusion: This study demonstrates the potential for utilising time of use surveys to predict domestic water demand profiles on a national scale and at high time resolution.

Keywords: Building simulation; demand side management; domestic hot water; residential buildings; time-of-use survey.

LIST OF ACRONYMS

BPS : Building Performance Simulation
DEAP : Irish Dwelling Energy Assessment Procedure
DHW : Domestic Hot Water
DSM : Demand Side Management
EPBD : EU Energy Performance of Buildings Directive
EUI : Energy Use Intensity (kWh/m^2)
RES : Renewable Energy Sources
SAP : UK Standard Assessment Procedure
TFA : Total Floor Area (m^2)
TUS : Time-of-Use Survey

1. INTRODUCTION

1.1 EU Policy and Targets

Buildings are the largest energy using and CO_2 emitting sector in the EU at present, with residential buildings accounting for two-thirds of the sector's consumption [1]. The so-called "20-20-20" targets set by the EU challenge the building sector in terms of energy efficiency, greenhouse gas emissions and integration of renewable energy sources (RES). Furthermore, a series of EU directives has mandated each member state to improve the energy and environmental performance of dwellings. Through the Energy Performance of Buildings Directive (EPBD) [2] a series of reference buildings, representative of the national building stock, should be defined and a standard methodology developed for the calculation of their energy and environmental performances. Through Directive 2009/28/EC [3] on the promotion of energy use from RES, 20% of total energy consumption from RES is targeted by 2020.

1.2 Response of the Residential Sector

The direct response of each EU member state to the EPBD requirements is the development of national standard energy assessment procedures, such as the Irish Dwelling Energy Assessment Procedure (DEAP) [4] or the UK Standard Assessment Procedure (SAP) [5]. These methodologies enable the publication of building energy rating certificates and are key tools for policy makers to verify the implementation of current building regulations and to elaborate stricter ones in terms of fuel and energy conservation within dwellings.

As acknowledged by the US DoE [6], the integration of RES requires more flexibility from the power system. This is due to the variable and uncertain nature of RES, particularly wind and solar generation. Utilisation of the flexibility offered by demand side management (DSM) is one possible strategy. However, for residential buildings in particular, it is challenging to quantify this potential due to the wide range of electricity usage patterns, variability of electrical loads and uncertainty regarding human behaviour. The integration of new load types, such as electric vehicles, and the electrification of space and water heating loads, as anticipated by the IEA [7], further challenge the assessment of the associated flexible load resource capacity.

1.3 Modelling of Residential Sector

Richardson et al. [8] recognised that analysis of DSM in the domestic sector requires detailed and accurate knowledge of household consumer loads. By aggregating individual end-use loads, or groups of end-use loads, bottom-up approaches are capable of generating sufficient detail and are very useful for identifying the individual end-use contribution to the overall energy or electricity consumption of a national residential building stock [9]. In the past decade, several bottom-up building energy or electricity demand models have been developed to study domestic loads with high time resolution [10,11] and with high spatial resolution [12]. These models are usually based on time-of-use survey (TUS) data in order to extract the behavioural patterns of building residents, in terms of occupancy and use of electrical appliances. More recently, Neu et al. [13] proposed an approach to develop operational data at high space and time resolution, based on TUS data, as input to building performance simulation (BPS) archetype models, with each model being representative of a group of dwellings and their loads. By integrating these operational data inputs, EPBD reference dwellings can be converted into BPS archetypes [14]. This approach is in line with a power system perspective on the aggregated flexibility potential offered by smaller loads, such as residential ones, through the implementation of any DSM strategy [15]. Water heating systems in particular, due to their thermal inertia characteristics, offer significant potential for flexibility.

However, in detailed BPS archetype models, a prerequisite for the assessment of this potential is a knowledge of water consumption patterns at high time resolution [13]. As exemplified by Fidar et al. [16], the use of national standards is a possible way to estimate annual or monthly average water consumptions, even at a micro-component level (e.g. taps, shower, bath). However, when used as such, these are not sufficient to predict water and DHW consumption profiles at sub-hourly time resolutions and representative of individual buildings, or groups of buildings. With that regard, the current approaches to predict water and DHW consumption patterns rely upon the existence of water metering data, as illustrated by Vieira et al. [17,18] and Makki et al. [19] using the SEQREUS data [20]. However, the prediction of these consumption patterns is a challenge when water metering is not available at scale. The use of TUS data offers an alternative to metering in order to track the general patterns of domestic water consumption across large and representative groups of end-users. Browne et al. [21] considered this novel ‘proxy’ approach as being highly valuable, as well as a way to reduce the dependency on large and cost-intensive ‘infrastructural decisions’, such as metering.

1.4 Contribution and Approach

The paper deals with the development of analytical domestic hot water (DHW) demand profiles for detailed building archetype models, using an occupant focused approach based on TUS data. The Irish residential stock, whereby water metering is not available as yet, is used as a case study. The five EPBD Irish reference dwellings [22] are considered over different construction periods, representative of the majority of the national stock. They are converted into BPS archetypes by integrating high space and time resolution operational data. The bottom-up approach developed by Neu et al. [13], which applies Markov Chain Monte Carlo techniques to TUS activity data [8], is used to develop activity-specific profiles for occupancy and domestic equipment electricity use. It is extended to DHW demand profiles by combining the probability distributions for particular TUS activities with average daily DHW consumptions, as estimated through the UK SAP procedure [5], depending on the household size, day type (weekday or weekend) and season. The archetypes capture variations in DHW consumption, heat demand and energy usage for DHW heating, on a fifteen-minute basis. Results are verified by comparing them with those estimated through the DEAP approach.

2. METHODOLOGY

The set of EPBD Irish reference dwellings [22] is considered. They are modelled in detail through EnergyPlus and converted into a set of BPS archetypes by integrating the high space and time resolution operational data developed by Neu et al. [13], and in particular occupancy profiles. Focus is placed on the prediction of analytical DHW demand profiles based on TUS activity data.

2.1 Set of Archetypes

Table 1 introduces the two building categories considered, namely single family and multi-family buildings, further divided into five dwelling types, such as flats or detached houses, as well as their total floor area (TFA) and the share of the Irish residential building stock represented, according to the results from the Irish 2011 Census [23]. The set of reference dwellings is representative of approximately 82% of the Irish national dwelling stock. Each dwelling type is considered over different construction periods, namely existing and new dwellings. New constructions are dwellings being built in the last decade in accordance with the latest Irish building regulations [24], while existing constructions do not meet the standards set by these regulations [24], particularly in terms of insulation level of the buildings envelope, infiltration and ventilation levels or efficiency and control type of the space and water heating systems. Surveyed data within the Irish [23,25] is used to propose a breakdown between new and existing dwellings for each building category. The geometrical characteristics, construction types and materials, infiltration and ventilation levels, as well as the heating systems and control types, are in line with DECLG and SEAI [22], and adapted from the Irish building regulations [24] for both new and existing constructions.

Table 2 introduces the main characteristics of the DHW heating systems and control types assumed for both the new and the existing dwelling archetypes modelled through EnergyPlus (version 8.1) [26]. A more detailed and exhaustive description of the archetype models was presented by Neu et al. [27].

The number of rooms, layouts and floor plans are adapted from representative dwellings defined by Brophy et al. [28]. Fig. 1 shows a SketchUp drawing of each reference dwelling.

2.2 Operational Data: Occupancy

The occupancy profiles were developed and validated by Neu et al. [13], based on surveyed TUS data. These vary with the household size (1, 2, 3 and "4 or more" residents) and the day type (weekend or weekday). Two types of occupancy profiles are considered, namely normal and active profiles, as shown in Fig. 2. A normal occupant is a resident who is at home. An active occupant is defined as a normal occupant who is not sleeping, thus willing to use any domestic equipment, such as DHW, or to perform any action to restore comfortable indoor conditions, such as the operation of natural ventilation, depending on the active occupancy level and the performed activity type. Since only adult residents were surveyed in the Irish TUS data used [29], there is a risk of underestimating the use of any domestic equipment.

As shown in Table 3, the chosen household sizes of archetypes are similar to the number of residents calculated by the DEAP procedure, which varies with the TFA of the building. The average household size for both the EnergyPlus and the DEAP archetypes, weighted by the share of each dwelling type within the Irish national stock, is identical but greater than the national average number of residents per household, namely 2.7 residents [23]. While this might be a concern for the DEAP methodology, it is not for the household sizes considered in this work. Indeed, as shown in Table 3, the additional adult residents within the archetypes compensate for the missing national average number of children, namely 0.7 residents [23], and help mitigating the aforementioned risk of underestimating the use of any domestic equipment, including hot water demand [27].

Table 1. Set of EPBD Irish reference dwellings

Building categories	Dwelling types	Total floor area (m^2)	Share of national stock by construction period (%)		
			Total	New	Existing
Single family	Bungalow Detached	104 160	42.4	19.7	22.7
	Semi-detached	126	27.7	12.9	14.8
Multi-family	Mid-floor flat Top-floor flat	54	10.8	5.0	5.8

Table 2. Characteristics of the DHW heating systems and control types

Heating system characteristics	New dwelling	Existing dwelling
Boiler fuel type	Natural gas	Oil and coal
Nominal efficiency (%)	91.3	76.0
DHW tank set point	65ºC from 05:00 to 24:00	

Table 3. Household sizes assumed for the archetypes

Dwelling types	EnergyPlus methodology	DEAP procedure
Bungalow	3	3.0
Detached	≥4	4.4
Semi-detached	3	3.6
Flats	2	1.7
Weighted average	3.4	3.4

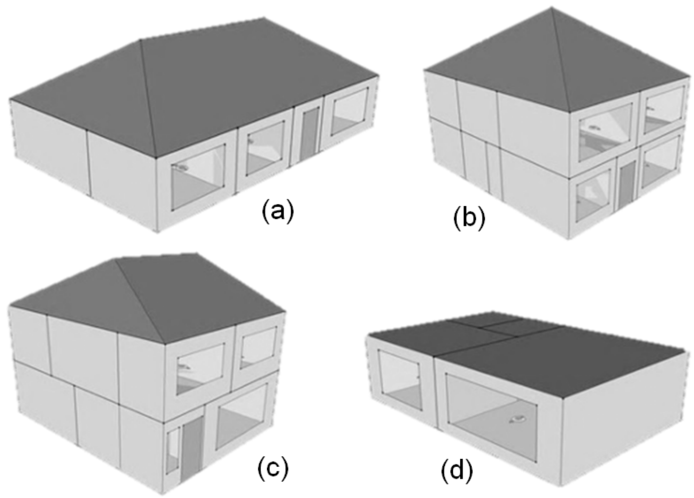

Fig. 1. SketchUp drawings of reference dwellings: (a) Bungalow, (b) Detached, (c) Semi-detached and (d) Flats

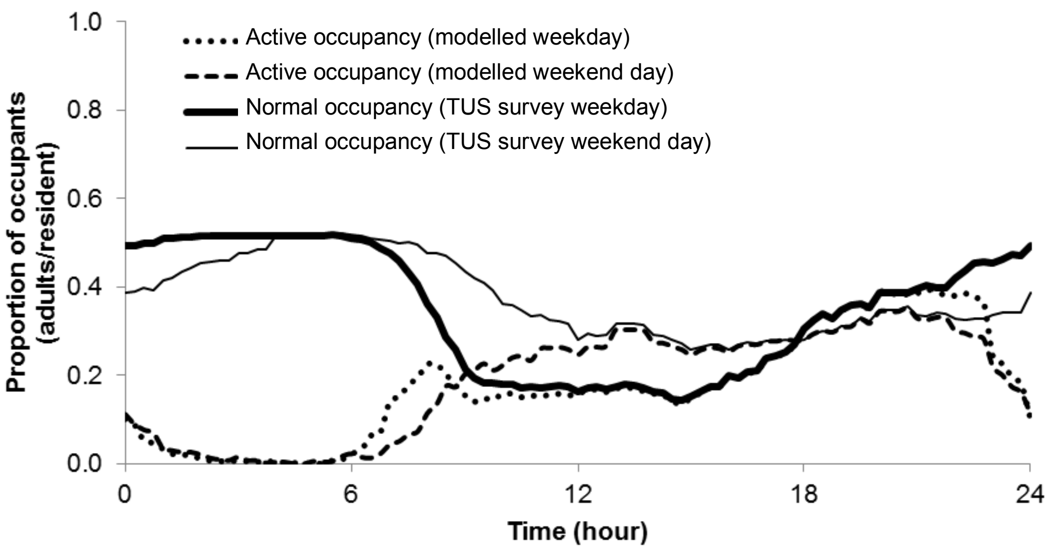

Fig. 2. Average daily modelled active occupancy and surveyed average daily normal occupancy: "4 or more" resident household (detached)

2.3 Operational Data: DHW Demand

Without any water meter installed in Irish dwellings, insufficient data is available to support the development of DHW demand profiles. Instead, a national standard energy assessment procedure, compliant with the EU EPBD requirements [2], provides an estimation of the average daily DHW consumption for the reference dwellings considered in Table 1, each of them being representative of a share of the Irish residential housing stock. While the Irish DEAP methodology [4] is based on the assumed household size only, which in turn is based on the dwelling TFA, the UK SAP methodology [5] also takes into account the monthly variation of the average daily DHW consumption and is believed to be a more accurate correlation. As a result, it is utilised to estimate the monthly and annual averages of daily DHW consumption for each archetype, as detailed in Table 4 and Fig. 3. Considering Table 4 and correcting for occupancy, using the household sizes set out in Table 3, small variations are observed for each archetype across each methodology. The resulting monthly average of daily DHW consumptions (Fig. 3) are the basis for developing activity-specific daily DHW consumption profiles at a fifteen-minute resolution, depending on the household size, season and day type.

Four categories of DHW draw are considered: short draw (e.g. washing hands), medium draw (e.g. washing dishes), shower bath, and bath tub. Each category is assumed to be responsible for 14%, 36%, 40% and 10% of the total volume of hot water consumed per day, respectively, based on research studies conducted across European countries [30]. For example, considering the total average DHW consumption introduced in Table 4 for the bungalow and the semi-detached dwelling archetypes, namely 111 L/day (37 L/day-resident), each category of DHW draw is responsible on average for a hot water usage of 15.5 L/day (5.2 L/day-resident), 40 L/day (13.3 L/day-resident), 44.4 L/day (14.8 L/day-resident) and 11.1 L/day (3.7 L/day-resident), respectively. These values are in line with the baseline water use estimated by Fidar *et al*. [16] for a typical residential building located in the UK and considering the hot water consuming micro-components only (taps, shower, bath). Indeed, a total DHW use of 37.2 L/day-resident was assumed, with short and medium draws together responsible for 52% (19.25 L/day-resident) of this volume, while the remaining share (48%, 17.95 L/day-resident) is associated with shower and bath draws.

Initially, the standard sub-hourly probability distribution functions developed by Jordan and Vajen [30] for each category of DHW draw are considered, as presented in Fig. 4.

The TUS "personal care" activity [29], hereafter referred to as the TUS "washing" activity, is a hot water consuming practice which is, by definition [31], representative of the "bath tub" and "shower bath" categories of draw. Each of the "short" and "medium" draws could not be associated with any specific and unique activity from the Irish TUS dataset, due to its relatively low resolutions in time (fifteen-minute time-scale) and types of activity surveyed [31]. Consequently, the standard probability distributions of these two categories of DHW draw are substituted by the unique distribution of the TUS "washing" activity type of draw (Fig. 5), thus assumed to be responsible for 50% of the total volume of hot water consumed per day.

Table 4. Average daily DHW consumption assumed for the archetypes

Dwelling types	EnergyPlus methodology		DEAP procedure	
	(L/day)	(L/day-resident)	(L/day)	(L/day-resident)
Bungalow	111.0	37.0	107.1	35.2
Detached	159.6	32.3	141.3	32.4
Semi-detached	111.0	37.0	121.2	33.8
Flats	86.0	43.0	71.6	42.7

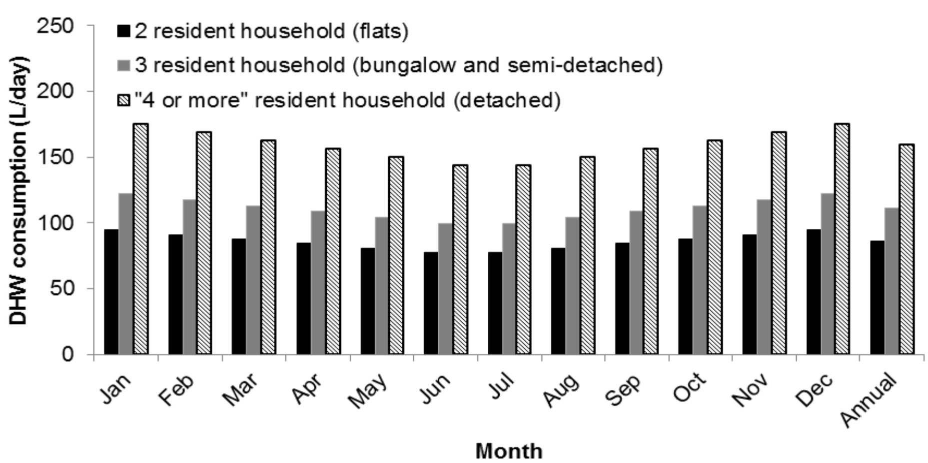

Fig. 3. Monthly variation of DHW consumption for each EnergyPlus dwelling archetype

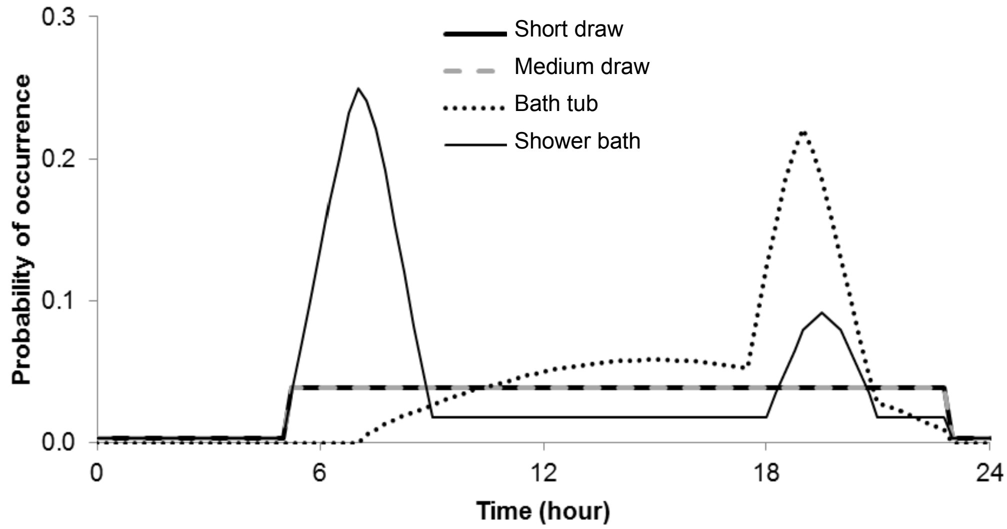

Fig. 4. Probability distribution of the DHW draw categories over a day at a fifteen-minute time resolution [30]

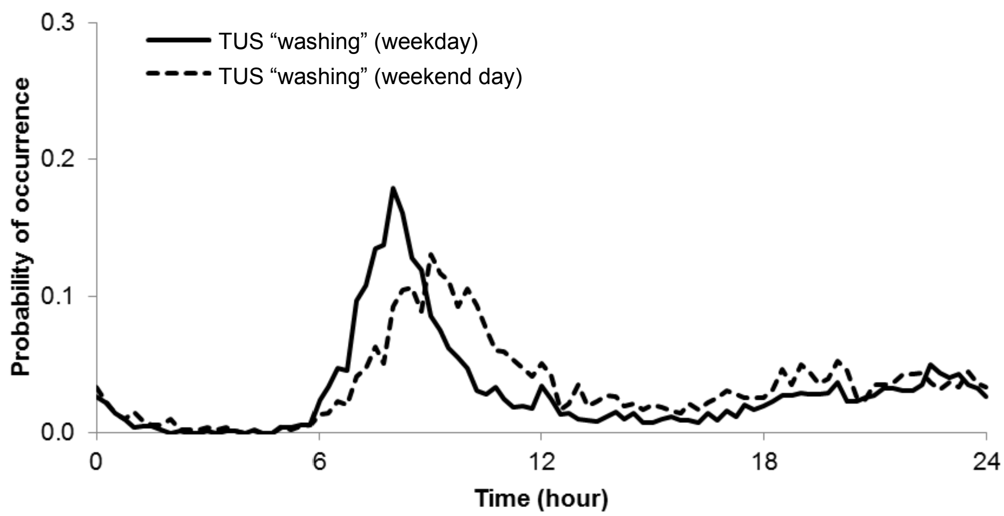

Fig. 5. Probability distribution of the TUS "washing" activity over a day at a fifteen-minute time resolution

3. RESULTS AND DISCUSSION

This section provides an example of the final DHW consumption profiles over a day at a fifteen-minute time resolution. The impacts of their integration within the EnergyPlus archetypes are discussed, including their ability to capture the variations in heat demand and energy usage for DHW heating at the same fifteen-minute time-scale. Energy use intensities estimated through the approach based on TUS data are compared with the estimations from the DEAP approach.

3.1 DHW Daily Consumption Profiles

By fitting the monthly average volumes of DHW consumed per day (Table 4, Fig. 3) within the final DHW draw probability distribution functions, the average daily DHW consumption rate profiles are generated at a fifteen-minute time resolution. Fig. 6 considers the detached dwelling archetype to illustrate the resulting variations in DHW consumption over a weekday and a weekend day, based on the average daily volume of DHW demand estimated for such dwelling type, namely 159.6 L/day (Table 4, Fig. 3).

Considering Fig. 6, the main peak of DHW daily consumption occurs in the morning, around 8 am for a weekday and 9 am for a weekend day. Another noticeable peak of consumption occurs in the evening, especially for weekend days. As expected, these peaks of DHW daily consumption match the peaks of probability of occurrence from the probability distribution function of the Irish TUS “washing” activity (Fig. 5). A greater resolution of the TUS data used, in terms of DHW consuming activities reflecting the short and medium draw categories (Fig. 4), would allow the daily probability distributions, and the DHW daily consumption profiles, to be further tailored to the case study of interest. Furthermore, a similar approach could be adopted to extend the prediction of residential DHW demand to the total water demand.

3.2 DHW Annual Energy Use Intensity

Figs. 7 and 8 shows the annual DHW heating energy use intensity (EUI) for new and existing dwellings, respectively, as calculated by DEAP and EnergyPlus.

Except for the semi-detached and the existing multi-family (flats) dwelling types, similar energy use intensities are observed when comparing the DEAP and the EnergyPlus approaches, especially for existing dwellings. However, even with these outliers, a difference of 8% is observed on a national scale for new dwellings, as per Fig. 7, and of 7.9% for existing dwellings, as per Fig. 8. Sources of discrepancy include the differing approach for considering DHW consumption, which is standardised by DEAP while dynamically modelled within EnergyPlus based on occupant behaviour. Furthermore, the DEAP methodology accounts for distribution circuit heat losses but does not detail how they are calculated, while EnergyPlus assumes an adiabatic distribution pipe network, and heat losses are estimated by reducing the DHW tank insulation to compensate for this assumption.

Despite the difference in DHW heating EUI for the semi-detached dwelling type (Fig. 7), similar values are also observed for the other new dwelling types, and the EnergyPlus semi-detached model behaves consistently for each construction period, with a similar error observed for each of them. Considering the DEAP approach in Fig. 8, there is a significant underestimation of the DHW heating EUI for the existing flats. This directly relates to the assumption made in DEAP that for flats, there is no difference in the DHW EUI between new and old construction periods, despite significant differences in heating system efficiency, whereas an increase by an average factor of 1.7 is estimated for all other dwelling types. EnergyPlus predicts an increase by an average factor of 1.8 for all dwelling types.

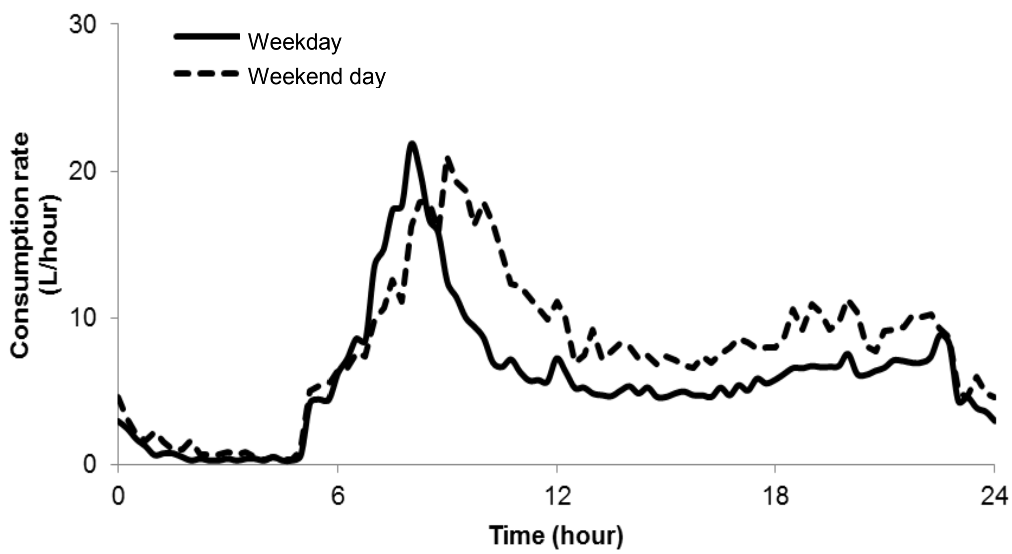

Fig. 6. DHW consumption profiles over a day at a fifteen-minute time resolution: “4 or more” resident household (detached)

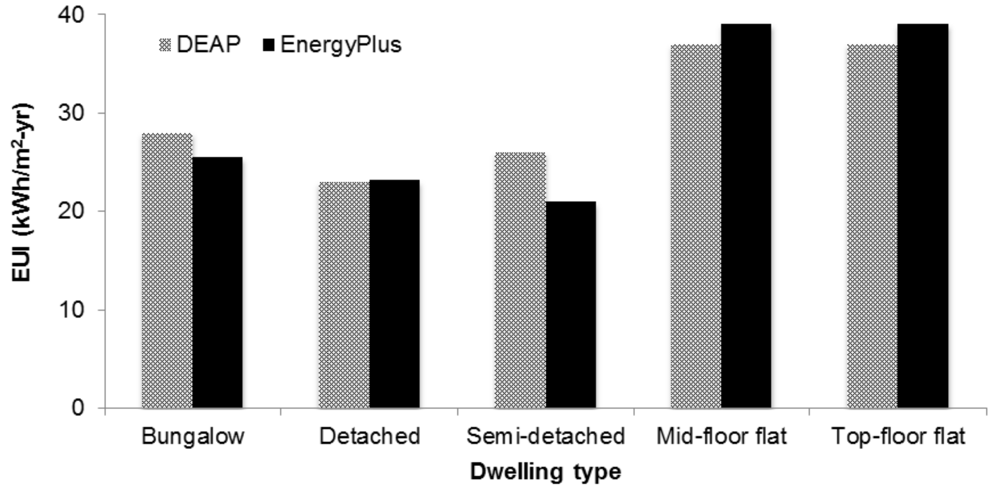

Fig. 7. Annual DHW heating EUI: new dwelling archetypes

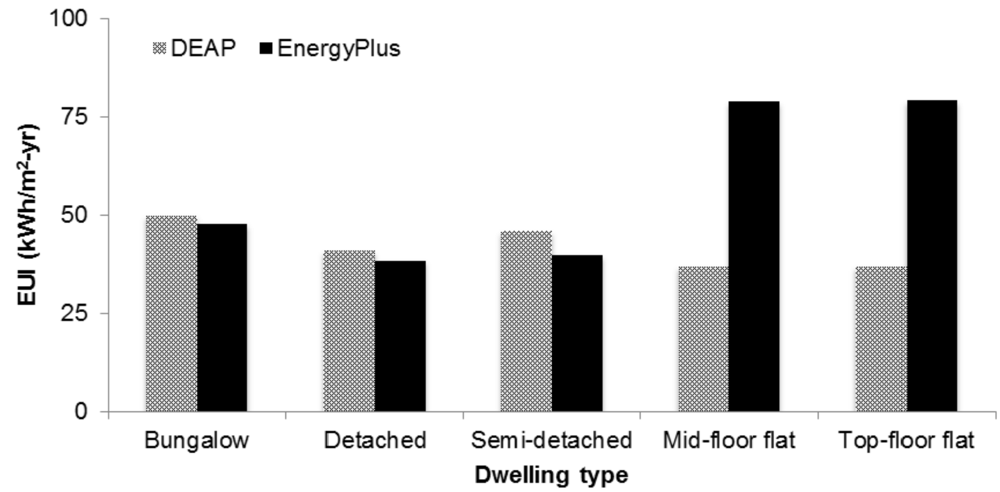

Fig. 8. Annual DHW heating EUI: Existing dwelling archetypes

Table 5. Average daily and maximum heat demand for DHW heating

Construction periods	**Dwelling types**	**Average daily heat demand (kWh/L)**		**Maximum heat demand over a 15-min interval (kWh *at "time"*)**	
		February	**July**	**February**	**July**
New	Bungalow	0.063	0.057	3.36 *at 20:15*	3.39 *at 08:15*
	Detached	0.062	0.056	3.45 *at 09:00*	3.44 *at 07.45*
	Semi-detached	0.062	0.057	3.45 *at 05:00*	3.40 *at 08:30*
	Top-floor flat	0.064	0.058	3.35 *at 10:00*	3.36 *at 08:45*
	Mid-floor flat	0.064	0.058	3.39 *at 08:30*	3.37 *at 08:00*
Existing	Bungalow	0.100	0.094	3.78 *at 05:00*	3.70 *at 05:00*
	Detached	0.088	0.081	3.71 *at 05:00*	3.67 *at 05:00*
	Semi-detached	0.102	0.095	3.66 *at 05:00*	3.65 *at 05:00*
	Top-floor flat	0.108	0.103	3.72 *at 05:00*	3.62 *at 05:00*
	Mid-floor flat	0.108	0.106	3.67 *at 05:00*	3.47 *at 05:00*

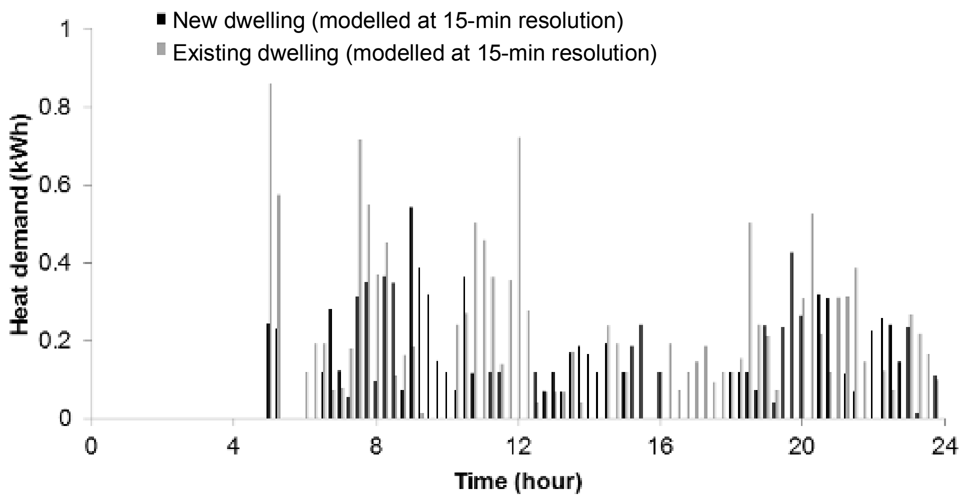

Fig. 9. Average heat demand profiles for DHW heating over a day at a fifteen-minute resolution: "4 or more" resident household (detached), February

3.3 Daily DHW Energy Use Profile

Table 5 quantifies the average daily heat demand (kWh/L), corrected for the daily DHW consumptions presented in Table 4, and the maximum heat demand over a fifteen-minute interval (kWh) of the new and existing dwelling archetypes, in winter (February) and summer (July) for DHW heating purposes.

The impact of building regulations on the average daily heat demand (kWh/L) for DHW heating is significant. Compared to existing buildings, decreases of approximately 36% and 38% are calculated for new dwellings, on a national scale, in winter and summer, respectively (Table 5). However, the impact on the maximum heat demand is much less significant, with a decrease of less than 10% for new constructions, compared to the existing ones, on a national scale, in both winter and summer (Table 5).

The seasonal variation of daily heat demand for DHW heating (kWh/L) is similar for both new and existing dwellings (Table 5): reductions ranging from 2% to 10% are observed, respectively, between December and July. However, for both new and existing dwellings, the seasonal variation of maximum heat demand for DHW heating is insignificant.

Independent of the season and dwelling type, the maximum heat demand for DHW heating of existing dwellings occurs in the early morning, around 5 am, at the beginning of the DHW heating operation schedule (Table 2). However, the maximum heat demand for DHW heating of new dwellings occurs later in the morning, from 8 am to 9 am, when the DHW consumption is at its highest (Fig. 6).

Fig. 9 above illustrates the variations of the average heat demand for DHW heating purposes over a day, during the winter season (February), on a fifteen-minute time-scale, and using the detached dwelling archetype as an example. The profiles for new and existing detached dwellings are uncorrelated (Fig. 9 above), emphasizing that heat demand for DHW heating not only depends on the DHW heating operation times but also on other factors such as the DHW consumption (Fig. 6). As suggested in Table 5, the greatest peaks observed for existing houses are located at the beginning of the DHW heating operation schedule, around 5 am (Fig. 9 above), while those for new dwellings are seen later in the morning, around 9 am, when the DHW consumption is at its highest (Fig. 6). Compared to the new archetypes, the poor insulation level of the DHW tank installed in existing dwellings explains these observations. Outside of the scheduled heating period, the hot water temperature falls below the cut-in temperature (55°C) whereas for new archetypes, it stays above the limit until the consumption peaks.

4. CONCLUSION

A methodology based on TUS activity data is developed for predicting analytical DHW consumption profiles at a high time resolution, depending on the household size, day type and season. DHW consumption rate profiles are generated and successfully integrated within a set of BPS archetype models, representative of the majority of the Irish national dwelling stock. As a result, the archetype models capture the variations in DHW consumption, heat demand and energy usage for DHW heating, on a fifteen-minute basis. The Irish BPS archetype models are found to be accurate to within 10% of the Irish standards, as exemplified using the DEAP methodology, for DHW heating annual energy requirements. Furthermore, the dwelling archetypes capture the seasonal variation, as well as the impact of building regulations, on both the average daily and maximum heat demand for DHW heating purposes, on a national scale. At a sub-hourly level, the maximum heat demand for DHW heating of existing dwellings is observed at the beginning of the DHW heating operation schedule, independent of the season and dwelling type. On the other hand, the maximum heat demand for DHW heating of new dwellings occurs at the peak period of DHW consumption.

A greater resolution of the TUS data used, in terms of hot water consuming activities reflecting each category of draw considered, would improve the accuracy of DHW daily consumption profiles for each case study of interest. Moreover, a similar approach could be adopted to predict not only DHW consumption but also total domestic water consumption. Further features of the archetype models will include the electrification of water heating systems, as well as the development of a methodology for the assessment of the demand response potential, embedded within residential BPS archetypes, through the implementation of load shifting strategies. Finally, the archetypes modelled are key to scaling up the potential flexibility resource from individual representative buildings to a national scale.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Buildings Performance Institute Europe. Europe's buildings under the microscope: A country-by-country review of the energy performance of buildings. Brussels; 2011.
2. European Commission. Directive 2010/31/EU of the European Parliament and the Council of the European Union of 19 May 2010 on the energy performance of buildings (recast). 2010;L153:13-35.
3. European Commission. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union. 2009;L140:16-62.
4. The Sustainable Energy Authorithy of Ireland. Dwelling Energy Assessment Procedure (DEAP): Irish official method for calculating and rating the energy performance of dwellings. Manual version 3.2.1. Dublin, Ireland, the Sustainable Energy Authority of Ireland; 2012.
5. Department of Energy & Climate Change. The Government's Standard Assessment Procedure for Energy Rating of Dwellings - SAP 2009 version 9.90. Watford, UK, Building Research Establishment Ltd on behalf of the Department of Energy & Climate Change; 2011.
6. US Department of Energy. Load Participation in Ancillary Services. Workshop report. Washington, USA, US Department of Energy; 2011.
7. International Energy Agency. Technology Roadmap_Energy-efficient Buildings: Heating and Cooling Equipment. Paris, France, International Energy Agency; 2011.
8. Richardson I, Thomson M, Infield D. A high-resolution domestic building occupancy model for energy demand simulations. Energy and Buildings. 2008; 40(8):1560-1566.

9. Swan LG, Ugursal VI. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renewable and Sustainable Energy Reviews. 2009;13(8):1819-1835.
10. Richardson I, Thomson M, Infield D, Clifford C. Domestic electricity use: A high-resolution energy demand model. Energy and Buildings. 2010;42(10):1878-1887.
11. Widén J, Wäckelgård E. A high-resolution stochastic model of domestic activity patterns and electricity demand. Applied Energy. 2010;87(6):1880-1892.
12. Chiou YS, Carley KM, Davidson CI, Johnson MP. A high spatial resolution residential energy model based on American Time Use Survey data and the bootstrap sampling method. Energy and Buildings. 2011;43(12):3528-3538.
13. Neu O, Oxizidis S, Flynn D, Pallonetto F, Finn D. High resolution space - time data: Methodology for residential building simulation modelling. In Building Simulation 2013: 13th Conference of International Building Performance Simulation Association; Chambéry, France; 2013.
14. Corgnati SP, Fabrizio E, Filippi M, Monetti V. Reference buildings for cost optimal analysis: Method of definition and application. Applied Energy. 2013;102(0): 983-993.
15. Ma O, Alkadi N, Cappers P, Denholm P, Dudley J, Goli S, et al. Demand Response for Ancillary Services. IEEE Transactions on Smart Grid. 2013;1988-1995.
16. Fidar A, Memon FA, Butler D. Environmental implications of water efficient microcomponents in residential buildings. Science of the Total Environment. 2010;408(23):5828-5835.
17. Vieira AS, Beal CD, Stewart RA. Residential water heaters in Brisbane, Australia: Thinking beyond technology selection to enhance energy efficiency and level of service. Energy and Buildings. 2014;82(0):222-236.
18. Vieira AS, Stewart RA, Beal CD. Air source heat pump water heaters in residential buildings in Australia: Identification of key performance parameters. Energy and Buildings. 2015; 91(0):148-162.
19. Makki AA, Stewart RA, Beal CD, Kriengsak P. Novel bottom-up urban water demand forecasting model: Revealing the determinants, drivers and predictors of residential indoor end-use consumption. Resources, Conservation and Recycling. 2015;95(0):15-37.
20. Beal C, Stewart RA. South East Queensland Residential End Use Study: Final Report. Technical Report No. 47. City East, Queensland, Australia, Urban Water Security Research Alliance; 2011.
21. Browne AL, Medd W, Anderson B. Developing novel approaches to tracking domestic water demand under uncertainty-a reflection on the "up scaling" of social science approaches in the United Kingdom. Water Resources Management. 2013;27(4):1013-1035.
22. Department of the Environment, Community and Local Government of Ireland and the Sustainable Energy Authority of Ireland. Report on the Development of Cost Optimal Calculations and Gap Analysis for Buildings in Ireland under Directive 2010/31/EU on the Energy Performance of Buildings (Recast) - Section 1: Residential Buildings. Dublin, Ireland, AECOM for the Department of the Environment, Community and Local Government and the Sustainable Energy Authority of Ireland; 2013.
23. Central Statistics Office. Census 2011 - Profile 4: The roof over our heads - Housing in Ireland. Cork, Ireland, Central Statistics Office; 2012.
24. Department of the Environment, Community and Local Government of Ireland. Building Regulations 2011 - Technical Guidance Document L. Dublin, Ireland, Department of the Environment, Community and Local Government of Ireland; 2011.
25. The Economic and Social Research Institute. Housing National Condition 2001/2002. Survey Dataset. Dublin, Ireland the Economic and Social Research Institute; 2009.
26. UIUC and LBNL. EnergyPlus Documentation - Version 8.1. Manual. USA, The Board of Trustees of the University of Illinois and The Regents of the University of California through Ernest Orlando Lawrence Berkeley National Laboratory; 2013.
27. Neu O, Sherlock B, Oxizidis S, Flynn D, Finn D. Developing building archetypes for electrical load shifting assessment: analysis of Irish residential stock. In CIBSE ASHRAE Technical Symposium; Dublin, Ireland; Chartered Institution of Building

Services Engineers, American Society of Heating, Refrigerating and Air Conditioning Engineers; 2014.
28. Energy Research Group & Environmental Institute, University College Dublin. Homes for the 21st century: The Costs & Benefits of Comfortable Housing for Ireland. Dublin, Ireland, Energy Research Group & Environmental Institute, University College Dublin for Energy Action Limited; 1999.
29. The Economic and Social Research Institute. Time-Use in Ireland 2005. Survey Dataset. Dublin, Ireland, The Economic and Social Research Institute; 2005.
30. Jordan U, Vajen K. Realistic Domestic Hot-Water Profiles in Different Time Scales. Universität Marburg, D-35032 Marburg, Solar Heating and Cooling Program of the International Energy Agency (IEA SHC), Task 26: Solar Combisystems; 2001.
31. The Economic and Social Research Institute. Time-use in Ireland 2005. Survey Report. Dublin, Ireland, The Economic and Social Research Institute; 2005.