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Explaining shifts in UK electricity demand using time use data from 1974 to 2014

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ABSTRACT

Peaks in electricity demand generate significant negative environmental and economic impacts. As a result, recent policy and research attention has focused on the potential for temporal flexibility of demand, especially in the context of intermittent low-carbon generation. Much of this work emphasises the need to understand what makes up the peak and to engineer solutions to meet this 'normal' consumption. However, today's patterns of temporal consumption may only be a snapshot of continuing change. This paper uses UK household time-use survey data to analyse change in temporal patterns of activities over the last 40 years to shed light on apparent temporal shifts in overall UK electricity demand. The results highlight long term evolution in when and where people work, travel, eat, use media and carry out social activities. In particular they suggest that changing patterns of labour market participation may be contributing to shifts in food related, personal/home care and media activities which correlates with shifts in electricity demand. We conclude that both stable and dynamic social structures and forms of organisation have direct implications for policy debates around current and future flexible demand-side solutions.

1. Introduction

Peaks in electricity demand cause significant negative environmental and economic impacts. In many countries, peak demand periods require carbon intensive and costly dispatchable generation and cause difficulties for constrained capacity local low voltage (LV) distribution networks. With different intensities depending on the season, evening peaks repeat themselves throughout the year and are typically the highest levels of electricity demand in countries with temperate climates, including the UK where the residential sector is responsible for about one third of overall electricity demand and up to 40% of peak demand (Torriti, 2015).

Such peaks cause imbalances between demand and supply so that electricity prices in wholesale markets can fluctuate from less than €0.04/kWh to as much as €0.35/kWh (Torriti, 2015). In a decarbonised future, peaks are likely to remain a daily network balancing issue where capacity margins are slim, particularly in seasons where the problem is exacerbated by weather (e.g. winter in the UK and summer in parts of the U.S.) and where the integration of intermittent renewables in the supply mix has to be set alongside shifts to electric vehicles and heat pumps (Strbac, 2008) which may both exacerbate evening peaks. It has been suggested that with 30 GW of variable renewables and inflexible nuclear generation, this may require the curtailment of up to 25% of wind energy in the UK due to the increased need for fossil fuel generation to operate part-loaded in order to provide required ancillary services (Strbac et al., 2016). Given the policy imperative to move from fossil-based to renewable sources, the need to change demand at relatively short notice is becoming known in the energy demand literature as a flexibility problem (Grunewald and Diakonova, 2018) with an estimated potential market value of ~£8billion per year (National Infrastructure Commission, 2016).

Managing peak demand through interventions to achieve temporal flexibility is therefore likely to be even more important to the future of electricity provisioning. Intervention aimed at mitigating peaks in residential electricity demand is far from straightforward (Strengers, 2012, 2011) and attempts to-date have not always been successful. For instance, in Italy the effects of Time of Use tariffs on peak demand were minimal due to the loss of the price signal in combination with high penetration of zero-cost renewables during peak periods (Torriti, 2012). A wide-ranging review of a number of other studies has shown similarly underwhelming results (Frontier Economics, Sustainability First, 2012) although the quality of this evidence base is in some doubt (Frederiks et al., 2016). More recent trials have contributed conflicting results with some reporting consumer demand response of up to 10%

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(Schofield et al., 2016) but others reporting lower (Carroll et al., 2014) or non-existent effects (Srivastava et al., 2018).

This lack of clarity has lead recent academic and policy research to focus on understanding the activities that make up the peak and thus 'produce' the demand patterns observed (Torriti et al., 2015; Walker, 2014). This has illustrated how the timing of energy demand is dynamic, social, cultural, political, historical and bound up with the evolving temporal rhythm of society. It is therefore clear that electricity demand is shaped by the synchronicity, sequencing and inter-weaving of activities and practices (Anderson, 2016; Shove and Walker, 2014; Torriti et al., 2015) so that we should not expect a simple alteration in tariff to automatically shift consumption. Further, a small but growing body of work has focused on improving understanding of which everyday activities contribute to residential peak demand, in part to assess what levels of temporal flexibility there might be when electricity-using activities are enacted (Torriti, 2017; Torriti et al., 2015). However, unless reporting on experimental manipulation or interventions (Higginson et al., 2013; Schofield et al., 2014), such point in time studies are unable to provide empirical evidence of actual or potential change.

Furthermore, in addressing single time-points these studies ignore the constantly changing social milieu into which any interventions must be placed. This risks conceiving current 'norms' of temporal social organisation as historically fixed so that fixed solutions can satisfy the 'need' embedded within these norms (Shove, 2017). As Shove explains, 'normal' patterns of energy demand constantly evolve and so solutions must be devised which avoid lock-in to potentially transitory, and possibly unsustainable, 'normal' levels of demand. This risk can be mitigated by understanding how current norms of consumption have evolved and one non-experimental approach is to analyse how temporal patterns of household energy demand have changed over time alongside known changes in overall demand and its associated generation (Staffell, 2017).

As we discuss below, since historical data on temporal consumption patterns are essentially absent, at least for the UK, recent work has turned instead to historical time use surveys as a way to understand how electricity-demanding activities have evolved (Anderson, 2016; Durand-Daubin and Anderson, 2018). Although not able to precisely indicate how current consumers might respond to demand side interventions or tariffs, such analysis can nevertheless provide indicators of how consumption may have changed over time, for whom and why.

Building on this work, this paper presents analysis of the changing timing of high-level aggregates of reported time-use activities using national UK household time use diary data from 1974 to 2014. Having highlighted a number of substantial energy-related changes, the paper then investigates changing patterns of evening peak period (16:00–20:00) activities and consequential electricity demand with a focus on food related activities, personal/home care and media use which are known to be electricity-intensive (Palmer et al., 2013b, 2013a; Widén et al., 2009), have seen notable change and are likely to be driven by wider social transitions such as evolving patterns of employment (Anderson, 2016; Durand-Daubin and Anderson, 2018).

After this introduction, the paper provides an overview of trends over time in household energy demand (Section 2); describes the methods and time use data underpinning this research (Section 3); presents findings from the analysis on changes in activities constituting energy demand over four decades and specifically during evening peaks (Section 4); and discusses the implications of this work (Section 5).

2. Trends over time in household energy demand

In most developed countries long run datasets of yearly aggregated electricity demand are largely available with time spans of decades. In the energy economics literature, these datasets are typically used for cross-section analyses of the dynamic relationship between energy demand and either price (Bernard et al., 2011; Garcia-Cerrutti, 2000) or income (Asafu-Adjaye, 2000; Sari and Soytas, 2007) and in other work to assess the degree of energy demand reduction associated with the uptake of various energy efficient technologies. These datasets are generally intended to capture and analyse trends in annual demand (Palmer and Cooper, 2013). In contrast, whilst historical whole system hourly demand profiles are available[1] and long-running annual energy use surveys exist (Communities and Local Government, 2018; Energy Information Administration, 2015), there is very limited historical information on the sub-daily distribution of demand and thus the shape of *residential* electricity load profiles. Indeed, where suitable data has been collected (Isaacs et al., 2010), we have found no analysis of changes in the timing of demand. Although Palmer and Cooper (2013) offer some time-series analysis of overall demand based on trends in appliance load patterns,the lack of historical temporal demand data makes tracing the changing composition of residential peak demand extremely difficult.

This is unfortunate as it is known that there has been both an overall reduction in whole system demand and changes to demand profiles over the last decade in the United Kingdom at least (Staffell, 2017, p. 469). This is clearly shown in Fig. 1 which further disaggregates overall England and Wales electricity demand data for 2006–2011 by weekdays vs weekend days. Demand profiles have universally reduced but with differing magnitudes according to time of day and day of the week. Evening peak weekday consumption remains high in January but the difference between weekdays and weekend days has diminished. Morning peaks are no longer visible on weekend mornings in January and the trend towards increased evening demand compared to morning or mid-day demand on all days in July is clear. Although it is likely that embedded solar generation contributes to this mid-day summer dip, it may also be that need for increased heat and light in January is masking similar changes in evening energy-demanding habits in the winter.

More importantly for current and future 'energy flexibility' policy, when normalised within year and month (Fig. 2) there has clearly been a relative decrease in mid-day demand and the evening peak is relatively higher and later. As noted above, this is especially visible in July but the same pattern is also to be seen in January with a particularly notable relative uplift in Sunday evening demand. Unfortunately, it is not yet possible to disaggregate this data into residential and other customer types and there has also been little analysis of the changes in domestic activities which might contribute to the changing shape of residential and thus overall system demand peak. However recent studies using time-use data have hinted that changing labour market participation and consequential changes in the timing of domestic tasks may play a role (Anderson, 2016; Durand-Daubin and Anderson, 2018).

Whilst there have been a small number of in-depth household electricity-use studies, with the exception of the New Zealand HEEP study (Isaacs et al., 2010) these have tended to focus on a single year in order to capture both intra-day and inter-seasonal variation. For example the Household Electricity-Use Study 2010/11 (DECC/DEFRA, 2011) monitored electricity consumption at an appliance level in 250 owner-occupied households across England (Jason Palmer et al., 2013b; Palmer and Cooper, 2013). Similar studies took place in Sweden in 2008, where 400 households were studied over 12 months (Widén and Wäckelgård, 2010), and in France where a series of studies monitored 100 homes for a year in 2007 (Wilke et al., 2013). Not only are these studies relatively small scale and potentially non-representative, but more importantly they cannot provide insights into the historical components of peak demand. As a result we have no data that can *directly* explain how and why temporal patterns of residential electricity demand have evolved over time, how they contribute to the later and sharper peak identified in Fig. 2 and how this may change in the future (Love and Cooper, 2015; Walker, 2014).

In the absence of such data, time use datasets can potentially shed

[1] E.g. https://www.entsoe.eu/db-query/consumption/.

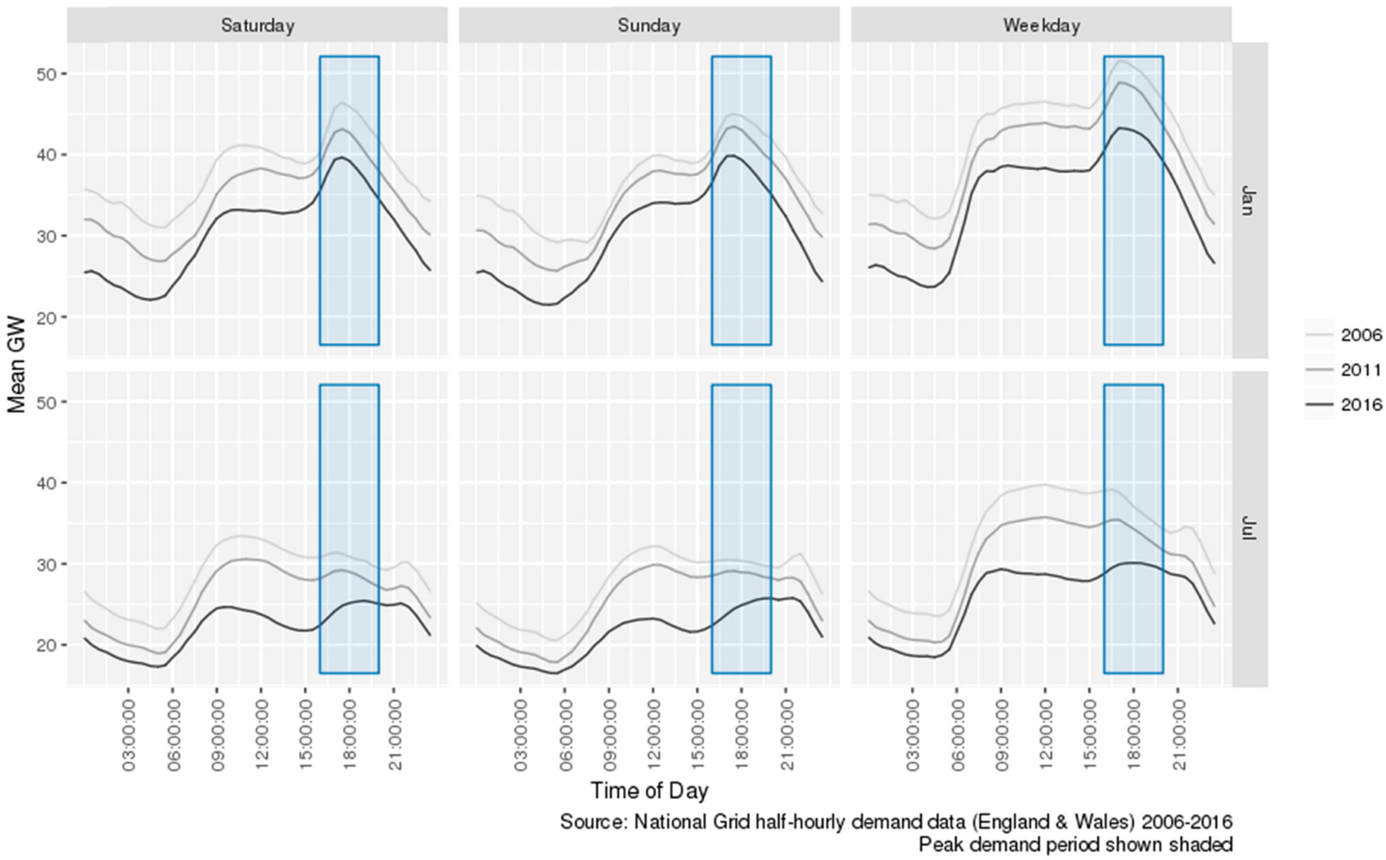

Fig. 1. Mean half-hourly demand (MW), weekdays vs weekend days, January vs July, England & Wales, 2006, 2011 and 2016.

light on trends in the timing of activities over recent decades. Recent work has used such data to analyse aggregate (non-temporal) changes in demand (Sekar et al., 2018), derive and validate load profiles of residential electricity demand (Widén et al., 2009; Richardson et al., 2010; McKenna and Thomson, 2016), synthetically represent occupancy patterns in different countries (Torriti, 2012) or analyse change in particular activities (Anderson, 2016; Durand-Daubin and Anderson, 2018). However, as Torriti (2014) notes there has been a lack of longitudinal or repeated cross-sectional analyses of such data to provide evidence on the changing temporality of everyday life and provide explanations for the changing shape of observed aggregate demand. This paper is an initial attempt to fill this gap in the continued absence of more directly applicable 'socio-technical' data (Love and Cooper, 2015).

The remainder of the paper presents analysis of change in the temporal distribution of reported activities from 1974 to 2014 in the UK. After introducing the data used, the paper provides descriptive analysis of changes in activities at all times of day before we focus on changes in the peak demand period. We then examine patterns for different age groups to highlight change in those of working age compared to older age groups. Finally we use regression modelling approaches to extend the descriptive analysis for food related, personal/home care and media activities to analyse the factors associated with the patterns revealed by the descriptive analysis.

3. Data and methodology

The analysis is based on four nationally representative UK time use surveys from 1974, 1983/5 ('1985'), 2000/1 ('2000') and 2014/5 ('2014'). The 1974, 1985 and 2000 data were obtained from the Multinational Time Use Survey (MTUS, (Gershuny et al., 2012)) 'World 6' sample and the UK Time Use Survey 2014–2015 (Gershuny and Sullivan, 2017) was obtained from the UK Data Service and converted to MTUS format.

Table 1 to Table 3 show the age and employment status distributions for the representative samples for each survey. These clearly demonstrate the changing age structure of the UK population over this period with an increasing proportion of older people. There has also been a notable decrease in the proportion of men of working age in full-time employment alongside an increase for women. Given the ongoing gendered nature of many energy-using domestic activities (Anderson, 2016; Moreno-Colom, 2015) these trends provide an important context to the patterns of time-use we discuss below.

Main and secondary activities recorded in the time use diaries were initially coded into a highly aggregated set of 10 activities to more easily depict change over time at a coarse level. The derivation of this coding is detailed in Appendix A for reproducibility and Table 4 highlights the coding of potentially electricity-demanding activities by indicating the significance of their peak power demand. As can be seen laundry, cooking and media use accounted for 8 + 20 + 14 ~= 42% of evening peak demand in the UK Household Electricity Use Study (Palmer et al., 2013a). In the longer term we might expect zero-carbon policies to further prioritise the use of potentially zero-carbon electricity as the dominant hot water and cooking energy source. If so changes in these practices will become even more relevant.

Of course it would be expected that nearly all home-based activities recorded in the diaries would require light and heat, especially in winter in temperate latitudes such as the UK even though heat in the UK is currently predominantly provided by gas (Torriti, 2012). Note also that the study cited (Palmer et al., 2013a, p. 19) lists 20% of peak demand as unknown but acknowledges that this is likely to be switched appliances that could not be identified using the study methodology but which are therefore likely to be associated with activities reported in the diaries.

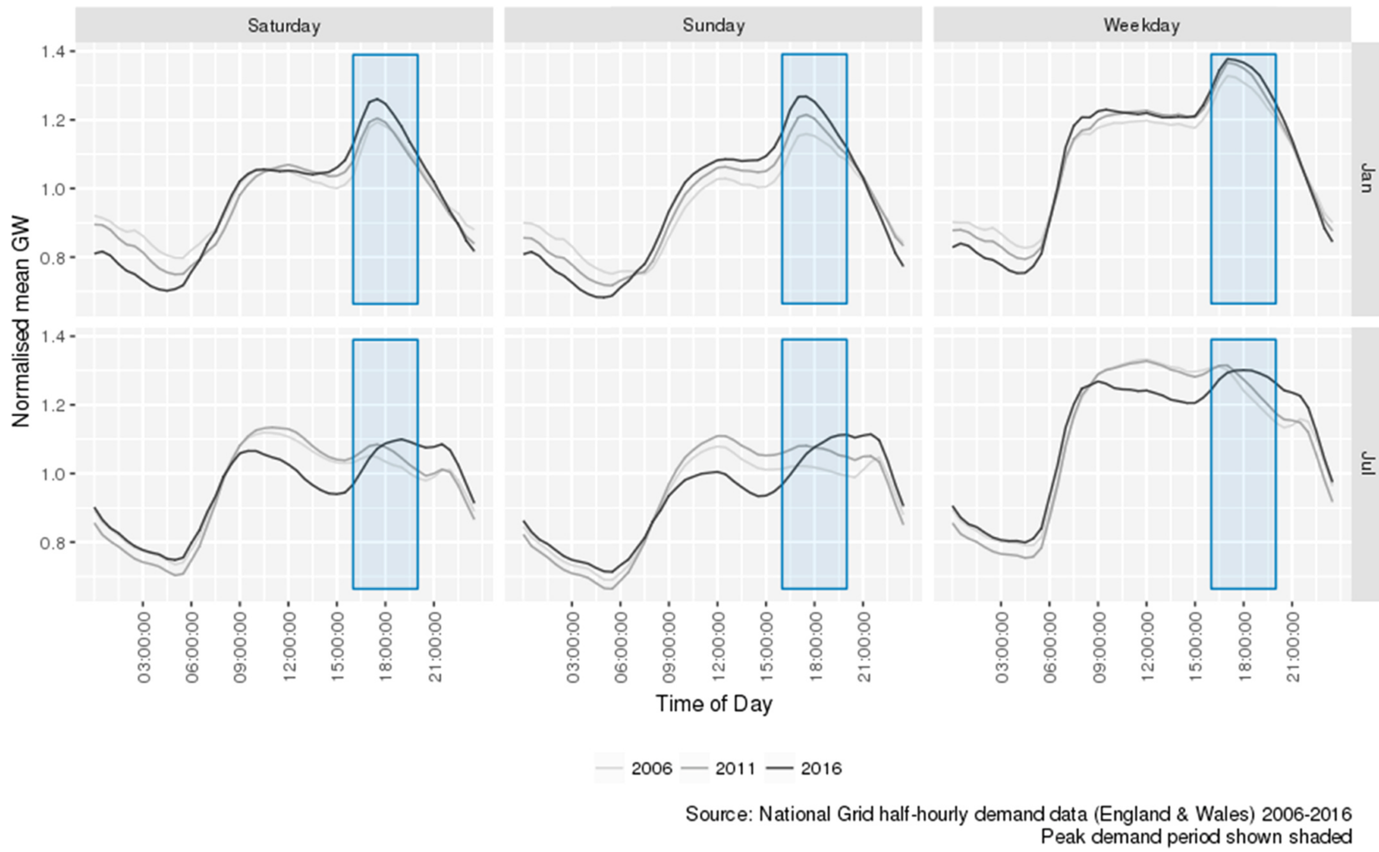

Fig. 2. Normalised[2] mean hourly demand (MW), weekdays vs weekend days, January vs July, England & Wales, 2006, 2011 and 2016.

As the component time-use diaries of the MTUS and the UK 2014–2015 survey used different time-durations in which to collect data, Anderson's (2016) 'any X in a half-hour' coding method was used to enable comparison over time. We acknowledge the imprecise nature of this indicator and note that apparent change over time should be carefully and conservatively analysed. We also note in particular that the measure is not suitable for use in the estimation of imputed kW demand profiles which, as other studies have shown, requires much more highly granular data (McKenna and Thomson, 2016; Widén et al., 2009).

We also note that reported activities such as cooking and laundry are not necessarily exactly temporally correlated with electricity demand since hot water may be pre-heated, food may be left to cook relatively unattended and washing machines/tumble driers proceed without active control once they are set to run. This is also the case for television where the appliance may be on but not being actively watched (and thus not recorded in a diary) as recent studies have shown (Durand-Daubin, 2013). As a result this is at best a 'social and technical' (Love and Cooper, 2015) analysis in the absence of more tightly integrated and directly linked 'socio-technical' data.

In addition, the components and appliances used in the categories of activities may have changed over time as is clearly the case with in-home leisure and cooking. Finally, social norms or expectations in reporting levels and types of activities may have changed over the years of data collection. This may mean that apparent increases or decreases in reporting do not reflect 'actual' change but unfortunately there is no obvious way to mitigate any of these uncertainties in this data (Gershuny et al., 2012).

The distinction between activities recorded as 'at home' or at other locations was preserved to enable analysis of 'out of home' activities that might affect 'in home' demand profiles. In addition, due to differing age thresholds for sample recruitment in the underlying datasets, only data for those aged 16 and over were used. We acknowledge that

Table 1
Respondent distributions by age (MTUS 1974–2014, weighted, row %).

	16–25	26–35	36–45	46–55	56–65	66–75	75 +
1974	18.71	21.40	18.16	20.17	12.47	7.10	1.99
1985	16.73	25.49	21.41	17.47	11.64	5.49	1.77
2000	12.06	19.41	19.17	17.82	13.11	11.54	6.90
2014	13.72	17.38	16.44	17.32	14.23	11.98	8.92

Table 2
% of men aged 16–64 by work status (MTUS 1974–2014, weighted, row %).

	Full-time	Missing	Not in paid work	Part-time	Unknown job hours
1974	92.39	0.22	4.50	2.02	0.86
1985	65.65	0.00	19.61	11.13	3.61
2000	69.95	5.10	19.53	5.42	0.00
2014	68.14	0.09	22.40	9.00	0.00

Table 3
% of women aged 16–64 by work status (MTUS 1974–2014, weighted, row %).

	Full-time	Missing	Not in paid work	Part-time	Unknown job hours
1974	31.29	0.04	38.51	26.46	3.70
1985	22.24	0.00	42.83	33.39	1.54
2000	34.29	3.93	33.05	28.73	0.00
2014	40.35	0.03	31.83	27.47	0.00

[2] Half-hourly mean divided by overall half-hourly mean for that month and year.

Table 4
Summary of potentially electricity-using acts.

Aggregated Activities (Total number of MTUS codes)	*MTUS 'energy using' codes*	*Rationale*	*Power demand estimates*
1. *Sleep (3 codes)*	–	–	
2. *Personal/home(14 codes)*	MTUS # 4 wash, dress, care for self	Shower, hair drier etc	Showers: 2% of peak demand (Palmer et al., 2013a, p. 19)
	MTUS # 20 cleaning	Use of cleaning appliances and hot water	Water heating: 1% of peak demand (Palmer et al., 2013a, p. 19)
	MTUS # 21 laundry, ironing, clothing repair	Use of washing machine, tumble drier, iron	Laundry: 8% of peak demand (Palmer et al., 2013a, p. 19)
	MTUS # 22 maintain home/vehicle, including collect fuel	Use of power tools	
	MTUS # 54 knit, crafts or hobbies	Use of power tools	
7. *Food: Cooking or eating (3 codes)*	MTUS # 6 meals or snacks in other places (including at home)	i.e. not at work/school	
	MTUS # 18 food preparation, cooking	Use of oven, hob, microwave	Cooking: 20% of peak demand (Palmer et al., 2013a, p. 19); Cold appliance 10%
9. *Work: Work or work related (8 codes)*	MTUS # 8 paid work at home	Use of powered appliances or tools	Media/AV: 14% of peak demand (Palmer et al., 2013a, p. 19)
10. *Education: Education or related (4 codes)*	MTUS # 16 homework	Use of powered appliances	Media/AV: 14% of peak demand (Palmer et al., 2013a, p. 19)
11. *Shop: Shopping/service use (3 codes)*	–	–	
12. *Social/leisure: Voluntary, civic, leisure or social activities (15 codes)*	MTUS # 48 receive or visit friends	Potentially increased need for heat & light	Lighting: 14% of peak demand (Palmer et al., 2013a, p. 19)
13. *Sport: Sport or exercise (5 codes)*	–	–	
14. *Media: Media use incl. read, TV, radio, PC, internet (6 codes)*	MTUS # 56–61 covering all aspects of media use	Use of powered appliances	Media/AV: 14% of peak demand (Palmer et al., 2013a, p. 19)
15. *Travel (7 codes)*	–	–	
16. *Not recorded (1 code)*	–	–	

this may mean that the electricity demand implicated in activities such as media and ICT use will be under-represented.

Table 5 shows the overall distribution of the 10 DEMAND 'any in a half hour' activities as main acts and highlights apparent increases in Personal/home activities together with a substantial decrease in population-level rates of reported work (c.f. Table 2) and sleep. Table 6 on the other hand shows that secondary acts were rarely recorded and with unknown reliability. In common with other studies (Anderson, 2016; Durand-Daubin and Anderson, 2018), secondary acts were therefore not included in the analysis that follows.

4. Results

4.1. Patterns of population change over time

Initially we provide an overview of the changes in time use patterns across the full 40 year period, divided between activities carried out 'at own home' and away from home. This will give an initial sense of the character and extent of change in the temporal structure of everyday life and explore how changes outside the home influence changes within.

Fig. 3 shows the percentage of half hours in which the ten

Table 5
% of main acts reported ('Any in a half hour', weighted, MTUS 1974–2014, column %).

	1974	1985	2000	2014
Education	0.27	0.61	0.54	0.84
Food	9.94	10.78	11.69	10.32
Media	10.94	11.76	12.94	13.85
Personal/home	11.68	16.70	15.55	16.03
Shopping	1.69	2.34	2.26	2.42
Sleep	36.84	31.15	31.75	30.73
Social/leisure	7.75	8.31	7.41	6.81
Sport	1.10	1.14	2.06	1.75
Travel	5.34	5.21	6.74	6.70
Work	14.41	11.37	8.58	8.32
X: Not recorded	0.03	0.63	0.49	2.24

Table 6
% of secondary acts reported ('Any in a half hour', weighted, MTUS 1974–2014, column %).

	1974	1985	2000	2014
Education	0.00	0.03	0.02	0.05
Food	2.11	3.15	2.29	2.26
Media	7.10	1.96	3.83	4.23
Personal/home	1.84	4.25	2.90	3.53
Shopping	0.11	0.40	0.05	0.21
Sleep	0.24	0.77	0.50	0.81
Social/leisure	2.51	4.74	6.36	5.92
Sport	0.04	0.10	0.04	0.13
Travel	0.14	0.25	0.01	0.09
Work	0.04	0.12	0.05	0.36
X: Not recorded	85.84	84.23	83.95	82.41

aggregated 'DEMAND' activities were recorded from 1974 to 2014 aggregating all days of the week but separating 'in home' from 'out of home' activities to understand how the latter may affect the former. Perhaps unsurprisingly, the major shape of the plots (sleep - > work and travel - > home activities - > sleep) do not appear to have changed substantially over time. However, personal/home care has diminished and spreads more into the evening; food related activities at home in the middle of the day – corresponding to lunch time - were much more pronounced in 1974 than in 2014 and appear also to have pushed later in to the evening. This is mirrored by a similar apparent shift to later media use and is reflected in both the apparent fall in reported out of home evening leisure and elongated evening out of home work and travel. However we should also note that conceptions and components of media use may have changed substantially between 1974 and 2014 with the emergence of multiple media appliances per home and indeed per person, often (now) used simultaneously.

To make these changes more visible, Fig. 4 shows the percentage point change from 1974 to 2014 for the percentage of half hours in which selected activities were reported between the hours of 06:00 and 24:00 and by weekdays vs weekend days. Panel A shows changes in work and travel while Panel B shows domestic energy using activities.

There is evidence of a small increase in work at home during

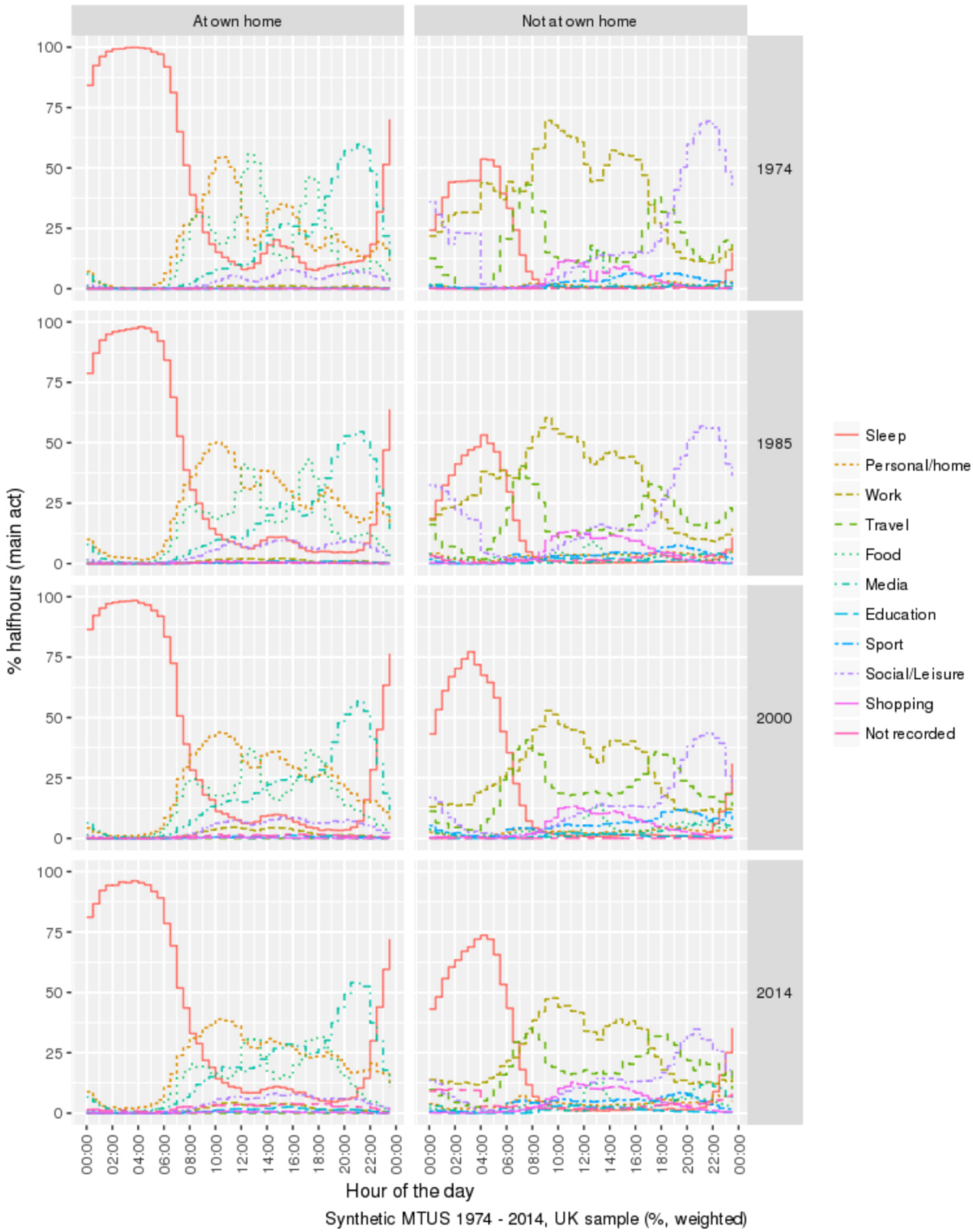

Fig. 3. Percentage of half hours in and out of the home with 'any' 'DEMAND' activities (all respondents aged 16 +).

weekdays but the magnitude reflects that this is still a rare activity at the population level. As we would expect, the greatest reduction in reported out of home work is on weekdays although there has also been a reduction in reported work on Saturday mornings both of which may be due to an increased percentage of post-working age respondents in the population (see Table 1).

On the other hand, food related activities in the home have declined markedly in early mornings and lunch times on all days suggesting a smearing out (or skipping) of breakfast, which appears to have shifted earlier on Sundays, and the reduction in home-based lunch. Food-related activities at 17:00 have also reduced substantially on weekdays and Saturdays while Sunday lunchtime food activities have reduced substantially (> 20% points on this measure) and like weekdays, have increased in the later evening.

Media use shows a general increase on weekdays throughout the day but a notable decrease around 17:00 prior to the apparently delayed eating and this pattern is repeated for weekends. In contrast personal/home care activities have reduced substantially on weekday and weekend mornings but appear to have been pushed into early mornings and later evenings on weekdays and Sunday as other studies

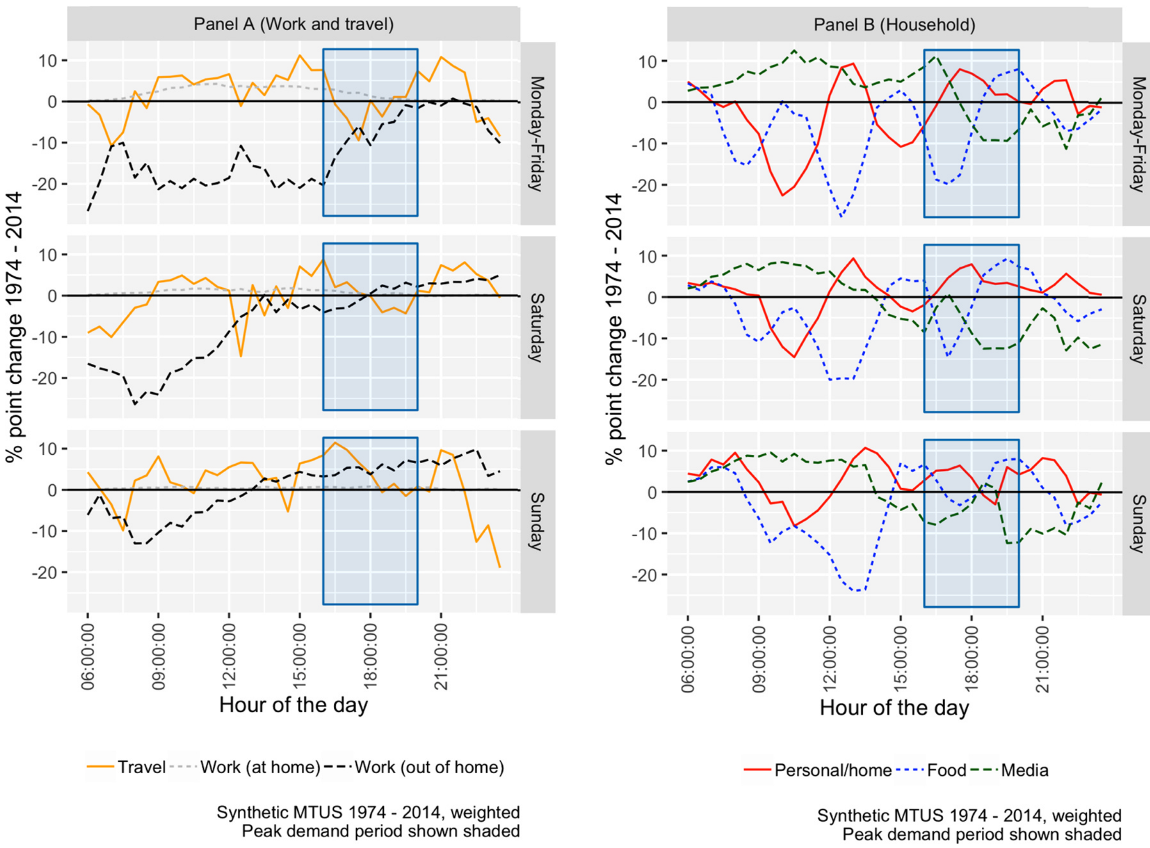

Fig. 4. Percentage point change 1974–2014 (all respondents aged 16 +, Monday-Friday, Saturdays, and Sundays, all activities 'at home' except Travel or where labelled).

have concluded (Anderson, 2016).

Overall, these general trends in activities provide background information on the structure of everyday life, and highlight specific, distinct and substantial changes over the 40 year period as a whole. However, of particular interest to energy demand is that home-based media activity increased substantially between 16:00 and 17.30 p.m. on weekdays, whilst home-based food activity decreased between 16:00 and 18.30 p.m. on all days and then increased after 18.30 when media use declined. The symmetry between the decrease in the early hours of the evening and the increase in the later hours of the evening suggests that food features a time substitution effect such that eating shifts to later in the evening in place of media use. Thus there may be no change in the number of people having dinner, only a time shift to later in the evening, which has implications for the timing of energy demand (Durand-Daubin and Anderson, 2018). Personal and home care also shows an increase in the 17:00–18:00 period on weekdays and Saturdays, and to some extent on Sundays, perhaps indicating end of work bathing on weekdays and evening preparation on Saturdays.

4.2. Drivers of shifting energy-demanding practices

As noted, many of the shifts described may correlate with social and demographic changes such as increased female participation in the labour market and, in particular, more people living for longer in their post-work retirement. In order to prevent such population ageing affects from masking changing patterns for those of working age, we now present similar analysis but distinguish between the working and non-working age groups to enable the analysis of change *within* these groups over time. In addition, whilst other social trends may remain uncertain it is clear that the future population will have a higher proportion of older adults over working age with just 9% of time use survey adult respondents were over working age in 1974 compared with 30% in 2014. By examining changes over time for this age group compared to those of working age we may therefore gain additional insights into the nature of future demand for this significantly growing demographic group.

Fig. 5 shows the percentage point change in selected acts for those aged 16–64 vs 65 + in each year for men and for women. Women appear to be reporting substantially less Personal/home care on weekday mornings (see also Anderson, 2016) but an increase at midday and especially in the evening peak demand period for those aged 16–64 who are now more likely to be in work (c.f. Table 3).

Whilst day-time media use has increased for all groups, it has decreased during the later evening peak period (18:00–20:00) at exactly the time that food related activities now appear to dominate and only reaches historical rates (0 change) much later in the evening.

The shifting of Personal/home care out of 'working hours' and the pushing of food related activities to later in the evening, especially for women aged 16–64 may be related not only to increased female participation in the labour market but also to the reported elongation of working hours and commutes (Chatzitheochari and Arber, 2009) which may be randomising home-coming times. In contrast those aged 65 +, whether male or female, also appear to have shifted substantial personal/home care to the middle of the day and are also eating later, but not as late as those aged 16–64. Instead, they may be filling the 'demand gap' left by the later eating 16–64 age group and together these may be leading to the relative shifts in demand noted in Fig. 2 and Fig. 5.

However, whilst plausible, the descriptive analysis does not allow us to robustly test the statistical significance nor magnitude of the factors that are associated with the apparent shifts in home-based food related, personal/home care and media activities during peak demand periods. To do this we present two Poisson regression models for each of these activities which tests the factors associated with the number of half

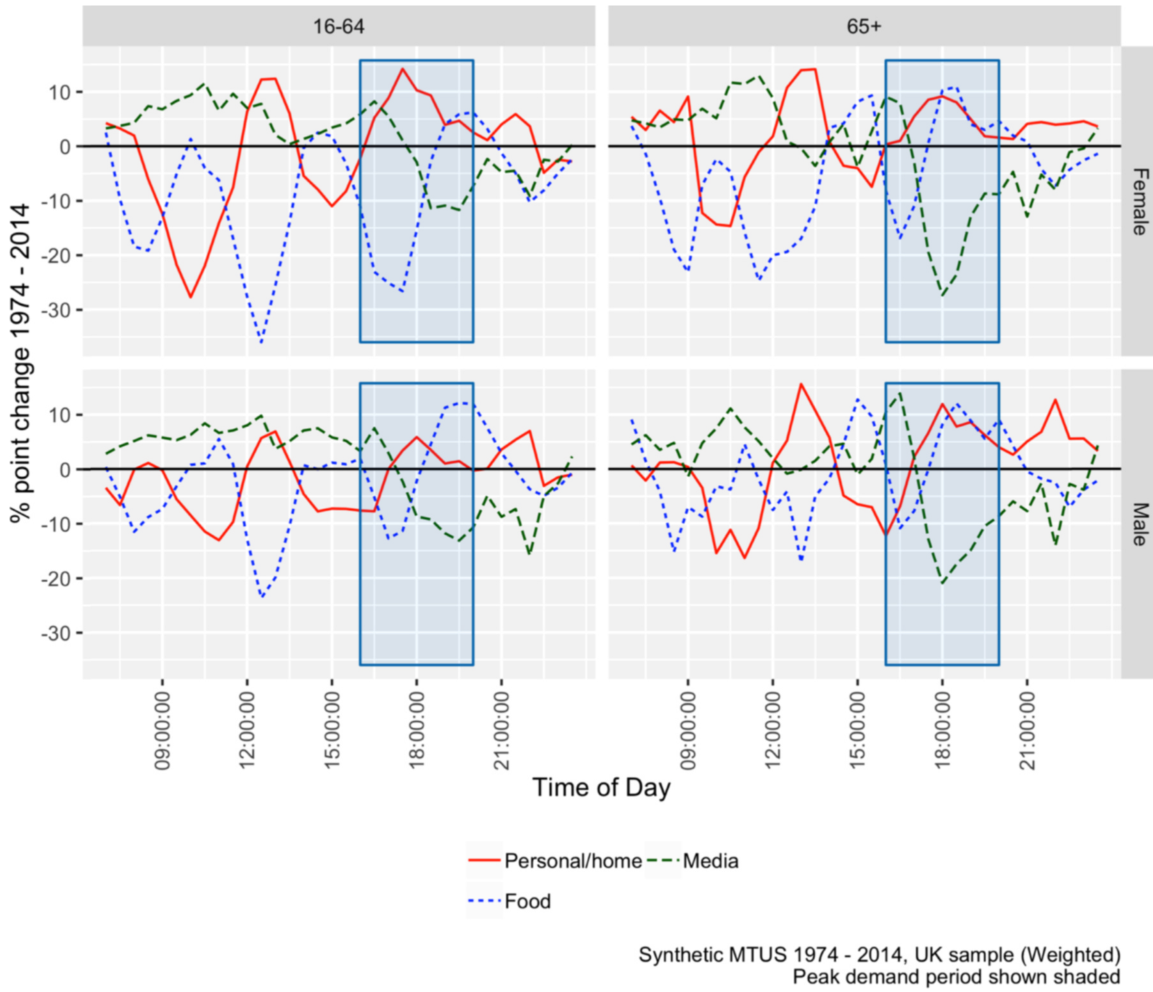

Fig. 5. % point change 1974–2014 (activities reported on weekdays at home only, weighted).

hours in which they were reported in specific time periods. For each activity we first assess the statistical effect of survey year and gender (sub-model one) to establish change over time and then gender interacted with work status (sub-model two) for all respondents to highlight shifts in domestic practices which remain strongly gendered (Moreno-Colom, 2015). We use Poisson regression to model the number of half hours in which the given activity was reported in those periods and so provide a rough proxy for a change in electricity consumed.

Table 7
Factors prediccting the number of food related half hours 16:00 –18:00.

	Early food: Model 1 All	Early food: Model 2 All
1985 (contrast = 1974)	0.263*** (0.221, 0.305)	0.001 (−0.022, 0.024)
2000	0.196*** (0.147, 0.244)	−0.062*** (−0.089, −0.034)
2014	0.082** (0.029, 0.134)	−0.195*** (−0.224, −0.165)
Female	0.717*** (0.679, 0.756)	0.367*** (0.335, 0.399)
Female* 1985	−0.325*** (−0.375, −0.275)	
Female* 2000	−0.342*** (−0.400, −0.283)	
Female* 2014	−0.352*** (−0.416, −0.289)	
Job: Full-time (not in paid work)		−0.293*** (−0.329, −0.257)
Job: Missing		−0.338*** (−0.520, −0.155)
Job: Part time		−0.158*** (−0.225, −0.092)
Job: Unknown hours		−0.271*** (−0.398, −0.145)
Female* Full time		−0.050* (−0.097, −0.003)
Female* Missing		0.0003 (−0.235, 0.236)
Female* Part time		0.128*** (0.056, 0.199)
Female* Unknown hours		0.232** (0.078, 0.377)
Constant	−0.041* (−0.074, −0.007)	0.344*** (0.313, 0.379)
Observations	33,041	33,021

Table Notes: Poisson regression coefficients and 95% confidence intervals using robust standard errors reported.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$; 95% confidence intervals use robust standard errors.

Table 8
Factors predicting the number of Personal/home care related half hours 16:00 –18:00.

	Early personal: Model 1 All	Early personal: Model 2 All
1985 (contrast = 1974)	0.391*** (0.334, 0.447)	0.507*** (0.474, 0.541)
2000	0.503*** (0.442, 0.565)	0.546*** (0.509, 0.582)
2014	0.471*** (0.407, 0.535)	0.507*** (0.467, 0.546)
Female	0.296*** (0.239, 0.353)	0.521*** (0.478, 0.564)
Female * 1985	0.180*** (0.110, 0.249)	
Female * 2000	0.062 (−0.015, 0.138)	
Female * 2014	0.046 (−0.033, 0.126)	
Job: Full-time (not in paid work)		0.108*** (0.062, 0.154)
Job: Missing		0.296*** (0.120, 0.472)
Job: Part time		0.038 (−0.047, 0.122)
Job: Unknown hours		−0.025 (−0.185, 0.134)
Female * Full time		−0.356*** (−0.416, −0.296)
Female * Missing		−0.401*** (−0.639, −0.163)
Female * Part time		−0.047 (−0.138, 0.044)
Female * Unknown hours		0.038 (−0.164, 0.240)
Constant	−0.643*** (−0.689, −0.598)	−0.777*** (−0.825, −0.730)
Observations	33,041	33,021

Table 7 shows the results for the 'early food' model. Overall, food related half-hours have increased since 1974 in this period (Model 1, coef. = 0.082 for 2014 compared to 1974) but the opposite is the case for women (Model 1, Female * 2014 coef = –0.352). Model 2 shows that those in full-time paid work reported fewer food related half hours in this period compared to those not in work (Model 2, coef = −0.293) and this was also true, but of lower magnitude, for those in part-time work. There was also an additional negative effect for women in full time work (coef = −0.05) but the opposite if they were part-time (0.128).

Similar analysis for Personal/home care (Table 8) shows that there has been an overall increase in half hours recording this activity in this period and that there is a strong positive effect for women overall and in 1985 compared to 1974 in particular (Model 1). Model 2 shows that women in full time work are much less likely to report Personal/home care in this period and this should be interpreted alongside the 'Female' and 'Full-time' coefficients as indicating that whilst there has been an overall increase for both these groups, the increase is much smaller for women in full-time work.

Finally, respondents were significantly more likely to report early media use in all years compared to 1974 (Table 9, Model 1) but overall women report less (Model 1, coef = −0.377). There is no interaction effect between gender and survey year but those in full-time work report significantly less (Model 2, coef = −0.967) although this effect is reduced slightly for women in full-time work (Model 2, coef = 0.194). However, as noted above it is also possible that media activities such as TV use have changed in nature such that they are more rarely recorded as primary acts.

Overall these results tend to confirm the conclusions of the descriptive analysis reported above. The apparent shifts in relative electricity demand appear to be associated with specific population groups and is at least partly driven by their changing labour market participation together, potentially, with changes to the labour market itself including length of work hours and durations of commuting. Increased labour market participation for women appears to have pushed a range of domestic tasks to later on weekday evenings. Some of the 'demand slack' created appears to have been taken up by older people who are now eating in the period 'vacated' by younger cohorts.

It would be tempting to use the results reported in Table 7 to estimate the consequences for actual electricity demand of fewer 'food half-hours' for households with at least one woman in full time work using imputed power values (c.f. (McKenna and Thomson, 2016; Widén and Wäckelgård, 2010)). However the cautions noted in Section 3 regarding the imprecision of the 'any in a half hour indicator' together with the vague relationship between reported activities and actual power demand (Durand-Daubin, 2013; Love and Cooper, 2015) advise against this. Nevertheless it is worth noting that analysis of changing energy demand for cooking has hinted not only at changes in food habits but also the switch from 'cooker' to 'electrical appliance' energy use for microwaves, kettles and cold appliances which may have offset any other savings (Palmer and Cooper, 2012, p. 38).

Table 9
Factors predicting the number of media related half hours 16:00 –18:00.

	Early media: Model 1 All	Early media: Model 2 All
1985 (contrast = 1974)	0.296*** (0.249, 0.344)	0.129*** (0.094, 0.164)
2000	0.302*** (0.248, 0.356)	0.215*** (0.177, 0.253)
2014	0.339*** (0.283, 0.394)	0.157*** (0.117, 0.197)
Female	−0.377*** (−0.432, −0.322)	−0.644*** (−0.678, −0.611)
Female * 1985	−0.050 (−0.120, 0.019)	
Female * 2000	0.116** (0.039, 0.193)	
Female * 2014	0.047 (−0.033, 0.127)	
Job: Full-time (not in paid work)		−0.967*** (−1.005, −0.930)
Job: Missing		−1.149*** (−1.379, −0.918)
Job: Part time		−0.560*** (−0.629, −0.490)
Job: Unknown hours		−0.409*** (−0.533, −0.286)
Female * Full time		0.194*** (0.128, 0.259)
Female * Missing		0.903*** (0.597, 1.209)
Female * Part time		−0.046 (−1.131, 0.038)
Female * Unknown hours		−0.067 (−0.277, 0.144)
Constant	−0.288*** (−0.326, −0.250)	0.422*** (0.385, 0.458)
Observations	33,041	33,021

4.3. Shifting practices, shifting demand

Having established that there is evidence of change in the timing of energy-demanding practices in the UK from 1974 to 2014 we now need to establish if these changes are implicated in the shifts relative demand described in Fig. 2 above. To do this we select the time-use data for 2000–2014 and compare half-hourly percentage point change in reported food, media and personal/home care for weekdays in this period with similar changes in overall electricity demand on weekdays in July in England and Wales for 2006–2016. We have chosen to do this for

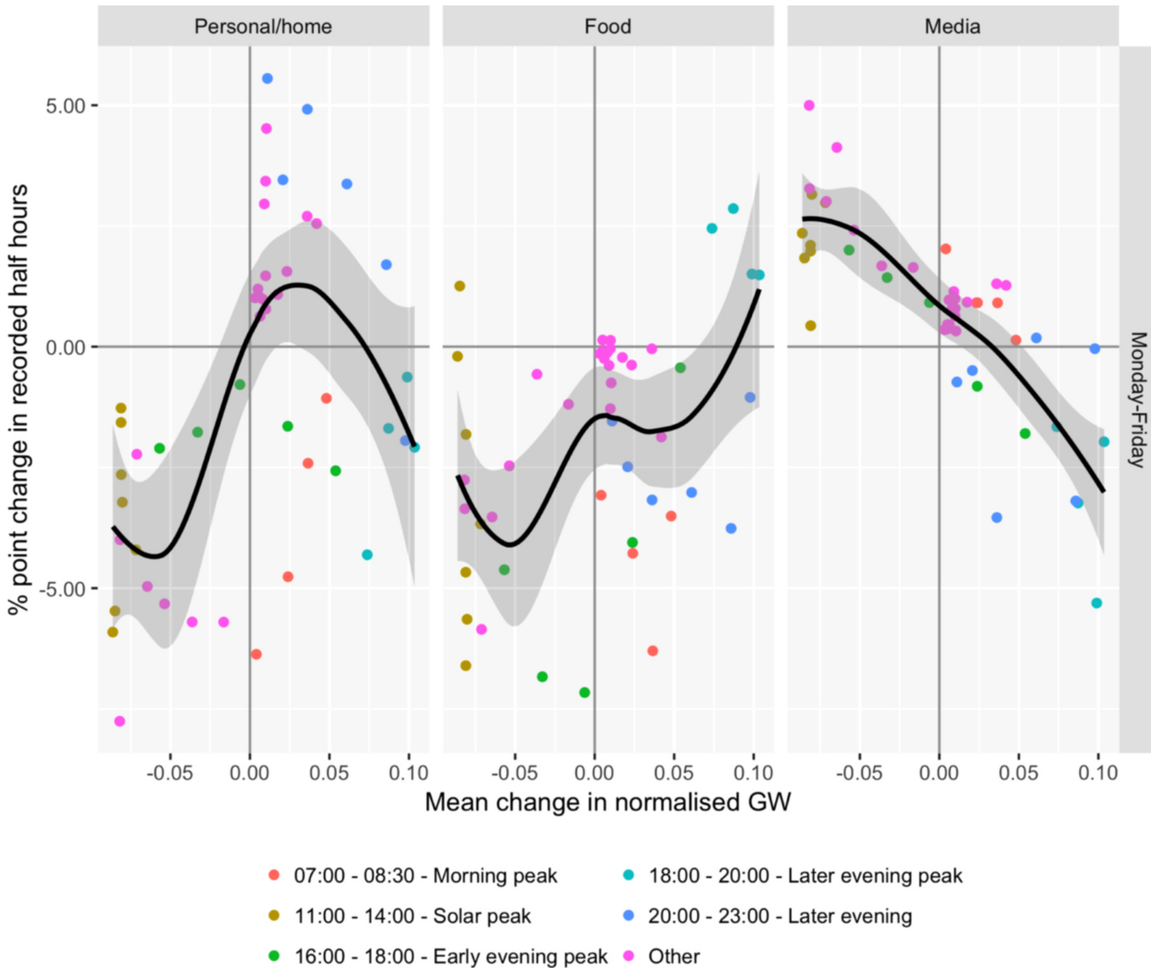

Fig. 6. Comparison of % point change in half hours reported and mean change in normalised GW demand (Source: MTUS 2000–2014, National Grid weekdays in July 2006–2016, best fit line: LOESS curve with SE).

July rather than taking mean values across the whole year in response to Fig. 1 and Fig. 2 which suggest that evening peak demand shifts are more visible in July where the 'masking' effects of lighting and heat demand are substantially reduced.

Fig. 6 shows the 2006–2016 change in overall mean normalised electricity demand for each half hour plotted against the percentage point change in reporting of the specified activity. Points are colour coded according to the period of the day. Thus we can see that the half-hours in which relative electricity demand reduces the most are all during the 'Solar peak' period but those where it increases the most are generally in the 'Later evening peak' or 'Later evening' periods.

We include a LOESS line of best fit together with the best fit line's standard error as a shaded region to indicate uncertainty. Were there to be a positive correlation between reported increase in the reporting of an activity and an increase in the relative electricity demand then we would expect a positive linear line of best fit.

The plots show that half hours with increases in reported Personal/home care (left panel, y axis > 0) are all associated with increases normalised electricity demand (x axis > 0 implying a shift in demand) and these occur in the 'Later evening' and 'Other' periods. Decreases in Personal/home care (y axis < 0) are less clearly associated reductions in relative GW demand with the exception of the 'Solar peak' but are found in several periods where normalised demand increased and this is reflected by the shape of the best fit line and the indicated uncertainty.

The middle panel (Food) shows why this might be. As we would expect from the previous analysis, increases in reported food activities are found in the 'Later evening peak' period when normalised electricity demand increased (so producing a more linear best fit line) and also in one half-hour of the 'Solar peak' (c.f. Fig. 4). As with Personal/home care, decreases in reported food activities tend to be associated with decreased normalised electricity demand but this is less consistent where normalised electricity demand has increased.

In contrast the right panel (Media) shows a clear negative association between change in reported media use and change in normalised electricity demand. Thus, increased media use was reported during the mid-day 'Solar peak' and 'Other' periods (c.f. Fig. 4) when relative demand declined but decreased use was reported in the 'Later evening peak' and 'Later evening' periods when relative demand increased.

It seems clear therefore that to the extent that relative electricity demand has shifted later (c.f. Fig. 2), this is partly to do with changes in Personal/home care, more to do with changes in Food related activities but very little to do with changes in Media use.

5. Conclusions and policy Implications

The paper began by noting the general decrease in UK electricity demand at all times of day, days of the week and seasons from 2006 to 2016. However the analysis also showed some evidence of shifts in overall electricity demand and this becomes especially clear when relative demand is analysed in summer (Fig. 2). In the absence of disaggregated residential electricity demand data over the same time frame, the paper presents analysis of repeated cross-sectional data on historical patterns of time use since 1974 to explain what underpinned these shifts in relative demand.

At the highest level, the analysis shows that the temporal structure of everyday life has been relatively stable on decadal timescales. Thus sleeping still happens overwhelmingly overnight, there are still relatively distinct time periods at which eating occurs, and for those people who are working, there is still a distinct working-day pattern.

However, even these apparently strongly structured elements exhibit different forms of change over the 40 year period linked to associated social, demographic and economic change in UK society. The overall results suggest that comparing 1974–2014, a higher proportion of the population are sleeping overnight rather than working, perhaps reflecting firstly a higher proportion of people across the population of retirement age and therefore not working at all, and secondly that there is less overnight shift work across the UK economy. Sleep also appears to end and start earlier, again a potential consequence of an ageing population.

In contrast, there has been a substantial reduction in the level of reported food related activities at breakfast and especially at lunch time with implied electricity demand reduction as noted in Fig. 2. There has also been an apparent shift to later eating for all age groups, especially for those of working age which appears to have either reduced or shifted evening media use as it gets temporally squeezed between later eating and sleep. There has also been a notable reduction in reporting of morning weekday and Saturday 'personal/home care'. Whilst this may reflect a reduction in the time spent doing these tasks, recent work suggests that it is more likely that especially household care tasks have been shifted from weekdays to the evening peak period, and especially to Sundays for those of working age (Anderson, 2016; Moreno-Colom, 2015).

Taken together these results may offer an explanation for the shift in aggregate demand shown in Fig. 2 despite residential demand being only one contributor to the overall picture of national electricity demand. In addition, the results also lead to five implications for evening peak electricity demand.

First, much of the recent policy debate emphasises the need for more flexible demand in the context of increased non-dispatchable renewable generation (Sanders et al., 2016). According to the UK Government's Clean Growth Strategy (HM Government, 2017), in an 80% renewables future, electricity demand is projected to increase by 3% (i.e. 10 additional TWh), with an increase in peak demand of 4% (i.e. 2.8 GW). Extra capacity and flexibility is proposed to originate from Demand Side Response (4.9 GW), storage (0.3 GW), clean generators (0.5 GW) and fossil fuels (1.2 GW). The Clean Growth Strategy does not specify the extent to which the residential sector will contribute to Demand Side Response, however this will need to be significant given that National Grid estimates user-led demand management and on-site generation participating in the Balancing Services contributed only ~ 700 MW of Demand Side Response in 2017. Whilst this paper's results suggest that the changes to the evening peak profile shown in Fig. 2 may be caused by ongoing change in people's routines, the highly interrelated and sequential nature of the activities analysed in the paper also implies that any estimate of the residential demand side flexibility potential would require a more thorough understanding of the trajectories of the social practices that create electricity demand. Further, attempting to engineer non-adaptive socio-technical solutions to meet current patterns of demand when these patterns are constantly evolving as explained in Shove (2017) and Walker (2014) may not lead to the desired effects of higher flexibility. If such solutions and interventions are only developed to meet current 'need' and their business case assumes this 'need' is fixed, then the risk of developing rapidly obsolete and uneconomic interventions is high. Analysis such as that presented here can help to understand the trajectories of change that must be considered and thus inform adaptive intervention design.

Second, shifting patterns of personal/home care and especially food-related behaviour in the evenings may be pushing energy demand towards a later peak than has previously been the case. This appears to be elongating the evening peak possibly as a result of somewhat less routinized 'home-coming' times based on longer work and commute hours. Although the translation between practices and specific energy demand in the UK is complicated by the use of both gas and electricity for cooking, nevertheless the implications for households where cooking energy is provided by electricity are clear. The introduction of Time of Use of tariffs will become more widespread if Ofgem mandates half-hourly settlement in the domestic electricity market (Elexon, 2013) and households who consume electricity at more expensive peak periods, and who are unable to change their consumption patterns, could end up paying significantly more. According to Government's figures 30% of consumers are concerned about paying their electricity bills (Department for Business, Energy and Industrial Strategy, 2017) and understanding the distributional effects of Time of Use tariffs becomes vital to ensuring affordability of energy bills, at the same time as making demand more flexible. In this respect, research on the 'locked-in' nature of different people's practices will be crucial to understanding the consequences for dynamic tariffs of the practices of different socio-demographic groups.

Third, the results suggest that electricity demand for cooking may have already shifted towards the evening peak due to the reduction in daytime food-related activities which is seen across all age groups, and it may also be shifting to later in the day, especially for women of working age due to increased labour market participation. It seems therefore that policies to encourage women in to the workforce (Lewis and Campbell, 2007) have also had consequences for the timing of energy demand. Whilst this may be having the effect of elongating the peak, it is possible that additional flexible work-hours policies may have the additional benefit of further de-synchronising 'home-coming' and thus further mitigating peaks in demand. However, as others have noted, social actors are rarely free to choose exactly when the evening sequence of activities can take place due to inter-locking schedules of dependents and partners (Shove and Walker, 2014; Torriti, 2017). Providing individuals with flexibility will therefore not necessarily translate into enacted and aggregated flexibility.

Fourth, the apparent reduction in media use reported as a primary activity could be considered a side effect of these shifts in food related activity if there is indeed a direct link between less media use and reduced electricity demand. However, the potential shift of some personal/home care to the evening peak period for those of both working and non-working age may be counteracting this reduction, especially where this may constitute laundry or tumble drying of clothes (Anderson, 2016; Higginson et al., 2013). As a result we are less optimistic than Staffell (2017) and suggest that supply-side reconfiguration towards low carbon non-dispatchable generation in combination with trends in residential consumption still presents a capacity shortage risk.

Fifth, and in contrast to the previous point, the results also highlight that a number of changes in the distribution of energy-demanding activities might work in favour of low carbon and especially photovoltaic generation. Staffell (2017) has suggested that minimum net demand may be a particular and unexpected future problem. Our paper shows that if this is indeed the case those aged over 65, who are an increasing proportion of the population, appear to have substantially increased their reporting of personal and home care activities during the middle of the day. If this could be combined with a re-configuration of food related activities such that energy for cooking was required during the middle of the day alongside the integration of solar photovoltaic generation and battery storage (Department for Business, Energy and Industrial Strategy, Ofgem, 2017) then the potential problems of minimum net demand and also mid-day local low voltage network overload (Strbac, 2008; Torriti, 2015) could be avoided at the same time as evening peak demand reduced.

Future work should further explore the shifting patterns of the individual practices that make up the high level aggregated activities reported here. Previous work has already considered eating (Durand-Daubin and Anderson, 2018) and laundry (Anderson, 2016) in some detail to 2005 but has not yet extended the analysis to 2014 while analysis of changes in the timing of media use is still largely missing (Morley and Hazas, 2015). Given the apparent reduction in evening media use described here, such analysis should include consideration of media use as a secondary or 'multi-tasking' activity which may produce substantially different results.

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Data and analytic code

National Grid half-hourly demand data is available from: https://www.nationalgrid.com/uk/electricity/market-operations-and-data/data-explorer

The MTUS is available from: www.timeuse.org/mtus/

The UK 2014–2015 Time Use Survey is available from: https://discover.ukdataservice.ac.uk/catalogue/?sn= 8128

The R code used to convert the 2014 UK Time Use Survey to MTUS form is available at: https://git.soton.ac.uk/ba1e12/UK-TU-2014/tree/master/convertToMTUS

The R code used to generate the 'any in a half hour' data from MTUS form is available at: https://git.soton.ac.uk/SERG/DEMAND/tree/master/Theme-1/changeOverTime/dataPrep

The R code used to produce the analysis reported in this paper is available at: https://git.soton.ac.uk/SERG/DEMAND/tree/master/Theme-1/changeOverTime/paper

APPENDIX A. - Codes associated with activities

Sleep
MTUS # 2 sleep and naps
MTUS # 3 imputed sleep
MTUS # 55 relax, think, do nothing
Personal/home
MTUS # 1 imputed personal or household care
MTUS # 4 wash, dress, care for self
MTUS # 19 set table, wash/put away dishes
MTUS # 20 cleaning
MTUS # 21 laundry, ironing, clothing repair
MTUS # 22 maintain home/vehicle, including collect fuel
MTUS # 23 other domestic work
MTUS # 27 pet care (not walk dog)
MTUS # 28 physical, medical child care
MTUS # 30 read to, talk or play with child
MTUS # 31 supervise, accompany, other child care
MTUS # 32 adult care
MTUS # 46 gardening/pick mushrooms
MTUS # 54 knit, crafts or hobbies
Food: Cooking or eating
MTUS # 5 meals at work or school
MTUS # 6 meals or snacks in other places (including at home)
MTUS # 18 food preparation, cooking
Work: Work or work related
MTUS # 7 paid work-main job (not at home)
MTUS # 8 paid work at home
MTUS # 9 s or other job not at home
MTUS # 10 unpaid work to generate household income
MTUS # 11 travel as a part of work
MTUS # 12 work breaks
MTUS # 13 other time at workplace
MTUS # 14 look for work
Education: Education or related
MTUS # 15 regular schooling, education
MTUS # 16 homework
MTUS # 17 leisure & other education or training
MTUS # 29 teach, help with homework
Shop: Shopping/service use
MTUS # 24 purchase goods
MTUS # 25 consume personal care services
MTUS # 26 consume other services
Social/leisure: Voluntary, civic, leisure or social activities
MTUS # 33 voluntary, civic, organisational act
MTUS # 34 worship and religion

Sleep
MTUS # 35 general out-of-home leisure
MTUS # 36 attend sporting event
MTUS # 37 cinema, theatre, opera, concert
MTUS # 38 other public event, venue
MTUS # 39 restaurant, cafe, bar, pub
MTUS # 40 party, social event, gambling
MTUS # 41 imputed time away from home
MTUS # 48 receive or visit friends
MTUS # 49 conversation (in person, phone)
MTUS # 50 games (social & solitary)/other in-home social
MTUS # 51 general indoor leisure
MTUS # 52 art or music
MTUS # 53 correspondence (not e-mail)
Sport: Sport or exercise
MTUS # 42 general sport or exercise
MTUS # 43 walking
MTUS # 44 cycling
MTUS # 45 other outside recreation
MTUS # 47 walk dogs
Media: Media use incl. read, TV, radio, PC, internet
MTUS # 56 read
MTUS # 57 listen to music or other audio content
MTUS # 58 listen to radio
MTUS # 59 watch TV, video, DVD, streamed film
MTUS # 60 computer games
MTUS # 61 e-mail, surf internet, computing
Travel
MTUS # 62 no activity, imputed or recorded transport
MTUS # 63 travel to/from work
MTUS # 64 education travel
MTUS # 65 voluntary/civic/religious travel
MTUS # 66 child/adult care travel
MTUS # 67 shop, person/hhld care travel
MTUS # 68 other travel
Not recorded
MTUS # 69 no recorded activity

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