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Eco-efficiency Rebound Effects Associated With Household Energy Using Products

Brett GIDDINGS and Miles PARK
University of New South Wales

Abstract

For designers, a key consideration to improve the environmental performance of new products and services is energy and resource efficiency (eco-efficiency). This is particularly important for household energy using products (EuPs) as they consume significant energy during the consumption (use) phase of their lifecycle.

EuPs incorporate many types of consumer electrical and electronic products, including televisions and computers as well as the many other powered kitchen, laundry, bathroom and personal electronic devices of which ownership, both individually and cumulatively has increased dramatically in modern households. A consequence of EuP ownership and changing behavioural patterns is that EuPs cumulative contribution to overall household energy use is increasing in Australia, at 4.7% per annum. This is despite the sustained efforts over many years to improve energy efficiency of individual EuPs that is claimed to have improved at a rate of 2% per annum since 1970. This begs exploration of the drivers underpinning this divergence between predicted energy conservation through efficiency and actual energy use. The aim of this study is to investigate why household energy use from EuPs continues to rise. Such situations are described as 'rebound effects' where 'designed in' energy savings are not achieved.

Exploring the proposition of the rebound effect, this study investigates design, ownership and use parameters of televisions (and peripheral equipment), washing machines, dishwashers and refrigerators benchmarked over a period of time. Drawing upon a variety of technical and behavioural criteria, data is mapped and presented for analysis to locate, identify and remark upon the qualities and significance of a likely rebound effect. Such information, where identified, highlights the hidden implications and significance of product use and user behaviour in shaping the success, or otherwise, of design strategies to conserve energy and consumption.

Keywords: rebound effects, eco-efficiency, user behaviour

Introduction

Energy use per person within the residential sector in Australia has been steadily increasing year on year (DEWHA 2008). Rather than any single contributing factor, this phenomenon can be seen as the result of a combination of converging societal, technological and behavioural factors such as, population and household dynamics, ownership, use and cost of Energy Using Products (EuPs).

Improving energy efficiency is often framed as a technological challenge without understanding and accounting for the influence of user behavioural (product use), ownership and cumulative consumption factors. Such 'soft' factors are often hidden and can appear as inconspicuous or secondary (Jackson 2006, Shove 2003), but from our analysis of specific household EuPs this consumption can be significant and cause energy rebound effects. The data presented in this paper aims to contextualise the importance of these factors and their significance to energy use in modern Australian households.

Energy, particularly electricity, is used for a wide range of optional and essential household purposes. Essential purposes being those required for reasons of health, sustenance and hygiene. Optional energy usage relates to non-essential energy using activities such as watching television and using entertainment devices. Optional energy usage may also include excessive consumption of products deemed essential such as extremely cold refrigerator thermostat settings and using a dishwasher or clothes washing machine at half capacity.

Whilst touching on refrigerator energy consumption, this paper focuses on products that are mostly of an optional nature; where behaviour, use and ownership become a major determinant in total energy consumption. The research underpinning this paper reveals that user influence on the energy demands of EuPs, where product use is essential, is outweighed by the actual design of the product and the technologies they employ (Harrington 2009, DEWHA 2008).

Energy Efficiency

Independent studies and Government policies concur that the primary way to reduce energy demand is through improved energy efficiency. Governments, in adopting energy efficiency policies and programs, recognise that energy efficiency provides the largest, most cost effective and most rapid way to cut greenhouse emissions (Herring and Sorrell 2009). End-use efficiency is projected to be the largest contributor to CO2 emissions abatement by 2030 (IEA 2009).

In addition to regulatory standards, technological developments of EuPs in energy efficiency have been significant, with the energy efficiency of household appliances claimed to have improved at 2% per annum since 1970 (Owen 2006). However, despite the successful implementation of regulatory standards and technological developments, household energy use attributed to these devices continues to increase. Growth in EuP energy consumption is the largest among major end-uses and has been estimated to increase from 70.5 PJ in 1990 to 169.4 PJ in 2020, an increase of 4.7% per annum (DEWHA 2008: 22). As consumers migrate to newer energy efficient products household energy use associated with EuPs is actually increasing not decreasing as predicted. It is this paradox, or notably, this rebound effect that is considered in this study.

Describing the Rebound Effect

The 'Rebound effect' is based upon the proposition that in making energy services cheaper, through more efficient use of that energy, greater use of those energy services is encouraged (Sorrell et al 2009). First coined by economists studying market dynamics in the energy sector during the 1980s, it can be loosely defined as the difference between the projected and actual savings (or losses) due to increased efficiencies. (Khazzoom cited in Greening et al, 2000: 390).

A direct or indirect rebound effect occurs when 'designed in' energy savings are partially achieved (described in this paper as 'unrealised savings'), not achieved, or even 'backfire' (where energy use increases rather than decreases) (Druckman et al. 2011, Sorrell. et.al. 2009). A direct rebound being that where demand or consumption of a product with improved efficiency increases or the resources consumed in its use increase; for example, refitting a house with energy efficient lighting and choosing to leave the lights on longer or install more lights as, individually, each light offers a substantial energy saving over the one it replaces. While an indirect rebound effect is the result of energy use re-allocation that occurs associated with the savings realised from efficiency gains.

Sorrell et al. (2009) offer a critical review of empirical studies of rebound effects. They note that despite growing interest in rebound effects, evidence is sparse partly due to the lack of suitable data, differing methodological approaches and terminology. Thus, conclusions found in the literature on the size of rebound effects vary from zero and insignificant (Lovins et. al. 1998, von Weizacker et. al. 1997) where there is little to no measured effect; to complete backfire (Dahmus & Gutowski 2005, Hanley et al. 2006, Herring 2006 cited in Alcott 2008) where the rebound is greater than 100% of the theoretical energy saving.

Methodology

The desktop study supporting this paper uses pre-existing Australian time series data to determine, map and interpret energy rebound effects of specific household EuPs. Where possible, data has been sourced from government-based entities such as the Australian Bureau of Statistics (ABS) or the Equipment Energy Efficiency Program (E3). Relevant sales and consumption data has primarily been acquired through industry marketing reviews.

Data sets from the above sources have been compiled over time intervals reflective of both the specific product in question and the availability of reliable references. Data gathered have been mapped against a range of key technical and behavioural factors. This visual interpretation of the data provides high-level energy use information for comparative purposes, rather than absolute results.

In many instances time series data has been normalised using a range of non-product related metrics such as household occupancy and average weekly earnings to provide a relative functional unit for comparison and mapping over time periods relevant to each product. The results of this data collation and mapping exercise have then been interpreted against the devised EuP rebound causes described below.

Rebound Causes	Description
Use and Behavioural	Changes in user behaviour such as increased frequency and duration of use
Design and Technology	Enhanced design features within products that diminish potential energy savings. Unrealised energy savings may occur due to the introduction of features or capacity/sizes increases
Cumulative Consumption	Pooled total ownership, multiple ownership per household or ownership per individual where demand overrides efficiency

Table 1. EuP Energy Use Rebound Criteria

Television

“Televisions are the product with perhaps the most dramatic transformation in recent years” (DEWHA 2008: 94). Flat screen LCD units (liquid crystal display) have mostly displaced CRT (cathode ray tube) televisions in the Australian market. The switchover to digital broadcasting and dramatic reductions in relative purchase cost have also resulted in a spike in multiple product ownership (TEC 2009).

Use and Behavioural Rebounds

Television ‘viewing hours’ is a commonly used measure for marketing and media monitoring purposes. However, television ‘hours-on’ is significantly greater than ‘viewing hours’ and is more representative of total energy consumption associated with how televisions and peripheral devices are used. Much literature exists describing ‘viewing hours’, however time series data for actually ‘hours-on’ is sparse.

Regardless of the availability of detailed time series data, the data that is available regarding ‘hours on’ indicates that from 1500 hours in 1986 projected use is set to reach 2800 hours in 2020 (DEWHA 2008). In addition to an increase in ‘viewing hours’, up to 3.11 hours per day in 2009 (ThinkTV 2010), the diversity of modern television functionality (watching DVDs/movies, playing video games and listening to digital radio) is contributing to this marked increase in ‘hours on’.

The increase in ownership of television peripheral devices required to undertake these additional functions, such as DVD payers and gaming consoles, also contributes to cumulative ‘hours on’ energy use.

Design and technology Rebounds

Whilst most types of EuPs in this study have over time become more energy efficient, television sets counter this trend. Energy consumption for a typical television has increased dramatically by 212% over the period surveyed for televisions, from 60 watts in 1975, to 187.2 watts in 2010 (DEWHA 2008).

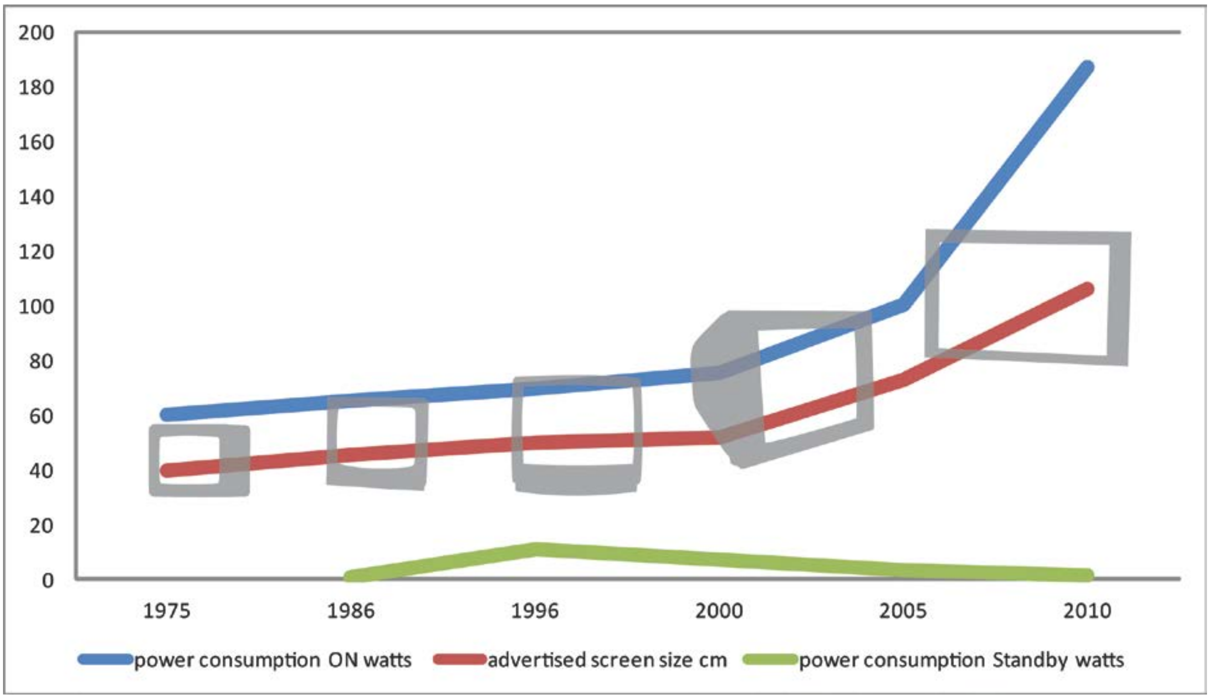

Figure 1. Television size and energy consumption
Source: DEWHA (2008)

Likewise, since 2006 the volume of sales of flat screen (LCD) and digital television has been equally dramatic. 82% of Australian households have converted to digital television (DBCDE 2011). Advertised screen size has also increased dramatically over the survey period for televisions, up from 40 cm in 1975 to 106cm in 2010. The continuing increase in screen size is significant in terms of television power demand as seen in Figure 1 (DEWHA 2008).

Television and peripheral device standby power also needs to be considered. Data reveals that approximately 50% of televisions are left in standby mode when not in use, the remainder being switched off or unplugged (DEWHA 2008). However, television standby power consumption is comparatively insignificant compared to on-mode power demands and has improved from 11 watts in 1996 to 1.7 watts in 2010 (DEWHA 2008). While the standby efficiency gains in television and peripherals are important, they are unrealised savings, as on-mode energy use time has increased, thereby proportionally decreasing standby power time. Some more recent television peripheral devices such as Internet streaming modems and media recorders are operated unswitched in an 'always-on' mode thereby rendering standby power mode obsolete.

The compounding effects of interdependent peripheral devices on energy use is much more evident during 'hours-on'. Improvements in energy efficiency and standby power of individual devices can backfire and is overwhelmed by both the television's energy consumption and the aggregated energy demand of all peripheral devices.

In combination, television and peripheral devices are likely to become one of the most significant contributors to residential end use energy demand over the next 10 years (DEWHA 2008). Not only have televisions become less energy efficient, but when combined with the growing range of interdependent peripheral devices a rebound in energy use is likely.

Cumulative Consumption Rebounds

Total television stock has increased quite dramatically since the mid-1970s. The number of households owning a television having increased from 90% to 99% and the number of units from 1 to 2.4 units per household (DEWHA 2008). Over the same period household occupancy size has decreased by almost 20%, down from an average 3.1 to 2.5 persons per household (ABS 2001, 2002, 2007 in AIFS 2010 and ABS 2010). There is now almost 1 residential television per occupant. Whilst it is likely that some existing stock is comprised of older televisions, data relating to these secondary (and tertiary) televisions was not available.

In addition, the ownership of television peripheral devices has increased substantially. In 1975 televisions were stand-alone devices, but by the mid-80s VCRs appeared in almost half of all households. In 2010 the majority of Australian homes contain DVD players, VCRs, and Set-top boxes and nearly 50% contain at least one gaming console (DEWHA 2008). As can be seen in Figure 2, the ownership and use of these peripherals is having a marked impact on the total energy consumption associated.

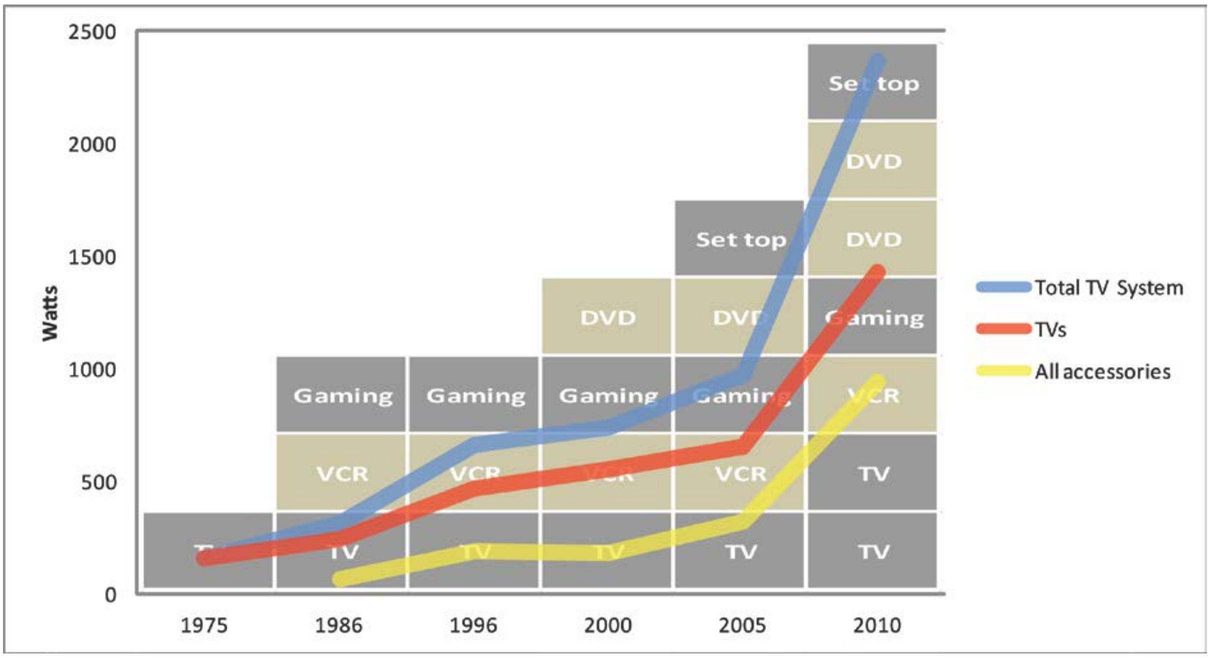

Figure 2. Television & Peripherals energy consumption
Source: DEWHA (2008)

Washing Machines

Washing machines are an integral product in modern Australian households. With 96% ownership across all households they account for 15-20% of total household water consumption, but only 3% of total electricity consumption (DEHWA 2008).

Use and Behavioural Rebounds

Washing machine energy demand is influenced by a combination of the technical specification (of the machine) and consumer behavioural characteristics. These include frequency of use, selection of hot or cold water, selection of wash mode, loading of the machine relative to capacity and machine performance.

Frequency of use is a critical factor in determining energy demand, however available time series data regarding the number of washing cycles per week is limited and has been noted as an area requiring further research (DEWHA 2008). Despite the lack of empirical data, estimates vary from 312 wash cycles per year (DEWHA 2008), to the Energy Efficiency program which assumes 365 wash cycles per year in the calculation underpinning its energy rating scheme (EES 2010), while the ABS indicates much higher frequency of use compared to DEWHA data

(ABS 2008). However, when viewed over a longer time frame, the frequency of washing cycles per year has increased dramatically. What was a weekly washing ritual, “has become a weekly never-ending spiral and revitalizing a steady stream of discarded clothing” (Shove 2003:131). Davis (2008) notes that due to an increase in the number of washing cycles a partial rebound is evident, despite efficiency improvements with washing machines.

Australian users generally fill clothes to 50% of the capacity of modern washing machines (Choice 2010). This is a significant behavioural trait as it takes as much energy and water to wash a full load as does a half load - unless the machine has the capability to be programmed for partial loads. As the Minimum Energy Performance Standards and Water Efficiency Labelling Scheme program are both based on energy and water consumption per unit of capacity, the Australian Consumers Association note that there is a need to review these parameters to better reflect user behaviour (Choice 2010).

Design and Technology Rebounds

Despite this tendency to half-fill and the inefficacies that entails, other factors contribute to improved resource efficiency. In 2008, 74% of households used cold water washing cycles, up from 61% in 1994 (ABS 2008). 80% of the total energy consumption of a warm-wash clothes wash being associated with warm water embodied energy (EES 2010-1). Converse to this tendency for cold water washing, is the growth in front load washing machine uptake over the survey period for washing machines (up from 5.1% in 1994 to 22.4% in 2008). This marked increase in front-load machines creates a rebound. Despite being significantly more water efficient these machines predominantly do not afford the option of energy efficient cold wash functions (EES 2010-1).

In addition to frequency of use, the propensity for half load washing and the shift to front-load machines suggests an energy rebound, but this is contingent upon other variables. Some of which demonstrate efficiency improvements whilst others represent unrealised savings. For example, front-load (warm wash) machine energy demand has actually increased marginally since 1994, from 275kWh to 290kWh per year as has specified load capacity up by 56% (EES 2010-1). If energy use is analysed from a per kg capacity basis we find that there has been a 32% reduction in use if total capacity has been used, which, as noted above, may be unlikely.

When we study the energy use per kg of washed clothing, and further; per person the machine is servicing, the demands become significantly different. Despite a user trend for only half-loading with clothes and shrinking household occupancy, the designed load capacity for washing machines is increasing. Top-load washing machine capacity increasing from approximately 2kg per person in 1994 to almost 2.6kg per person in 2008 and front-load machines from 1.7kg per person to 2.7kg (EES 2010-1).

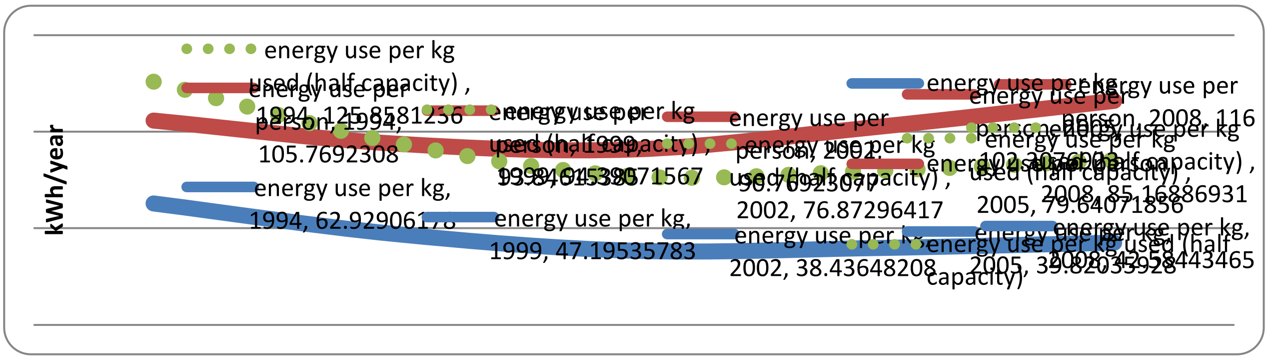

Figure 3. Front load Washing machine energy use

Source: Adapted from ABS (2001, 2002, 2007) cited in AIFS (2010) and EES (2010-1)

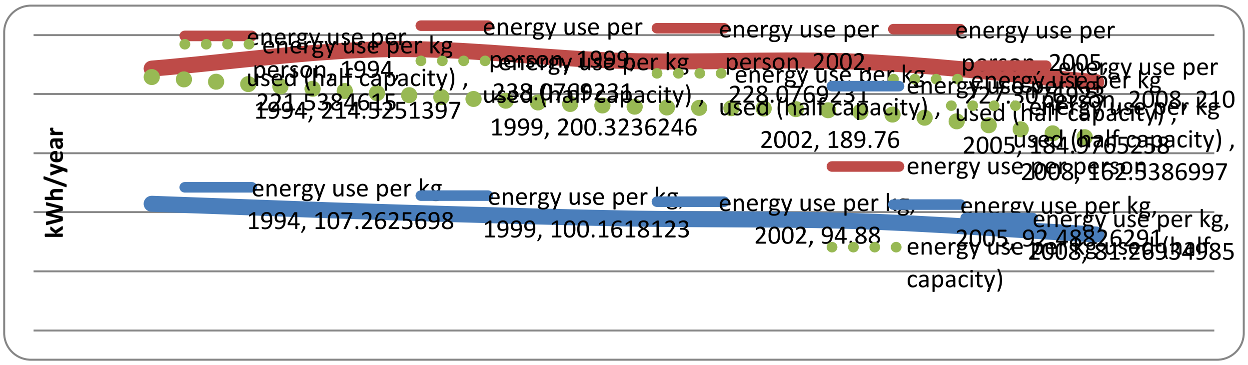

Figure 4. Top load Washing machine energy use

Source: Adapted from ABS (2001, 2002, 2007) cited in AIFS (2010) and EES (2010-1)

Cumulative Consumption Rebounds

Whilst the number of households in ownership of washing machines has risen by 2% since 1994 (DEWHA 2008), the cumulative energy rebounds associated with washing machines relate primarily to the ownership shift towards front load machines which are not aligned with Australian household behaviours. 1.7 million households in 2008 owned a washing machine that whilst 50% more efficient in warm wash mode than top load machines was largely incapable of delivering a cold wash function. When we consider that a high percentage of those users may have a preference for cold water wash cycles and the majority of the total energy consumption is associated with warm water embodied energy (EES 2010-1), a rebound is probable.

Dishwashers

Approximately 50% of Australian households own a dishwasher. As with washing machines, dishwasher energy use is to some extent optional based upon frequency of use.

Use and Behavioural Rebounds

Energy consumption data regarding dishwasher use varies greatly. DEWHA (2008) base their modelling estimates for dishwasher use at 175 cycles per annum, while the Energy Rating label methodology assumes a constant 7 washes per week (EES 2010-1), equating to 365 cycles per annum. Energy Australia (2010) bases NSW calculations upon four cycles per week assumptions, equating to 208 cycles per annum. Despite these discrepancies, ABS data, suggests that dishwasher use frequencies have remained relatively consistent (ABS 2008).

As with washing machines, another variable is loading. A study on dishwasher use in the home (Richter 2011) revealed that consumer behaviours and habits are producing inefficiencies. Approximately 20% of dishwashers are partially filled, with 40% or more of the baskets' space unused. Due to this inefficient loading behaviour "approximately every tenth dishwasher cycle could be saved if the dishwasher would be loaded to its full capacity" (Richter 2011: 186). In addition, other dishwasher use behaviours such as, pre-rinsing of plates under hot running water, repeated use of heavy-duty washing cycles or overuse of detergents adds further variance (Richter 2011). This indicates that 'hidden' behavioural rebounds are likely to occur due to variations between modelled energy efficiency projections (based exclusively on assumptions of frequency of use) and that of actual user behaviour. Such behavioural rebounds are likely, where product use is variable or optional.

Design and Technology Rebounds

Partly to accommodate standardised under bench voids in kitchens (EES 2010-1), the design and configuration of dishwashers has altered little since 1994. Energy and water use efficiencies have however increased dramatically, with energy use down by 40% from 494kWh to 297kWh per annum (EES 2010-1). These claims of energy efficiency, however, are difficult to substantiate due to unaccounted and variable behavioural factors described above and cumulative impacts.

Cumulative Consumption Rebounds

Household ownership of dishwashers has almost doubled since 1994. Increasing from only 24.4% in 1994 to 46% in 2008. This increase is set to continue to more than 60% by 2020 (DEWHA 2008).This rapid increase presents a clear example of cumulative demand overriding unit efficiency gains as the total number of dishwashers in Australia increased from approximately 1.57 million to more than 3.7 million units over a 14 year period. Whilst the energy efficiency of modern dishwashers in part alleviates cumulative energy demand, this spike in ownership contributes to a 142% increase in total dishwasher stock energy consumption.

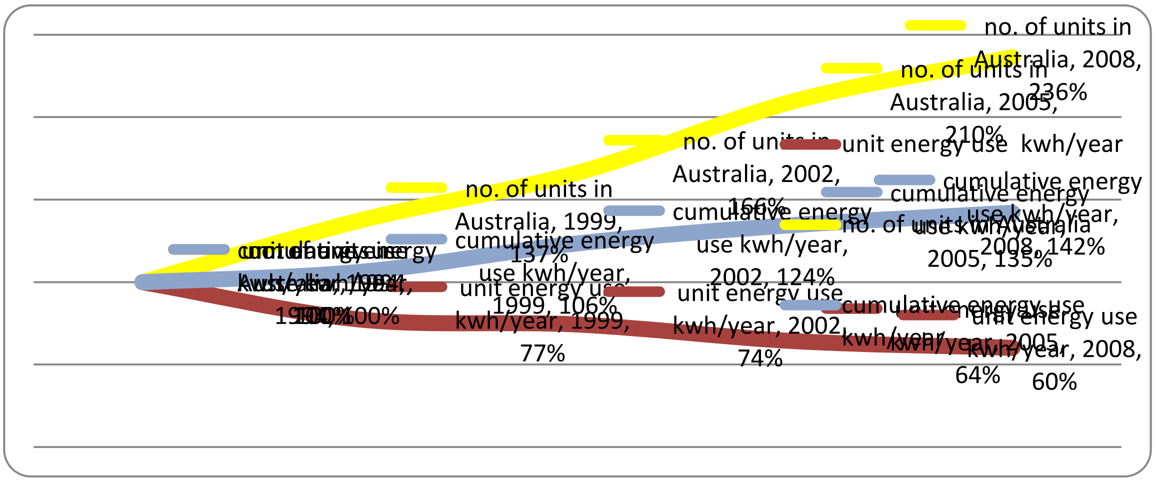

Figure 5. Relative changes in dishwasher ownership and energy use

Source: Adapted from ABS (2001, 2002, 2007) cited in AIFS (2010), DEWHA (2008) and EES (2010-1)

Refrigerators

Most households own a refrigerator that accounts for approximately 12% of residential electricity consumption (Harrington 2009).

Use and Behavioural Rebounds

Refrigerator use and ownership is largely essential and energy consumption mostly independent of consumer usage patterns (DEWHA 2008). Use and behaviour rebounds are limited to temperature thermostat setting preference, food loading, and frequency and duration of door openings. Data for these parameters is limited, however the selection of a low temperature can impact on energy demand by 3 to 4% per degree Celsius for freezer compartments and 1 to 2% for refrigeration compartments (Harrington 2009). The average household opens a fresh food compartment 30.6 times per day (EES 2010-1), however data describing the associated increase in energy demand is not available.

Design and Technology Rebounds

Despite decreasing household occupancies, since 1974 the standard size of a fridge/freezer has increased from 193 litres (Choice 1974) to more than 360 litres in 2008 (DEWHA 2008). Since 1993 however, the size of the fresh food or refrigeration compartment has remained relatively consistent, increasing in size by approximately 6%, while the freezer compartment capacity increased some 24%. The increase in freezer capacity parallels a gradual decrease in ownership of separate freezer units (DEWHA 2008).

Despite increasing capacity, fridge/freezer unit energy consumption has decreased by 2.9% per annum from 1993 to 2009 (EES 2010-1). This trend suggests much greater energy efficiency could be achieved through unrealised savings by limiting refrigerator volume to better reflect the trend of a declining number of occupants per household.

Cumulative Consumption Rebounds

Refrigerator ownership has remained static at close to 100% (ABS 2008), however total refrigerator stock has increased from 1.26 to 1.39 units per household (DEWHA 2008). As consumer behaviour and climate region is inconsequential to refrigerator energy consumption, the key variables are choice of unit (often dictated by design and technology) and the number of separate units per household (DEWHA 2008).

The impact of multiple ownership per household on energy consumption is likely to be much greater due to the likelihood that secondary fridges, often residing in spare rooms and garages, are likely to be less efficient older units (DECCW 2010) and filled to a fraction of their capacity.

Discussion

This research reveals that understanding the interplay between technical and societal, behavioural and consumptive practices is critical to limiting energy efficiency rebound effects. We perceive that eco-efficiency technologies can fail to deliver theoretical savings when ‘soft’ factors such as household dynamics, ownership, product use and affordability are incorrectly assumed or unaccounted for.

In numerous instances we note the influence of household dynamics resulting in the continual rise in household stock of EuP. The confluence of growth in the number of Australian households (doubling since 1975) with the increase in single person households and multiple ownership of EuPs within households contributes to a cumulative rebound effect. In addition, the trend is towards EuPs offering service to only one person, such as personal entertainment devices, computers and communication devices and multiple ownership of the same device such as televisions in bedrooms and living spaces. Many household EuPs also coexist in a growing ecosystem of dependent peripheral devices. Televisions are evolving as complex array energy consuming systems, as well washing machines, often co-dependent upon energy hungry clothes dryers. Our research has also revealed similar characteristics for electrical kitchen appliances and computers.

Through improving technologies energy efficiency is claimed to improve at a rate of 2% per annum since 1970 (Owen 2006). However, the full potential energy efficiency savings are often not fully realised. It has already been noted that rebound effects can occur due to the mismatch between projected technical energy efficiency savings and those that eventuate due to unaccounted behavioural and household consumption factors. However, in addition these unrealised savings are also due to a design rebound. Whilst miniaturisation has enabled many products to decrease in size many common household EuPs have increased in size or capacity. This can result in the energy efficiency saving potential of the technologies they utilise being unrealised. A case of one step forward, two steps back. This situation could equally apply to many other product sectors, such as transport and communications devices.

Relative to Australian average weekly income, the purchase price for many EuPs has fallen dramatically, resulting in EuPs being far more accessible to modern households. In 1975 the average television cost 570% of average weekly income, while in 2010 average television purchase cost is approximately equal to average weekly income (Choice 2010b). Even more remarkable is that during the past 12 months TV purchasing prices have dropped by 25% and are expected to decline by a further 25% over the next year (O'Rourke & Black 2011)

It is not the intention of this study to identify the underlying social and economic constraints contributing to the increase in residential EuP stock, however the decreasing relative cost of EuPs (shown in Figure 7) and the number of units in ownership appears to be related.

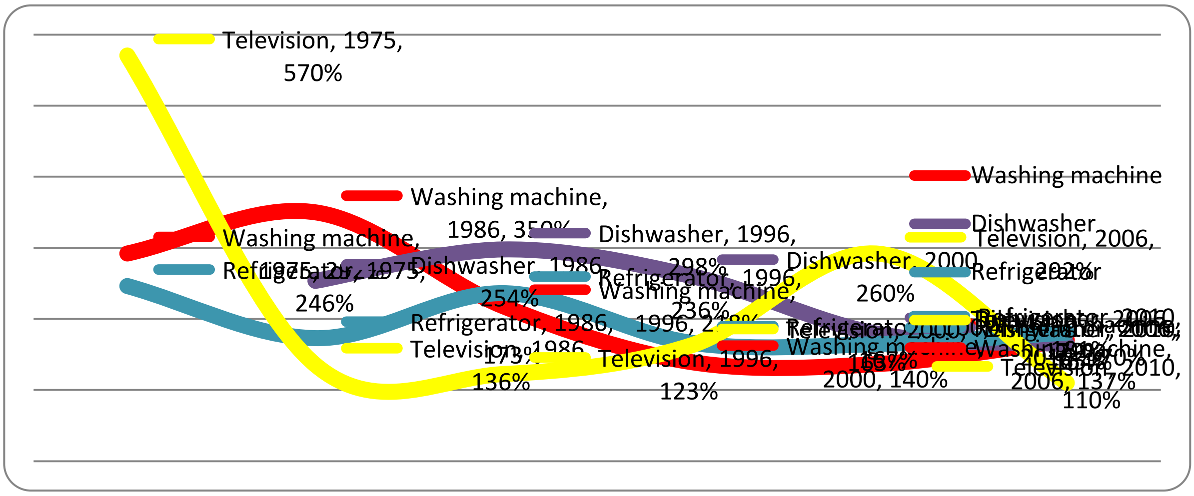

Figure 7. Purchase cost of EuPs as a percentage of weekly income

Source: Adapted from Choice (2010b)

Role of Design

The influence of behavioural and consumptive factors in shaping energy demand is likely to continue along current trajectories (DEWHA 2008) reinforcing the need to better understand how the design of products can intervene to minimise related energy rebounds.

Design can play a leading role in guiding energy use behaviour and minimising unrealised energy savings. This section concludes by outlining possible considerations to ensure behavioural, ownership and consumptive factors are better addressed to avoid energy use rebounds and maximise energy efficiency gains.

- With the increase of single occupant households products need to offer program settings or be reconfigurable for lower occupancy households. For example, appliances such as single-shelf dishwashers and load sensor washing machines may play a role in this space.
- Despite improved energy efficiency, too many products are left on standby mode. Designers have a key role to play in developing creative solutions that mitigate the need for standby energy demand.
- Persuasive design strategies and interactive technologies have the ability to guide user behaviour to minimise potential behavioural rebounds. This emergent field can influence sustainable behaviour by, for instance, encouraging people to turn off devices when not in use, determine appropriate washing load sizes or frequency of use.
- In instances where behavioural influence on energy use is minimal the focus should be upon design and technology changes that take advantage of unrealised energy savings potential. For example, as each new model refrigerator offers more novel features the potential for improved energy efficiency is compromised. Designers could refocus efforts upon developing other features that would radically improve efficiency. This could be achieved by offering a reduction in or variable capacity aligned to household occupancy, utilising recent improvements in motor compressor technology and interactive power management electricity grid technologies.

Conclusion

Many stakeholders reason that the primary way to reduce energy demand is through improved energy efficiency, despite this global energy intensity continues to worsen. Improving energy efficiency is often framed as a technological challenge without understanding and accounting for the influence of user behavioural (product use), ownership dynamics and cumulative consumption factors. It is these influences that we believe are equally important in shaping household energy use to avoid rebounds and realise the full potential of eco-efficient designs and technologies. Energy rebounds exist due to the mismatch between the expectations of technological determinist energy efficiency approaches and these ‘soft’ and indirect influences.

Having identified and grouped rebound effects into one of three categories: Use and Behavioural, Design and Technology and Cumulative

Consumption, this study uses time series data to determine and interpret energy rebound effects for specific household EuPs. The importance of these categories is dependent upon product type and associated user behaviour. For example; energy demand for washing machines and dishwashers is significantly influenced by Use and Behavioural variables including frequency of wash, load size and wash cycle selection. Design and Technology rebounds are significant for television. As screen size, and the number of interconnected peripheral devices increase, so does energy use. Cumulative Consumption rebounds are also prevalent for dishwasher and television ownership. With dishwasher stock doubling since 1993 and television stock increasing quite dramatically to almost 1 television per residential occupant. Moreover, the switch to digital and flat screen technologies, coupled with dramatic increases in affordability has created a surge in television ownership.

The identified rebound categories assist in formulating new design responses to reduce energy use in household EuPs. This study supports the growing understanding of the importance in addressing user behaviour in curbing escalating and increasingly unsustainable levels of demand and consumption. However, the absence of robust data for behavioural use characteristics for household EuPs and their contribution to energy rebound effects remains poorly understood. Improved data relating to product lifespans, product usage and how products are configured within an ecosystem of other EuPs within households (and within society in general) is required for decision makers to better account for energy rebounds.

In this paper we have attempted to expand the scope of energy rebound effects by placing products at the centre of the study. For designers, it emphasises the importance of considering behavioural use factors in achieving intended product energy efficiency predictions, as technological solutions alone can fail or only partially succeed. Until these 'soft' factors are considered as integral components to any eco-efficient design strategy, the full potential of intended efficiency 'improvements' will remain unrealised resulting in a rebound effect.

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