Designing for ‘Use Phase’ Energy Losses of Domestic Products

E. W. A. Elias*, **E. A. Dekoninck** and **S. J. Culley**
Innovative Design and Manufacturing Research Centre, University of Bath, Bath, UK
E-mail: E.W.A.Elias@bath.ac.uk
*Corresponding Author

Abstract: The energy efficiency of products can be established by calculating the energy losses of the product. This paper shows that there are two kinds of losses, intrinsic losses, determined by the technology and materials used to construct the product, and the user-related losses which are caused by varying and inefficient use of that product by the user. User-related losses are a significant proportion of energy use of products and are likely to increase in proportion as engineers use good design and technology to drive the intrinsic losses closer and closer to what the author’s call the theoretical minimum. The paper goes on to set out a theoretical frame work for understanding and calculating the intrinsic and user-related losses of products and concludes by suggesting the outline of appropriate design strategies for tackling them.

Key words: Design, energy efficiency, user behaviour, intrinsic losses, user losses, theoretical minimum

1. Introduction

Energy using products in the home account for over 13% of the UK’s domestic electricity use. Since 1970 domestic energy usage on household products has more than doubled and by 2010 consumer electronics will be the biggest single sector of consumer electricity consumption [**1**]. There have been many Life Cycle Assessment studies which show that the main environmental impacts of energy using domestic products occur during the use of the product. Rüdenauer et al., [**2**] in 2005 showed that 90% of the total energy use of a refrigerator came from the use phase, with the remainder coming from manufacture and disposal.

This paper presents a methodology that can assist designers and engineers in choosing an effective environmental design strategy for reducing all the elements in the ‘use phase’ energy consumption of their products. The methodology has at its heart the establishment of the type and size of energy losses of the product and concludes by suggesting an appropriate outline design strategy based on these results.

2. The Energy Losses of Products

This section describes a number of factors that should be considered when evaluating the energy losses of products. Intrinsic losses, which traditionally engineers have paid particular attention to and have been very effective in reducing, and the user-related losses associated with inefficient product use. In addition, two counterarguments relating to the energy efficiency of products are discussed to set them in the context of this work.

2.1. *Intrinsic Losses*

This approach being proposed is based on the principle of understanding and establishing the two kinds of energy losses for products, the first kind of losses, caused by the engineering design, materials and technology used in construction of the product will be called the *intrinsic losses*. Mennink et al. [**3**] carried out a series of tests on a 200 litre refrigerator to determine where the largest sources of energy losses were in the device. The product they tested

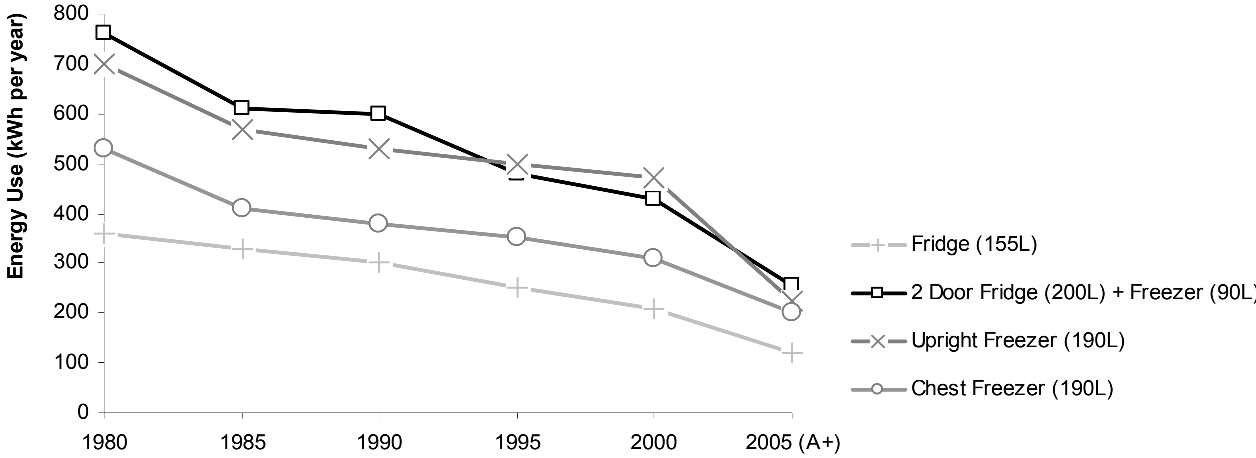

Fig. 1 The energy efficiency improvement of cold appliances, adapted from Rüdenauer et al. 2005 [**2**]

showed losses of 81% due to poor insulation of the walls and door. These losses are dependent on the engineering design of the device and are locked into the product at the point of design and manufacture. Poor insulation, waste heat, unnecessary movement of parts or any other form of un-optimised design can all cause what has been classed here as the intrinsic losses. Engineers have often focused on these intrinsic losses and have enjoyed considerable success in reducing them with improvements in technology and materials science. Figure 1 shows the steady improvement of energy efficiency for refrigerators and freezers since 1980, with all models reducing their energy use by at least a remarkable 60%.

2.2. User-Related Losses

The second set of energy losses that a product can encounter will be called *user-related losses* and are caused by the varying and inefficient use of the product. The use of a product will inevitably include a range of good and bad behaviours with good behaviour being more energy-efficient than bad. The leaving open of a refrigerator door unnecessarily, for example, can cause large energy losses and is directly related to the user behaviour. Palmborg [**4**], in 1986, and Gram-Hansen [**5**], in 2003, found that domestic energy use can differ by a factor of two, even when the equipment and appliances are identical. Wood et al. [**6**] cite studies, in 1978, 1981 and 1996, from the United States, the Netherlands and the UK which estimated that 26 - 36% of in-home energy use is due to people's behaviour and found that a major untapped route for achieving energy savings in the domestic sector is to identify and implement means for influencing the actions of end users before, during and after they use appliances. This is also supported by studies by Dennis et al. [**7**] who report that significant energy savings can be made by providing antecedent information about methods of energy conservation and cites a 60% reduction in unnecessary lighting use simply by putting signs near light switches.

The measure of energy efficiency, presented in the methodology being discussed in this paper, is based on a combination of intrinsic and user losses. For example a refrigerator with perfect insulation, potentially zero intrinsic losses, will still waste energy if the door is left open unnecessarily for extended periods of time, or an electrical device, which is not switched off when not in use, will use energy with no beneficial outcome, despite a high intrinsic efficiency. The inclusion of user losses, from the use and possible misuse of a product, adds a new dimension to the traditional measure of engineering energy efficiency calculations, giving a complete image of 'product-in-use' efficiency.

3. Calculating the Losses

Having established the importance of energy losses in products, this section goes on to develop a theoretical framework for calculating them. Figure 2 shows the experienced decline in energy use as product efficiency has improved for many products over time. As efficiency approaches 100% the losses decline to zero and what can be thought of as a theoretical minimum amount of energy required to perform a given function, for that product is reached.

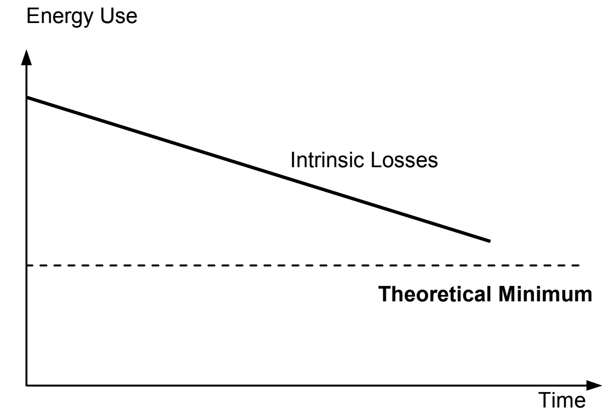

Fig. 2 The decline of total product energy losses over time due to improved technical design

Figure 3 shows how, over the same period of time, the user related losses, as a percentage of the total losses, will rise in proportion as the intrinsic losses of the device are reduced with new technology and incremental engineering improvements. For example if a product today had intrinsic losses of 75% and user related losses of 25% then over time as the technology improves the user losses will rise in significance.

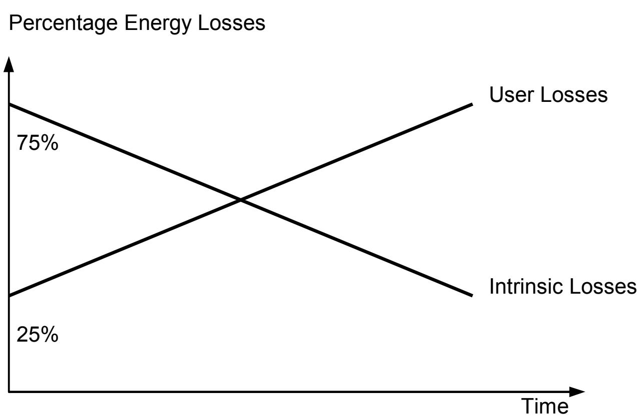

Fig. 3 The predicted rise and fall of User and Intrinsic losses over time

In order to determine the losses of a product a theoretical base case must be created. It is thus required to establish a theoretical minimum amount of energy required to carry this out, below which it is impossible to go, due to the laws of physics. The difference between this minimum value and the actual energy readings highlight the intrinsic losses of the product, figure 2. Any variation on the part of the user which prevents the product from performing the most efficient course of action is attributed to user-related losses. To establish this variation in use, user and product use studies must be undertaken with the results being developed into behaviour scenarios where each scenario shows an energy inefficient use of the product, the probability of each scenario occurring as well as their energy impact must also be considered in order to prioritise the redesign efforts.

To demonstrate this loss calculating process a typical electric kitchen kettle will be used with the scenario of boiling a single litre of water to be used in hot drinks. This is a simple example to demonstrate the process as the theoretical minimum can be easily calculated, for more complex products such as a modern LCD 32” television, the theoretical minimum is much harder to calculate. In order to make this calculation certain product aspects must be maintained, television size is one such aspect. The process should not make a judgement as to why the user requires a television of this size, changing the size would make minimum calculations meaningless as it is of course possible, but perhaps not pleasurable, to watch television on a portable hand held device, greatly reducing the energy required, but perhaps invalidating the function of the product. It is therefore important to keep essential product features, such as screen size, colour and sound quality constant across any comparison. The method used therefore for complex products such as this are based on looking at the best available products in the product category and then comparing the energy readings with research into future technology and their energy saving potential. Such research has already been carried out for a large range of energy using products by institutions involved in the EuP Directive and gives a good ‘best guess’ estimate on how large the intrinsic losses for the product will be.

3.1. *Theoretical Minimum*

To boil one litre of water, based on the specific heat capacity of water (4186 Joules / kg ^{o}C) and a starting temperature of 20^{o}C, requires 334,880 Joules of energy, or the equivalent of 0.093 kWh. A real 2 year old sample kettle took 2.5 minutes to boil a litre of water using 0.117 kWh (421,200 Joules). The intrinsic losses are therefore 0.024 kWh (86,400 Joules) with an intrinsic inefficiency of 26%, meaning that 26% of the energy required to boil water in this kettle is surplus to the theoretical requirements. This is shown as the base case in figure 4.

3.1 Behaviour Scenarios

However there are a number of different ways in which people can interact with a product and this can affect the energy consumption. For this example two scenarios have been generated, which consider the tendency of users to use a kettle in an energy inefficient manner and boil more water than is required.

Scenario A:

If over the course of a day, the same sample kettle described previously is required to boil four cups of water, on two occasions, two in the morning and 2 in the evening, totalling one litre, but the kettle is filled to its one litre capacity in the morning and boiled twice, once full and once half full. In this scenario the kettle would use an additional 0.059 kWh (210,600 Joules), assuming a linear relationship, to re-boil the remaining half litre a second time in the evening. In total 0.176 kWh (633,600 Joules) of electricity was used to perform a task that in ideal situations would require only 0.093 kWh (334,880 Joules), an increase of 89%. In this common domestic situation it is clear that the user losses are significant, 0.059 kWh compared to the intrinsic losses of 0.024 kWh, and could be easily greater if poor behaviour and product use was left unchecked.

Scenario B:

The same kettle is used and like Scenario A four cups of boiled water are required, totalling one litre of water, but instead of boiling the full capacity and then re-boiling half a litre later, the kettle is used on four separate occasions. Each time a single cup of water is required, but due to inaccurate or non-existent capacity measurement on the kettle, the kettle is slightly overfilled each time, resulting in an excess amount of water being boiled each time of 20% giving user-related losses of 0.023 kWh (84,240 Joules).

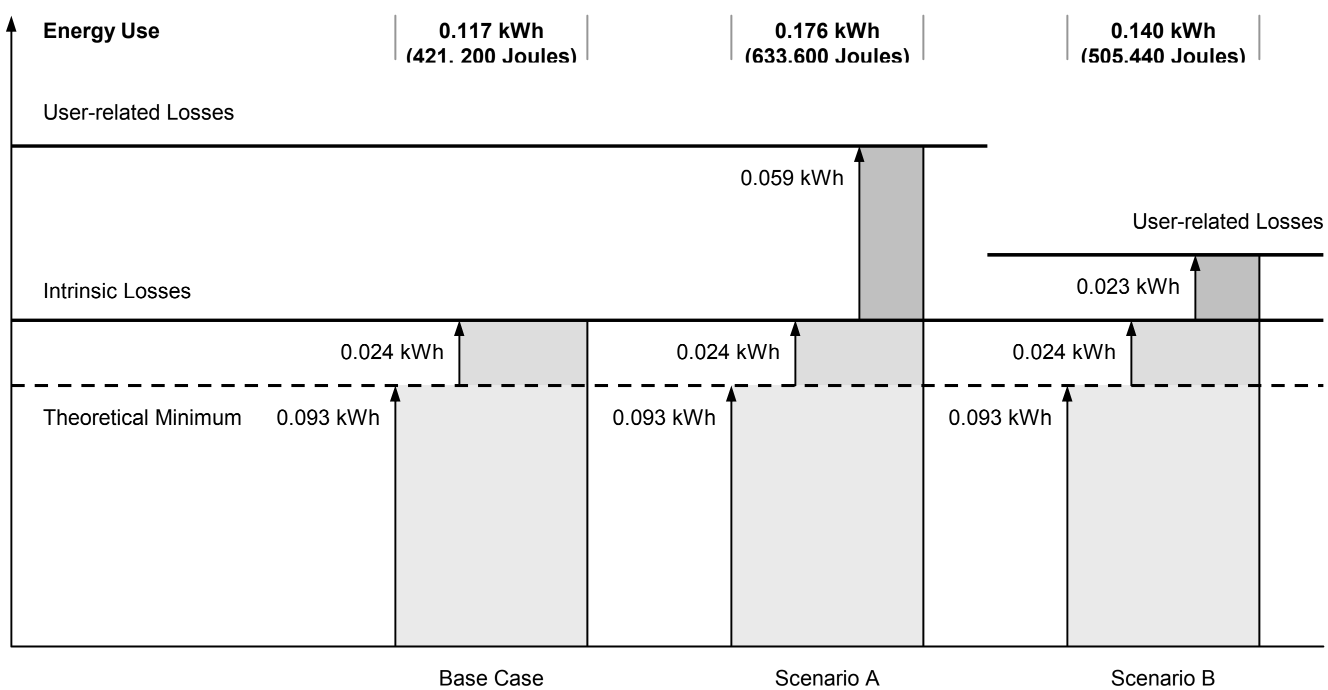

Fig. 4 A comparison of intrinsic losses to user-related losses from two typical use scenarios

This simple set of examples, summarised in figure 4 shows how the understanding of both the engineering science and the user behaviour is crucial in reducing energy consumption.

4. Reducing the Energy Losses of Products

With the calculation and demonstration of losses, as shown in figure 4, a design and engineering team can now more effectively target the largest causes of energy loss for each particular product, whether that be a technology-based design strategy to deal with high intrinsic losses, or a user-centred design strategy to tackle high user losses. Figure 4 highlights the significance of the user-related losses, in this example, for the two behaviour scenarios, which do not seem excessive and are a regular occurrence in UK homes and have been reported by the authors from observational studies undertaken [**8**]. Understanding the intrinsic and user-related losses shows that it may be more effective, to reduce overall energy consumption, by focusing the redesign efforts for the kettle on the user-related losses, designing ways to mitigate these behaviours and lock the user into a particular pattern of use, reducing or eliminating bad behaviour entirely.

One such product which attempts to do this is the Tefal QuickCup™ which is kettle that has been separated into two parts, a boiling section and a water reservoir. The boiling section only allows an amount of water equal to a single cup to be boiled at any one time. In this way the user would have to make a conscious effort to boil more water than required and then leave it in cups to cool, rather than the case now where users are often unaware of the contents within the kettle and inaccurate methods for filling result in over boiling of water without realising the impacts.

4.1. Tackling User-Related Losses

There are essentially three strategies for reducing the user-related losses of products, these are improving consumer education, providing feedback and User-Centred Eco-Design. Education and feedback methods have been extensively studied, Winnett et al. [**9**] reported a 10% reduction in energy-consumption after subjects had seen a 20 minute TV program about energy saving. Providing direct feedback in the form of real-time energy monitors in the home typically reduces energy usage in the home by between 5 - 15% [**10**]. User-Centred Eco-Design is a design strategy for creating new products that use highly efficient technologies but are also designed with the user, user's behaviour, product use or misuse in mind. Creating Eco-Designed products where the most intuitive and comfortable way of using and interacting with a product or system is also the most environmentally friendly [**8**].

User-Centred Eco-Design, or perhaps more specifically in this case a Behaviour Based Design approach, can work within the realms of existing user behaviours or aim to change them with a radical new product that achieves the same end function, but perhaps in a very different way. A User-Centred design could potentially create energy efficiencies independent of technology advances and intrinsic losses and thus creates lasting "future-proof" savings.

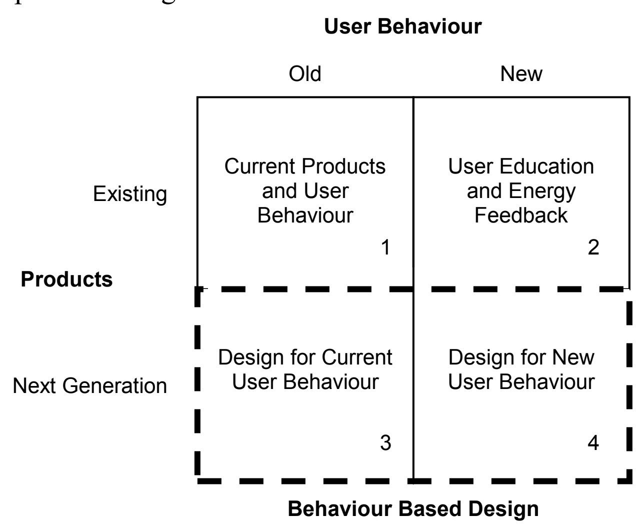

Fig. 5 A Decision Matrix for Deciding the Most Appropriate Strategy for Improving Energy Efficiency (adapted from Elias et al. 2007 [8])

Figure 5 illustrates design strategies based on this relationship between user behaviour and product design:

Square one (1) represents the current situation. The aim is to improve energy efficiency by moving from this square to any of the other three.

Square two (2) aims to change the behaviour of user's but keeps existing products. It is a strategy of improving user education and providing information and feedback so that the user may be influenced for the better. This is the traditional method of curbing inefficient product use and has been thoroughly researched. These methods do perform well but their results are often not sustainable, with the large initial savings reducing over time as users revert to old habits. Hayes and Cone [**11**] showed this to be the case with a study that they undertook on electricity use in a student housing complex, attempting to change behaviour through education. Initially after energy efficient information was distributed there was a 30% reduction in usage, but in a subsequent week the savings had quickly fallen to 9%.

Square three (3) is moving into a field of next generation products, where the design of the product has been changed for reduced intrinsic and user-related losses. This box represents a strategy which may focus more on the intrinsic losses of products, working within the existing boundaries of the current behaviour but also gives the potential for the development of products which can adapt to the current behaviour patterns, perhaps correcting inefficient use without the user being aware of any change. An example of this may be an automatic switch-off for a phone charger that turned itself off when not being used, preventing the user from ever leaving it on unnecessarily, but also allowing the current behaviour of many users' to forget to switch it off to continue.

Square four (4) requires new products to be designed which force a new behaviour. The Tefal QuickCup^{TM} is one such example where the user adopts a new way of performing the function.

Behaviour Based Design has the potential to produce sustainable energy use improvements, reducing the direct rebound effects by locking in good user behaviour through design. In much the same way that engineering design in the field of manufacturing changeover design, where the approach of *doing better things rather than doing things better,* McIntosh et al. [**12**] has guided machine and tooling redesign. Culley et al. [**13**] commented that if a task is made physically simple and straightforward it will be easier to sustain. In their unique 10 year retrospective study, it was shown that it was such design changes that endured and maintained performance, rather than relying on management discipline alone. In the traditional language of Eco-efficiency strategies and domestic goods, this translates into avoiding a reliance on consumer information and education. Rather, physical changes to a device that can prevent a return to old bad habits or working practises and thus *lock-in* the desired behavioural changes.

5. Conclusions

User-related losses are a significant proportion of energy use of products, figure 4, and are likely to increase in proportion as engineers continue their remarkable work using good design and technology to drive the intrinsic losses closer and closer to the theoretical minimum. However, much as they try, these approaches will not impact on the user-related losses. Thus this paper has set the theoretical frame work for understanding the intrinsic losses, user-related losses, theoretical minimum and outlined strategies for dealing with them.

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