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Quantifying the Energy Impacts of Use: A Product Energy Profile Approach

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Abstract

The behaviour and actions of users can impact on the energy efficiency of products. By using products unnecessarily or inefficiently even a product which has been designed and built with highly efficient technology or materials will still use or waste energy. This paper demonstrates and develops a methodology for quantifying the energy impacts of user behaviours. Measuring the amount of energy used by a specific user action is essential for engineers and designers to make decisions as to how best to approach the redesign of a product, creating lasting and beneficial energy savings.

Keywords:

Eco-Design, Efficient User Behaviour, Energy Use, Domestic Products

1 INTRODUCTION

Since 1970 the domestic energy use of household products has more than doubled and by 2010 consumer electronics in the home will be the biggest single sector of consumer electricity consumption [1].

During this time there has been a considerable amount of research and development undertaken to improve the energy efficiency of these products, with many products showing significant improvements in reduced energy use over time. However even a product with good efficiency from an engineering technology and materials point of view can have its environmental benefits mitigated by "poor" user actions. If the product is misused, used unnecessarily or excessively it will waste energy. An Australian study revealed that 15% of the electrical consumption associated with an electric kettle was unnecessary [2] and studies, in 1978, 1981 and 1996, from the United States, the Netherlands and the UK, estimated that 26–36% of in-home energy use is due to resident's behaviour alone [3].

This variation in use coupled with the fact that many domestic products use much more energy during the use phase of their life cycle than any other phase is of great importance to any strategy which aims to reduce the overall energy impact of a product. For example 72% of a washing machine's life cycle impact comes from electricity use during the use phase [4], 90% for a refrigerator [5] and 85% for a 32" LCD television [6].

As a result there is a large and growing body of research aimed at improving what can be thought of as the energy efficiency of users, with much of this work looking to improve the effectiveness of information campaigns, energy feedback and improving the awareness of the uses to the impacts of their actions. However research has shown that this "information led" approach is often ineffective or produces only temporary changes to behaviour [7] [8] [9]. Work is therefore being done to design products that can influence or adapt to bad behaviour [10] [11] [12] [13], creating products that either force good energy efficient behaviour or adapt to improve bad behaviour. Any design change will however have tradeoffs between the amount of energy saved by the new

device and the amount of energy it has taken to implement. For example one such design change maybe to build a refrigerator with a glass door, in order for the user to investigate what is in the fridge and come to a decision as to what they want before opening the door. This would reduce the amount of time that the user has to have the door open. The compromise here is whether the energy savings from opening the door less frequently or for a shorter period is greater than the energy loss due to the reduced thermal efficiencies of the glass door.

An American company has produced two identical refrigerators, one with a normal insulated door and the other with a glass door. The glass door model uses 81 kWh per year more than the normal model, in the industry standard energy use test for refrigerators, a 17.5% increase in electricity use [14]. Any improvement this design has to the user must make a saving of at least this before any real benefit is obtained.

It is therefore essential to be able to quantify the impacts users are having on energy use before any design change can be made.

This paper presents an approach which can be used to quantify these user-related impacts, presenting them in a graph of energy use, which the authors have called a Product Energy Profile, PEP.

2 PRODUCT ENERGY PROFILE (PEP)

The PEP process lays out a framework for how user-related energy impacts or losses can be calculated and what percentage of total energy use this represents, displaying this information in a visual format, Figure 1. It is based on three values: firstly the *user-related losses* that are connected to inefficient use. Secondly the *intrinsic losses*, which are the energy losses associated with the design and construction of the product, based on the intrinsic engineering technology and materials that have been used. And lastly a *theoretical minimum value*, which is an amount of energy that must be used in order for the product to deliver its designed function, below which it is impossible to go due to the laws of physics.

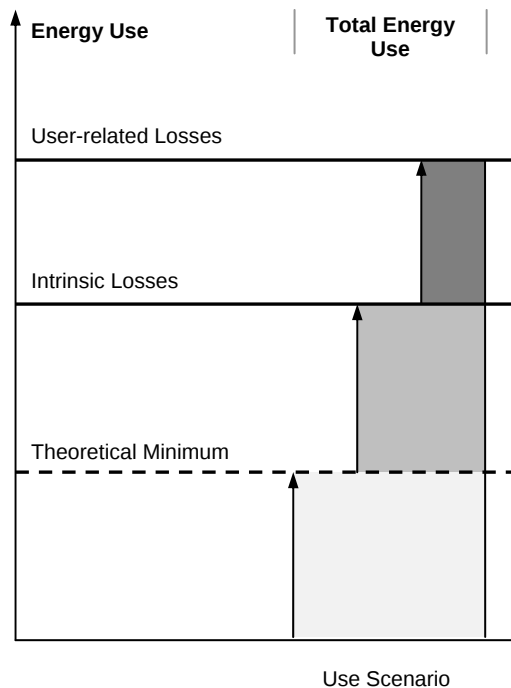


Figure 1: Product Energy Profile example graph

Figure 1 shows how the PEP graph is constructed for different use scenarios and allows a user to quickly identify which is the most significant area of energy loss. Each of these three values which make up the PEP will now be explained in greater detail.

2.1 User-Related Losses

The use of a product will inevitably include a range of good and bad behaviours with good behaviour being more energy-efficient than bad. Empirical studies have shown that energy use can vary by two or three times, even when the equipment used is identical [15] [16]. The user-related losses represent the amount of energy that has been used over and above the optimal use of a product. For example there is an optimal way of using products such as a kettle or television, which is called the base case scenario, from which all other comparisons are made. The base case is the most efficient way of using a product and hence has zero user-related losses and will change depending on the user's desired outcome from using the product. For a kettle an example base case might be boiling enough water for four cups of tea or a television could be watching a 45 minute programme. The most efficient way of doing this could be found experimentally and any variation from this would create energy losses.

Since an optimal way of using a product exists, the difference between this value and the actual energy use must be attributed to inefficient actions of the user and hence contribute to user-related losses.

In order to calculate what the user-related losses are, first the zero user loss base case scenario is made, based on a specific desired outcome, such as the four cups of tea or 45

minute TV programme. Then comparison scenarios are made, each maybe as a result of a different action by the user but the intention is to always end up with the same desired outcome. This will be demonstrated in much greater detail in section 3 but as a brief example here if the base case for a kettle was to boil four cups of water and the base case did this in one go with no extra water added, a comparison use scenario might be overfilling the kettle. The increase in the amount of energy required to boil this larger amount of water is therefore attributed as a user-related loss, since the desired outcome is still four cups of water. The application of these use scenarios quickly demonstrate the impact a particular behaviour or action of the user may have on the product energy efficiency and a whole range of scenarios can be created. It is however observational and test data that will determine how frequently these scenarios occur and thus give the full picture of energy efficiency [17].

Many of these use scenarios and the causes of much user-related loss maybe the fact that the product has been unintentionally designed in such a way that using it in an optimal way is difficult or inconvenient. This must be addressed as part of the redesign efforts so that the most intuitive way of using a product is also the most energy efficient [18] but the product also creates energy losses of its own independent of any user interaction and these have been called the intrinsic losses.

2.2 Intrinsic Losses

In 1998 a series of tests were carried out on a 200 litre refrigerator, a typical size for a European domestic setting, to determine where the largest sources of energy losses were in the device [19]. The product they tested showed losses of 81% due to poor insulation in the walls and door. These losses have not been determined by the way the product is used but are dependent purely on the engineering design and materials of the device and are locked into the product at the point of design and manufacture and thus are intrinsic to the design and construction of the product. Poor insulation, waste heat, unnecessary movement of parts or any other form of un-optimised technical design can all cause what has been classed here as the intrinsic losses.

Engineers have traditionally focused on these intrinsic losses and have enjoyed considerable success in reducing them with improvements in technology and materials science. Since 1980, all models of fridge and freezer have reduced their energy use by at least 60% when compared to an A+ rated machine in 2005 [5].

The PEP allows engineers and designers to look at the relationship between the user and intrinsic losses and decide which is the most important to focus their design efforts on, improving how it's used or improving what is used.

By taking energy measurements, from the product in question, whilst it is being used in the optimal base case scenario, it is easy and quickly possible to identify how much energy is being used by the product. This value is the total energy use of the product and not the intrinsic losses. The total energy use is of only a limited use if it is not compared with a theoretical minimum value for the delivered function of the product. Without this minimum value it is assumed that all the energy being used is a loss, or wasted, which is clearly not the case as some benefit to the user is being gained

through the use of the product. As a result the final piece of the graph is the theoretical minimum value.

2.3 Theoretical Minimum (TM)

As traditional measures of energy efficiency approach 100% the intrinsic losses decline to zero and what can be thought of as a theoretical minimum, TM, amount of energy required to perform a given function for that product is reached. This is a value below which it is impossible to go, due to the laws of physics, but still delivers the desired end result.

The concept of a desired end result is important to remember as it will have great affect on the theoretical minimum value. In the drying of clothes, for example, there are a range of more efficient designs for tumble dryers but the comparison cannot be made between a tumble dryer, with perhaps a large TM, and the hanging of clothing on a washing line outside, which it could be argued has a zero TM, since this shares none of the convenience or speed of the tumble dryer, the principle reason for using the device in the first place. Essential product features or functions must be kept constant when trying to establish a TM value.

For some products, such as a kettle, this may be an easy value to calculate. The laws of thermodynamics can easily give a value for the energy required to raise the temperature of water to 100°C. However for other more complex products this is more difficult, and perhaps impossible. The amount of energy required to create a moving image on a screen and all the associated controls and sound generation make calculating the TM for a television very hard.

Establishing a TM for a television and other more complex products can be done a different way. First the most efficient product in that class must be found, which adheres to all the requirements of the product being examined, such as screen size, image quality and colour etc... The energy value for running this product is then set as a benchmark and compared to reports on the future energy efficiency improvement potential for this technology. Coupling the most energy efficient current product, in its class, with the combined future improvement potential for this technology will therefore give a good estimate of the theoretical minimum.

The next part of this paper will take the PEP process as described in the previous sections and demonstrate it with a number of case study products, chosen due to their significance as high energy users in a typical domestic home but also because they will show a range of calculation techniques. The aim being to clarify the concepts involved.

3 PEP IN PRACTICE

To demonstrate the PEP approach this section will show how they can be calculated for three typical domestic energy products. These products are frequently discussed in popular literature for their energy impact. Their ease of reference for the general public make them ideal candidates. The three products in question are the electric kettle, television and refrigerator.

3.1 Kettle

The kettle is a simple example to begin with, the theoretical minimum can be easily calculated and most readers will have experience of many of the potential bad use scenarios. The

starting point of the process is to establish or declare the base case scenario, which is the desired outcome and the perfect use scenario. In this case the outcome is the boiling of one litre of water, the equivalent of four cups, to be used for hot drinks table 1 shows test data for a 2.8 kW kettle, using water with a starting temperature of 10°C, giving the amount of water being boiled, boiling times and energy usage:

Volume of Water (ml)	Recorded Boiling Time (seconds)	Simplified Boiling Time (seconds)	Energy Used (kWh)
250	53	60	0.047
500	88	90	0.070
750	112	120	0.093
1000	140	150	0.117
1250	168	180	0.140

Table 1: Kettle (2.8 kW) boiling test data

For ease of comparison the recorded boiling times have been simplified and rounded up to the nearest 30 second denomination and it is these times that have been used for all subsequent calculations. The data in table 1 suggests that there is an initial amount of energy required regardless of the volume being boiled (approximately 30 seconds or 0.023 kWh) and then a linear relationship between the amount of water being boiled (30 seconds for every 250 ml). Subsequently the most efficient way of boiling one litre of water is in a single go, as boiling it in four lots of 250ml will use approximately 60% more energy.

Theoretical Minimum

To raise the temperature of one litre of water to 100°C, based on the specific heat capacity of water (4186 Joules / kg °C) and a starting temperature of 10°C requires 377,100 Joules of energy, or the equivalent of 0.105 kWh.

The sample kettle took 2.5 minutes to boil a litre of water using 0.117 kWh (421,200 Joules). The intrinsic losses are therefore the difference between the two, 0.012 kWh (43,200 Joules) with an intrinsic inefficiency of 10% (the difference 0.012 / 0.117 = 10%), meaning that 10% 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 2.

Behaviour Scenarios

A standard kettle is easy to use and easy to use badly, many kettles do not have accurate systems for filling and require an element of pre-thought and planning in order to be used efficiently. For this example two scenarios have been generated, which consider the tendency of users to use a kettle in an energy inefficient manner by boiling more water than is required.

Scenario A: If over the course of a day, the same sample kettle described previously is used to boil four cups of water (250 ml each), on two occasions, two in the morning and two in the evening, totalling one litre. However in this scenario, the kettle is filled to its one litre capacity in the morning and

boiled twice, once full (1000ml) and once half full (500ml). In this scenario the kettle would use an additional 0.07 kWh (252,000 Joules), using the data from table 1. In total 0.187 kWh (673,200 Joules) of electricity was used to perform a task that in ideal situations would require only 0.105 kWh (377,100 Joules), an increase of 78%. In this common domestic situation it is clear that the user losses are significant, 0.07 kWh compared to the intrinsic losses of 0.012 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, however due to inaccurate, inconvenient or even non-existent capacity measurement on the device, the kettle is overfilled by 25%, resulting in an excess amount of water being boiled. In effect 1250ml of water is boiled, using 0.140 kWh (504,000 Joules), a user-related loss of 0.023 kWh (82,800 Joules).

Discussion

The results from figure 2 clearly demonstrate that the user-related losses for this product should be the focus of design attention since the intrinsic losses are so small in comparison and are relatively close to the theoretical minimum.

The test data, table 1, shows much higher intrinsic losses for boiling smaller amounts of water and in fact suggest that if the user is uncertain about how much water they require it is always better to boil more than boil an additional smaller amount later. This is clearly not a desirable feature of the

product. Ideally a proportional relationship is required where the intrinsic losses are constant, allowing users to be as precise as possible, with no penalties for using less and topping up, rather than being wasteful.

There are currently two products that may address this issue, the first is a kettle replacement product, which uses a through water element, only heating water when it is leaving the product. The standard model provides a fixed amount of hot water per activation (220ml) however a version exists that allows the user to vary how much water is heated. Experimental evidence shows that this product generates a cup of 220ml of water at 85°C in approximately 30 seconds, using an estimated 0.023 kWh (84,000 Joules). A second product worth mentioning here is a 'boiling water on demand' tap which is a kitchen tap that provides boiling water whenever needed. With a three litre capacity insulated tank this product keeps water at a constant near boiling temperature using 0.24 kWh (864,000 Joules) per day in standby heating to maintain this temperature. A high user of small quantities of boiling water would benefit from this product. However the author fears that the increased convenience this product offers will result in a much greater usage of boiled water than would have previously been required, the rebound effects of this product would therefore be large, negating any energy saving and in fact increasing it beyond previous levels.

3.2 Television

The second worked example is a more complex one, a modern 32" LCD flat screen television, using 150W to run. The theoretical minimum for a product such as this is much

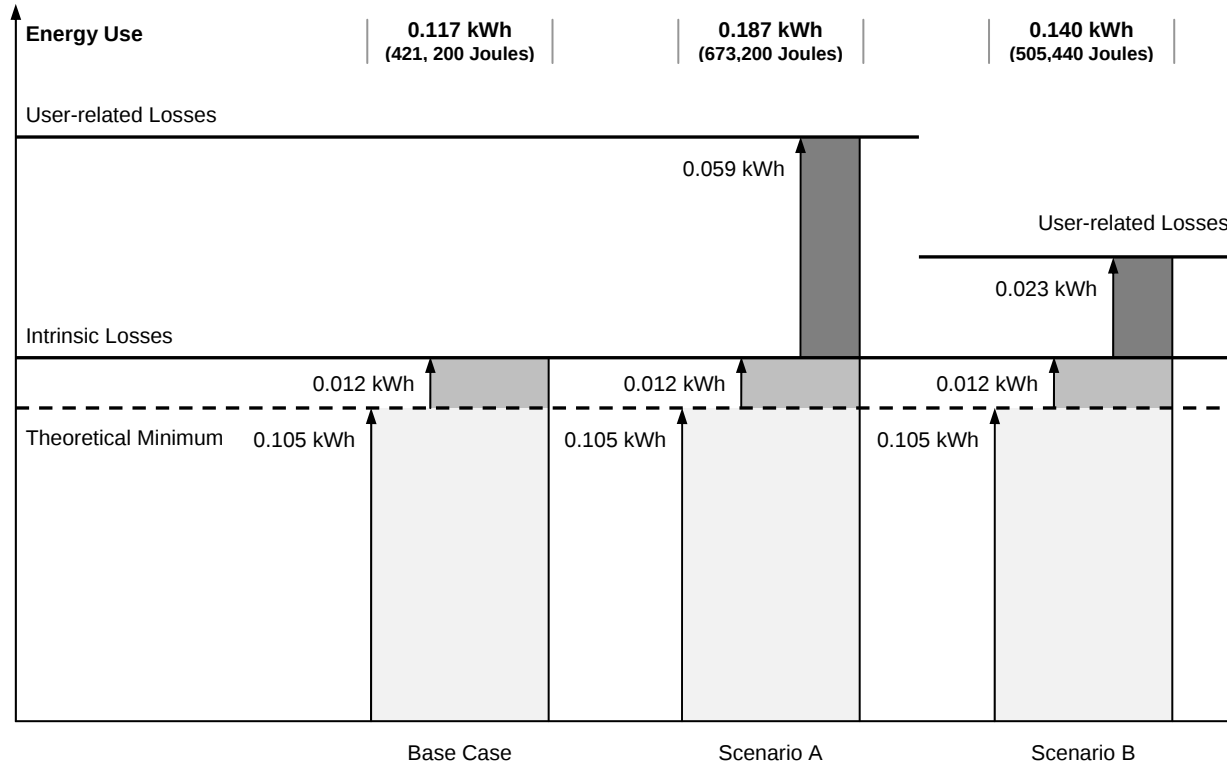


Figure 2: Product Energy Profile (PEP) for a Domestic Kettle

harder to calculate compared to the simplicity of a kettle and so a different approach is required. The size of the unit as a whole and the screen size are important features that must be preserved across any comparison and for this reason a theoretical minimum must be found that uses flat screen technology and a 32" screen.

Table 2, taken from an EU sponsored research report looking into a technology assessment of modern televisions as part of the EuP Directive preliminary reports [20], shows potential technology currently under development and a rough guide to their energy improvement potential for a 32" LCD television. Most of the improvements relate to the Back Light Unit (BLU) and any mutually exclusive improvements that cannot be implemented simultaneously have been removed from the table so as not to be double counted. Totalling the improvement potential from this table gives a minimum improvement of approximately 65%.

It can therefore be assumed that the 150 W television under investigation has a practical theoretical minimum of approximately 52.5 W and subsequently intrinsic losses of 97.5 W. For the purpose of these calculations it is assumed that standby power consumption is one watt, however many new televisions of this type use considerably less.

The base case for this PEP, figure 3, is the UK's average of 3.6 hours of watching television per day with no standby time. Again two scenarios have been created which present typical uses of the television from which the user-related losses can be found.

Scenario A: In this scenario the television is on for an additional hour per day but is not being watched or used in any beneficial sense. This could occur when users who are watching television may then leave the room to prepare a meal or do some other activity only to return later to watch a following program. In addition to this the television is left on standby for the remaining 19.4 hours of the day, an addition of 0.019 kWh (69,840 Joules).

Scenario B: This scenario may be more typical of people or children with televisions in their bedrooms and is that of the user falling asleep with the television on, waking several hours later to find the television still on and turns it off. This would create considerable user-related losses and is probably not a daily occurrence for most users. For this particular scenario information was used from a 15 week study in which the on/off times of a user's television was monitored, table 3, and found that such a scenario happened between 6 - 14 times over the 15 week period.

Total time monitored:	2520 hours
Total on time:	631 hours (25%)
Average on time:	1.87 hours
Average on time per day:	6 hours
Longest on time:	16.77 hours

Table 3: Television on/off data over a 15 week period

Option	Specification of improvement	Improvement potential	Cost factor / availability
BLU driver / inverter circuitry improvement	Advanced BLU driver / inverter circuitry with electrical efficiency of η 80 to 85%.	Good 5-10% improvement	Cost neutral electronic components and board design (cost trade-off possible)
LED-BLU	Very new – not yet mature – BLU type allegedly very high power saving potential due to low power requirements and capability of image controlled selective dimming. No known hazardous substances (however, material composition diverse, manufacturing and electronic packaging unknown).	Excellent >25% improvement	Cost increase currently very limited availability, could improve with mass application within next five years, IP issues unknown
LCD panel design	General improvement of optical properties of functional layers, color filter and pixel design (e.g. RGB + White pixel), electrical driving scheme resulting in higher light utilization. This in turn can reduce the number of necessary lamps and power consumption accordingly.	Unknown	Unknown proprietary technology
Efficient polarizer / fewer lamps	Reflective polarizer (e.g. marketed by 3M) or prismatic film achieves a higher utilization of the lamp's randomly emitted light. This in turn can reduce the number of necessary lamps and power consumption accordingly.	Excellent >25% improvement	Cost increase proprietary technology
Direct power supply for BLU	Direct power conversion from mains input to BLU. Avoid lower voltage intermediate steps. Very good potential for electrical efficiency improvement.	Very Good 10-25% improvement	Unknown BLU supplier relation issues, power board design

Table 2: LCD television potential technology improvement, adapted from the EuP Preparatory Studies [20]

The probability of a scenario occurring highlights the next important stage of the PEP approach and has been briefly discussed in section 2.1. Once a whole range of scenarios have been created, it is important to establish how often these scenarios happen. It would be an alarmist strategy to create a high impact scenario with overwhelming user-related losses and ignore the fact that it has never yet been witnessed or happens only rarely.

Discussion

The television has a more evenly spread energy profile, figure 3, with 65% of the base case being intrinsic losses, compared with just 10% for the kettle. With such a high energy using product, inefficient behaviour has a dramatic impact on energy use, rising by 31% in Scenario A with the addition of a single extra hour worth of on time and over 19 hours of standby use. In Scenario B the user losses raise the total energy use of the product by two thirds, from the base case, and as can be seen from the test data of table 3, this is perhaps not an unlikely scenario. A study in 2005 investigated how 10 participants used appliances around the home; in particular how long the television was used for and if anyone was watching it at the time [21]. The results showed that 90% of participants left the television on only to hear the sound, with times ranging from 5 minutes to over an hour a day. They go on to discuss the idea of a “blind” mode for the television where if no one is watching, it could automatically dim or even turn off the screen. This makes good sense as even an energy efficient television would use 8 - 10 times more electricity than a radio.

3.3 Refrigerator

The third and final worked example shown here is that of a typical domestic, single door, 200 litre refrigerator, using 250 kWh a year. The energy data for this example has been adapted from a refrigerator study [19] in which the author’s calculated 81% (202.5 kWh) of the energy used was lost due to the insulation of the door and walls, 11% (27.5 kWh) was from the addition of food (taken to be 4kg a day) and 8% (20 kWh) from door openings (24 times a day for 5 seconds each). The theoretical minimum for this product is, like the television, also difficult to calculate. In the refrigerator study [19] the author’s go on to conclude that a fridge using less than 50 kWh a year is feasible and thermodynamic analysis of cooling 4kg of food (assumed to be the equivalent of 4 litres of water) every day from room temperature of 21°C to a temperature of 5°C suggests an energy requirement of 27.16 kWh per year. A compromise between the two of 39 kWh, 0.107 kWh per day, would therefore be a reasonable assumption.

Behaviour Scenarios

The base cases for all three product examples discussed in this paper, although showing no user-related losses, have included an element of user interaction in the intrinsic losses. This is a fundamental assumption of the base case, as without any user interaction the product would not be being used. For the kettle it was the requirement to boil one litre of water and for the television a watching time of 3.6 hours was included. The fridge is no different and for this base case it will include the 2 minutes worth of opening time taken from the study, 20 kWh per year. The intrinsic losses will therefore

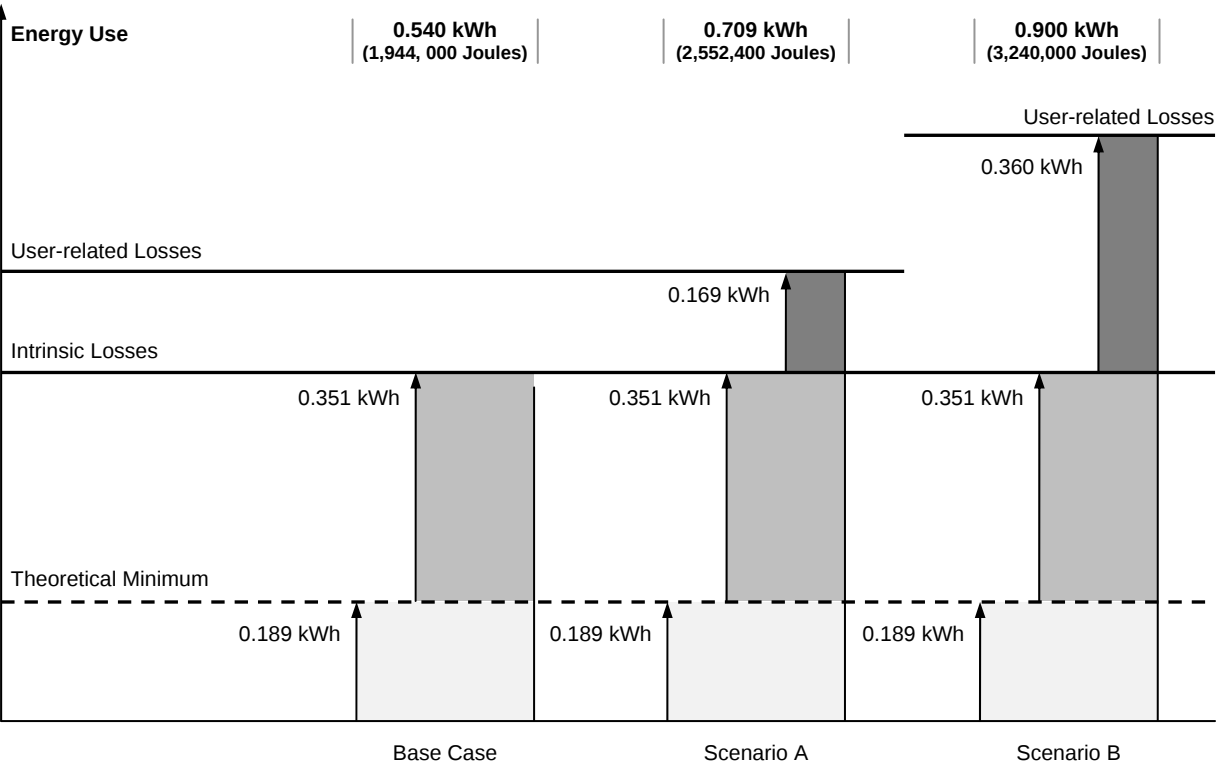


Figure 3: Product Energy Profile (PEP) for a 32" LCD Television

be the total energy use minus the theoretical minimum and divided by the number of days in a year, for a daily figure (250 kWh – 39 kWh / 365 days = 0.578 kWh per day).

Scenario A: The door is opened for an additional 2 minutes in the day, due to time required to think about and search for what food is required, a common occurrence in the use of cold appliances [17] [22], creating user-related energy losses of 0.053 kWh.

Scenario B: This scenario uses information from a video study of a young family using their kitchen and fridge for making breakfast [22]. In this study the fridge was opened a total of 21 times and on three occasions the fridge was left open for a total of 191 seconds. If this situation were repeated in the evening, the fridge would have been opened 42 times (at 5 seconds a time) with an additional 352 seconds for the six extended open periods, creating user-related losses of 0.248 kWh over the day.

Discussion

Figure 4 shows the PEP for a typical 200 litre refrigerator and the impacts of some common behaviours in relation to the total energy use. This product is dominated by considerable intrinsic losses caused mainly by poor insulation. In scenario A a doubling of the time the door is open represents only 7% of the energy used by the product, a relatively insignificant amount when compared to the intrinsic losses, but interestingly it is a similar amount to scenario A of the kettle where an additional 500ml of water was boiled unnecessarily. Scenario B however represents a much higher usage with

27% attributed to the user’s actions and overtaking the daily energy use of the heavily used television from figure 3. Comparing the PEPs of different products provides an interesting comparison to be made as to the relative energy use of different products but also raises a point about the ease to which energy might be saved from one product only to be wasted by inefficient behaviour in another. Awareness among users of the energy impact of products is commonly discussed in literature on this subject and some products do not make it clear to the user that they are wasting energy. For example the user is only aware that the kettle has wasted energy after they have poured the required amount of boiled water and discovered water remaining and the state of the fridge does not change when the door is open to when it is closed. There is perhaps a great deal of scope available to changing the way products react to how they are used, encouraging or even forcing efficient behaviour.

4 CONCLUSIONS

In conclusion the Product Energy Profile (PEP) approach demonstrates a method for showing the significance of user-related losses as a proportion of total product energy use. User-related losses are likely to remain and may grow as a percentage of energy loss as engineers tend to focus on the intrinsic losses, driving them closer and closer to the theoretical minimum. A new design approach is needed that addresses and influences the way the product is used. This approach is currently being developed by a growing number of researchers. What has been missing is a way of identifying the relative importance of these user losses compared to the total energy use of the product and whether any designed

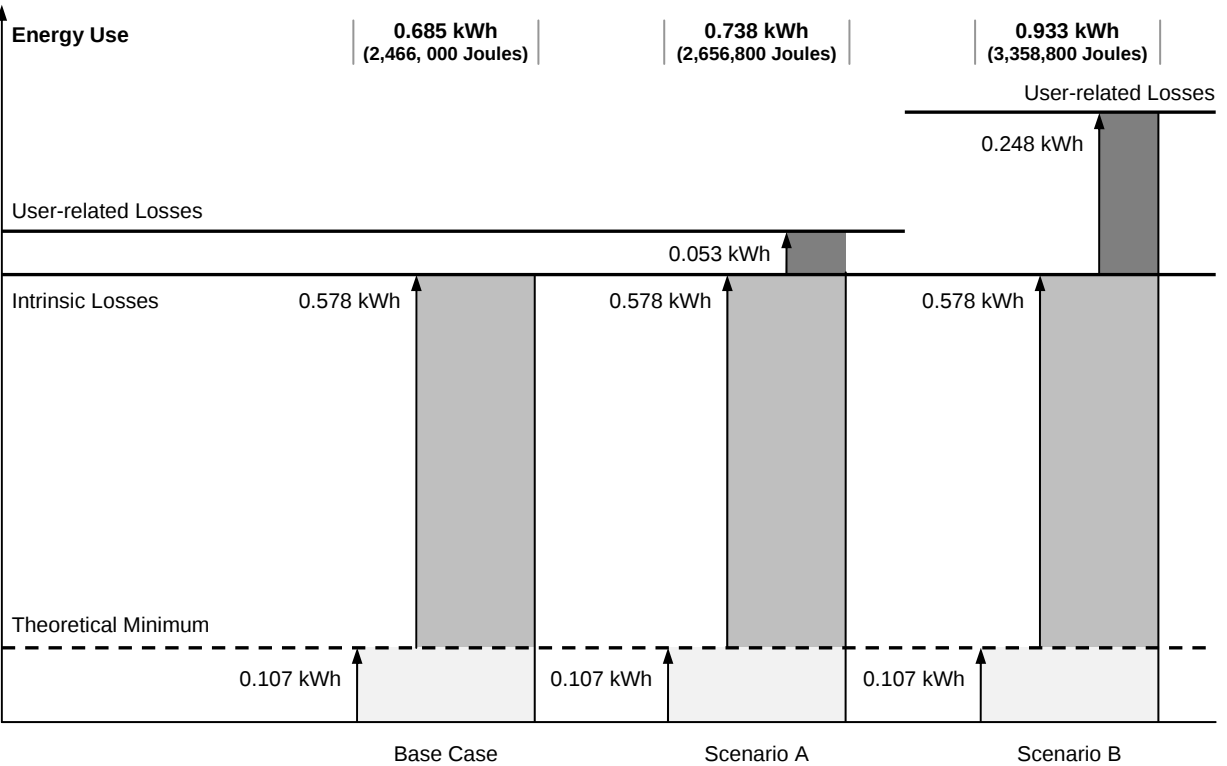


Figure 4: Product Energy Profile (PEP) for a 200 litre refrigerator

improvement would actually provide a net gain in efficiency.

The Product Energy Profile framework presented in this paper aims to fill this gap, providing a methodology for quantifying the energy efficiencies of product use, from the energy required to deliver the desired function to the amount of energy wasted through careless actions. The data for these actions must now be gathered with the use of real life observation and data collection techniques to give a more accurate sense of the likelihood of an action occurring.

Understanding these numbers and the resulting PEP provides a structure from which engineers and designers can work in confidence to reduce user-related energy losses by locking in good energy efficient user behaviour at the design stage.

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