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Quantifying greenhouse gas abatement delivered by alternative computer operating system displacement strategies

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Abstract

End user computing generates 1% of global greenhouse gas emissions caused by production processes and subsequent electricity consumption during use. The concept of displacement has the potential to reduce this environmental impact by repurposing computers at the end of their perceived useful lifespan to extend longevity. Doing so removes the immediate requirement for new devices to be manufactured, therefore potentially slowing global demand and reducing embodied emissions proportionately. However, existing research implies that a combination of improving energy consumption efficiency experienced by new devices, plus ongoing inefficiency associated with aging devices, may be sufficient to counter the abatement gains achieved by displacement. Such energy efficiency gains are due to both continuing hardware and software innovation. As an example, recent research substantiates that alternative operating systems, such as Google Chrome OS, reduce electricity consumption when compared to other popular operating systems. As such, it is reasonable to suggest that repurposing legacy Microsoft Windows computing devices with a version of Chrome OS software will counter the new device efficiency theory and deliver abatement via the process of displacement. Consequently, the objective of this research is to test this hypothesis by quantifying greenhouse gas abatement values delivered by alternative computer operating system displacement strategies and compare the result to the impact of new device manufacture and use. This is achieved via a field experiment measuring the electricity consumption of two legacy notebooks operated in the workplace before and after repurposing occurs. To enable comparison with a new device strategy, two contemporary notebooks are also measured and the embodied carbon footprint contribution recorded. When compared, the results determine two key outcomes. Firstly, a 19% average electricity consumption reduction is experienced further to repurposing the legacy Windows devices with Chrome OS Flex, enabling the notebooks to exhibit energy efficiency equivalent to new devices. Secondly, the earliest point at which the legacy ongoing electricity consumption emissions and combined new device manufacturing emissions plus use phase emissions intersect, is during the 91st year of new ownership. Consequently, as almost a century must pass to compensate for manufacturing emissions, then displacement utilising alternative operating systems should be prioritised, where feasible, if global end user computing emissions are to be meaningfully addressed.

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1. Introduction

End user computing generates in excess 1% of global greenhouse gas annual emissions [1-8]. This is caused by the yearly manufacturing of 460 million devices [9-11] and the associated electricity consumed by 4.2bn active users [12, 13]. In context, the resulting pollution is equal to annual pre pandemic aviation emissions [14] and therefore represents a potential source of abatement. Life cycle assessment research indicates that the total carbon footprint of end user computing devices is predominantly generated by embodied and use phase emissions [15-18]. Specifically, the contribution of the embodied phase ranges from 12% to 97% and conversely use phase emissions from 3% to 88% [19, 20-33]. Whilst the two phases are identified as the majority contributors, the body of research clearly indicates that the proportionate representation of the two dominant phases differs significantly. Such divided opinion arguably causes the success of computer greenhouse gas abatement strategies, such as displacement, to be difficult to quantify. The rationale being, that if each contributing emissions source cannot be accurately defined, then the environmental impact of extending an existing computer's useful lifecycle to displace the carbon footprint created by manufacturing a new replacement device remains theoretical. As embodied emissions are a fixed value, determined by assessing raw material acquisition and manufacturing processes for global warming potential [16, 34-40], it is reasonable to speculate that the incongruity of opinion is related to the variability of the use phase emissions. A considerable body of research supports this opinion, identifying significant differences in electricity consumption amongst similar and even identical end user computers [41-56]. As the consumption value, measured in kilowatt hours (kWh), is key to calculating the use phase greenhouse gas emissions, then such inconsistencies will drive incongruent results. The reason for the differing electricity consumption values is caused by two influences. Firstly, the power draw (watts) required by each computer to respond to operational modes, such as off, sleep, idle and active, is determined by the computer design and differs between products due to both architecture and operating system [57]. Secondly, the influence of human-interaction upon the device is defined by unique users. This influence includes how long the device is retained (years), how many cumulative hours it is used for during this time and what percentage of time is spent in the various operational modes [58]. As this 'use profile' is arguably infinite [58] then such an influence will cause even two identical computers to deliver different electricity consumption results. To further complicate the variability of use phase emissions, the location in which the device is operated will also influence the greenhouse gas quantification. The reason for this is due to use phase emissions being calculated by multiplying the electricity consumed value (kWh) by the greenhouse gas conversion factor published annually by each government where the energy is consumed [59]. The factor is created to reflect the carbon intensity of the electricity supply grid. As such it is reasonable to state that the same research conducted in different geographies will generate different proportionate emissions results. As an example, in North America, where transition to solar, wind and water sourced energy has been slow, a conversion factor of 0.45322 exists [60]. Comparatively, where adoption of green energy has proved faster, such as the United Kingdom, the resulting conversion factor is 0.21233 [59]. As such, 10 kWh of electricity consumed in the former will create 4.5 $kgCO_2e$ greenhouse gas emissions compared to the latter of 2.1 $kgCO_2e$ thus increasing or decreasing the percentage contribution of end user computing use phase emissions.

Such complexity, coupled with contributing factors such as company asset management, depreciation accounting and hardware refreshes to keep pace with new applications [61] cause computer retention rates to be between three and five years [18, 23, 31, 63]. Where a 'second use' does exist, if the device is sold or repurposed rather than disposed of, then this additional retention period is between two and three years [62, 64]. However, extending the lifecycle beyond five years is subject to research opinions that suggest the diminishing energy efficiency performance of the existing device undermines the sustainability case for displacement of new devices [61-62, 65-70]. The rational being that advancements in computer energy efficiency innovation during the lifespan of the current device may be sufficiently significant to warrant the purchase of the new low energy computer. This concept has been further enhanced by prevailing research identifying that newly popularise operating systems, such as Google Chrome OS, can reduce energy consumption by as much as 57% when compared to legacy operating system devices such as Windows and Mac OS [57]. However, if all or part of this operating system delivered energy efficiency could be realised by legacy devices repurposed with a version of Chrome OS Flex, then the case for displacement would arguably improve. The rationale being that the ongoing electricity consumption would be sufficiently reduced causing any new device operational efficiencies to be diminished and the impact of new device manufacturer to become proportionately greater. In order to test this hypothesis, the objective of this research is to substantiate the percentage of electricity consumption reduction that an alternative operating system can achieve when used to repurpose a legacy device. Doing so enables the ongoing concomitant greenhouse gas emissions results from the repurposed device to be compared to the manufacture and use phase environmental impact of a new device. Using the resulting data, an exact point in time can be determined when the two values intersect. Consequently, if proven to be beyond the three years suggested by the 'second use' retention period research [62, 64] then the case for displacement as a key sustainable computing strategy is substantiated.

2. Methodology

The summary methodology is threefold. Firstly, to accurately quantify the annual scope 2 greenhouse emissions values for two legacy end user computing devices in both their manufactured state (Windows OS) and when repurposed with a new version of the Chrome OS Flex operating system. Doing so determines kWh values experienced in both variations, the percentage reduction delivered by the new software and the extrapolated annual ongoing use phase emissions of the legacy devices. Device selection criterion is based upon the notebooks being between 3-5 years in age to reflect average device retention periods as previously noted [18, 23, 31, 63]. Secondly, to quantify two prospectively low carbon footprint replacement devices for embodied scope 3 emissions and to measure these devices for electricity consumption using the same method as the legacy devices. Doing so allows for the initial manufacturing environmental impact to be documented, plus ongoing new device electricity consumption efficiency and concomitant scope 2 emissions to be determined to enable comparison with the legacy device results. Two devices are measured to represent both a new Windows operating system device and a new Chrome OS device. The device selection criterion in this instance is based upon both devices being recently produced and therefore feasible of delivering improved energy efficiency through innovation. Additionally, both devices must have a published carbon footprint report available to allow for scope 3 quantification. As an example, it is noted that whilst companies such as Acer, Asus and Google produce highly efficient Chromebooks as identified in prior research [57], all three companies do not produce product carbon footprint reports. Thirdly, to plot both data sets against a cumulative carbon footprint y axis (kgCO_2e) and a time duration x axis (years) to determine the point in time when the ongoing legacy use phase emissions equal the combined embodied and use phase emissions of the new devices. In doing so, evidence will be produced to determine the abatement impact of displacement strategies based upon alternative operating systems. The energy consumption measurement is based upon Energy Star test set up and conduct parameters [71] to ensure accuracy by specifically adhering to International Electrotechnical Commission standards [72-73]. Before testing begins, the notebooks are charged to 100% then power drained 0% twice before being fully charged ahead of measurement. This is undertaken to create parity across differing brands and models by ensuring equivalent battery calibration. The input power source is an alternating current (AC) mains supply with a UK 230 V ac voltage source. In order to ensure consistency, the ambient room temperature is controlled at 20^{o}C. In order to ensure measurement accuracy, instrumentation used to meter power draw (W) and energy consumption (kWh) meet the IEC standards. Specifically, the metering equipment is proven to be accurate to within 0.2%, enabling ten times higher precision than required by associated standards. In accordance with international non-user present benchmarking and manufacturing design standards the sleep/alternative low power mode is set to activate after no more than 30 minutes of user inactivity. Additionally, the display sleep mode is set to activate after no more than 15 minutes of user inactivity. Where applicable, screen brightness is switched to 100% on all equipment under test to ensure parity between differing models and brands. Each device is measured for energy consumption (kWh) whilst subject to an ad hoc working day for 60 days between the hours of 9am and 5pm. Business style user operations including productivity and video based tasks are conducted each day as and when required to reflect a 'natural working day'. In order to generate annual greenhouse gas emissions values created in a standard business environment, the kWh for each working day are multiplied by what is determined as a working year. The rationale being that the study is designed to determine the impact of displacement within a commercial setting as part of an organisation's sustainable information technology strategy. As such, the working year is calculated as 232 days due to the exclusion of weekends and the 28 days paid holiday mandated by the UK Government [74-75] from a standard calendar year. This annual energy consumption value per device is then multiplied by the United Kingdom electricity conversion factor [59] to generate a kilogramme carbon dioxide equivalent (kgCO_2e) value as per international GHG accounting protocol [76]. Consequently, these values together with the scope 3 values extracted from relevant manufacturer published product carbon footprint documents [77-78] are committed to .xls spreadsheets to enable the comparative graphs to be generated.

3. Results

Examining the legacy devices, the HP Elitebook 820 notebook when installed with a Windows operating system consumes 27.38 kWh of electricity annually in the workplace (table 1). This equates to 5.81 kgCO_2e of use phase greenhouse gas emissions. When re-imaged with the Chrome OS Flex operating system this value is reduced by

20% to 21.81 kWh and emissions of 4.63 $kgCO_2e$. The Dell Latitude 5450 notebook when installed with a Windows operating system proved 28% more energy efficient, consuming 19.72 kWh of electricity annually in the workplace and producing concomitant emissions of 4.19 $kgCO_2e$. When re-imaged, this value reduced by 18% to 16.24 kWh (table 1) and emissions of 3.45 $kgCO_2e$. As the architecture and components of both devices remained the same during each measurement period it is reasonable to state that the alternative operating system delivers an average energy efficiency gain and consequential use phase emissions abatement of 19%.

Table 1. Device use phase electricity consumption (kWh), scope 2 and 3 greenhouse gas emissions ($kgCO_2e$) results

End User Computing Device	Operating system	Average Daily Energy Consumption (kWh)	Annual Energy Consumption (kWh)	Annual Scope 2 GHG Emissions ($kgCO_2e$)	Embodied Scope 3 GHG Emissions ($kgCO_2e$)
HP EliteBook 820	Microsoft Windows 10	0.118	27.38	5.81	NA
HP EliteBook 820	Google Chrome OS Flex	0.094	21.81	4.63	NA
Dell Latitude 5450	Microsoft Windows 10	0.085	19.72	4.19	NA
Dell Latitude 5450	Google Chrome OS Flex	0.07	16.24	3.45	NA
Microsoft Surface Laptop 3	Microsoft Windows 10	0.091	21.11	4.48	111
HP Chromebook 360 14	Google Chrome OS	0.05	11.65	2.46	195

Google describes the efficiency capability, in the context of Chromebooks, as being attributed to the operating system being able to optimise device performance. This is due to a focus on power management capabilities that enable efficient charging and what is termed a 'light' Linux based kernel that creates less power demand on components. Examining associated research comparing energy consumption between new Microsoft and Chrome OS native devices, it is apparent that an average of 42% electricity consumption reduction is achievable by using Chrome OS [57]. As such, it is reasonable to speculate that in line with research such as Boyd's examination of semi-conductor evolution [61], whilst the operating system is undoubtedly delivering a reduction in energy consumption, aspects of original manufacturer Chromebook designs may also be contributing to the results of the prior research [57] and the new device tested in this research. To examine this hypothesis, the physical architecture of both the Chromebooks included in the earlier research and the relevant Chrome OS and Chrome OS Flex devices from this research are identified and compared (table 2). All nine devices as examined for key components including screen size, processor, hard drive and memory. The rationale being that a similarity common to all original manufacturer devices may become apparent when aligned with electricity consumption values.

Examining all device specifications does indicate why the original end manufacturer Chromebooks exhibit higher efficiencies beyond the 18-20% reduction delivered by the new operating system applied to the repurposed devices. As highlighted in table 2, the additional efficiency is delivered by component differences involving a combination of incorporating reduced thermal design power central processing units, embedded multi-media card storage and low power double data rate memory. Those devices incorporating a combination of all three components prove the most efficient and as each is replaced with standard components, electricity consumption increases. Specifically, the two repurposed devices use none of the energy efficient component types, opting instead for a standard central processing unit, solid state hard drives and standard double data rate memory. Consequently, both notebooks rank last in relation to electricity consumption efficiency despite now installed with the Chrome OS Flex software (table 2). The reason for this is that the new components all require less power draw to operate and therefore will, when subjected to human-computer interaction, exhibit lower electricity consumption values. As an example, central processing units with a reduced thermal design use smaller semi-conductors allowing for more transistors. Consequently, these models will utilise less electricity to dissipate heat via the cooling system. The most efficient Chromebook, being the Asus C434T, uses an Intel Core m3-8100Y central processing unit based upon the reduced thermal design. Equivalent in processing power to the non-reduced thermal design Intel Core i5 included in the repurposed devices, the more energy efficient processor utilises 14mm semiconductors as opposed to 22mm semiconductors. Consequently, available benchmark tests indicate that cooling systems of computers with an i5 require a maximum of 65W to dissipate whereas computers with a m3-8100Y, as an example, require only 5W. The common theme of embedded multi-media card to facilitate hard drive storage within the Chromebooks delivers energy advantages over the repurposed devices that incorporate solid state drives. The benefit is that compared to the most efficient solid state storage, the embedded storage requires approximately 85% less power draw to operate at 0.5 watts. Finally, the low power version of double data rate memory used in the Chromebooks requires a supply voltage of 1.8 V compared to the standard DDR memory used in the repurposed devices that requires 2.5 V, thus further reducing energy consumption. As such, it is unsurprising that the most efficient Chromebook exhibits all three architectural differences, consuming 9.56 kWh annually. This being 70% and 128% lower than the repurposed Dell and HP devices respectively. As one or more of these components begin to be replaced by the less energy efficient variants then the devices reduce in efficiency accordingly. As an example, the Google Pixelbook and Acer 714 both measure similar electricity consumption of 12.65 kWh and 12.76 kWh having only one of the three energy efficient components present. Notably, the Pixelbook equals the Acer Spin 13 device that includes two of the components. However, in this example the energy gain will be achieved by the Google device having a smaller screen of 12.3" compared to the Acer Spin 13 device at 13.5". As such the latter device will require more power draw to light and populate the larger viewing area.

Table 2. Device electricity consumption (kWh) and components comparison for Chromebooks and repurposed Chrome OS Flex devices

End User Computing Device	Annual (kWh)	Screen Size	Processor	Hard drive	Memory
Asus C434T Chromebook	9.56	14"	Intel® Core™ m3-8100Y	64GB eMMC	8GB LPDDR3
Acer 14 CP5-471 Chromebook	11.34	14"	Intel Celeron 3855U	32GB eMMC	8GB LPDDR3
HP x360 14 G1 Chromebook	11.65	14"	Intel® Core™ i5-8350U	64 GB eMMC	8GB DDR4
Acer R13 Chromebook	11.92	13.3"	Media Tek M8173C	32GB eMMC	4GB LPDDR3
Acer Spin 13 Chromebook	12.62	13.5"	Intel Core i5-8250U	64GB eMMC	8 GB LPDDR3
Google Pixelbook C0A	12.65	12.3"	Intel Core i5 7Y57	128GB SSD	8 GB LPDDR3
Acer 714 Chromebook	12.76	14"	Intel® Core™ i7	64GB eMMC	16 GB DDR4
Dell Latitude 5450 Chrome OS Flex	16.24	14"	Intel Core i5-5300U	500GB SSD	4GB DDR4
HP Elitebook 820 Chrome OS Flex	21.81	12.5"	Intel® Core™ i5-5200U	256GB SSD	8GB DDR4

Consequently, it is reasonable to find that the Chrome OS Flex version of the Chrome OS operating system does deliver a validated 18-20% energy reduction when replacing Windows operating systems on identical devices. However, the additional feasible 22% energy efficiency documented in the earlier research [57] is evidently delivered by component innovation. As such, Boyd's [61] opinion that the constant evolution of improving device energy efficiency will erode displacement gains is supported by this evidence. However, to determine the effect of innovation gains, both the scope 2 energy consumption and scope 3 embodied emissions for the new devices must be examined and compared to the repurposed legacy devices.

The new Microsoft Surface Laptop consumed 21.11 kWh of electricity per year producing 4.48 kgCO_2e of use phase emissions (table 1). This positions the device as 23% more energy efficient than the equivalent Windows variant of the legacy HP EliteBook and 7% less efficient that the Dell 5450. As before, examining the architecture highlights that whilst all three notebooks utilise variations of the Intel i5 processor and solid state hard drives, the new Microsoft device is the only Windows notebook to employ low power double data rate memory. Whilst this may partially explain the efficiency gain when compared to the HP EliteBook, the result is incongruous with the Dell device that remains more energy efficient. Whilst both notebooks have similar screen sizes, it is notable that the Microsoft device includes four times the amount of memory as the Dell device, plus the new device processor operates at between 15-25W compared to the legacy device at 15W. Whilst not tested as part of this research, it is reasonable to surmise that these two factors are responsible for energy efficiency related gains being nominal in this instance. Compared to the repurposed devices, the new Microsoft device remains 3% more efficient than the HP EliteBook with Chrome OS Flex having conceded 87% of the improvement experienced when comparing like for like operating system variants. Further to repurposing the Dell device the efficiency gap widens to 23% due to the legacy notebook's improved electricity consumption. With respect to the embodied emissions, Microsoft states that producing the Surface 3 device produces 111 kgCO_2e of greenhouse gas emissions [78]. In context of proportionate representation, based upon the measured electricity consumption values and extrapolated to an average retention period of 5-years [18, 23, 31, 63], this indicates that when operated in the United Kingdom the notebook has a total carbon footprint of 133.4 $kgCO_2e$. This is represented by an 83% embodied emissions contribution [78] and a 17% use phase emissions contribution.

Comparatively, the HP Chromebook 360 benefits from electricity efficiency delivered by the factory installed Chrome OS and embedded multi-media storage. Consequently, the annual energy consumption is 11.65 kWh generating 2.46 $kgCO_2e$ of concomitant use phase emissions (table 1). The value is 45% lower than the Surface Laptop and 57% and 41% less than the Windows versions of the HP EliteBook and the Dell 5450 respectively. In relation to the repurposed devices, the efficiency gap is lessened to 47% and 28%. Whilst significantly more efficient than the Surface Laptop, it is notable that the HP Chromebook has a 43% higher embodied emissions value of 195 $kgCO_2e$ [77]. In context of proportionate representation, using the same approach as before, the total carbon footprint is therefore 207.3 $kgCO_2e$. This is represented by an 94% embodied emissions [77] contribution and a 6% use phase emissions contribution.

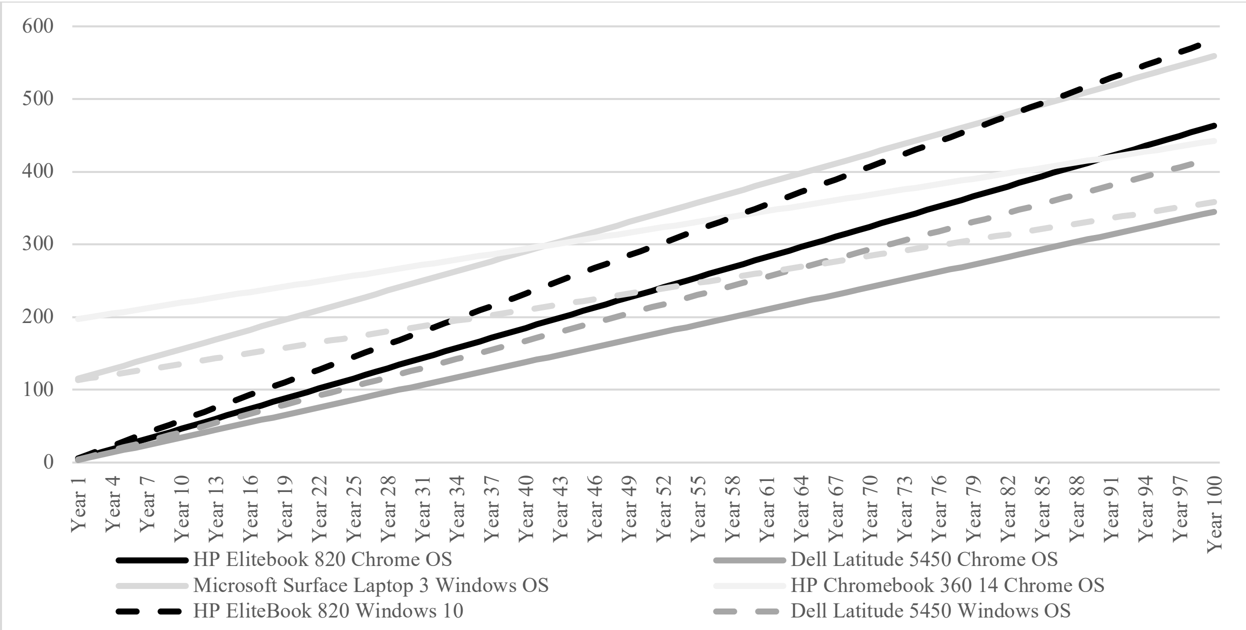

Figure 1. Cumulative greenhouse gas emissions ($kgCO_2e$) generated by end user computing devices

The significance of the manufacturing emissions and improved energy efficiency influences upon the displacement strategy is examined by extrapolating the data cumulatively across a number of years to define the point whereby the new device emissions intersect the repurposed device emissions (figure 1). The rationale used for this is that annual values for the repurposed devices include only the ongoing electricity consumption results. The point being that the embodied emissions impact has already been accounted for 5-years prior and the decision at this point is to either dispose of or continue with the device. The annual values for the new devices include both embodied and use phase emissions in year one and then only cumulative use phase emissions in all subsequent years. The reason in this instance is to represent the impact of new device production and to examine if energy efficiency innovation is sufficient to compensate.

As highlighted in figure 1, the impact of embodied emissions is such that the first point of intersection between the repurposed devices and the new devices occurs in the 91st year of use. This is the moment when the cumulative embodied and use phase emissions value of the most efficient new device, the HP Chromebook 360, become equivalent to the least efficient repurposed device, the HP Elitebook. Notably, such is the energy efficiency of the repurposed Dell Chrome OS Flex device that intersection by either new device does not occur within the first century. Plotting the same data for the legacy devices in their original Windows format indicates that the HP devices intersect in the 59th year highlighting the 32 years of incremental abatement delivered by the energy efficiency of the Chrome OS in the first example. Notably, the HP Chromebook 360 intersects with the Surface Laptop 3 device in the 42nd year of use. This indicates that the energy efficiency gap between the two devices of 45% plays a significant role in the reduction of the total carbon footprint. The rationale being that although the HP device scope 3 emissions are 43% higher than the Microsoft device, the long term impact rests with energy consumption. However, as even extended retention periods are determined to be no more than 8-years [62, 64] then arguably the focus returns to ensuring both embodied and use phase emissions remain as low as innovation and production manufacturing process allow for.

To theoretically highlight the importance of this, the lowest sources of emissions from the new devices is combined. Using the manufacturing impact of the Microsoft device together with the HP Chromebook use phase annual emissions value, a feasible best in class hybrid notebook is created. The rationale being that this notebook could simply be installed with an alternative replacement operating system. However, even in this theoretical example, the new device impact does not erode the displacement gains within the 8-year retention period. Instead, it is not until year fifty-two when the projection intersects the HP Elitebook Chrome OS Flex variant and as before, the ongoing use phase impact of the repurposed Dell device is not equalled in the first one hundred years of use.

4. Summary

The research substantiates that, where feasible, displacement strategies are preferential to purchasing new devices when considering environmental impact. The reason being that proportionately, the embodied emissions dominate the use phase emissions by, in this example, between 5-16 times. Consequently, even in the most preferential instances, several decades will pass before the greenhouse gas impact of manufacturing can be compensated for by electricity efficiency innovation delivered by new devices. It is however recognised that as research suggests, even extended total retention periods are unlikely to exceed eight years [62, 64]. As such, it is reasonable to propose that both a low manufacturing and use phase carbon footprint must be identified when selecting new equipment. Whilst the embodied emissions will be defined by the manufacturer, seeking out devices with reduced thermal design power central processing units, embedded multi-media card storage and low power double data rate memory, coupled with operating systems such as Chrome OS and Chrome OS Flex will, as determined, contribute to subsequent use phase emissions abatement averages of 42% [57]. In relation to existing equipment prone to obsolescence following average retention periods of between 3-5 years [18, 23, 31, 63], alternative operating system displacement strategies will reduce the total carbon footprint ahead of inevitable replacement. Specifically, it is substantiated by this research, that electricity consumption efficiencies of between 18-20% are achievable by using Google's Chrome OS Flex to repurpose legacy computers. Doing so offers two distinct abatement opportunities. Firstly, to lower ongoing use phase emissions and secondly to spread the pollution attributed to the existing manufacturing phase by several years; thus displacing product purchasing cycles by a potential 60% based upon extending lifespans from five to eight years.

In conclusion, the research highlights the impact of new equipment manufacturing is not recoupable through electricity efficiency innovation for almost a century. Consequently, it is reasonable to suggest that if the 1% of pollution caused by end user computing [1-8] is to be meaningfully addressed, then both displacement strategies in the short term based upon alternative operating systems and environmentally sympathetic new device selection play a crucial role in achieving the objective.

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