Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 224 (2023) 296–305

Procedia Computer Science

www.elsevier.com/locate/procedia

The 13th International Conference on Sustainable Energy Information Technology (SEIT)
August 14-16, 2023, Halifax, Nova Scotia, Canada

Greenhouse gas abatement via repurposing computers

J. Sutton-Parker [a,*] and R. Procter [a, b]

[a,] *University of Warwick, Computer Science Department, Coventry, CV4 7AL, United Kingdom*
[b,] *Alan Turing Institute for Data Science and AI, London, NW1 2DB, United Kingdom*

Abstract

The purpose of this research is to generate findings to support the reduction of computer supply chain greenhouse gas emissions. This is achieved by answering the question, 'can greenhouse gas abatement be delivered by alternative computer operating system displacement strategies?' We hypothesised that extending the useful lifespan of end user computing devices to 8 years by repurposing a device with a new operating system can reduce scope 3 supply chain emissions, which account for 73% of an end user computing device's carbon footprint. To test the hypothesis, we measure the carbon footprint reduction delivered by repurposing 3,150 obsolete desktop computers, which were installed with a Linux based operating system to become thin clients and support a remote working solution for a major financial institution during the recent Covid-19 pandemic. We calculate scope 3 supply chain emissions avoided by not purchasing new thin client solutions. Legacy device power consumption is also measured and extrapolated to represent the one-year period of use and compared with that of new devices to calculate the excess scope 2 emissions of the former. We find that while new devices reduce scope 2 emissions, this gain is outweighed by the reductions in scope 3 emissions from not replacing the legacy devices. Furthermore, we find that the new Linux based operating system reduces energy consumption by 22% compared with Microsoft Windows. We also calculate the financial gains from the repurposing strategy to test the perception that sustainable information technology adoption is costly. Finally, the impact of remote working on commuting emissions is estimated. In conclusion, the findings show that repurposing end user computing devices contributes meaningfully to sustainability strategies from both an environmental and financial perspective.

Keywords: Computer carbon footprint; supply chain greenhouse gas emissions; sustainable information technology.

* Corresponding author. Tel.: +44-(0)7976-818-530.
E-mail address: Justin.Sutton-Parker@warwick.ac.uk

10.1016/j.procs.2023.09.040

1. Introduction

A body of associated research [1-7] explores the feasibility of reducing the 1% of annual global greenhouse gas (GHG) annual emissions generated by end user computing [8-17] to contribute to climate action strategies and associated net zero strategies within businesses. This is achieved by testing speculative barriers, developing solutions to specifically identified issues and determining the impact of sustainable information technology strategies enabled by the findings. This includes the improvement of use-phase GHG quantification to include the influence of human-computer interaction upon power draw [1, 5, 6]. Enabling data parity within product carbon footprint reports to enable meaningful assessment and procurement of devices based on sustainability criteria [4]. Quantifying the positive environmental impact of information technology enabled remote working and extending device lifespans to displace scope 3 supply chain emissions [3, 5, 7]. A common theme within the research is alternative operating systems to Microsoft's Windows software offer the capability to improve energy efficiency and extend device lifespans. Initially, notebooks installed with Google Chrome OS software exhibited 46% lower energy consumption than comparative Windows devices when measured for electricity consumption in the workplace [1]. Further testing revealed that Windows devices faced with obsolescence remained viable when Windows was replaced with the Chrome OS Flex variant operating system [5]. Specifically, application and hardware compatibility and security issues caused by the former OS being no longer supported by Microsoft were overcome. Additionally, it was determined that the new OS caused the device to consumed 19% less. The findings were tested in the field in an impact case study with Nordic Choice Hotels [18]. Specifically, the organisation avoided 1.5 million $kgCO_2e$ due to lowered scope 2 and scope 3 emissions delivered by reduced electricity consumption efficiency and the absence of new device procurement.

While this example demonstrates how the useful lifespan of a device can be extended by retaining the original function as a standard mobile or desktop computing device, the opportunity to achieve longer retention periods may also be accomplished by the act of repurposing: i.e. when a device no longer performs its initial function and, via modification, assumes a new purpose. This provides companies with multiple options to extend device lifespans to at least 8 years. In this way, it is feasible to reduce scope 3 supply chain emissions by 37.5% when compared to a device kept for 5 years [7] as the purchase of a new device is displaced by 3 years in each procurement cycle. Currently, research indicates an average retention period for computers to be 5 years [19-22] before obsolescence forces replacement. The necessity to replace a device is often caused by the operating system becoming unsupported by the vendors as noted. Since 2020, companies such as Google have recognised the need to support longer device retention cycles to reduce the impact of device production and now offer Chrome OS updates for 8 years. While Microsoft offers potential support for 10 years, operating system development ceases after 5 years with only security patches being supported to the end of the total period. Additionally, depending upon when in the lifecycle of the operating system the device is purchased; this period may also be reduced. This nuance also influences retention periods for devices operating variations of the Apple MacOS. Currently, Apple will supply security patch updates for 3 years after each new release and the software is superseded on average every 36 months.

Consequently, retention periods are usually restricted to 6-years at the most while in second use cases, 8 years is considered feasible [19, 21-22]. In a wider context, extending useful lifespan is imperative if the current 1% contribution to global GHG emissions is to be reduced. Research shows the average contribution of scope 3 emissions to the end user computing device total carbon footprint is 73% [4]. As such, as more than 460 million devices are produced annually with 10% growth anticipated during the next decade, extending useful lifespan addresses the predominant source of emissions by reducing demand ahead of growth if broadly diffused. Additionally, in the future, scope 3 percentage contribution to each device's total carbon footprint will increase as the carbon intensity of national grids lessens as renewable energy production increases. As an example, the United Kingdom's national electricity grid currently creates 212 gCO_2e of scope 2 GHG emissions per 1 kWh of electricity [23]. As such, an average notebook consuming 21 kWh/y of electricity will generate 4.5 $kgCO_2e$ of scope 2 emissions in 2022. However, as the government strategy is to adopt 100% renewable energy by 2035, it is feasible for this value to reduce to 0.38 $kgCO_2e$ annually based upon the suggested sources of future electricity production [24]. Consequently, whereby the use-phase was previously responsible for 27% of the product's total carbon footprint, in 2035 this proportional contribution will potentially decline to just 1.4%.

The opportunity to test the hypothesis that repurposing will contribute to GHG abatement arose in 2020. Further to the Corona virus pandemic emerging in the UK, a financial institution faced the problem of limited secure remote working capability for employees. Specifically, 3,150 or 86% of employees did not have the ability to work remotely. Considering offices were inaccessible from March 2020 with only a small number of employees returning by October 2020, the barrier, if left unaddressed would impact productivity as employees would be unable to connect to internal IT systems. To overcome this, the company decided to expand the existing remote working solution that serviced 495 or 14% of users. To achieve this, new thin client hardware could be purchased or existing legacy hardware that was due to be recycled could be repurposed. The latter option appealed to the organisation as it complemented existing sustainability commitments, including achieving a net zero carbon investment portfolios by 2050 and a 20% reduction in scope 1 and 2 emission intensity within occupied premises per full-time employee. Specifically, it was decided to install the IGEL OS onto 3,150 existing Dell OptiPlex 7010 small form factor desktop computers that were due for recycling having reached the end of a five-year useful lifespan.

Combined with existing monitors, the new 'office in a box' solutions were shipped to the home addresses of employees. Now connected securely to internal IT systems via broadband and internet technologies, the virtual desktop technology solution enabled a fully functional user interface, while application processing and data storage occurred within the company's data centres. Having enabled employees to work throughout the 2020 travel restrictions experienced, the company and IGEL agreed to facilitate field experiments to determine the environmental impact generated by the repurposing strategy. Specifically, GHG emissions avoided by repurposing including both displaced scope 3 supply chain emissions and on-going scope 2 emissions comparative efficiencies are quantified. Additionally, reduced scope 3 commuting emissions by the remote working are estimated to substantiate wider reaching contributions to organisational net zero strategies. Finally, financial savings from avoiding purchase of new devices are calculated to corroborate prior findings that sustainable IT strategies are capable of driving cost reduction. The value of this is that companies create barriers to the adoption and diffusion of sustainable IT strategies based predominantly upon declaring insufficient budget is available to consider the transition to green IT [2].

2. Method

The repurposing includes converting Dell OptiPlex 7010 desktop computers into thin client computers. This is achieved by replacing the Microsoft Windows 7 Pro operating system with IGEL OS. Combined with an existing 24" monitor, the strategy avoids the purchase of two possible alternative solutions. The first is a new HP T640 IGEL OS thin client computer that would have utilised with the legacy monitors and the second an LG 24CN650N IGEL OS all in one (AiO) integrated desktop computer. As such, to quantify scope 3 production, transport and end of life emissions avoided, secondary GHG kgCO_2e supply chain data is sourced from manufacturer product carbon footprint reports for both new devices [25]. As end-of-life processing emissions are also avoided by extending the useful device lifespan of the legacy desktop computers, this value is also included within the calculation [26].

Research suggests that new devices will most likely be more energy efficient than older computers due to on-going component innovation [19, 27-33]. Based on related research [1, 5, 6], it is anticipated that continuing with legacy desktop computers will increase scope 2 electricity generated use-phase emissions. However, as research also indicates alternative operating systems are capable of reducing energy consumption [1, 5], scope 2 emissions calculation is undertaken for legacy and potential new devices. Specifically, the Dell OptiPlex 7010 desktop is measured for energy consumption in the workplace in both original Windows 7 Pro and repurposed IGEL OS formats. While measuring the device in the new format in isolation enables calculation relating to repurposing, the original format measurement enables determination if Linux based operating systems other than Chrome OS also reduce energy consumption. The two new HP and LG devices are also measured for electricity consumption in the workplace. During the process, an Acer 24" B246WL monitor is also measured when using the Dell and HP devices. It is noted that such measurement is not required for the LG AiO as the device format includes a computer integrated into a 24" monitor. Physical measurement is necessary as research shows the Energy Star typical energy consumption value used to populate the use phase emissions data within product carbon footprint reports does not include impact of human-computer interaction upon power draw during the active mode. Such an oversight causes scope 2 quantification to be on average 30% inaccurate. As the computers are used in a business environment and will be predominantly in the active state, then this omission must be addressed.

While the test set-up for the field watt metre measurement activity is based upon Energy Star parameters [34] and international standards [35, 36], the methodology includes measurement of all modes to ensure the active state is considered. Specifically, each device is measured for energy consumption (kWh) for five 8-hour periods whilst experiencing business style productivity and video-based tasks in the workplace to reflect a 'standard working week'. From this, an average one-hour kW value is determined. To ensure the use-profile (hours of use per year) required by the Kawamoto et al. [37] data flow is specific to the financial organisation users, analytics data showing the time computers are switched on is collected. This is achieved by deploying node-based software shown to be highly accurate in prior research [6] within a group of 132 sample employees. Extracted for 30 days, the percentage of 'on time' is converted to an 'hours per day' value daily and multiplied by the previously determined 1-hour kW value. The daily value is then extrapolated to 1 year based upon 232 working days in total to reflect the financial organisation's employees being subject to time off for weekend, paid and public holidays related with UK operations [38-39]. Scope 2 emissions values are then determined by multiplying the kWh/y results in each instance by the UK electricity carbon conversion factor for the relevant year [40].

Scope 3 commuting emissions avoided are calculated from secondary data that details commuting average journeys within the UK by miles, frequency and mode [41]. This data is proportionately applied to the number of employees now remote working and multiplied by the relevant annual UK transport conversion factors for the period [40]. All data is presented using tables in order to clearly determine the GHG emissions reductions and financial savings achieved by the displacement decision. Finally, to generate the financial costs related to both replacement and repurposing options, four key inputs are determined: 1) cost of the new operating system software; 2) avoided cost of recycling the existing devices; 3) purchase cost of the new devices; 4) electricity costs associated with both solutions. Each unit value is determined by speaking to the relevant supplier of IT and utility services. The results of the supply chain, use-phase, commuting and financial calculations are presented in the following section.

3. Results

The scope 3 emissions data are identified via the relevant carbon footprint data published by each respective manufacturer. In this example, both Dell and HP employ the Product Attributes to Impact Algorithm lifecycle assessment methodology [42] and using the mean value for each relevant data point enables parity between the legacy repurposed and new thin client devices. Comparatively, supply chain data specific to both the LG AiO device and the Acer monitor used in the experiment is not available as neither company produces computer product carbon footprint reports. To compensate, nineteen available reports for integrated desktops with a 24" screen from alternative brands and twenty-one reports for 24" monitors were examined and an average scope 3 value determined for each [25, 26, 43-45]. The lack of available data from two of the world's largest electronics manufacturers reflects limitations experienced in related research, which found that only 22% of end user computing products have published emissions information [4]. The proposed thin client desktop computer, the HP T640 has a supply chain value of 115 kCO_2e per device (Table 1). This value is two thirds lower than a standard desktop computer exhibiting an average scope 3 emissions value of 342 kCO_2e because processing and storage occurs remotely within the data centre [4]. The manufacturing environmental impact is lower in this example than a standard desktop like for like replacement. However, had the financial services company proceeded to purchase 3,150 new thin client devices, then 362,250 kgCO_2e of scope 3 supply chain GHG emissions would have been generated to enable the emergency remote working policy.

In relation to the legacy computer, 1.1% of the Dell OptiPlex 7010's 218kgCO_2e total carbon footprint is attributed to end of life treatment (Table 1) equal to 2.4 kgCO_2e per unit [26]. If repurposing had not occurred, 7,553 kgCO_2e would also have been realised during recycling and disposal. Consequently, combining both sources of supply chain pollution 369,803 kgCO_2e scope 3 emissions has been avoided by adopting a displacement strategy. The second AiO thin client option has a notably higher scope 3 value of 459 kgCO_2e (Table 1) due to the integrated display. Hence 1,453,403 kgCO_2e of supply chain emissions is avoided by continuing with the legacy product rather than adopting the AiO product. For the purposes of comparison, using existing 24" monitors for the repurposed Dell device and potential new HP device avoids 984,406 kgCO_2e of supply chain emissions from the production of new devices plus 12,600 kgCO_2e of end-of-life processing emissions.

To determine the scope 2 electricity generated GHG emissions a combination of analytics and field metering is undertaken. The analytics data determines that of the ten operational hours between 8am and 6pm, the repurposed devices are active for 8.65 hours per day or 86.5% of available work hours. The duration is increased compared to the council computer user on-time determined in previous research as 70% [7]. Therefore, the results validate the Kawamoto et al. [37] finding that job role influences the annual computer energy consumption. As previously noted, further research suggests that the proposed new thin client devices are most likely to consume less energy than the existing desktop devices due to on-going energy efficiency innovation [19, 27-33]. Additionally, it is reasonable to assume that fewer component parts that contribute to the lowered scope 3 emissions will require less power draw overall. In this example, the electricity consumption findings also concur.

Table 1. Single unit GHG missions (kgCO_2e) and energy (kWh) data for the repurposed and potential new end user computing devices

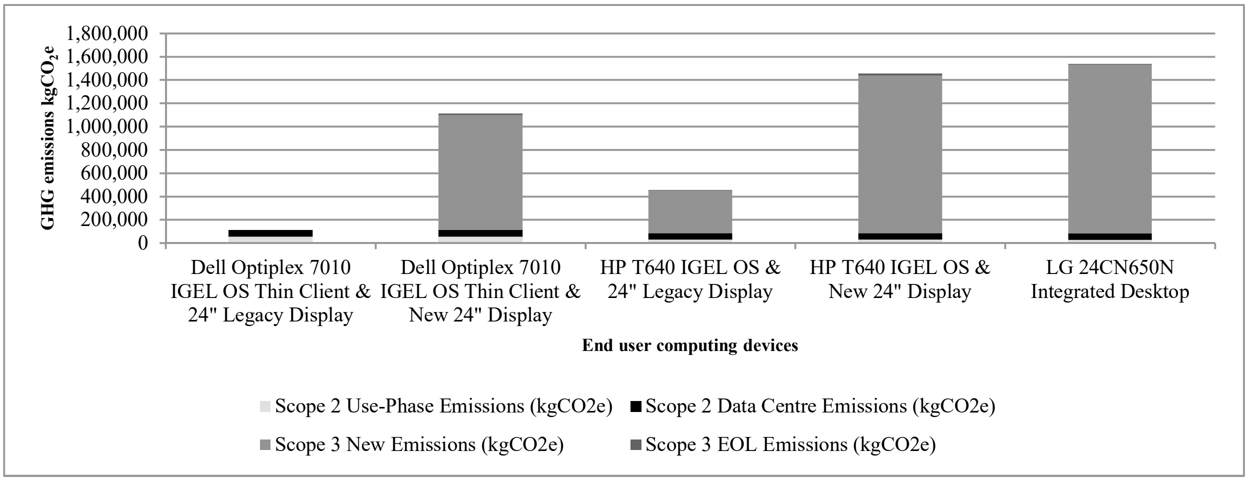
Device / Operation	**OS**	**kWh/y**	**Scope 2 (kgCO_2e/y)**	**Scope 3 Supply Chain (kgCO_2e)**	**Scope 3 EOL (kgCO_2e)**
Dell OptiPlex 7010 desktop	Windows 7 Pro	70.44	16.42	218	2.398
Dell OptiPlex 7010 desktop thin client	IGEL OS	54.99	12.82	218	
HP T640 desktop thin client	IGEL OS	18.86	4.4	115	
LG 24CN650N integrated desktop	IGEL OS	37.33	8.7	459	
Acer 24” B246WL monitor	NA	22.68	5.29	313	4
Data Centre energy consumption	NA	18.00	4.20	NA	

During the measurement phases the existing Dell 7010 desktop computer with a Windows 7 Pro operating system generated an hourly electricity consumption of 0.0351 kW. Triangulated with the analytics data and extrapolation to one-year, the legacy desktop in its original format consumes 70.44 kWh/y. When repurposed with the IGEL OS, the device consumed 0.0274 kW and 54.99 kWh/y; exhibiting a reduction of 22%. From a device energy consumption perspective, the results concur with research showing that alternative Linux based operating systems are capable of reduced power draw between 18-20% [1, 5]. However, in this earlier research, Chrome OS Flex software was used to continue a device’s original function as a notebook. The change of use from a desktop to a thin client in this current research means that some of the reduction experienced by the device is most likely due to offloading computational and storage activities to the data centre. As such, whereby the like for like displacement strategy can claim the full concomitant scope 2 abatement, repurposing to thin client devices cannot. This is because the scope 2 carbon footprint of the data centre infrastructure reduces the efficiency gain. An average 1,000 user virtual infrastructure data centre server environment will consume in the region of 17,660 kWh/y. Therefore, for the purpose of GHG emissions calculation it is reasonable to add approximately 18 kWh/y to the electricity consumption value for both the legacy and proposed new thin client devices. Realistically, the energy efficiency gain related to legacy devices is reversed when compared to the original desktop function to represent a 3.6% increase to 72.99 kWh/y.

Setting aside the data centre consumption overhead, the repurposed device remains 191% more energy intensive than the HP T640 device measuring 18.86 kWh/y. As the two computers are installed with the same IGEL OS operating system the energy efficiency improvement exhibited by the new device is delivered by innovation and specifically component architecture. Earlier research identifies three key common components reduce power draw: 1) reduced thermal design power central processing units; 2) embedded multi-media card storage; and 3) low power double data rate memory [5]. The legacy device includes none of these, whereas the new HP thin client includes two. As an example the thermal design power of the Dell device is 60W compared to 15W enabled by the Ryzen R1505G chipset present in the HP device. Additionally, the legacy device storage is a hard disc, whereas the new devices utilise low power flash storage. Hence, for each retained legacy unit 36.13 kWh/y of additional electricity is consumed. From a concomitant scope 2 emissions perspective, this means 26,534 kgCO_2e of additional use-phase emissions are generated during one year by repurposing devices. As such, the 369,803 kgCO_2e already avoided by displacement is reduced creating a total emissions abatement of 343,269 kgCO_2e.

As the LG device has an integrated display, to achieve comparison between the legacy device and the new AiO device, consumption values must consider the use of a similar sized monitor. To achieve this an Acer 24” B246WL monitor is measured for electricity consumption when connected to the Dell repurposed thin client. The stand-alone monitor consumes 0.0113 kW and 22.68 kWh/y creating a combined display and repurposed thin client value of 77.67 kWh/y. Comparatively the LG 24CN650N integrated desktop consumes only 48% of this value at 37.33 kWh/y. Hence, retaining the legacy device consumes 40.34 kWh/y more energy per device than transitioning to the new AiO. This equates to an increase in avoidable scope 2 emissions during 2020 of 29,625 $kgCO_2e$.

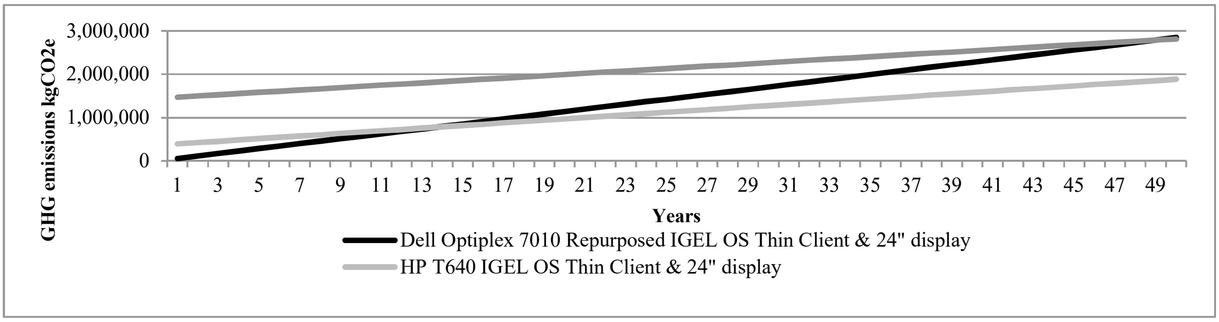
Figure 1. Scope 2 and 3 GHG emissions ($kgCO_2e$) comparison between repurposed and potential end user computing devices



However, placed into context of the total carbon footprint, as indicated in Figure 1, scope 3 emissions impact of new purchases far outweighs gains achieved by improvements in energy consumption. Specifically, the repurposed thin client option using existing monitors that the financial services company proceeded with, generates a carbon footprint consisting of only scope 2 emissions generating 113,661 $kgCO_2e$ GHG emissions during the one-year period. Purchasing new HP hardware yet retaining legacy monitors raises the value by 302% to 456,941 $kgCO_2e$, with 81% of the total attributed to supply chain emissions. Taking the next step and repurposing the Dell desktop while buying new displays raises the value again by 879% from the actual strategy to 1,112,211 $kgCO_2e$. In this example, 90% of the total footprint is attributed to scope 3 emissions. Replacing legacy computers and displays entirely with new equipment increases this again by 1,180% to 1,455,491 $kgCO_2e$ in the case of the HP device and 1,252% to 1,537,522 $kgCO_2e$ in the case of the LG device. In both examples the supply chain emissions account for 94% and 96% of the total emissions created. Consequently, it is reasonable to suggest the company avoids between 343,280 $kgCO_2e$ and 1,423,861 $kgCO_2e$ of GHG emissions by repurposing and retention of existing displays.

The finding concurs with earlier research [5] that the high proportionate contribution of supply chain emissions to product total carbon footprint causes on-going abatement gains achieved by energy efficiency innovation to become less significant. The cumulative scope 3 and on-going scope 2 emissions generated by a new product will not offset the scope 2 inefficiency for many years beyond the average device useful lifespan of 5 years [19-22]. Using the same approach as the earlier research [5], the supply chain and continued generation of annual use-phase emissions are forecast for the repurposed device and the new HP thin client, both with an existing display, and the new LG AiO. As shown in Figure 2, 14 years pass before the energy efficiency improvement delivered by the HP device causes the cumulative carbon footprint to intersect. Comparatively, the LG device does not achieve this until the 49th year due to the raised scope 3 caused by the integrated 24" display.

Figure 2. Cumulative carbon footprint ($kgCO_2e$) comparison between repurposed and new devices

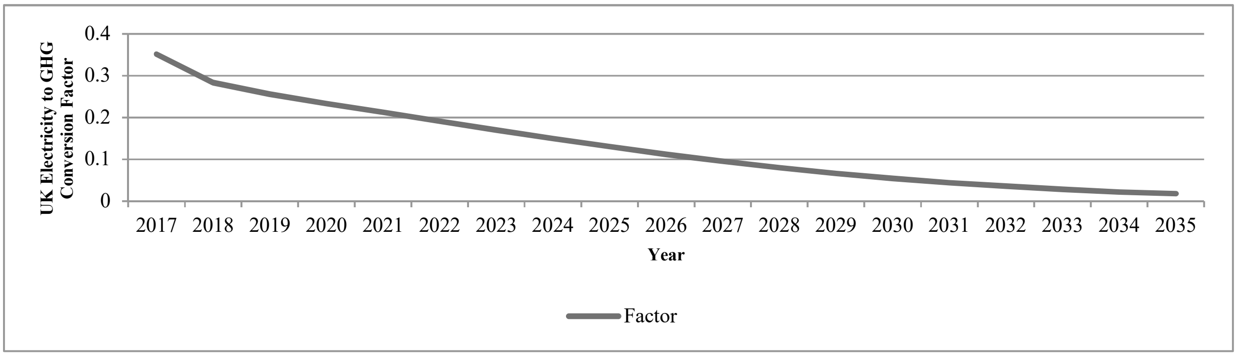


In both cases, the point when energy efficiency finally offsets the manufacturing and distribution impact is far sooner than found in earlier research [5], where it occurred in the 91st year. The reason for this is twofold. Firstly, the raised energy consumption associated with legacy desktop devices when compared to the extreme energy efficiency attributed to new thin client devices creates an increased annual energy saving for the latter. As an example, in the earlier research a difference of 10.16 kWh/y was found between the repurposed notebook and the new Chromebook. Whereas, in this example, the combined repurposed desktop and existing display consumes 77.57 kWh/y and the HP device using the same display consumes 41.44 kWh/y. Consequently, 36.13 kWh/y of electricity consumption and 8.4 kgCO_2e concomitant emissions is avoided annually. Secondly, the scope 3 carbon footprint of the HP thin client device is 41% smaller than that of the Chromebook being 115 kgCO_2e and 195 kgCO_2e respectively. As such, the HP device has less initial supply chain emissions to offset than the device used in the previous research [5].

However, while there is uncertainty about carbon intensity data relating to future energy, the likelihood of increasing percentages of low carbon electricity being available must be considered. As previously noted, the UK government suggests that the national grid will be predominantly carbon free by 2035 [24]. Based upon historical reductions in electricity to GHG conversion factors [40, 46-48] highlighting rates of renewable energy adoption, this is feasible. As Figure 3 highlights, the conversion factor for 2035 will reach 0.01792 if the already achieved carbon factor percentage reduction is projected. As such, plotting the gains achieved by the new devices causes no intersection to occur at all as all devices plateau at this point from an on-going cumulative scope 2 emissions contribution meaning that the impact of producing and supplying the devices is never overcome.

Having substantiated the environmental value of device repurposing, the strategy's impact upon profitability is examined. Previous research indicates the greatest barrier to the adoption of sustainable IT adoption is cost [2] due to the perception that such strategies do not offer a sufficient return on investment when compared to the realised positive environmental impact. However, if the financial expenditure related to the repurposing strategy proves lower than the new device strategy, this perception is challenged and the case for sustainable IT adoption strengthened. In this example, as the organisation has decided to proceed with repurposing, avoided costs associated with device procurement and disposal can be assessed and compared to incurred costs, such as on-going elevated utility costs and software licensing. As indicated in Table 2, the total avoided costs associated with the most likely replacement solution, the HP device, is £1,304,100. Ninety-seven percent of the capital expenditure is related to the procurement of the new device, with 3% attributed to collection and processing of legacy devices. Incurred costs total £330,933, including £100 per legacy device spent on the new IGEL OS software, plus an additional cost of £15,933 attributed to higher electricity consumption exhibited by the repurposed devices when compared to the new alternative. It is noted that this latter cost could be considered as irrelevant as the actual payment would be made by the company employee as the devices are operated at home and not in the office.

Figure 3. United Kingdom projected electricity to GHG emissions (kgCO_2e) conversion factors



However, for the purposes of this research the cost is accounted for as part of overall operational expenditure to enable fair comparison between the two options. Consequently, when compared to the most likely new solution alternative, the overall displacement solution reduces cost for the remote working period by £973,167. However, had the company selected the AiO device the avoided costs increase to £1,764,00, due to the higher procurement value of £1,719,900. Comparatively, incurred costs also rise to £332,746 due to the increased difference in energy efficiency delivered by the integrated desktop resulting in an annual utility cost of £17,746. Hence, it is feasible that the overall saving delivered by the sustainable IT solution is £1,431,254. In both eventualities, the results concur with similar impact case studies and undermine cost versus impact assumptions by further substantiating that displacement strategies using repurposing do reduce capital and operational costs while avoiding GHG emissions as previously determined.

Table 2. Single unit GHG missions (kgCO_2e) and energy (kWh) data for the repurposed and potential new end user computing devices

Description	Type	Units	Cost Per Unit (£)	Total Cost (£)	Expenditure Category
Dell OptiPlex 7010 desktop disposal	Avoided cost	3,150	14	44,100	Capital
HP T640 thin client procurement	Avoided cost	3,150	400	1,260,000	Capital
IGEL OS software license	Incurred cost	3,150	100	315,000	Capital
1 year additional electricity cost (HP)	Incurred cost	113,810	0.14	15,933	Operational
LG 24CN650N AiO procurement	Avoided cost	3,150	546	1,719,900	Capital
1 year additional electricity cost (LG)	Incurred cost	126,756	0.14	17,746	Operational

Though the focus of the research is to determine environmental benefit delivered by the repurposing strategy, it is reasonable to suggest that remote working will also reduce GHG emissions. Transport is the UK's largest GHG emissions source 26% [49] caused by 540bn miles of passenger travel. Of this 98bn miles is attributed to commuting and business travel [41]. Focusing specifically on commuting (Table 3) the most popular mode of transport is by car (62%). While the government enforced travel restrictions during the pandemic, it is important to determine scope 3 commuting emissions avoided during the period and whether continuation of the practice - in full or even partially - will reduce the organisation's future commuting emissions and contribute to the company's wider strategy to reduce its carbon footprint. To estimate the most likely impact, secondary national transport statistics and data are applied to the user group. To ensure that the positive impact is not subject to exaggeration, modes of transport such as public transport that would operate whether the staff travelled or not are removed from the calculation. Consequently, it is reasonable to suggest that 1,260,841 kgCO_2e (400 kgCO_2e per employee) of commuting emissions was avoided in 2020 due to adoption of the remote working solution. As the results indicate, almost 99% of the pollution is generated by car travel, consistent with research showing alternative sustainable transportation modes must be prioritised if companies are to reduce commuting carbon footprints [3]. Looking ahead, should the financial services organisation maintain remote working for at least two-days per week, scope 3 commuting emissions will decline by 40% to 756,505 kgCO_2e.

Table 3. Commuting avoided scope 3 GHG missions (kgCO_2e) estimate

Mode	% of Total	Employees per mode	Average Distance (miles)	Commuting Days	Total Distance (miles)	2020 Scope 3 kgCO_2e
Walking	9.89	312	0.78	232	56,375	0
Bicycle	4.40	139	3.75	232	120,582	0
Car	62.34	1,964	9.98	232	4,546,696	1,244,512
Motorcycle	1.10	35	6	232	48,233	8,800
Bus	5.49	173	5.6	232	224,677	37,286
Underground	3.29	104	8	232	192,347	8,513
Rail	4.40	139	24.75	232	795,841	47,312
Taxi	1.10	35	4	232	32,155	7,529

4. Summary

The findings support several of the research's objectives. Firstly, the legacy Dell desktop computer exhibits 22% reduced energy consumption when repurposed with the Linux based operating system. As with similar Windows to Chrome OS comparative research, the results further substantiate that useful lifespan extension can be achieved via alternative operating systems and in doing so, concomitant scope 2 GHG reduction is achieved. Secondly, the results substantiate that displacement strategies based upon repurposing will reduce total IT related emissions. Considering the computer hardware in isolation, the range of GHG emissions avoided by the financial organisation is between 343,279 and 1,423,861 kgCO_2e depending upon which solution is considered to have been avoided by the repurposing strategy. While both values are valid, comparing the two results it is clear that replacing both the existing displays and the legacy desktops with an integrated desktop solution increases the impact significantly, raising the emissions value by 315%. In both examples, it is supply chain emissions that contribute predominantly to the potential carbon footprint. The effect is sufficiently dominant that even when including the additional data centre energy and end of life disposal values for the legacy equipment, the HP manufacturing and supply emissions are responsible for 79% of the new IT carbon footprint, while the LG option equates to 94%. This is emphasised by the examination of on-going cumulative emissions to determine the point at which efficiency gains offset the immediate impact of supply chain emissions. Specifically, 14 years of use must pass for the thin client device and 49 years for the AiO device. Both values are far beyond even the extended feasible life span of 8-years proposed by displacement strategies. This outcome further emphasises that seeking out low carbon footprint devices and retaining them for as long as is practical is important to reduce the 1% contribution to global GHG emissions already caused by end user computing.

Thirdly, as shown by previous research, commuting emissions reduction enabled by remote working solutions are significant. Estimated to avoid 1,260,841 kgCO_2e scope 3 emissions, working from home during the pandemic period increased the total feasible abatement range for the strategy to between 1,604,120 and 2,684,702 kgCO_2e. The maximum avoided emissions for the 2020 period is equivalent to the pollution caused by 9,570,447 petrol car miles [23]. In context, such an environmental impact requires 11,485 acres of trees to sequester the resulting carbon dioxide from the atmosphere [50]. Finally, together with the financial savings demonstrated, the findings challenge the perception that sustainable IT increases business costs while delivering limited positive environmental impact. Having proven the capability to reduce annual per capita emissions by as much as 852 kgCO_2e per employee, the repurposing solution saves the company between £973,167 and £1,431,254 across twelve months by utilising existing assets in a new and innovative manner. As the 1% global GHG contribution generated by end user computing is driven predominantly by manufacturing and subsequent electricity use [8-17] it is sensible to examine alternative options to new product purchase. In this instance, the findings substantiate the value of both environmental and financial benefits of displacement strategies based upon repurposing. By doing so, the findings further contribute to evidence that such sustainable IT strategies support UN aspirations to apply innovation to existing technologies to reduce societal emissions [51]. Adopted at scale, the findings suggest that such strategies and the subsequent changes to human-computer procurement and user behaviours experienced, can help to bridge the current 32GtCO_2e gap that is preventing cessation of global warming beyond 1.5^{o}C [52].

References

[1] Sutton-Parker, J. (2020), ‘Determining end user computing device Scope 2 GHG emissions with accurate use phase energy consumption measurement’. Volume 175, 2020, Pages 484-491. doi.org/10.1016/j.procs.2020.07.069. 1877-0509. Procedia Computer Science. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.
[2] Sutton-Parker, J. (2020), ‘Quantifying resistance to the diffusion of information technology sustainability practices in the United Kingdom service sector’. Volume 175, 2020, Pages 517-524. doi.org/10.1016/j.procs.2020.07.073. 1877-0509. Procedia Computer Science. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.
[3] Sutton-Parker, J. (2021), ‘Determining commuting greenhouse gas emissions abatement achieved by information technology enabled remote working’. 1877-0509. Procedia Computer Science. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.
[4] Sutton-Parker, J. (2022), ‘Is sufficient carbon footprint information available to make sustainability focused computer procurement strategies meaningful?’. 1877-0509. Procedia Computer Science. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.
[5] Sutton-Parker, J. (2022), ‘Quantifying greenhouse gas abatement delivered by alternative computer operating system displacement strategies’. 1877-0509. Procedia Computer Science. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.
[6] Sutton-Parker, J. (2022), ‘Can analytics software measure end user computing electricity consumption?’ Clean Technologies and Environmental Policy. 1618-9558. New York, USA: Springer.
[7] Sutton-Parker, J. (2022), 'Determining the impact of information technology greenhouse gas abatement at the Royal Borough of Kingston and Sutton Council’. 1877-0509. Procedia Computer Science, Volume 203, 2022, Pages 300-309. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.
[8] Andrae, A. S. G., and Edler, A.T., (2015). ‘On global electricity usage of communication technology: trends to 2030.’ Challenges 6, 117e157.
[9] Bekaroo, G., Bokhoree, C., Pattison, C. (2014), ‘Power Measurement of Computers: Analysis of the Effectiveness of the Software Based Approach’. New Delhi, India: International Journal of Emerging Technology and Advanced Engineering
[10] Belkhir, L., and Elmeligi, A. (2017) ‘Assessing ICT global emissions footprint: Trends to 2040 & Recommendations’. Oxford: Science Direct
[11] Global e-Sustainability Initiative. (2008), SMART 2020: Enabling the low carbon economy in the information age. Figure 3.1 The global footprint of PCs – desktops and laptops: 19. Brussels: GESI
[12] Global e-Sustainability Initiative. (2012), ‘SMARTer 2020: The Role of ICT in Driving a Sustainable Future.’ The ICT Industry’s GHG Emissions: 22. Brussels: GESI
[13] Global e-Sustainability Initiative. (2015), ‘#SMARTer2030 ICT Solutions for 21st Century Challenges.’ Executive Summary: ICT Solutions for 21st Century Challenges: 8. Brussels: GESI

[14] Global e-Sustainability Initiative. (2019), 'Digital with Purpose: Delivering a SMARTer2030'. Brussels: GESI
[15] Malmodin, J., Moberg, A., Lunden, D., Finnveden, G., and Nina Lovehagen. (2010), 'Greenhouse Gas Emissions and Operational Electricity Use in the ICT and Entertainment & Media Sectors.' Volume 14, Number 5. Page 707. Journal of Industrial Ecology.
[16] Malmodin, J., Bergmark, P., Lunden, D., (2013). The future carbon footprint of the ICT and E&M sectors. In: On Information and Communication Technologies.
[17] Malmodin, J. and Lunden, D. (2018). 'The Energy and Carbon Footprint of the Global ICT and E&M Sectors 2010–2015'. Journal of Sustainability. Basel, Switzerland: MDPI.
[18] Sutton-Parker, J. and Google. (2022), 'Modernising and extending device lifecycles to support climate action: Nordic Choice Hotels impact case study.' California, USA: Google.
[19] Prakash, S., Kohler, A., Liu, R., Stobbe, L., Proske, M., Schischke, K. (2016), 'Paradigm Shift in Green IT – Extending the life-times of computers in the public authorities in Germany. New Jersey: Institute of Electrical and Electronics Engineers.
[20] Teehan, P. and Kandlikar, M. (2012), 'Sources of variation in life cycle assessments of desktop computers. J. Ind. Ecol. 16 (no. S1), S182eS194.'
[21] Thiebaud, E., Hilty, L.M., Schluep, M., Widmer, R., and Faulstich, M. (2017), 'Service lifetime, storage time and disposal pathways of electronic equipment: A Swiss case study.' Journal of Industrial Ecology.
[22] Williams, E. and T. Hatanaka. (2005). Residential computer usage patterns in Japan and associated life cycle energy use. In Proceedings of the International Symposium on Electronics and the Environment, New Orleans, LA, USA, 16–19 May 2005, pp. 177–182.
[23] Department for Business Energy and Industrial Strategy and Department for Environment Food and Rural Affairs. (2021), 'UK Government GHG Conversion Factors for Company Reporting'. London: Crown Copyright.
[24] HM Government. (2021), 'Net Zero Review Final Report'. London: The Stationery Office Limited
[25] HP Inc. (2021), 'Product Carbon Footprint Reports: Notebooks'. Palo Alto: HP Inc.
[26] Dell. (2021), 'Select Product Carbon Footprint Assessments'. Roundrock, Texas.
[27] Bakker, C., Wang, F., Huisman, J., den Hollander, M., (2014), Products that go round: exploring product life extension through design'. Amsterdam: Journal of Cleaner Production
[28] Boyd, S.B. (2012), 'Semiconductor LCA: the road ahead'. Springer: Life-cycle assessment of semiconductors.
[29] Cooper, D. R., and Gutowski, T.G. (2017), 'The environmental impacts of reuse: a review'. Journal of Industrial Ecology.
[30] Deng, L., Babbitt, C.W., Williams, E.D. (2011), 'Economic balance hybrid LCA extended with uncertainty analysis: case study of a laptop computer'. Amsterdam: Journal of Cleaner Production.
[31] Schischke, K., Kohlmeyer, R., Griese, H., Reichl, H., (2003), 'Life cycle energy analysis of PCs – Environmental consequences of lifetime extension through reuse'. 11th Lausanne: LCA Case Studies Symposium
[32] Vadenbo, C., Hellweg, S., Astrup, T. F. (2017), 'Let's be clear(er) about substitution: a reporting framework to account for product displacement in life cycle assessment.' Yale: Journal of Industrial Ecology.
[33] Wolf, M. A., Chomkhamsri, K., Brandao, M., Pant, R., Ardente, F., Pennington, D. W., Manfredi, S., de Camillis, C., Goralczyk, M. (2010), ILCD handbook general guide for life cycle assessment'
[34] Energy Star. (2020), 'Energy Star Program Requirements for Computers version 8.0'. Washington, USA: USEPA
[35] International Electrotechnical Commission (IEC). (2011), 'Standard IEC 62301:2011 household electrical appliances measurement of standby power.' Geneva, Switzerland: IEC
[36] International Electrotechnical Commission (IEC). (2012), 'Standard IEC 62301:2012 desktop and notebook computers measurement of energy consumption.' Geneva, Switzerland: IEC
[37] Kawamoto, K., J. Koomey, B. Nordman, R. Brown, M.A. Piette, M. Ting, M., and Meier, A., (2001), 'Electricity Used by Office Equipment and Network Equipment in the U.S.: Detailed Report and Appendices' LBNL-45917: 3
[38] HM Government. (2019), 'Rests and Breaks at Work.' London: The Stationery Office Limited
[39] HM Government. (2020), 'Holiday Entitlement Rights.' London: The Stationery Office Limited
[40] Department for Business Energy and Industrial Strategy and Department for Environment Food and Rural Affairs. (2020), 'UK Government GHG Conversion Factors for Company Reporting'. London: Crown Copyright.
[41] HM Government. (2019), 'Department for Transport: Transport Statistics.' London, UK: Crown Copyright
[42] Massachusetts Institute of Technology (MIT). (2016), 'Intended Uses and Limitations of the Product Attribute to Impact Algorithm (PAIA) Model. Massachusetts: MSL
[43] Asus. (2022), 'Product Environmental Information: Eco Products'. Taipei City, Taiwan.
[44] Lenovo. (2022), 'ECO Declarations and Product Carbon Footprint Information Sheets'. Quarry Bang: Hong Kong.
[45] Microsoft. (2022), 'Eco Profiles.' Redmond: USA
[46] Department for Business Energy and Industrial Strategy and Department for Environment Food and Rural Affairs. (2017), 'UK Government GHG Conversion Factors for Company Reporting'. London: Crown Copyright.
[47] Department for Business Energy and Industrial Strategy and Department for Environment Food and Rural Affairs. (2018), 'UK Government GHG Conversion Factors for Company Reporting'. London: Crown Copyright.
[48] Department for Business Energy and Industrial Strategy and Department for Environment Food and Rural Affairs. (2019), 'UK Government GHG Conversion Factors for Company Reporting'. London: Crown Copyright.
[49] Department for Business Energy and Industrial Strategy (BEIS). (2020), 'Provisional UK greenhouse gas emissions national statistics 2020'. London: Crown Copyright
[50] United States Environmental Protection Agency. (2022), 'Greenhouse Gas Equivalencies Calculator'. Washington United States Congress
[51] United Nations Environment Programme. (2019), 'Emissions Gap Report'. Table ES1 Page 8. Nairobi, Kenya: UNEP
[52] Intergovernmental Panel on Climate Change (IPCC). (2022), 'Climate Change 2022: ARG WGIII SPM'. Switzerland: IPCC