A Thesis Submitted for the Degree of PhD at the University of Warwick

Permanent WRAP URL:

http://wrap.warwick.ac.uk/180282

warwick.ac.uk/lib-publications

The impact of end user computing carbon footprint information on human behavioural change and greenhouse gas emission abatement

Justin Sutton-Parker

Justin.Sutton-Parker@warwick.ac.uk
0000-0001-8208-3644

Thesis

Submitted to the University of Warwick for the degree of Doctor of Philosophy in Computer Science

November, 2022

Acknowledgements

Declaration

I hereby declare that I am the author of the work presented in this thesis entitled 'The impact of end user computing carbon footprint information on human behavioural change and greenhouse gas emission abatement' and it is an original work and has not been submitted to any college, university or any other academic institution for the purpose of obtaining an academic degree.

Publications

Sutton-Parker, J. (2022b), 'Can analytics software measure end user computing electricity consumption?' Clean Technologies and Environmental Policy. 1618-9558. New York, USA: Springer.
Available at: https://link.springer.com/article/10.1007/s10098-022-02325-x

Sutton-Parker, J. (2022c), 'Quantifying greenhouse gas abatement delivered by alternative computer operating system displacement strategies'. 1877-0509. Procedia Computer Science, Volume 203, 2022, Pages 254-263. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.
Available at: https://www.sciencedirect.com/science/article/pii/S187705092200638X

Sutton-Parker, J. (2022d), 'Is sufficient carbon footprint information available to make sustainability focused computer procurement strategies meaningful?'. 1877-0509. Procedia Computer Science, Volume 203, 2022, Pages 280-289. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.
Available at: https://www.sciencedirect.com/science/article/pii/S187705092200641X

Sutton-Parker, J. (2022e), '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.
Available at: https://www.sciencedirect.com/science/article/pii/S1877050922006433

Sutton-Parker, J. and Procter, R. (2022), 'Determining greenhouse gas abatement achieved by repurposing end user computing devices'. Warwick, UK: University of Warwick, Computer and Urban Science Dept. (currently in peer review with Procedia Computer Science)

Sutton-Parker, J. (2021), 'Determining commuting greenhouse gas emissions abatement achieved by information technology enabled remote working'. Volume 191, 2021, Pages 296-303. doi.org/10.1016/j.procs.2021.07.037. 1877-0509. Procedia Computer Science. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.
Available at: https://www.sciencedirect.com/science/article/pii/S1877050921014320

Sutton-Parker, J. (2020a), '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.
Available at: https://www.sciencedirect.com/science/article/pii/S1877050920317737

Sutton-Parker, J. (2020b), '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.
Available at: https://www.sciencedirect.com/science/article/pii/S1877050920317506

Media Articles & Government Strategy Documents

Google and Sutton-Parker, J. (2022), 'Modernising and extending device lifecycles to support climate action: Nordic Choice Hotels impact case study.' California, USA: Google.
Available at: https://chromeenterprise.google/os/sustainability/

Google and Sutton-Parker, J. (2022) 'Sustainability Calculator'. California, USA: Google.
Available at: https://sustainableitwithchromeos.com/

Sutton-Parker, J. (2021), 'Sustainable IT, COP 26 Special Edition'. London, England: My Green Pod, The Guardian.
Available at: https://www.mygreenpod.com/magazine/my-green-pod-magazine-sustainable-it-special-issue-november-2021/

Dahlmann, F., and Sutton-Parker, J. (2020), 'The Cost of Running IT is the Next Sustainability Challenge'. Page 105. Paris, France: The Council on Business and Society.
Available at: https://cobsinsights.org/2020/12/01/the-cost-of-running-it-the-next-sustainability-challenge/

Sutton-Parker, J. (2020), 'Time I.T. Changed: The Digital Transformation Edition'. London, England: My Green Pod, The Guardian.
Available at: https://www.mygreenpod.com/magazine/my-green-pod-magazine-september-2020/

HM Gov., (2022b), 'Greening government ICT: annual report 2021 to 2022'. London, England: Crown Copyright
Available at: https://www.gov.uk/government/publications/greening-government-ict-annual-report-2021-to-2022

Abstract

End user computing generates 1% (0.56 GtCO$_2$e) of global greenhouse gas emissions due to annual production of 460 million new devices and electricity consumed by 4.2bn active users. The United Nations suggests combining existing technology with human behavioural changes has the potential to reduce societal greenhouse gas emissions. In context, improving human-computer interaction to lower both manufacturing and use emissions has the potential to support this strategy. Such changes would align with Sustainable Development Goal 12, responsible consumption and production and ultimately goal 13, climate action. However, this research hypothesises that current information used to select and use computing devices based upon sustainability criteria is potentially inaccurate and limited, therefore creating a barrier to success. Generating eight published papers, the three field experiments, a survey and exploratory research prove the speculation to be correct. Three specific issues are identified. Firstly, exclusion of the influence of human-interaction upon computer power draw within current energy consumption benchmarks. Secondly, mixed methodologies used to present use-phase emissions in product carbon footprint reports. Thirdly, information presented to stakeholders to promote information technology abatement strategies lacks business and tangible context to appeal to role-based interests and needs. Three solutions are developed to overcome these barriers and are subsequently tested in five impact case studies. The findings determine that the creation of meaningful end user computing carbon footprint information is capable of positive impact upon human behavioural changes and greenhouse gas emissions abatement. Specifically, the case studies determine 9.3 million kgCO$_2$e of emissions to be avoided by adopting sustainable device selection and displacement (2.1 million kgCO$_2$e), computer re-purposing (1.4 million kgCO$_2$e) and remote working enabled by information technology (5.8 million kgCO$_2$e). This indicates that if adopted at scale, the newly proposed approach to end user computing emissions quantification and presentation is capable of contributing to the United Nations' strategy and goals to utilise existing technology to support climate action.

1. Chapter 1: Introduction

It is evident that since the Industrial Revolution, anthropogenic interference has already caused 1.0°C of global warming (IPCC, 2018a). A further increase to 1.5°C will be reached between 2030 and 2052 if increases in greenhouse gas (GHG) emissions continue at the current rate (IPCC, 2018a). However, scientists calculate that by reaching and sustaining net zero global anthropogenic CO_2 emissions by mid-century, global warming will halt on a multi-decadal scale and temperature gains will begin to peak (IPCC, 2018a). To achieve this goal, it is calculated that the world cannot rely solely on key GHG abatement strategies, such as vehicle electrification and renewable energy transition (DfT, 2019a; b; IEA, 2019; UNEP, 2019). This is because evidence indicates that the rapidity of adoption and associated abatement will not be sufficient to bridge the projected $32GtCO_2e$ annual emissions gap forecast for 2030 (UNEP, 2019). As an alternative, scientists and governments agree that all aspects of human pollutant activity must be examined and low carbon alternatives researched and diffused during the next decade to compensate for this limitation (IPCC, 2018a). Specifically, the United Nations (UN) Environmental Programme (UNEP) suggests that to bridge the gap, the world must combine existing technology with innovation to drive behavioural changes capable of reducing societal emissions (UNEP, 2019). Considering the criterion, this research proposes end user computing as a candidate technology for participation in this alternate strategy. Doing so specifically aligns with UN Sustainable Development Goal (SDG) number 12 (UN, 2015), responsible consumption and production, and ultimately SDG 13, climate action.

1.1. End user computing carbon footprint

As a mature technology, end user computing generates in excess 1% of global GHG annual emissions (Andraea and Edler, 2015; Bekaroo et al., 2014; Belkhir and Elmeligi, 2017; GeSI, 2008, 2012, 2015, 2019; Malmodin et al., 2013; Malmodin and Lunden, 2018) contributing significantly to environmental pollution, global warming and ultimately climate change. The emissions are caused by the yearly manufacturing of 460 million devices (Gartner, 2021; Statistica, 2020; 2021) and associated electricity consumed by 4.2bn active users (Datareportal, 2021; IEA, 2021a) during what is termed the 'use-phase' of a computer's life cycle. In context, end user computing emissions are equal to annual pre pandemic aviation emissions (IEA, 2021b). As such, it is therefore reasonable to suggest that changes to associated human behaviour, such as environmentally aware device selection (Energy Star, 2012) and longer device retention periods (Bakker et al., 2014; Deng et al., 2011; Prakash et al., 2016; Sahni et al., 2010; Schischke et al., 2003) could deliver meaningful GHG abatement (Energy Star, 2012) as raw materials are safeguarded and electricity consumption reduced.

For this to occur, it is reasonable to suggest that those responsible for information technology (IT) strategic planning and computer selection and procurement must be presented with valid and comparable product carbon footprint data. Currently, such data is included within reports published by computer manufacturers highlighting the four stages of the product life cycle including production, transport, use-phase and end of life processing emissions (Apple, 2022; Dell, 2022; HP, 2022; Lenovo, 2022; Microsoft, 2022). To determine the carbon footprint of end user computer products a standardised process is followed that evolved from historic global abatement strategies. Further to the creation of the United Nations Framework Convention on Climate Change (UNFCCC, 1994) treaty to address human interference within the climate system, the subsequent Kyoto Protocol (1997) required participating countries to commit to targets and actions to reduce long term GHG emissions. In order to classify emissions uniformly and achieve parity between emissions results, an international GHG accounting protocol (WBCSD and WRI, 2004) was created. To enable identification of which human activities cause

the greatest emissions impact, each source is categorised into three scopes. Scope 1 relates to direct emissions generated by on-site combustion of fossil fuels such as natural gas, refrigerants and fuel emissions from company owned vehicles. Scope 2 includes indirect emissions focusing on the impact of electricity and steam purchased for consumption. While Scope 3 includes the overall supply chain and therefore has a wide variety of sources. These include purchased goods, transportation and distribution of goods, end of life processes and employee commuting (WBCSD and WRI, 2013). Consequently, when determining GHG emissions for end user computers, scopes 2 and 3 are included within reports to represent electricity consumption when in use and the supply chain associated with the purchased goods, product distribution and end of life processing of electronic equipment. As such, scope 1 emissions are not included in end user computing GHG emissions impact determination.

To uniformly quantify GHG emissions a unit called the carbon dioxide equivalent (CO_2e) was created (WBCSD and WRI, 2004) to represent all of the gases in a single standardised kilogram measurement ($kgCO_2e$). The unit includes the predominant contributor to global warming (IPCC, 2023) carbon dioxide (CO_2) (76%), plus methane (CH_4) (16%), nitrous oxide (N_2O) (6%) and fluorinated gases (HFC, PFC, SF_6) (2%) and is formulated based upon the global warming potential of each gas.

To calculate scope 2 and 3 GHG emissions $kgCO_2e$ values for end user computers, participating manufacturers follow an agreed international standard framework (ISO, 2018a). For scope 2 emissions calculation, an annual estimated typical energy consumption (eTEC) value measured in kilo-watt hours per year (kWh/y) is required to represent electricity purchased for use. The source of this electricity consumption value is generated by Energy Star energy efficiency computer benchmark testing results (Energy Star, 2020). The benchmark is undertaken for the majority of new computers to ensure that each model released to the market complies with energy efficient electronic equipment design legislation (EU, 2009; CAER, 2021). First created in 1992 (Johnson and Zoi, 1992), Energy Star certified laboratories continue to test devices by connecting computers to a watt meter to measure the standard unit of electricity power draw in watts (W) when in low power modes such as off, sleep and idle. The results are then multiplied by uniform assumptions as to how long (hours) a computer will spend in each mode during one-year (Energy Star, 2020) to create the published eTEC value. This annual consumption value is then multiplied by location specific electricity to GHG emissions conversion factors to produce the scope 2 $kgCO_2e$ value. The conversion factors are produced by nations participating in the Kyoto Protocol (1997) as part of the original agreement. Each value represents the amount of carbon in grams per kilo-watt hour (kWh) present in each nation's electricity supply for any given year. As carbon intensity will differ between nations due to differing percentages of low carbon energy sources adopted locally within each electricity grid, then manufacturers select a carbon conversion factor for the country or region the products will predominantly be sold (Apple, 2022; Dell, 2022; HP, 2022; Lenovo, 2022; Microsoft, 2022). To complete the scope 2 quantification for the total lifespan of a computer, manufacturers then multiply the resulting annual $kgCO_2e$ value by a particular number of years that they believe the device will remain in use.

For end user computing scope 3 $kgCO_2e$ emissions manufacturers rely on lifecycle assessment (LCA) software such as the product attribute to impact algorithm or PAIA (MIT, 2016), Ganzheitliche Bilanz (holistic balance) known as GaBi (Sphera, 2022) and SimaPro (2022). Each is an application that pairs process and flow activities for each stage of the supply chain with $kgCO_2e$ values retrieved from common life cycle inventory (LCI) databases, such as Ecoinvent (2022). As such, production, transport and end of life emissions for each new computer can be calculated based upon how manufacturing is undertaken, what materials are included, where the product is manufactured and destined for use and what is required to dispose of the product.

1.2. End user computing environmental control policies

Because of the recognised 1% contribution of end user computing devices to global GHG emissions (Andraea and Edler, 2015; Bekaroo et al., 2014; Belkhir and Elmeligi, 2017; GeSI, 2008, 2012, 2015, 2019; Malmodin et al., 2013; Malmodin and Lunden, 2018), environmental impact control measures exist at both a manufacturer and end user level. The concept is to ensure that while computer product carbon footprint calculation is achievable, manufacturers are encouraged to reduce the amount of GHG emissions attributed to each new device and end user organisations encouraged to purchase devices that comply with environmental certifications.

For manufacturers, the control measures influence each stage of design and production with some requirements being mandatory due to local and regional legislation and others relying on voluntary participation. To restrict the use of hazardous substances (RoHS) in computer component materials, initiatives exist in several countries and regions (RoHS WW, 2022). In Europe and major computer manufacturing countries such as China, RoHS directives are enforceable by law (China ROHS, 2006; EU, 2002a and 2006b). However, while several American states have laws similar to RoHS (COEHHA, 1987; DTSC, 2004) the United States (US) has no national and enforceable equivalent. Product design is controlled by legislation ensuring that if a brand wishes to sell products within a specific market, all computers must adhere to eco-design, packaging and waste principles plus energy efficiency legislation (EU, 1994, 2002a and b, 2005a and b, 2006b, 2009 and 2012; CAER, 2021; COEHHA, 1987; DTSC, 2004; UNEP, 1987). Similarly, manufacturing plants are subject to international standards to ensure that operations conducted to produce computers meet environmental quality requirements (ISO, 2015a and b). However, similar to the RoHS initiatives outside of Europe and China, such standards are not mandatory.

To encourage manufacturers to participate in voluntary control measures two strategies exist that both influence consumer selection. The first is in the form of environmental labels and declarations often called eco-labels or third-party certification. As previously noted, energy efficiency is benchmarked by Energy Star (2020) with power draw and eTEC results from participating manufacturers publicly available via a dedicated product comparison website (Energy Star, 2022). From a material content and manufacturing perspective, third-party eco-labels, such as the Electronic Product Environmental Assessment Tool (EPEAT, 2022) and TCO Certified (2022) award certification levels determined by a computer's estimated impact upon the environment. In this example, carbon footprint values are not examined nor included in the scoring mechanisms used to attain eco-label certification. Instead the assessment focuses on areas such as compliance with RoHS and battery directives (EU, 2006b), what percentage of post-consumer recycled plastic is used during production, modularity to enable ease of repair, energy efficiency (Energy Star, 2020) and high recyclability upon disposal. While results for both eco-labels are publicly available online, the same information appears together with the relevant Energy Star data compiled within an Eco-Declaration form (ECMA, 1996). Again while not including any carbon footprint data, the production of this international voluntary form enables a single source to declare conformity to recognised eco-label and energy efficiency criteria.

The second strategy focuses on encouraging organisations responsible for selecting and purchasing end user computers at scale to seek out models that comply with environmental control measures. Doing so increases demand for computers that have met the standards and in turn adds pressure on manufacturers to participate beyond mandatory directives and legislation. As an example, public sector end user computer procurement legislation and frameworks have been created recently in Europe (EC, 2021a; b; EU, 2022a), the United Kingdom (UK) (DEFRA, 2011; 2017; 2020; HM. Gov., 2018b; d; 2021; LUPC, 2021) and the United States (US) (OEERE, 2022; USEPA, 2015; 2020a; b; US Gov., 1993; 2021)

to drive selection of environmentally compliant computers. In the US, the Federal Acquisition Regulation Part 23.7 (US Gov., 2021) mandates that all computers purchased by federal agencies must bear the EPEAT (2022) and Energy Star (2020) labels. Similarly, in Europe the UK's greening information and communication technology (ICT) policy (DEFRA, 2020) and the European green public procurement criteria for computers directive (EC, 2021a; b) require public sector organisations to procure end user computers that comply with the eco-label and energy efficiency standards. Considering governments represent some of the largest computer purchasers in the world due to the volume of employees (BEIS, 2022a; Eurostat, 2022; OPM, 2022) manufacturers excluded from such procurement frameworks due to nonparticipation in voluntary sustainability certification will most likely suffer a significant loss of market share (Robalino and Lempert, 1999). It is however noted, that to date the sustainable information technology legislation such as this is restricted to the public sector and excludes commercial sector organisations and private consumers.

1.3. Sustainability as a selection criteria issue

Examining the current procurement legislations within the public sector, a lack of specificity potentially causes the legislation to become less effective from a GHG emissions abatement perspective. To achieve procurement compliance, buying organisations can simply ensure that new computer equipment meets the defined sustainability criteria by selecting from lists of qualifying equipment. These are accessible via government online catalogues such as the Federal Energy Management Program (OEERE, 2021), the EU Ecolabel Product Catalogue (EU, 2022a) and the National Desktop and Notebook Agreement (LUPC, 2021). However, as a label such as Energy Star and EPEAT is indicative of compliance but does not define a product's carbon footprint, it is feasible that organisations are buying computers deemed to be within an acceptable environmental impact range rather than seeking out products that will deliver incremental and meaningful emissions abatement. As an example, Microsoft's Surface Laptop 3 has a published total carbon footprint of 138 $kgCO_2e$ (Microsoft, 2022) compared to 809 $kgCO_2e$ attributed to a Lenovo ThinkPad P51 (2022). While the similarly functioning notebooks meet current sustainability buying criteria, the latter is theoretically six times more harmful to the environment due to the increased carbon footprint. Such examples suggest that better informed choices based upon access to specific carbon footprint data to accompany certification labels, may contribute to GHG emissions abatement. The concept is simple in the fact that organisations can select appropriate devices with the lowest total $kgCO_2e$ value knowing that they have also been ethically produced.

To confidently adopt this extra level of inspection information presented by manufacturers in published computer product carbon footprint reports must be accurate and comparable to facilitate the activity. As previously described, the current process for classification and quantification of values presented in computer carbon footprint reports suggests that accuracy and parity already exists having followed GHG accounting protocols (WBCSD and WRI, 2004) and reporting standards (ISO, 2016; 2018a; b). However, this research argues that this is not the case and hypothesises that currently both accuracy and meaningful comparison are significantly compromised due to the following reasons.

Firstly, scope 2 emissions values included in product carbon footprint reports are currently derived from the Energy Star benchmark eTEC value. As described, the test set up and conduct (Energy Star, 2020) measures only the low power modes (off, sleep and idle) and therefore excludes measurement of active-state power draw when human-computer interaction is experienced. Existing research finds that computers of the same type will experience increased and varied power draw requirements when in the active-state depending on variables such as operating systems and applications (Dandridge, 1989; Johnson and Zoi, 1992; Kawamoto et al., 2001; Koomey et al., 1995;1996; Lovins and Heede, 1990;

Newsham et al., 1992; Nguyen et al., 1988; Norford et al., 1988; 1990; Piette et al., 1985; 1991; 1995; Roth et al., 2002; Rotourier et al., 1994; Smith et al., 1994; Szydlowski and Clivala, 1994; Yu, et al., 1986). As such, it is reasonable to suggest that current computer scope 2 GHG emissions calculation methodology does not reflect real world use. The omission of the influence of the active-state in scope 2 calculations is questionable from a compliance perspective too. Specifically, the GHG emissions accounting requires values to be reported as *'neither under nor over actual emissions'* (WBCSD and WRI, 2004). Using the current practice, the likelihood of under reporting is high. In the example of a notebook, Energy Star applies mode weightings determining that during the use-phase a computer will spend 15% of each year of use switched off, 45% in sleep mode and the remaining 40% in idle mode (Energy Star, 2020). As such, it is suggested that no time during each year of ownership will the computer experience human-computer interaction when the power draw will be at its highest. From an accuracy perspective for anticipated concomitant scope 2 emissions, this approach is counterintuitive as computers are purchased for use.

Setting aside the exclusion of the active state within the eTEC calculation, a second issue relating to the validity and therefore comparability of scope 2 emissions data exists. As noted, the current international standards for lifecycle assessment and calculation of product carbon footprint data (ISO, 2016; 2018a; b) require the use-phase emissions to be included although no specified duration beyond one-year is determined. Consequently, current end user computing product carbon footprint reports include a varied number of years of use depending upon the brand (Apple, 2022; Dell, 2022; HP, 2022; Lenovo, 2022; Microsoft, 2022). The impact of this lack of consistency in approach causes total carbon footprint values between brands to become incomparable. As an example, one brand may include only three years of use (Microsoft, 2022) and comparatively another (Lenovo, 2022) may include five years. In doing so the latter brand has added 66% more use-phase emissions causing any total carbon footprint values to increase accordingly. Without prior knowledge of this, buyers may be misled by choosing devices that in fact have a higher carbon footprint if the scope 2 data is harmonised to, as an example 5 years in all cases.

The lack of parity is arguably driven by the retention habits of users and therefore no manufacturer's choice of the amount of years is effectively wrong. As an explanation, existing research concurs that the initial 'first use' retention period of an end user computing device is between three and five years (Hart, 2016; Prakash et al., 2016; Thiébaud et al., 2017; Teehan and Kandliker, 2012; Williams and Hatanaka, 2005). This is predominantly influenced by factors such as company asset management and depreciation accounting plus refreshes forced by a necessity to keep pace with new applications (Boyd, 2012). Where a 'second use' exists, if the device is sold or repurposed rather than disposed of, then this additional retention period is between two and three years (Prakash et al., 2016; Thiébaud et al., 2017). Consequently, it is reasonable to conclude that the lifetime input for the use profile ranges from three years to eight years before disposal. However, research suggests that the diminishing energy efficiency performance of the existing device undermines the sustainability case for extending the lifecycle beyond five years (Bakker et al., 2014; Boyd, 2012; Cooper and Gutowski, 2017; Deng et al., 2011; Prakash et al., 2016; Schiscke et al., 2003; Vadenbo et al., 2017; Wolf et al., 2010). This is based upon advances in energy efficiency innovation during the lifespan of the current device being sufficiently significant to warrant the purchase of the new low energy computer. As such, to achieve an indication of the use-phase value and percentage impact upon the entire lifecycle assessment, manufacturers predominantly select lifetime values of five or less years.

A third issue is similarly related to the scope 2 value and causes the lack of parity to expand. As previously discussed, manufacturers select electricity to GHG emissions conversion factors based upon

the region that devices will be predominantly marketed. As such, a product carbon footprint report created for publication in the US will present far higher scope 2 carbon emissions than that of one created for a European market. This is because the carbon intensity for the latter is far lower due to increased levels of low carbon energy adoption in Europe compared to the US (Carbonfootprint, 2020). Consequently, even if two brands do include the same number of years of use in reports it is highly likely that the difference in conversion factor will cause the data to again become incomparable.

The three issues are certainly recognised within the small print included within the product carbon footprint reports of manufacturers. In fact, all manufacturers include disclaimers that the presented data can be considered as highly inaccurate in relation to the use-phase emissions (Apple, 2022; Dell, 2022; HP, 2022; Lenovo, 2021; Microsoft, 2022). The inaccuracy certainly creates confusion that causes environmental purchasing intention to become misguided or even prevented by a lack of comprehension and comparison (Kumar et al., 2017). As such, unless a solution to inaccuracy and a lack of parity is developed organisations will arguably be left with little choice other than to revert back to relying on third-party certification. However, beyond the example of potential missed opportunities to identify low carbon footprint devices, specific details in new sustainable computer procurement legislation may evolve further to force the issue.

Specifically, the words 'hard targets' (DEFRA, 2020) are now included within the UK procurement legislation. This determines that all future information technology purchases must be accompanied by scientific data and targets capable of supporting GHG abatement and net zero initiatives. However, it seems reasonable to determine that reliance on current third-party labels does not offer such a detailed response. Equally, faced with the potential lack of accuracy and parity contained in current product carbon footprint reports, existing end user computing GHG emissions data also does not meet the emerging criteria. Consequently, for the UNEP abatement bridging strategy (UNEP, 2018) to be applied successfully to end user computing, it is hypothesised that organisations buying and using devices require information that achieves three currently unachievable key criteria: firstly scope 2 values that reflect the active state and therefore credibly reflect potential use-phase emissions created in the workplace; secondly parity between brands to assure that carbon footprint comparison is being undertaken on a like for like basis to achieve maximum abatement; thirdly, contextual data that enables results representation based upon the organisation's IT strategy such as retention periods and location of use. Therefore, the data used to select and use end user computing devices is made relevant to the specific organisation, rather than dictated by manufacturer selected parameters. Achieving all three would remove existing complexity, incomparability and validity doubts. Most importantly, doing so may lead to the creation of meaningful data capable of enabling changes in procurement and retention behaviours. Doing so will drive abatement of the 1% contribution of end user computing to global GHG emissions and realise both UNSDG 12 and 13.

1.4. What is the barrier preventing immediate action?

The answer to harmonisation of product carbon footprint data presentation arguably lies in a yet to be developed dynamic version of existing static publications. Creating an application that allows for IT and procurement teams to determine the influence of device retention and location of use factors would generate parity by equalising inputs such as time and conversion factors. Currently no literature or research exists to imply this has been attempted. However, to achieve this advance, use-phase data included in such a practice must include the impact of the active state in a meaningful way. The lack of active state power draw measurement during the benchmark process represents the greatest barrier to immediate action. Referring back to the original body of research that led to the Energy Star

benchmarking process (Dandridge, 1989; Johnson and Zoi, 1992; Koomey et al., 1995 and 1996; Lovins and Heede, 1990; Newsham et al., 1992; Nguyen et al., 1988; Norford et al., 1988; 1990; Piette et al., 1985; 1991; 1995; Rotourier et al., 1994; Smith et al., 1994; Szydlowski and Clivala, 1994; Yu, et al., 1986), it is reasonable to suggest that the mechanical watt metre technique developed in the 1980s and 90s and used to measure thousands of desktop computers could be employed again today to overcome the exclusion. The practice is highly accurate and generates kWh values representative of all influences upon the use profile, including the active state. However, the watt metre technique requires the computer subject to measurement, to remain static and connected to a constant power source. As 86% of end user computing devices are now mobile (Gartner, 2021; Statistica, 2020; 2021), this is no longer practical and the technique is recognised as being limited to small numbers of academic research projects and causing a research field to be starved of data (Karpagam and Yung, 2017). The concept of end user computing mobility as a barrier is supported by Greenblatt et al. (2013) who conclude that organisations and researchers wishing to assess end user computing device environmental impact in the field avoid the practice almost entirely due to scale and mobility factors that drive cost, logistics and time issues. The prevailing issue is also reflected in contemporary research papers attempting to quantify global end user computing GHG emissions (Belkhir and Emeligi, 2018). Without sufficient recent and substantiated use-phase data, the researchers rely instead upon data produced often over twenty years previously.

Recognising the issue of continued reliance upon obsolete computer electricity consumption data, Kansel (2010) and Bekaroo et al., (2014) attempted to overcome scale and mobility by using software based measuring tools. The idea was to replace the watt metre with network distributed and node based software capable of reporting computing electricity consumption via the internet as devices moved location. However, in both cases the Microsoft software (Kansel, 2010) and HP's Power Assistant (Bekaroo et al, 2014) experienced imitations. This included achieving 59% accuracy and the HP software being compatible with only HP computers (Bekaroo et al, 2014). As such, alternative approaches remain theoretical and without further research, the barrier preventing immediate action remains.

1.5. Research objectives and scope

The initial objective of this research is to focus upon delivering three practical advances that overcome the speculative barriers and therefore generate meaningful end user computing data. This includes developing a new methodology to improve the accuracy of scope 2 GHG emissions calculation; creating a practice capable of delivering parity to scope 2 data represented within product carbon footprint reports; creating a framework capable of adding context to both scope 2 and scope 3 end user computing GHG electricity consumption and emissions data to improve resonance with stakeholders. Achieving all three objectives will ensure that those responsible for end user computing selection, procurement, use-phase emissions reporting and sustainable information technology strategy forming will experience confidence that the data presented is relevant to their specific activities.

The subsequent objective is to the test the new practical advances in five case studies to determine the positive impact achieved by delivering meaningful information. This includes changes to current end user computing related behaviour caused by the new approaches and the consequential abatement of associated GHG emissions.

The decision to focus on scope 2 GHG emissions initially is because the issues of active state exclusion and limited parity affecting use-phase emissions appear, while not conclusive, to be evident even before more thorough examination. This suggests this specific subject is worthy of research and key to the success of achieving all of the objectives.

Consequently, taking into consideration the UNEP bridging strategy (2019) to leverage existing technologies and subsequently reduce societal emissions, the overarching aim of this thesis is to answer the primary research question:

- Can *meaningful* end user computing carbon footprint information drive human behavioural changes to abate greenhouse gas emissions?

The word meaningful is intentional. It relates to the surety that may be delivered by achieving the objective of enabling validity and parity to be introduced to product carbon footprint data through improved accuracy, harmonisation and context to the scope 2 emissions contribution. As noted, such surety may then cause information technology and procurement teams to respond to the emerging hard targets (DEFRA, 2020) and begin to confidently adopt the suggested end user computing sustainability strategies or behaviours that reduce GHG emissions. To achieve this, the research must complete six distinct stages.

The first is substantiation that excluding the active state from calculations has a meaningful impact upon typical energy consumption and concomitant GHG emissions calculation. This is essential as without first validating the hypothesis, the research arguably has no grounds upon which to progress.

Secondly, current theories and research suggesting new device procurement is preferable to continuing with existing devices due to on-going energy consumption innovation must be challenged to displace supply chain emissions (Bakker et al., 2014; Boyd, 2012; Cooper and Gutowski, 2017; Deng et al., 2011; Prakash et al., 2016; Schiscke et al., 2003; Vadenbo et al., 2017; Wolf et al., 2010). Should an application that harmonises carbon footprint data be achieved, the inclusion of retention periods beyond five-years must be substantiated as a valid and beneficial proposition.

Thirdly, if proven to cause substantial error to scope 2 calculations, alternate yet scalable methods of capturing the influence of the active state on power draw must be tested and developed. By doing so use-phase emissions values reflective of real-world use case scenarios can be achieved. Fourthly, the issue of limited parity among existing computer product carbon footprint reports must be explored and substantiated to validate the necessity to change current methods of presentation.

Fifthly, determination of current awareness and opinion relating to sustainable information policies and the perceived environmental impact must be undertaken to ensure any solutions produced to overcome the issues appeal to all stakeholders by meeting substantiated role based needs and interests.

Finally, having developed solutions to the findings, the methods and tools produced must be tested in the field. This is to substantiate that the research is capable of delivering potential positive environmental impact and is therefore representative of advancement in the field of computer and urban science.

With this in mind, the research scope is defined by being able to reach a point when the primary research question can be tested with credibility. As such, seven secondary research questions are designed to sequentially build evidence and achieve the final objective of testing the speculative hypothesis. These are:

- RQ1 'Does the current end user computing use-phase energy consumption methodology accurately reflect device electricity use when subjected to human-interaction?'
- RQ2 'Can the influence of computer specifications upon electricity consumption contribute to forming universal active state power draw increments?'
- RQ3 'To what extent is greenhouse gas abatement delivered by alternative computer operating system displacement strategies?'

- RQ4 'Can analytics software accurately measure end user computing electricity consumption?'
- RQ5 'Is sufficient carbon footprint information available to make sustainability focused computer procurement strategies meaningful?'
- RQ6 'To what extent is sustainable IT resisted and what barriers to diffusion are key to success?'
- RQ7 'Can data be generated, structured and dynamically presented in order to create meaningful product carbon footprint data?'

By answering these research questions, four specific contributions to the research field are achieved. Firstly, the barrier related to the inclusion of the active state within current typical energy consumption values will be removed. As indicated in the literature review, this barrier has existed since 1992 and has yet to be overcome. Achieving a solution to this issue will cause concomitant scope 2 calculations to reflect anticipated real-world use and become closer to meeting GHG accounting protocol standards that require emissions values to be reported as *'neither over nor under those actually produced'* (WBCSD and WRI, 2004).

Secondly, existing research indicating that displacement does not deliver sufficient GHG emissions abatement to warrant adoption will be contested. By challenging this school of thought and proving otherwise, empirical findings will be produced to substantiate the positive environmental impact of extended device useful lifespans. In turn, if adopted at scale, product demand and scope 3 supply chain GHG emissions may be reduced.

Thirdly, parity will be delivered to scope 2 product carbon footprint data currently causing use-phase GHG emissions to be disproportionately represented within published reports. Overcoming this issue will subsequently simplify the process of device assessment, comparison and selection. Doing so will ensure that procurement of new end user computing devices will be conducted in compliance with new legislations that require valid science-based data to support sustainable hardware choices.

Ultimately, achieving the objectives related to all three of these technical issues will enable the fourth contribution. This is to generate proof via the case studies that end user computing is a substantiated and viable contributor to meaningful global GHG emissions abatement.

From a geographical scope perspective, while the research is conducted in the UK, the organisations identified in the input stage to support the research and the impact case studies operate internationally. Consequently, the research includes and considers geographic variables to cater for locations globally. These include differing policies and legislation plus electricity to GHG emissions conversion factors relevant to each country or region included in each stage of the research. As such, the scope of the research is considered to be applicable globally and not restricted by the original research location.

1.6. Thesis structure

Further to the initial introduction, literature review and methodology, the subsequent sections of the thesis are structured by stages defined by the impact value chain framework (Clark et al., 2004). The reason for this is explained in full within the methodology (page 29) and outlined in figure 1 (page 29). Further to documenting these five stages (figure 1, page 29), the conclusions section pragmatically reviews the effectiveness of the processes undertaken and examines if the gaps discovered by the literature review are answered. Considering this perspective and the 4-year horizon of the research period, recommendations and limitations are suggested and determined to enable future research relating to this topic.

2. Chapter 2: Literature Review

2.1. End user computing use-phase emissions

Although consensus was reached in the mid nineteen eighties (Piette et al., 1985; Roach, 1985; Schultz 1984) that the then new phenomenon of end user computing electricity loads was impacting office building utility design, the earliest identification of concomitant GHG emissions contributing to climate change emerged five years later. Specifically, Norford et al. (1990) linked the estimated 40 billion kWh of annual US computer energy consumption to the production of 30 million tCO_2 GHG emissions. The significant source of pollution was determined by Michaels et al., (1990) to be caused by personal computing installations having doubled in the previous four years, from one computer per 12.5 employees to one per 7.2 employees. DeLaHunt (1990) concurs, quantifying one hundred percent adoption in large offices (>30,000 sq/ft), with end user computing exceeding cooking and task lighting power requirements by between five and over one hundred times intensity per square foot.

The environmental impact has accelerated during three and half subsequent decades due to twenty-four million commercial desktop computers determined by Koomey et al. in 1995, growing to an estimated 4.2bn active users today (Datareportal, 2021; IEA, 2021a). Consequently, contemporary research estimates the current end user computing carbon footprint as responsible for in excess 1% of global GHG annual emissions (Andraea and Edler, 2015; Bekaroo et al., 2014; Belkhir and Elmeligi, 2017; GeSI, 2008; 2012; 2015; 2019; Malmodin et al., 2013). Examining each paper, it becomes quickly apparent that due to the scale of end user computing the methodology and results are unsurprisingly based upon extrapolation. However, what is arguably surprising is the potential lack of validity associated with the use-phase data relied upon to generate the scope 2 emissions value in each case.

Created as an initiative to examine the impact of information technology upon the environment by UNEP, the Global e-Sustainability Initiative (GeSI) published a research paper that can be considered the first of its kind to quantify the carbon footprint of end user computing at a global scale (GeSI, 2008). Specifically, personal computers such as desktops and notebooks are identified to be responsible for 148 million tCO_2e representing 1% of all GHG global emissions. Of this, 75% is attributed to the consumption of electricity during the use-phase. This places the findings at the extreme end of the proportionate contribution to the total product carbon footprint compared to related contemporary field research indicating the value to be between 3% to 75% as shown in table 1 (Choi et al, 2006; Duan et al., 2008; Hart, 2016; IVF, 2007; Hischier, et al., 2007; Kemna et al., 2005; Kim et al., 2001; Lu et al., 2005; PE International, 2008; Sahni, S. et al., 2010; Socolof et al., 2005; 2017; Tekawa et al., 1997; Teehan and Kandliker, 2012; Williams, 2004).

Of the findings, Adams (GeSI, 2008) notes that unlocking clean technology in information technology will be crucial to a low carbon future. The opinion is shared by Melville (2010) and Dedrick (2010) commenting that the subject is worthy of empirical analysis. The recommendation is made based upon observation that the data sources included within the global research are unclear; the researchers had not undertaken recent physical observation and relied instead upon legacy data. Such data was likely to have been produced by the pair although the most recent field measurements conducted by either party were in 1996 (Koomey et al., 1996) and 1998 (Nordman et al., 1998). This indicates the possibility of the data being, at best, a decade old and no longer relevant. The more likely outcome is that no physical measurements were taken. Instead assumptions made and together with computer secondary install base statistics, data is applied to the Kawamoto et al., (2001) and (Roth et al., 2002) data flow that accounts for unit quantities, device lifespan and the use profile and originally designed by both Koomey and Nordman (Kawamoto et al., 2001). This hypothesis is supported by confirmation that a stand-by value of 15W is assumed together with a 14 hours per day use-phase. The length of 'active' time applied could be considered excessive and ultimately responsible for the 75% use-phase finding. Specifically, the result is

contrary to contemporary lifecycle assessment field studies that indicated the use-phase to be lower than the manufacturing phase (Duan et al, 2009) reaching a maximum of 49% and operating times to be in the region of 4.3 hours use per day (Choi et al., 2006).

Table 1. The proportionate contribution of GHG emissions by scope to the total carbon footprint

Source (research paper)	Scope 2 GHG Emissions (electricity)	Scope 3 GHG Emissions (supply chain)
Belkhir and Emeligi, 2018	14%	86%
Choi et al, 2006	10%	90%
Duan et al, 2009	49%	51%
GeSI, 2008	75%	25%
GeSI, 2012	22%	78%
Hart, 2016	34%	66%
Hischier et al., 2007	3%	97%
IVF, 2007	20%	80%
Kemna et al., 2005	15%	85%
Kim et al., 2001	70%	30%
Malmodin et al., 2010	22%	78%
Sahni, S. et al., 2010	68%	32%
Teehan and Kandliker, 2012	62%	38%
Tekawa et al., 1997	20%	80%
Williams, 2004	20%	80%
Average	**34%**	**66%**

Note table 1. Scope 2 GHG emissions contribution is represented by the percentage of use-phase GHG emissions as part of the total product carbon footprint highlighted in each research paper. The scope 3 GHG emissions represent the supply chain emissions including production, transportation and end of life processes.

Malmodin et al.'s (2010) paper examining the carbon footprint of end user computing devices delivers a similar opinion, noting that the GeSI (2008) paper is *'based on rough, unspecified, obsolete data and on extrapolations'*. To avoid similar issues, Malmodin et al. (2010) focus upon on secondary yet empirical end user computing energy consumption data as a foundation. Without assumption-based power draw and use profile values, subsequent extrapolation to a global level will create defendable accuracy. Despite this focus on validity, the objective of generating accuracy with empirical research is arguably not achieved due to the reoccurring issue of data obsolescence. As an example, to calculate scope 2 emissions, the average combined desktop and notebook consumption used to generate this finding is 101.6 kWh per year, per device. This value is noted as derived from a series of related research papers that inspect computer consumption values in the workplace (Koomey et al., 1995; Roth and McKenney 2007; Sanchez et al., 1998). These papers also rely upon secondary data reaching back twenty years in some instances when the field measurements were initially undertaken (Acquaviva and Hartman 1993; Arthur D. Little Inc. 1993; Dandridge 1994; Froning 1994; Ledbetter and Smith 1993; Lovins and Heede 1990; Newsham and Tiller 1994; Norford et al., 1990).

Consequently, excluding the Energy Star benchmark results appropriately applied to the stand-by values (IVF, 2007), the most recent empirical research referenced was generated sixteen years prior to publication and suffers from concerns that using aged empirical data for assessments of end user computing emissions is unreliable due to the very obsolescence Malmodin et al. (2010) attempt to avoid (Intellect, 2016). The source of obsolescence is driven by factors such as innovation in the electronics industry that either decrease power requirements, as per Moore's Law (GeSI, 2008; McManus, 2002) or contrarily increase power requirements (Boyd, 2012; Deng et al., 2011) as computers assume more diverse tasks such as video streaming.

Surprisingly, GeSI's subsequent 2012 re-examination of the carbon footprint of end user computing relies upon Malmodin et al. (2010) for power inputs, arguably creating the same legacy data inaccuracy as introduced by Koomey and Nordman. Switching the source data reduces the use-phase contribution from 75% to 22% (GeSI, 2012). At first examination the new results suggest an admission of error in the first

paper as even Moore's law (GeSI, 2008; McManus, 2002) indicated innovation cannot deliver efficiency of this magnitude in such a short period. However, much of the reduction is attributed to a significant transition to mobile computing reflected in the findings. During this period, notebook adoption increases from 16% (GeSI, 2008) to 45% of market share (GeSI, 2012) and desktop computer use decreases from 84% to 55% accordingly. Being that notebooks are at this time measured as 75% more energy efficient than desktop computers (Urban et al., 2014; Van Heddeghem et al., 2014) then the significant reduction is perhaps credible.

In this revised version, the annual emissions value of end user computing however doubles to 297 million tCO_2e representing 0.75% of global emissions (GeSI, 2012). While not alluded to, this suggests that quantities of devices have grown exponentially, since if energy reduction has declined by 53% then the twofold impact must be caused by device manufacturing. Belkhir and Emeligi, (2018) question this accuracy suggesting that in fact end user computing emissions are less prevalent with only a 14% of the total product carbon footprint being derived from use-phase emissions. To substantiate this new value, the researchers concede that as indicated by Williams (2004) energy consumption of computing devices is prone to wide variations and rely upon a recent life cycle assessment for power data (Teehan and Kandliker, 2012). However, in doing so the paper suffers again from data obsolescence as Teehan and Kandliker (2012) also rely on secondary data. While every effort is made to ensure an extensive number of sources are considered, of the thirty data references used to generate electricity consumption calculations, twenty-seven do not conduct any form of device measurement. Instead, they follow the same path back to the 1990s data that the Malmodin et al. (2010) and later GeSI (2012) papers build upon.

As an example, Roth et al. (2002) derive power draw from computer nameplate ratings; a practice previously proven as highly inaccurate by Norford et al. (1988). To compensate, Roth assumes a 20-50% reduction based in accordance with previous research on the subject (Kunz, 1997; Hosni et al., 1999; Komor, 1997; Norford, 1988) confirming that the input is again an assumption. Of the three sources that do conduct field power measurements, one is Kawamoto et al (2001). This paper did initially record device data, albeit five years earlier (Koomey et al., 1995) meaning that the consumption data at the time of the 2018 paper was twenty-three years old and as such obsolete. Consequently, this reduces the independently measured papers to two, whereby Porter et al. (2006) measured only fifty domestic personal computers and Moorefield et al. (2008) measured only eighty-seven mixed device types for just two weeks. In context, both sources are between twelve and fourteen years old and Moorefield notes that the scale of the study is not extensive enough to be statistically valid and arguably should therefore be excluded from a global assessment.

Evidence that the four papers reviewed (Belkhir and Emeligi, 2018; GeSI, 2008; 2012; Malmodin, 2010) are lacking in validity is notable. While GHG impact research exists relating to sub-categories of information technology, such as telecommunications (Scharnhorst, 2008) and electronic media (Enroth, 2009; Gard and Keoleian, 2003; Moberg et al., 2010; Reichart and Hischier, 2003; Toffel and Horvath, 2004), very few recent papers examine end user computing device emissions at scale. The reason in all cases is that no recent field data is included within the calculations of the use-phase. Instead, obsolete secondary data that is not reflective of current human-computer interaction is employed creating a perspective some twenty years out of date.

However, this deconstruction is not conducted to undermine the activity, results and impact of the work to date as it is clear that effort has been made to examine and include all available data sources. Rather it is undertaken to highlight that such research is only as accurate as the use-phase data included. In relation to contemporary use-phase energy consumption data, it is clear that the field of industrial ecology and specifically, life cycle assessment are bereft of recent and extensive field measurement data. The opinion is supported by Karpagam and Yung (2017) noting that their work was made all the more difficult by what is described as a field that is *data starved* due to a complete lack of information.

Consequently, if the apparent data scarcity begins in the late 1990s as reflected in the four papers, then it is reasonable to suggest that before the problem can be addressed, the academic imperative is to review why this has happened.

2.2. End user computing use-phase data scarcity

Examining extant research reaching back to the mid-1980s when personal computers began to emerge as new productivity tools reveals an answer to the issue of current data scarcity. Specifically, a surge of field data accounting for the impact of human-computer interaction upon power draw occurs between 1984 and 1996 before declining ten years later. In the initial stage researchers were able to produce approximate use-phase energy consumption data due to a rudimentary technique that emerged to compensate for computers becoming a new and significant electricity use load in office buildings. Rooted originally in environmental engineering, researchers simply measured annual increases between total building consumption as more computers were adopted (Piette et al., 1985; Schultz, 1984; Roach, 1985; Yu et al., 1986).

Nguyen et al. (1988) subsequently refined the practice to include the survey of computer types to attribute power demand to specific models given that not all computers require the same amount of power to operate and therefore utility planning could be more specific if manufacturer power data was considered. However, two subsequent and linked papers (Harris et al., 1988; Norford et al., 1988) challenged these findings, hypothesising that the survey method could be inaccurate as the reliance on manufacturer name plate rating data was at the time neither validated by a third-party nor subject to standardised testing. To substantiate this, the research team used portable watt meters placed between desktop computers and the power source to measure actual electricity consumption of each personal computer in both W and kWh. Additionally, habitual use such as active and non-active times was monitored to contextualise the data, thus creating the concept of a 'use profile'. The combined results indicated that considerable variations in power draw and therefore electricity consumption existed between computers even of the same make and model. Examining the use profile data, it was clear that the disparity was caused by how many hours per day users were actively working at the computers and what types of software applications were being used. As such the concept of human-computer interaction affecting computer power draw was substantiated.

Having created an accurate methodology to quantify end user electricity consumption, the watt metering practice was quickly threatened by scale and innovation. On-going field experiments included only small numbers of computers which meant that in a world of exponential growth and innovation, any data produced would rapidly become obsolete (Newsham and Tiller, 1992). Prevailing European research concurs, noting that the proliferation of computers within offices was so rapid that the total end user computing power load in Europe for 1990 was estimated between 3-4GVA and expected to reach 13GVA in 1995 (Roturier et al., 1994). In context, such growth would require one or more 1,000 MVA power plants to be built each year to meet demand unless the most energy efficient computer models were identified and promoted (Roturier et al., 1993).

In response, there is a notable change in objective reflected by the on-going body of research as computer scientists transitioned from the original goal of accurate use-phase measurement, to one of proving computer electricity consumption efficiency as key to both energy supply security and environmental protection (Norford et al., 1990). As an example, Koomey et al., (1992) field research found that to achieve power draw reduction at scale, both computer efficiency design and user behaviour must be considered. This opinion was based upon field measurements determining that business computers remained switched on permanently, creating high levels of wasted energy. The justification for the practice by office managers was that the cost of electricity was perceived lower than the cost of lost productivity as the user waits for the device to resume.

Using secondary data sources from prior field experiments (Harris et al., 1988, Lovins and Heede, 1990), Johnson and Zoi (1992) concur, finding that computer on time during off-peak periods such as weekends, was 80%. Building upon the data, Newsham and Tiller (1992) calculated that such power mismanagement caused an average of 1,138 kWh/y additional consumption per computer. The findings added validity to both Koomey et al. (1992) and Norford et al. (1990) earlier indication that end user computing was a source of both GHG emissions generation and abatement opportunity.

The timing of the development in attitudes towards computer use is relevant. During the period of examining computer load and energy inefficiencies the first Intergovernmental Panel on Climate Change research findings (IPCC, 1990) were published defining the gravitas of electricity derived GHG emissions upon global warming. The findings were discussed during the 1992 United Nations Conference on Environment and Development designed to bind political leaders to a new blueprint for international action on the environment (UN, 1992). Consequently, the US government recognised the link between computer use and climate change (Norford et al., 1990) and included a policy to address the problem as part of the prevailing National Action Plan for Global Climate Change (Energy Star, 2012). The policy called for the formation of a national computer energy efficiency programme called Energy Star (Energy Star, 2012). Johnson and Zoi (1992) described the approach that awarded any end user computing device capable of achieving <30 W power draw in a low power state a distinctive third-party certification label, as a transition from 'command and control' to 'prevention'. The US Environmental Protection Agency (EPA) had now shifted the emphasis from environmental engineering planners onto device manufacturers to produce energy efficient computers.

However, manufacturers remained slow to respond as there was no legal requirement to do so as the Energy Star programme was voluntary. As an example, while over seventy manufacturers had joined the Energy Star programme for marketing exposure, very few energy efficient personal computer products had yet reached the commercial market (Szydlowski and Clvala, 1994). Recognising this, Roturier and Harris (1993) emphasised Johnson and Zoi's (1992) suggestion that if a major international government moved to procure only energy efficient computers then this would add pressure to manufacturers to improve efficiency by design or lose market share. Consequently, the US government updated policies to create a carrot and stick approach (Robalino and Lempert, 1999). Under executive order 12845 (USA Gov., 1993), all US government agencies were required by law to purchase only computers bearing the Energy Star logo. As a further caveat to support human-computer interaction impact findings (Koomey et al., 1992; Newsham and Tiller, 1992), the order also included a requirement that all newly purchased computer equipment must include a standby feature to reduce energy consumption. Considering the fact that the US government was at the time the world's largest buyer of computers, the emphasis to abate end user computing scope 2 GHG emissions at scale had begun (Szydlowski and Clivala, 1994).

The concept of successfully introducing the Energy Star <30W efficiency threshold and power management features caused researchers to examine further methodologies of predicting a computer's anticipated typical energy consumption (Rotourier et al., 1994). As such, use-phase field researchers in the US, Europe and Asia (Norford and Dandridge, 1993; Piette et al., 1995; Rebsdorf, 1993; Roturier et al., 1994; Roturier and Harris 1993; Smith et al., 1994) began to recommend that the Energy Star benchmark be advanced to enable such as concept. Specifically, strict pre-sales end user device energy measurement standardisation should be undertaken to further develop granularity of power draw when in low energy modes. The concept was supported by data emerging from on-going and extensive use-phase field research (Koomey et al., 1995; 1996; Lapujade and Parker, 1994; MACEBUR, 1998; Nordman et al., 1996; 1997; 1998). The data proved that automatic efficiency management systems were both reducing electricity consumption among measured device by between 26-85% annually and generating use patterns indicating the proportionate amount of time computers spent in a stand-by state.

The guiding premise of the proposed standardisation was that in all cases, test procedures should be designed to support associated national and international energy conservation legislations and standards

(US Gov., 1993; Rebsdorf, 1993). Additionally, conduct should reflect existing test practices for mature electronic equipment such as the American Society of Testing of Materials energy test (Norford and Dandridge, 1993). Arguably critical to the eventual publication of the Energy Star eTEC available today (Energy Star, 2022) researchers recommended that results must include clear identification of power draw (W) when in modes such as idle, stand-by and sleep (Roturier and Harris, 1993; Roturier et al., 1994). As such, ten years on from the initial identification of computers as a new and significant power use load (Piette et al., 1985; Roach, 1985; Schultz 1984; Yu et al., 1986), momentum for change had been achieved from both a policy and scientific perspective. Through a combined driver of the US (USA Gov., 1993) and European governments (Rebsdorf, 1993) now restricting purchases to Energy Star certified devices and the global connection between computer use and GHG emissions generation and climate change (Energy Star, 2012; Koomey et al., 1995; Norford et al., 1990) the opportunity to create a mandatory and contextual energy consumption benchmark certification arose.

However, specification of the metrics for the proposed stringent benchmark process required final clarification beyond the current single low power mode energy efficiency threshold. At this juncture, it is reasonable to note the four components required to achieve this objective had already been researched and substantiated. Firstly, Norford et al. (1988) had proven that physical device metering was the most accurate method of measuring computer energy consumption and therefore a suitable test conduct methodology could be formed. Secondly, their work, together with Piette et al. (1991; 1995) created an asset profile and categorisation approach that would enable the organisation of different computer types, such as desktops and notebooks, into categories making data easy to structure. Thirdly, appropriate operational modes such as on, stand-by and off had been identified and proven as essential to efficient computer management (Koomey et al., 1995; 1996; Lapujade and Parker, 1994; MACEBUR, 1998; Nordman et al., 1996; 1997; 1998). Fourthly, inclusion of use profile inputs such as time spent in each mode had been substantiated as necessary if a typical electricity consumption value was to be calculated (Koomey et al., 1992; 1995; 1996; Lapujade and Parker, 1994; MACEBUR, 1998; Newsham and Tiller 1992; Nordman et al., 1996; 1997; 1998; Norford et al., 1988).

In 2001, the framework that employed all of these components to create what was called a unit energy consumption value was produced by a project designed to estimate total electricity being consumed by information technology in the US (Kawamoto et al., 2001). Undertaken by a team including Koomey and Nordman, the data flow specifically included the inputs of quantity and computer type to generate asset profile data and model specific power values plus time spent in differing modes to generate use profile data. Less than one year later, Roth et al. (2002), quantified what was alternatively called the annual electricity consumption of over thirty types of office equipment. Conducted to advance computer efficiency standards programs in the US and specifically Energy Star, the refined approach crucially expanded the low energy states used by Kawamoto et al. (2001) from low and off to standby, sleep and off.

Consequently, the new and revised version of the Energy Star Certification (Energy Star, 2007) process was born. While the requirements retained the original minimum power threshold, several more rigorous criteria were added (Energy Star, 2007) to create a definitive energy efficiency benchmark and ultimately the objective of a typical energy consumption value. The programme now required one unit of all newly manufactured computer models to undergo asset profile classification, energy consumption measurement and applied use profile quantification before releasing the product to international markets. To enable this at scale, Energy Star Certification Bodies and Laboratories were accredited across the globe to service the participating and now condensed (through merger and acquisition) fifty-seven end user computing device manufacturers (Energy Star, 2022).

The previously recommended standardisation (Norford and Dandridge, 1993; Piette et al., 1995; Rebsdorf 1993; Roturier et al., 1994; Roturier and Harris, 1993; Smith et al., 1994) was achieved by a strict and consistent test set up and conduct procedure (Energy Star, 2007) conducted in accordance with

International Electrotechnical Commission (IEC) Standards of IEC 62301 (IEC, 2011) and IEC 62623 (IEC, 2012). Asset profile was defined by computer type (e.g. notebook or desktop computer), brand, model name, model number, processor type, central processing unit (CPU) speed, CPU cores and memory. Power requirement (W) was defined by measuring the equipment under test (EUT) with a watt meter with a proven +/-2% accuracy in four no-user present modes including off, sleep and idle (a process since expanded to short and long idle) (Energy Star, 2020).

Use profile was defined by applying assumed times the computer is anticipated to spend in the measured modes throughout one year. As previously noted, today it is assumed by the benchmark framework that a notebook will spend 15% each year in 'off' mode, 45% in sleep, 10% in long idle, and 30% in short idle. To translate this into meaningful information similar to Kawamoto et al. (2001) and Roth et al. (2002) unit energy consumption, the power and mode weightings are used to create the eTEC value. This is achieved with the equation:

$$eTEC = 8760 / 1000 \times (POFF \times TOFF + PSLEEP \times TSLEEP + PLONG\_IDLE \times TLONG\_IDLE + PSHORT\_IDLE \times TSHORT\_IDLE)$$

Source: Energy Star (2020)

The value '8760' represents hours in a year and this is divided by 1000 to create a kWh value. The output is then multiplied by the results for the measured P (power) by an assumed T (time) % spent in each mode. As a result, interested parties can access an entirely consistent eTEC (kWh/y) value for any given end user computing device before purchase to evaluate which model generates the lowest use-phase energy consumption value. Such information is accessed via published online documentation, as suggested originally by Smith et al. (1994), including the Energy Star database (Energy Star 2020), manufacturer websites and within the previously discussed LCA focused Eco Declaration (ECMA, 2021).

Creating the comprehensive pre-sale benchmark during a fourteen-year research period produced a considerable wealth of use-phase field data which continues to be cited today (Belkhir and Emeligi, 2018; GeSI, 2008; 2012; Malmodin et al., 2010). In completing the process, it is reasonable to suggest both the original environmental engineering and subsequent computer science objectives had been achieved. The rationale is threefold.

Firstly, office utility planners could now access power draw data (W) associated with popular computers from an online repository to plan construction or refreshes of building electricity supplies. Secondly, end user computing electricity consumption had become subject to stringent testing and therefore energy efficiency was being addressed at the source by manufacturers wishing to remain attractive to large organisations subject to policy. Thirdly, the emerging eTEC values had overcome the issue of data obsolescence driven by innovation and scale.

Consequently, a new and expansive data pool updated in near real time has been generated from 2001 to date, arguably removing the necessity to rely upon field measurement to identify energy efficient computers. However, while the benchmark represents an answer to the majority of the original research objectives, the Energy Star Certification process ignores the key influence of human-computer interaction that drove the realisation of a use profile in the first instance. Specifically, the 'active' power draw included within eTEC equation. Consequently, increases in power draw and therefore concomitant GHG emissions caused by user activity, is not quantified unless measured in the field. Considering the active state is measured by researchers (Koomey et al., 1992; Newsham and Tiller, 1992; Norford et al., 1988) and proven to cause several times the power draw of low power modes such as idle, it is reasonable to state that any future consideration of a computer's total carbon footprint must include the active state.

To achieve the re-introduction of the human-computer interaction impact ultimately requires field measured data as substantiated by the methodology applied to the four prominent end user computing GHG quantification papers previously examined (Belkhir and Emeligi, 2018; GeSI, 2008; 2012;

Malmodin et al., 2010). However, three external influences including a refocus towards data centre electricity consumption measurement, emerging carbon footprint assessment and a rise in popularity of mobile computing devices begin to emerge at the end of the 20th century that cause the practice of field measurement to rapidly decline and become virtually obsolete by 2010 (Greenblatt et al., 2013; Karpagam and Yung, 2017; Malmodin et al., 2010). The effect was that as demonstrated contemporary research papers requiring use-phase data had to rely on field data generated before this time.

The first influence is the evident re-focus of key researchers away from end user computing devices towards the objective of defining data centre energy consumption and efficiencies as the internet boomed. Speculatively, the change of focus indicates that researchers considered the Energy Star benchmark and typical energy consumption value as sufficient in respect to end user computing use-phase analysis. As such, effort was therefore considered better spent analysing new and ominous computing power loads generated by data centres (Belkhir and Emeligi, 2018). As an indication, Romm et al. (1999) and Romm (2001) argue the internet was key to global warming due to the impact of data centre computing and changes to travel caused by new online shopping habits. Laitner (2000) follows a similar hypothesis, concurring that new data centre energy demands will cause climate change issues; a subject assessed by Koomey et al. (2000) indicating that the new information-based economy will cause dramatic changes to national infrastructure and particularly energy demand.

The reasoning for the refocus is perhaps best substantiated by Koomey et al. (2001) calculating that data centre capacity had grown exponentially from under one million square foot in 1998 to 17 million square foot in 2001 to become the dominant consumer of electricity within the field of information technology. Furthermore, Koomey (2007) later substantiates the position by calculating that servers in data centres consume more energy than all of the world's televisions and require the power of fourteen 1000 MW power plants to operate. The consequence of the refocus causes end user device field measurement to decline with little evidence of further data emerging beyond the papers already reviewed. As such it is reasonable to deduce that this is reason enough to explain why the reviewed contemporary papers, such as Belkhir and Emeligi (2018), rely on use-phase measurements from research conducted during the mid to late 1990s.

In relation to the second influence, it is also reasonable to suggest that additional academics would adopt and expand end user computing energy consumption research due to the continued growth in computer user numbers (Statistica, 2021). This is certainly the case, although the objective of research conducted after 1997 transitions away from determination of accurate use-phase emissions values previously led by the field of computer science, to a focus upon the total carbon footprint of the product. Specifically, industrial ecologists take up the mantle at the turn of the century, focusing instead upon product lifecycle stages, dominated by the examination of manufacturing impacts rather than energy consumption.

The change in objective once again was driven by a variety of factors including further climatology updates, the advent of carbon footprint reporting and the harmonisation of LCA practices. With regards to climatology, further IPCC reports in 1992 (IPCC, 1992a; b; c) and 1995 created urgency to address the impact of human activities such as manufacturing and related consumption (IPCC, 1995a; b; c). The findings indicated there was limited evidence that developed nations were addressing GHG emissions abatement and climate change was determined to be accelerating. From 1990 to 1995 global CO_2 emissions rose 4% to 6,305 million metric tons CO_2 representing a 28% increase in the concentration of carbon emissions since preindustrial times (IPCC, 1995a; b; c). The concern that GHG particles exist for over a century in the atmosphere raised the likelihood that as emissions grow, the focus was switching to limiting damage rather than preventing it.

Consequently, academics pressed for increased environmental consciousness in particularly manufacturing processes (Sarkis, 1995) and for product related human and eco-toxic emissions to be addressed by government policy (Guinee, et al., 2011). As such, with energy consumption potentially

already scrutinised by the Energy Star programme, the accuracy of quantifying the remaining lifecycle phases, such as embodiment, took precedent (Tekawa et al., 1997) and inadvertently causes use-phase data scarcity to increase. Prevailing advances in ecology and corporate strategy were also enabling such change as practical methodology and application in the workplace evolved. As an example, further to IPCC reports determining anthropogenic interference as the cause of global warming, Rees and Wackernagel (1996) examined the theory of measuring the impact or 'load' of a specific population on nature. By focusing on the natural resources required to maintain an individual's existence, the researchers created what they describe as an ecological accounting tool. What they had actually achieved was the delivery of a framework for the calculation of what would eventually become the 'carbon footprint'. This is notable, as the measurement would become the standardised output format for consumer facing industrial ecology processes such as LCA.

The impetus for welcoming such reports was assisted by a second publication one year later that popularised the concept of corporate social responsibility (CSR). Elkington's work (1997) linked the concept of environmental gains to financial efficiency and profit within commercial organisations. Expanding considerably upon an original concept of Spreckley (1987), the author discussed the concepts and benefits of companies adopting a non-traditional approach to accounting called the Triple Bottom Line. In simple terms profit remained a key outcome of the bottom line although the new approach included two further performance elements associated to social wealth creation (people) and environmental responsibility (planet). Consequently, CSR became quantifiable and with carbon footprint calculation now feasible, demands for products that could respond to the United Nations Sustainable Development Agenda 21 (UN, 1992) became a reality (Guinee et al., 2011).

The concept of LCA as a framework to determine the total environmental impact of end user computing devices is subsequently introduced by Tekawa et al. (1997). Recognising that the use-phase electricity consumption phase is not the only stage of impact, the researchers create data relating to raw material content, bill of materials, production processes, transportation, use and disposal. These quantifications are then applied to existing lifecycle inventory databases producing global warming potential values for GHG emissions, acidification, neutrification and resource consumption. The initial results indicated that of all the lifecycle phases, the use-phase was in fact the most impactful when the global warming potential was applied. The findings indicated that the original focus to date by environmental engineers and computer scientists was well placed.

However, conducted in the field of industrial ecology, it is notable that the electricity consumption value used within the paper does not adopt the methodologies already advanced by computer scientists. Instead, as the key objective was to accurately determine the embodied environmental impact, no energy consumption measurement is undertaken. To compensate, the power draw value (W) used is derived from the name plate rating W value already noted as highly inaccurate by Norford et al. (1988) and multiplied by an assumed use profile of 8 hours of active time per day for 247 days per year for 7 years. While logical from a calculation perspective, the approach arguably over emphasises the use-phase by a range between +71% and 233%. This is because of the assumed constant active mode and the lifespan that when compared to subsequent associated research is overstated by as much as four years (Hart, 2016; Prakash et al., 2016; Teehan and Kandliker, 2012; Thiébaud et al., 2017; Williams and Hatanaka, 2005).

The elevation of the importance of embodied emission quantification and consequential assumed power use and use profile data inputs sets the tone for prevailing LCA research. The consequence is that instead of the new researchers continuing field use-phase measurement, a further decline occurs. As an example, Atlantic Consulting (1998) conducts a LCA study on behalf of the European Union to determine the average impact of end user computing devices from what is described as a cradle to grave device retention period. To create use-phase consumption values no field data is collected. Instead, the lifetime of the computer is based upon standard financial accounting depreciation (5 years), while the electricity consumption (kWh) is derived from assumed averages from survey four-years prior (EU Com., 1994).

Further evidence of use-phase assumptions becoming the norm continues into the new millennium as highlighted by Kim et al. (2001). While noting very specific secondary data sources for lifecycle metrics such as material extraction and manufacturing, the energy consumption phase is simply noted as 'assumed' with no actual kWh value declared. To formalise the process Kenma et al. (2005) note that LCA research and quantification gains further structure following the implementation of the newly formed Framework Directive on the Eco-design of Energy-using Products 2005/32/EC (EU, 2005).

Created to drive the production of low carbon footprint computers, the new process includes the completion by manufacturers of a template for the use-phase consumption stage. Like the objective of the Energy Star programme, the emphasis of use-phase data production and availability is shifted away from researchers to the manufacturer. As such, inputs required to complete the template include power draw (W) for operational modes including 'on', 'stand-by' and 'off'. Notably, as is the issue with the Energy Star benchmark, the framework is not explicitly asking for energy consumption data that includes human-computer interaction. The 'on' mode would be described as 'active' state if this were the case. As such, as no field use-phase data exists at this juncture, the only compliant course of action open to the manufacturers is to populate the 'on' value with the 'idle' W value generated during the Energy Star no-user present benchmark. The consequence being that any product carbon footprint generated using the data will again exclude the impact of human-computer interaction on power draw. In reaction, Williams and Hatanaka (2005), on having no other choice than to use no-user present benchmark data from Dell for power values during LCA research, conclude that:

'Despite the importance of usage patterns, quantitative data describing them is decidedly scarce. Existing analysis of energy use of IT equipment has been based on plausible assumptions regarding such key factors as computer lifetime and hours used and not actual data.'

Williams and Hatanaka (2005)

Refocusing of the original end user computing use-phase research to data centre and internet centric studies at the turn of the century (Koomey, 2007; Koomey et al., 2001; Romm, 1999; 2001) plus the relegation of importance of use-phase emissions accuracy by new researchers in the field of industrial ecology (Kim et al., 2001; Tekawa et al., 1997; Williams and Hatanaka, 2005) was limiting end user computing use-phase measurement. However, as noted it took a third influence to all but eradicate the practice.

Quite simply, this was a transition away from desktop computers to mobility that accelerated in the 21st century (Gartner, 2006; IDC, 2006, Statistica, 2020). Specifically, the fact that Norford's 1988 original concept of accurately measuring the electricity consumption of a computer relies upon the positioning of a watt metre between the device and the power source (plug socket) created an insurmountable problem as computers became subject to constant relocation. At the time when the methodology was created, mobility was not an issue as all computers were bound to the desktop. However, Piette (1991) notes that a new form factor of mobile devices called 'notebooks' begin to appear in energy audits in the early 1990s.

As technologies such as Wi-Fi enable mobile working and behaviours such as remote working begin to proliferate (Laitner, 2000; Romm, 1999; 2001; Mills, 1999) popularity for mobility and mobile devices increases (Gartner, 2006; IDC, 2006, Statistica, 2020). The transition becomes cumulatively extensive until reaching today's balance of desktops now accounting for only 14% of all end user computing devices (Gartner, 2021; Statistica, 2021). Consequently, with 86% of personal computers now mobile (Gartner, 2021; Statistica, 2021), research undertaken for the Lawrence Berkley National Laboratory (Greenblatt et al., 2013), a body renown for much of original environmental engineering papers, notes that research literature relating to end user computing device field measurement is very limited. The reason given is that while device metering is the most accurate method for gathering use-phase electricity consumption data, due to mobility it is very costly, logistically challenging and time consuming and as

such, mostly avoided. As discussed in the introduction, companies have attempted to overcome the problem of mobility using software to enable the 'measuring component' to move with the device. However, Bekaroo et al. (2014) note that, to date, alternate methods remain unsuccessful.

2.3. Filling the data gap

As the literature review indicates, end user computing use-phase energy consumption and concomitant scope 2 emissions quantification can only be considered meaningful if the active state is represented within the calculation. Without such inclusion the credibility of use-phase data becomes questionable. Therefore a lack of parity between product carbon footprint reports will continue to exist even if use-phase data are harmonised for contextual influences such as location and lifespan. Without accuracy, concepts that widen the appeal of sustainable information technology strategies among business stakeholders, such as the triple bottom line (Elkington, 1997), cannot be leveraged to increase diffusion as utility cost and GHG abatement remains conjecture.

Consequently, it is reasonable to suggest that if changes to procurement, use and reporting behaviours are to be influenced; conducting research that begins by overcoming the initial electricity consumption data gap is the gateway to success. However, as the introduction outlines, this first step is one of six required to substantiate the research as having made a valid contribution. Specifically, the research must also produce solutions and ultimately test the positive environmental impact delivered by changes experienced within organisations using computers at scale. Therefore, as business represents such scale, it is reasonable to suggest that CSR literature is an appropriate source to look beyond computer science and industrial ecology to identify a model suitable to apply structure to this research

Examining extant literature, it is evident that the early focus on social responsibility theory outlined by Spreckley (1987) and initial advances measuring CSR performance (Clarkson, 1995; Preston, 1988) tied to social prosperity have evolved. Specifically, research frameworks now also include practical quantification of environmental impact (Clark et al., 2004, Maas, 2009; Zamojska1and Próchniak, 2017). Such impact considers activities conducted outside existing operations that generate outputs and outcomes (Clark et al., 2004) capable of driving environmental impact among end users (Kolodinsky et al., 2006). Considering anticipated behavioural changes will include stakeholders' decision making and ultimately computer user behaviour at scale then such approaches are appealing.

Notably, one such model used to plan for, deliver and measure environmental impact within corporate producers and users alike is known as the impact value chain model (Clark et al., 2004, Maas, 2009; Zamojska1and Próchniak, 2017). Following stages including an input phase designed to gather resources, activities, outcome and output phases designed to test a hypothesis and develop solutions plus a final impact phase to measure effectiveness, the model proves suitable to support the research ambition.

Circling back to computer science and LCA practices, Romm (GeSI, 2012) notes that, *'when people are ready to change behaviour, that's when information technology's impact could be greatest'*. Arguably, if organisations are currently bereft of meaningful information enabling such decision based behavioural change a barrier will continue to exist unless challenged.

Specifically, not seeking a solution may prevent the proposed concept of end user computing GHG emission abatement contributing to the UNEP GHG emissions gap strategy (UN, 2019) and the UNSDGs (UN, 2015) number 12 (responsible consumption and production) and 13 (climate action). Consequently, as indicated to be necessary by this literature review, examination and development of a solution or set of solutions to generate meaningful information is required if end user procurement and use behaviours are to be realised and abatement achieved. Equally, as defined by CSR, such solutions must be measured from an environmental impact perspective if they are to prove credible and to contribute to scientific and practical advances in both the short and long-term.

3. Chapter 3: Methodology

As previously indicated the research structure and methodology includes traditional stages of introduction, literature review and conclusions. Notably what would usually form the results and discussion section is replaced by the impact value chain model identified in the literature review. The reason for this is further explained in section 3.2 below.

As such, the methodology section focuses on detailing the approaches used for both the literature review and all five subsequent stages determined by the selected model.

3.1. Literature review: approach used to gather literature

It is necessary for the literature review to consider the symbiosis of computer science, associated LCA aspects of industrial ecology and the topic of sustainability in general. In context, computer science delivers constant efficiency innovations potentially capable of limiting the impact of increasing end user computing activity, while industrial ecology practices, such as LCA, advance methods used to quantify the impact of computers upon the planet. Whereas, sustainability has broad influences including climatology, corporate, national and global policy plus legislation designed to accelerate environmentally positive behaviours. As such, literature related to these fields and topics must be examined and discussed to understand prevailing methodologies and linked opinion.

To counter a predisposed axiology for positivism, the literature review sets aside existing perceptions that incongruence in end user energy measurement and presentation exists and instead seeks external academic opinion and reasoning. This pragmatic and value free approach allows a realistic view to be outlined while avoiding unsubstantiated conclusion. To gather and review relevant academic papers, research publications, related books, technical papers, computer manufacturer opinion, policy and legislation documents various search criteria are used. While not exhaustive, search tools such as Google, Google Scholar and Scopus are used in conjunction with keywords including:

- Industrial Ecology
  - Computer carbon footprint, lifecycle assessment, lifecycle inventory, device lifespan, use-phase emissions, embodied emissions, end of life emissions, greenhouse gases, environmental impact, displacement, harmful substances, sustainable manufacturing, sustainability, digital pollution, information technology and climate change, global warming, ecological policy, recycling, waste from electrical and electronic equipment (WEEE), environmental legislation, responsible business, raw material consumption

- Computer Science
  - Human-computer interaction, power loads, electricity consumption, energy efficiency, component efficiency, design regulations and standards, benchmarks, certification programmes, use-phase emissions, carbon footprint reports, environmental design, environmental compliance, energy management systems, computer engineering, sustainable design, energy / electricity / use profile / asset software measurement

- Sustainability
  - Climate change, GHG emissions abatement strategies, global warming, environmental quality standards, sustainability management, computer procurement frameworks, GHG accounting, sustainable development goals, global warming treaty, directives, corporate social responsibility, environmental social and governance, climate change legislation

3.2. Methodology: The impact value chain model

To answer the primary research question, 'Can meaningful end user computing carbon footprint information drive human behavioural changes to abate greenhouse gas emissions?' a research model capable of supporting multiple research techniques that build towards an impact measurement stage is required.

To enable this approach the impact value chain model (Clark et al., 2004) previously noted in the literature review is selected. This is because the model is effective for research that delivers either positive social or environmental impact and is therefore widely adopted within sustainability focused research (Maas, 2009; Zamojska1and Próchniak, 2017). Specifically, as the intention is to support UNSDG 12 and 13 (UN, 2015) then substantiation of positive environmental impact delivered by the research is deemed equally as critical to success as is overcoming the previously identified technical barriers associated with computer electricity consumption and scope 2 GHG emissions.

Importantly, the model offers the ability to form steps designed to eventually achieve environmental impact by undertaking the process of 'back casting' (Robinson, 1990). This process enables envisioning of a sustainable future followed by looking backwards to identify the processes required to deliver such change (Bibr, 2018). In this instance the future is represented by the final impact phase of the model (figure 1) when case studies are conducted to measure positive environmental delivered by the research. As such, working logically backwards from this initially theoretical result allows for analysis as to what potential gaps exists currently preventing immediate achievement of the goal. By determining this it is possible to decide what activities and solutions are required to enable success. Using the impact value chain model as a template, the methodology is therefore defined by five key stages of input, activities, output, outcomes and impact (figure 1).

Figure 1. Impact value chain model populated to reflect the final research process
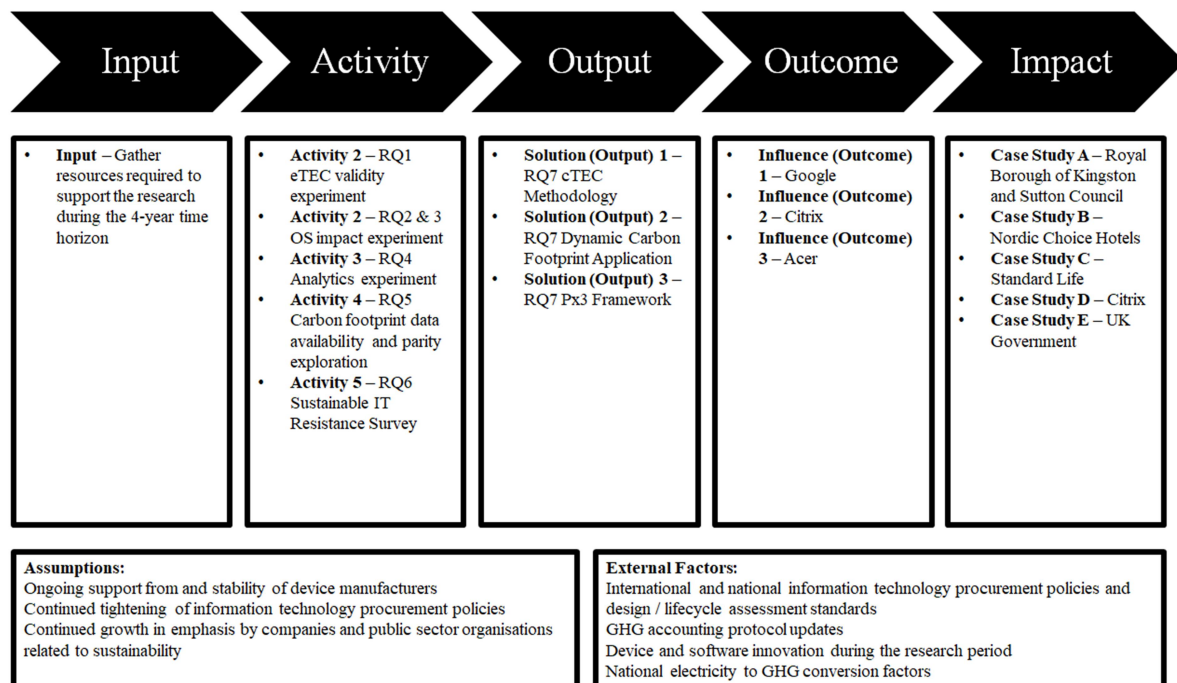
Note figure 1. The impact value chain model template is derived from the Warwick Business School Strategic thinking and planning – skills and tools. IB2C60 – AISP: Global Environment of Business' (Dahlmann, 2021)

Each stage is described as follows:

- Input – identifying and gathering the resources required to undertake all subsequent stages of the research.
- Activities – conducting five research activities that address specific existing barriers preventing the realisation of the envisioned impact stage as hypothesised by the introduction and validated by the literature review.
- Output – the production of three tangible practices that enable current barriers to be overcome and therefore meaningful end user computing carbon footprint information to be produced and used during the case studies.
- Outcome – establishing the effect and influence of the output upon individuals involved during the development of the solutions ahead of the impact case studies.
- Impact – five case studies designed to determine if the research output has driven behavioural change within the organisations in relation to procurement and use of end user computing devices and quantification of the relevant GHG emissions abatement achieved.

As highlighted in figure 1, assumption made at this point is that manufacturers and vendors are willing to participate in such research as without their assistance two issues may arise. Firstly, equipment and software required for testing will not be available unless purchased. Secondly, willing case study organisations may prove difficult to access without introduction.

Limitations of the study are anticipated in the fact that while the ultimate goal is to enable widespread positive environmental impact from responsible production and consumption of end user computing equipment, the research is restricted to five specific examples of impact. Therefore, driving climate action on a global scale via the delivery of meaningful GHG emissions information to change behaviours is limited in substantiation to the results defined by the impact case studies. Pragmatically, to believe otherwise suggests a predisposed axiology for positivism that may detract from the credibility and short-term value delivered by the research

3.2.1. Methodology Stage 1: Input

The objective of the input stage is to identify the resources required to complete the research and gain commitment from third parties capable of supplying them. From a physical supply perspective, this includes notebooks required for electricity consumption measurement in activities 1 and 2 plus analytics software required for activity 3. Similarly, from a relationship perspective, activities 3 and 4 plus the impact case studies require suitable candidate organisations willing to participate in the research. To determine if the hardware, software and potential participant organisations are available, meetings are conducted with major device manufacturers plus operating system and software analytics vendors during 2019 to confirm commitment to the research time-horizon. Access to the global technology organisations is realised via existing business connections within each company. The unstructured interactions include the positioning of existing scientific evidence related to the impact of end user computing upon GHG emissions and the environment, plus a high-level explanation of the range of positive impact available through sustainable device selection and use as positioned in the introduction. Delivered with an accompanying presentation, an example of this can located via the International Association of Microsoft Channel Partners (IAMCP, 2020).

Apple, Microsoft and Google were initially approached to participate in the research as the three global technology companies are responsible for 91% of combined end user computing operating systems (Statistica, 2021). By gaining support from companies responsible for the software installed upon various

brands of end user computing devices, the likelihood of other manufacturers becoming involved in the research was improved. This proved correct as both Acer and IGEL committed resources as findings progressed. However, Apple did not respond, giving no reason for the stance. Fortunately, Microsoft and Google decided to support the research (see Acknowledgements for specific stakeholders) with a view to initially supplying hardware to test the issue of typical energy consumption data excluding the influence of human-computer interaction upon power draw. The decision was based upon both companies agreeing that the literature review supported the hypothesis and it was a problem they both admitted to encountering. Computers were supplied by all parties to support activity one, although subsequently published findings led to Microsoft disconnecting with the research. The reason being that, as discussed in full below (chapter 4), it became clear the legacy operating system fared better from an efficiency and therefore environmental perspective using existing methodologies that avoid inclusion of the active state. Google conversely recognised the results as positive from their perspective and subsequently made introductions to Acer, the world's fifth largest hardware manufacturer (Statistica, 2021) and producer of 16% of all Chromebooks. Comparatively, IGEL, a software vendor producing thin client operating systems, recognised that similar efficiency may be achieved for their offering called IGEL OS. As such, in year 3 (figure 2) IGEL engaged with the research to determine positive environmental impact that could be achieved via the adoption of their replacement operating system (IGEL, 2022).

To develop alternative methods of measuring device electricity consumption in the field that may overcome the barriers of mobility and scale highlighted by the literature review, further software vendors were contacted. This includes Citrix Systems and Lakeside Software. As both companies focus on user experience data, then either software may have proven appropriate to also capture power related measurements regardless of location. While Citrix proved irrelevant from this aspect as the processing occurred predominantly in the data centre, the company offered assistance in relation to asset profiling used in activity 4 and impact case study A by way of convenient organisations open to supporting sustainable information technology research. The reason given was that the concept of low energy devices being identified would suit a sustainable information technology approach for thin client computing that may also speculatively reduce commuting to access IT emissions. Comparatively, Lakeside Software proved highly relevant due to the analytics distributed node-based software being capable of reporting device resource utilisation across internet technologies. As such the company was instrumental in testing an alternative theory to watt metre measurement, although it is noted that further to publication of the results, the vendor disengaged due to inaccuracies in power calculation described in detail in the activity section.

Included within the input phase are assumptions and influencing factors anticipated to affect the research (figure 1) if subject to change. These are brand solvency, continued resource involvement plus associated policy and legislation evolution. While Microsoft disconnected after the first year, the issue was overcome as Acer committed product resources including notebooks and desktop devices installed with the Windows operating system in years 3 and 4 (figure 2) enabling the research to progress. From a solvency perspective, all manufacturers and vendors remained in operation and commercially viable ensuring equipment and evaluation software was available throughout the four-year research period. From a compliance perspective, policy and legislation relating to the abatement of IT emissions tightened during the research time horizon. This caused increased impetus from particularly Acer, Citrix, IGEL and Google as each organisation accelerated interest in leveraging the research findings to drive outcomes as discussed below (see chapter 6, outcomes).

Figure 2. Manufacturer support duration for the research

Manufacturer	Year 1				Year 2				Year 3				Year 4			
Acer																
Citrix																
Google																
Microsoft																
IGEL																
Lakeside																

As such, the input stage accomplishes its goal, ensuring that the research remained viable throughout the time horizon from both a manufacturer, end user participation and a global relevance perspective. While stakeholders may change and evolve throughout the forty-eight-month period, sufficient resources are committed and retained to ensure that the research continues from hypothesis to conclusion. Overall the input phase duration is four months with on-going involvement continuing in most instances from 2019-2022.

3.2.2. Methodology Stage 2: Activity

Stage 2 is designed to conduct activities examining the barriers reflected in the hypothesis and discussed in the introduction and literature review. Specifically, five activities are conducted including three field experiments, an exploratory review and a survey. The first field experiment determines the percentage of error introduced to the calculation of use-phase emissions due to the exclusion of active state power draw. The second examines the impact of operating systems and components upon electricity consumption efficiency to determine if differing specifications uniformly influence the active state power draw. This activity also acts to enable a demonstration and discussion to determine the importance of device useful lifespan extension to support displacement.

The third experiment tests the feasibility of an alternative method of measuring end user device electricity consumption using analytics software to overcome mobility and scale issues (Greenblatt et al., 2013). The fourth activity, an exploratory review, examines availability and parity of existing product carbon footprint data. While the fifth determines resistance to the adoption of sustainable information technology within large sized businesses to ensure any resulting solutions developed in the output stage address speculative barriers preventing diffusion.

Each activity is published via relevant scientific journals (Sutton-Parker, 2020a; b; 2022b; c; d) to achieve two outcomes. Firstly, to experience peer review when answering each specific supplemental research question therefore ensuring impartial credibility and to counter any concept of research bias. Secondly, to ensure that participating organisations identified during the input stage remain engaged as they realised the impact of their involvement and subsequently leverage the research results (see chapter 6, outcomes) in the short-term as well as further to completion of the entire research time horizon.

3.2.2.1 Activity 1 (Experiment to answer RQ1)

The secondary research question addressed by activity 1 is:

- RQ1 'Does the current end user computing use-phase energy consumption methodology accurately reflect device electricity use when subjected to human-interaction?'

As noted, the objective of the experiment is to determine if the existing practice of calculating annual device typical electricity consumption using only low power mode measurements is significantly different to those including the active state within the calculation. If proven to be so, then potentially it is possible that uniform incremental electricity consumption will become apparent within the findings, therefore indicating that a percentage increase in the eTEC value could be applied to correct the potential inaccuracy reflect in subsequent product carbon footprint reports.

The research technique used to achieve this is a field experiment. The reason for this method is to capture real life electricity consumption data using Energy Star test set-up and conduct methodologies (Energy, 2020) and to compare the results to Energy Star eTEC values. In doing so, parity of results and comparison is achieved. This ensures research bias is avoided by not relying on secondary active state data that does not specify exact models tested, nor produce any range of perceived error (Dandridge, 1989; Johnson and Zoi, 1992; Kawamoto et al., 2001; Koomey et al., 1995;1996; Lovins and Heede, 1990; Newsham et al., 1992; Nguyen et al., 1988; Norford et al., 1988; 1990; Piette et al., 1985; 1991; 1995; Roth et al., 2002; Rotourier et al., 1994; Smith et al., 1994; Szydlowski and Clivala, 1994; Yu, et al., 1986).

Twenty-seven end user computing devices supplied by the manufacturers identified in the input phase are measured for power draw and electricity consumption in the workplace using a watt metre. The duration of each measurement period is five-days between 9am to 5pm with a one 30-minute break included to reflect standard working practices. The results are extrapolated to one-year and compared to the annual Energy Star eTEC results for each device. This is undertaken to determine the difference between annual typical electricity consumption calculation conducted using only low power modes (the existing practice) and those that include the influence of the active state power drawer (the proposed practice).

To examine if a pattern emerges within the power draw (W) data for certain device types (e.g. notebooks or desktop computers), measured computers are categorised by percentage power draw (W) increases exhibited from the idle mode to active state including 0-25%, 26-50%, 51-75%, 76-100% and >101%. The value of doing so is to determine if a simplified 'uplift' to the short-idle mode results could be applied to all existing Energy Star data to represent an active state W value.

Additionally, using the field measured kWh data and the published eTEC data the results are used to highlight the possibility of procurement teams selecting devices that are indicated as being the most efficient using existing benchmark practices when in fact they are not when measured in the field. The value of this is to emphasise the need to introduce active state measurement to facilitate accurate use-phase emissions representation.

The rationale for focusing upon a workplace environment rather than a consumer environment is that the sustainable procurement legislation defined in the introduction is applicable to public sector and commercial organisations rather than individuals. As such, the impact of inaccurate electricity consumption and concomitant scope 2 GHG emissions is arguably most applicable in the workplace. The test set-up and conduct is undertaken in accordance with the existing Energy Star (2020) practice to ensure parity between results. A full technical explanation is included with the Appendix.

The limitation of the approach is that while twenty-seven devices creates a credible data set for comparison, many more models of computers exist and as such it is feasible that differing results may be produced by various specifications. This probability is expanded upon in activity 2.

The time horizon for activity 1 is six months due to the 5-day periods required for all twenty-seven devices plus the time spent collating the results and producing the results below (Sutton-Parker, 2020b).

3.2.2.2 Activity 2 (Field experiment to answer RQ2 and RQ3)

Activity 2 was originally designed to challenge the previously discussed opinion that new more energy efficient devices will deliver less environmental impact than retaining existing computers for longer periods.

However, results from activity 1 (chapter 4, 4.1) revealed an unexpected outcome in relation to the active state power draw results for Chrome OS devices. Consequently, while activity 2 proceeds as planned to answer research question 3, the energy consumption results produced in activity 1 are re-examined at a specification level to answer research question 2:

- RQ2 'Can the influence of computer specifications upon electricity consumption contribute to forming universal active state power draw increments?'
- RQ3 'To what extent is greenhouse gas abatement delivered by alternative computer operating system displacement strategies?'

To answer research question 2, data from activity 1 are compared in order to determine if common operating system and component specifications produce similar increases in power draw and electricity consumption. Specifically, percentage increases from the idle mode power draw (W) to the active state power draw (W) are this time mapped against operating system, display size, CPU, memory and storage types to determine if a uniform pattern emerges. As before, while more complex than focusing simply on device type, the value of comparing the results at a more granular specification level is again to determine if a simplified 'uplift' to the short-idle mode results could be applied to all existing Energy Star data to represent an active state W value.

To answer research question 3, the energy efficiency exhibited by Chrome OS in activity 1 is leveraged to contest the new device versus existing device efficiency and environmental impact opinion. Specifically, two Windows computers measured for electricity consumption in activity 1 are re-imaged to become Chrome OS devices and measured again using the same test set up and conduct process. The devices are selected based upon them being between 3-5 years in age. This is to reflect the computers having reached the end of average device retention periods as previously noted. The new power draw and electricity consumption values are then compared to the results from activity 1 to determine the percentage influence to energy efficiency attributed to the new operating system. The value of doing this creates data substantiating that existing computers may in fact have the capability to experience reduced energy consumption via innovation and that the effect is not isolated to new devices.

To compare the total carbon footprint impact of new devices (scope 2 and 3) to the on-going scope 2 impact of the existing devices, two new and prospectively low carbon footprint replacement devices are identified from activity 1. Scope 3 data is determined by accessing manufacturer carbon footprint reports with scope 2 data being determined by the previous field measurement.

The combined scope 2 and 3 new device GHG emissions and existing scope 2 emissions are plotted against a cumulative carbon footprint y axis ($kgCO_2e$) and a time duration x axis (years). This enables the point in time when the on-going legacy use-phase emissions equal the combined embodied and use-phase emissions of the new devices to be calculated. In doing so, evidence is produced to determine whether buying new devices is positive or negative from an environmental perspective when compared to extending existing device lifespans.

The limitation of this experiment is that only two computers are re-imaged with the replacement operating system (Chrome OS Flex). As noted in activity 1, results may differ when the operating system is applied to further device types and models. Additionally, the experiment is limited to one type of

alternative operating system and as such others may deliver similar efficiency gains. The opportunity to examine this latter hypothesis is enabled by case study C (chapter 7, 7.3) when a second Linux based operating system is tested in a similar way. The time horizon for activity 2 is two months based upon the measurement period required for the two devices (Sutton-Parker, 2022c).

3.2.2.3 Activity 3 (Field experiment and asset profiling to answer RQ4)

During the planning process and based upon the literature review, it is deemed most likely that activities 1 and 2 would not reveal a uniform increase in electricity consumption across devices when subjected to the influence of the active state. As such a need to further investigate alternative methods of accurate field electricity consumption measurement capable of overcoming issues of scale and mobility remains. Consequently, a third combined field experiment and asset profile exercise is conducted as activity 3 to answer the fourth research question:

- RQ4 'Can analytics software measure end user computing electricity consumption?'

The value of the experiment is twofold. Firstly, it is conducted to test the feasibility of using analytics software to capture both asset and use profile data regardless of scale, mobility and location. Secondly, the experiment enables examination of the accuracy of the resulting use-phase electricity consumption values. To achieve this, the following summary structure is used:

- Identify a candidate organisation
- Determine a suitable time horizon
- Determine a test set up and conduct for the organisation
- Determine a test set up and conduct for the control user
- Determine a comparison test for the asset profile data collection
- Measure the electricity consumption of end user computing devices for both the organisation and control subject
- Document the results
- Discuss the results
- Summarise and conclude
- Make recommendations and state limitations

Three considerations influenced the selection of the subject organisation. Firstly, more than fifty mobile users were required to test the capability of the software in relation to scale and mobility. This is to ensure the number of users is sufficiently significant to produce both device type and model variety. Secondly, operations within multiple countries were preferable to enable location capture to support the feasibility of identifying national based GHG conversion factors. Thirdly, a company already using the software for its intended use of digital experience management to avoid reluctance or delay related to the installation of new software that may be perceived as an unplanned cost or a network security issue.

To meet the criteria, the analytics software vendor Lakeside was contacted and asked if they could propose a customer willing to participate in the research. The vendor has over three thousand active customers and the likelihood of a positive response was high. Perhaps surprisingly, Lakeside themselves agreed to be the test organisation as they use the analytics software as part of their business operations and were highly interested in exploring sustainability options both internally and to promote to customers. The profile of the candidate organisation subsequently met all proposed criteria enabling one hundred and eleven devices across eight countries to be measured.

The time horizon of the experiment was thirty days. This is determined by certain predefined reporting aspects built into the analytics software that offers both a daily and monthly cumulative report. Additionally, 30 days represents one month and as such can be extrapolated during the results and discussion to create annual values. It is recognised that the optimum duration would be one year although this experiment is to test feasibility plus the accuracy of the control subject. As such it proved unfeasible for the control subject to remain in one location and connected to a watt metre for a period any longer than one month. The test setup was relatively simple as Lakeside already uses the analytics software and as such analytic database nodes resident on the end user computing devices were pre-installed and already collecting the required data at five second intervals.

To ensure that the asset and use profile data inputs identified as critical to the use-phase consumption and concomitant GHG quantification were captured, a specific dashboard was created within the software's visualizer capability. As such, data sets including computer name, device manufacturer, model, serial, chassis format and age, power average in W, energy consumption in kWh, on-time (OT) observed (representing the period in hours and minutes that the notebook was 'on' and drawing electricity) and location were able to be extracted at the end of the 30-day period. The format is a simple Microsoft .xls Excel file.

The conduct for the main body of users required no intervention or awareness. This was decided upon to ensure that the automatically captured data reflected the extraneous variables such as a multitude of unique user profiles experienced in a real-life setting. If the user was made aware that measurement was occurring, then this may change natural use patterns. However, as the control user was required to adhere to certain conditions to ensure comparison between the active time and watt metre readings, the following approach was employed in this instance only.

The control user was a single mobile user measured by both the analytics software and an accurate watt meter for use profile values to enable future comparison of results. This extra measure is undertaken to determine whether the electricity consumption values produced by the analytics software matched the accurate watt metre kWh results. Similar to the main cohort of users, the software was previously loaded and automatically reporting whereas the watt metre required specific set up. To ensure that the notebook energy consumption measured by the watt meter was not altered by any additional power demands such as plug sharing or peripheral devices, elements of the Energy Star benchmarking test set up (Energy Star, 2020) were incorporated in the test set up as they are proven to enable accuracy. These include:

A. The 'Input Power' using alternating current (AC) mains supply must be connected to a voltage source appropriate for the intended market (country). In this case the UK where nominal supply voltage is 230 V +10%/−6% to accommodate transformer settings of 240 V
B. Connected to a watt meter meeting the IEC 62301 standards plugged in between the input power and the mains supply
C. No peripheral devices were used or attached during the experiment
D. The notebook was connected to the power source for 24 hours per day for the duration of the experiment

It is noted that as per the Energy Star (2020) recommendations the notebook remains connected to a power source. This is undertaken to ensure the watt metre continues to collect energy data as unplugging the device from the power source will register a pause in power draw by the watt meter but not by the software. As such, removing the device from the power source would invalid the comparison of both data sources. As such, the notebook can be considered the equivalent to a desktop in this instance by the fact

that it is required to remain static throughout the process. To safeguard that the notebook energy consumption measured by the software was not affected by the loss of Wi-Fi signal during the experiment a local area networking (LAN) cable was connected directly to the broadband router via the Ethernet port. It was confirmed by the software vendor that the network interface card (NIC) is included in power monitoring. The notebook was operated by one consistent user throughout. To mirror real world use, no restrictions were placed upon when the notebook could be used during each twenty-four-hour measurement period with the exception noted below. As both the watt meter and software are capable of measuring the time per day that the notebook is 'on' and drawing energy, the following modes were measured.

A. OT representing the period in hours and minutes that the notebook was 'on' and drawing electricity. This is not to be confused with the 'active' measurement used in experiment 2 as it also includes periods of time when the notebook has transitioned to other modes such as short or long idle

B. 'Off' representing the period that the notebook was either switched off or had powered down and was potentially no longer drawing energy

To enable comparison to existing TEC and active use comparative research, Energy Star recommendations were used for most part of the experiment as follows:

C. Display Sleep Mode was to initiate after 15 minutes of user inactivity as per Energy Star recommendations.

D. Sleep mode was set to initiate after 20 minutes of user inactivity as per Energy Star recommendations.

Deviations to this test set up were included in the experiment on certain days to test the capability and accuracy of the software. These included changing the power settings for the device to disable the sleep and/or 'turn off the display function'. To test if certain aspects of the software required the user to be actively logged in and working for energy consumption reporting to occur. This is explained in full in the results discussion. While the software data collection is automated the watt meter daily energy consumption (kWh) values and OT (hours and minutes) were noted manually from the LCD screen at the same time to maintain consistency.

As the experiment include testing both the use-phase emissions data capture and the asset profile data capture capabilities of the software a comparison of capability for the latter is required in addition to the electricity consumption control user. Without alternative methods of asset profile capture against which to compare the results to, any findings may prove less meaningful. As such, two further asset profile exercises are undertaken at two separate large organisations using online questionnaire and asset management software reporting techniques. The results of all three approaches are then compared for ease of collection and accuracy.

Further to receipt of university ethical research consent, a simple online questionnaire was created using Survey Monkey to enable an online product asset profiling exercise conducted at the University of Sussex. The following questions are posed for each device type including desktops, notebooks, tablets, thin clients workstations and monitors:

1. How many (insert device type) computers does your organisation have? (numeric response)
2. What models are most popular? (typed descriptive response)

3. What percentage of the total (insert device type) install base does each model represent?

From the collected data, quantities of devices by device type and model were then generated to form the asset profile for the university. Feedback was verbally requested in a statement from the information technology manager to assess the ease of data collection from an end user perspective (see chapter 4, 4.3).

For the second alternative device profile exercise, a Citrix customer, Ossur agreed to participate. The limb manufacturing organisation uses Lan Sweeper asset management software and provided an asset data extract. In the form of a Microsoft .xls Excel file extension spread sheet, asset profile inputs such as quantity, manufacturer and model were indicated together with international device location.

The limitation of this experiment is that the control user represents just one device. It is feasible that errors relating to the reporting of electricity consumption outlined by the results section may be different when undertaken on differing device types or models.

The time horizon of activity 3 is six months. While actual measurement only required one month, additional discussions with the software vendor before and after the experiment led the research to consume one half of the second year (Sutton-Parker, 2022b).

3.2.2.4 Activity 4 (Exploratory research to answer RQ5)

The objective of the fourth activity is to determine if sufficient and credible data exists to enable organisations to meaningfully respond to the increasing sustainability focused procurement legislation and policies discussed in the introduction. Should limitations, such as availability and limited parity, be found to be widespread, then two outcomes will have been achieved. Firstly, it will be proven that organisations are not currently equipped to respond to legislation therefore further validating the requirement for a solution. Secondly, by examining an increased data set of device carbon footprint information, the speculation of limited parity identified in the introduction is tested. In doing so, the findings will potentially contribute to a solution defined in the output stage (chapter 5, 5.2). As such, activity 4 is designed to answer the secondary research question:

- RQ5 'Is sufficient carbon footprint information available to make sustainability focused computer procurement strategies meaningful?'

To achieve the objective, the methodology includes qualitative data gathering and exploratory research designed to identify gaps in current carbon footprint data availability and parity. A key process to ensuring credibility of the resulting data is to conduct the activity in a manner that does not simply document what is available by publication but identifies instead what isn't available when compared to current computer install base data. As an example, examining manufacturer web sites for product carbon footprint is limited to revealing data that can be inspected and allows no determination of limitations associated with availability. As such, as over 460 million end user devices are manufactured annually (Gartner, 2021; Statistica, 2021), it is reasonable to suggest that this scope be narrowed to the inspection of computer models exhibiting contextual relevance. Consequently, it is determined that models of end user devices used within organisations subject to sustainable procurement and GHG emissions reporting represent the most relevant computers to be included in the research.

To achieve this, an asset profiling exercise of end user computing estates is conducted using asset management software and survey techniques developed in activity 3 within six large willing participant organisations (see chapter 4, 4.4). Doing so generates a sizable, varied and unbiased pool of equipment asset profile data structured by type, make and model. Secondly, further to sorting and filtering the profile data by unique model, it is attempted to locate the associated product carbon footprint reports from

manufacturer websites. To ensure the task is thorough, where reports do not exist, the manufacturer is contacted directly to request the missing data. Using data tables, the existence of a carbon footprint report is noted either positively or negatively against each unique model. Where reports do exist, information and data points such as the methodology used to produce emissions data, the scope 2 and 3 emissions values, the number of years included within the use-phase calculations, annual typical energy consumption values and electricity to GHG emissions factors are documented.

Finally, the results are discussed to determine the complexity and limitations revealed by the findings in the context of how organisations are expected to respond to policies using the currently available data. The value of doing so will confirm the speculative issues outlined by the introduction relating to methods used to present use-phase data and contribute to the output stage when a solution is created to address the discovered problems.

The limitation for this exploratory work is the number of participating organisations. The reason for this is that certain brands that do not yet produce carbon footprint reports may be more or less prevalent in a wider selection of organisations causing the results to differ.

The time horizon for the final activity was six months due to the extensive asset data capture exercise undertaken, the examination and interpretation of several hundred product carbon footprint reports and generation of the results below (Sutton-Parker, 2022d).

3.2.2.5 Activity 5 (Survey to answer RQ6)

In order to facilitate the design of solutions created in the 'output' stage (see chapter 5) of the impact value chain model, a survey is conducted (Sutton-Parker, 2020a) to answer the sixth research question:

- RQ6 'To what extent is sustainable information technology resisted and what barriers to diffusion are key to success?'

The value of doing so is perceived to assist the framework design by substantiating that focusing upon the triple bottom line approach (Elkington, 1997) would, if presented with meaningful data including planet, people and profit metrics, create the greatest resonance with stakeholders thus improving the potential success and likely impact of the case studies. To test the hypothesis and gauge the level of resistance, a survey was conducted involving over five hundred service sector managers. Asking ten questions, the data creates what is termed as 'intensity of resistance percentages' generated for the three specific categories of awareness, action and barriers. The questions were designed to document the existing depth of awareness of GHG legislation and consequential policies, what related actions were already in place to respond to legislation and what barriers exist from embracing sustainable information technology practices. The questions are:

1. Are you aware the UK Service Sector is subject to annual mandatory Greenhouse Gas emissions reporting?

2. Does your organisation have a CSR policy that includes strategies to reduce GHG emissions?

3. Does your organisation have a specific CSR / sustainability strategy for information technology?

4. Does your organisation measure IT end user computing device electricity consumption?

5. Does your organisation measure and report IT related to greenhouse gas emissions?

6. Are you or your team responsible for or influence the CSR policy setting for your organisation?

7. Are you or your team subject to performance measurements related to IT sustainability?

8. How much of a priority is IT sustainability is for your business, beyond mandatory reporting requirements?

9. What barriers, if any, are holding you back from building a more sustainable IT model for your business?

10. Which of the following statements do you think best describes the impact IT departments can have on how a business reduces carbon emissions, improves sustainability and generally embraces greener practices by default? A) IT departments have some impact and can make an important contribution but it will be in line with other departments, B) IT departments have more of an impact than any other department as IT can drive widespread and crucial change across the whole business, C) IT departments can have an impact but it can't drive major change in the business, D) IT departments have no impact)

Discussed in the context of a sector and job role level, the results highlight differing responses to the resistance of adopting sustainable information technology practices and to identify key issues. Conducted online in 2019 in accordance with ESOMAR (2020) principles that ensure General Data Protection Regulation (GDPR) directives are adhered to (EU, 2016) including participant obfuscation, the survey targeted and received responses from 503 people in decision making managerial roles. All worked in commercial companies of 250+ people or the public sector in the UK Service Sector.

The limitation of the research is that it is conducted in the UK service sector market and therefore may not reflect issues experienced globally.

3.2.3 Methodology Stage 3: Solutions (three outputs to answer RQ7)

The output stage is used to form solutions based upon the findings of activities 1-5 that can be used in the final impact case study stage. As the main research question is positioned to examine if meaningful end user carbon footprint data will drive behavioural change to abate GHG emissions, then it is reasonable that the output stage is dedicated to tools that will generate the meaningful data. Consequently, stage 3 is designed to answer the seventh and final secondary research question:

- RQ7 'Can data be generated, structured and dynamically presented in order to create meaningful product carbon footprint data?'

The objective of this phase is to design and produce solutions that will achieve three outputs. Firstly, a practice and methodology that will enable the representation of the active state within typical electricity consumption data. Doing so will overcome the impact of the omission within current use-phase scope 2 GHG emissions representation. Secondly, to produce an application that is capable of harmonising existing manufacturer product carbon footprint data to deliver parity and simplicity to the process of device assessment and procurement based upon sustainability criteria. Thirdly, a framework tool that enables end user computing emissions data to be meaningfully presented to key stakeholders within organisations using a variation of Elkington's triple bottom line approach (Elkington, 1997). Doing so will overcome the barriers defined by the survey conducted in activity 5 and therefore create the greatest probability of behaviour change to be adopted and subsequent abatement achieved. As each solution builds upon the findings of the activities stage the approach to achieving each output is discussed in full

within the results section. The actions, such as development, are driven specifically by the results and therefore are neither subject to research techniques nor to be disclosed within the methodology.

However, it is noted that to ensure the functionality of the second solution created, interaction and feedback was undertaken from those involved in the pilot testing of the application. Specifically, potential users identified to test the resulting application experience an unstructured group instruction session. The purpose of the one-hour session conducted by conference call is to explain the context of the tool and to convey how the tool can be accessed by the pilot group of twelve users from fifteen unique organisations (see chapter 5, 5.2.2). The group is determined by the criteria of being responsible for an end user computing estate exceeding two hundred and fifty people and therefore being subject to the procurement legislation discussed within the introduction.

Further to accessing and using the tool, direct user feedback is requested from each stakeholder to determine the likelihood of the tool being adopted moving forward. This stage is achieved by an online survey accessed by a quick response (QR) code further to a six-week user testing period. The questions are:

1. Are you currently aware of legislations and policies relating to the procurement of end user computing devices based upon sustainability criterion? (Answer: Yes, or No)
2. Before using this tool were you aware that computer hardware carbon footprint reports are not comparable due to differing methodologies used to calculate the GHG emissions? (Answer: Yes, or No)
3. Before using this tool, were you able to credibly identify, assess and select end user computing devices based upon scope 2 (electricity consumption) and scope 3 (supply chain) GHG emissions? (Answer: Yes, No, or Partially).
4. Do you find the tool enables you to credibly identify, assess and select end user computing devices based upon scope 2 (electricity consumption) and scope 3 (supply chain) GHG emissions? (Answer: Yes, No, or Yes but I would like more models and brands to select from).
5. Do you find the tool to be simple to use? (Answer: Yes, No, or Somewhat).
6. Rank the tool's features in order of importance to you:
a. Ability to select device types
b. Ability to select brands
c. Ability to select retention periods
d. Ability to select location of use
e. Ability to sort by the total carbon footprint
f. Ability to sort by supply chain GHG emissions
g. Ability to sort by electricity consumption GHG emissions
h. Ability to compare multiple devices by carbon footprint
i. Ability to produce a carbon footprint report specific to your parameters of retention period and location of use
7. Do you find the data supplied to be simple to comprehend? (Answer: Yes, No, or Somewhat).
8. Do you believe that you will use the tool to assist you in the future when identifying end user computing devices with the lowest carbon footprint? (Answer: Yes, No, or Yes if more models are included further to the pilot stage).
9. Do you feel the tool will enable you to create and support sustainability strategies that will abate future end user computing GHG emissions? (Answer: Yes, No, or Somewhat).
10. Please offer any feedback you have in relation to the tool. (Free type)

As detailed in chapter 5, the reason for this survey is to further substantiate awareness levels related to current sustainable information technology legislation investigated in activity 5 and the lack of parity in current carbon footprint information determined by activity 4. Additionally, it is to determine if the tool

fulfils a current gap in capabilities to include sustainability as a criteria during device selection and whether the tool may need improving in order to increase the likelihood of wider diffusion.

The time horizon for the output stage of the impact value chain model is concurrent with the research as each is developed and refined as the findings are achieved. However, each output required a minimum of three months based upon instances of design, technical development, user testing and feedback. Consequently, nine months of the research was dedicated to the output stage.

3.2.4   Methodology Stage 4: Influence (Outcome)

Before applying the solutions created by the output stage to the final impact case studies, the outcome stage is utilised to determine the influence of the research upon people and organisations identified by or related to the input stage. Doing so enables behavioural changes to be discussed within influential organisations that, beyond the specific case studies, may assist in the diffusion of meaningful end user computing carbon footprint information and promote the abatement of associated GHG emissions in the long term. The rationale relates back to the pragmatic perspective that the isolated case studies do not represent the total feasible impact of the research, more so a quantifiable effect at a specific point in time. To achieve this objective, outcomes directly caused by the research are documented in summary and then a statement is requested from each stakeholder within the participant organisation as to how they perceived their involvement in the research process.

3.2.5   Methodology Stage 5: Impact case studies (Primary RQ)

The final impact phase utilises the technique of case study to identify behavioural changes and to quantify consequential GHG emissions abatement caused by the presentation of meaningful end user carbon footprint information. This is undertaken in five organisations, all known to the information technology companies, all in excess of two hundred and fifty users and therefore all subject to either mandatory emissions reporting legislation and sustainable procurement policies outlined previously.

In each instance, the cTEC methodology enables electricity consumption measurement of both before and after end user computing devices, the Dynamic Carbon Footprint application delivers device specific scope 3 supply chain data and the Px3 framework calculates and presents GHG, cost and equivalent information. Doing so answers the primary research question:

- Primary RQ 'Can meaningful end user computing carbon footprint information drive human behavioural changes to abate greenhouse gas emissions?'

The case studies are varied in relation to technique, engagement and GHG emissions focus. The first long-term case study conducted with the Royal Borough of Kingston and Sutton represents a two-year research engagement. It includes the anticipated end user computing scope 2 electricity consumption and scope 3 supply chain GHG emissions and cost calculation plus an unexpected calculation of scope 3 commuting to access information technology GHG emissions. The latter was decided to be within scope of the case study as the information technology team wished to respond to a new policy focusing upon increased sustainable transport adoption via the medium of technology enabled remote working.

The second and third case studies are conducted with Nordic Choice Hotels and Standard Life and represent short-term engagement lasting just three months on average. Both case studies examine the impact of extended device lifespans using differing techniques. The first uses Chrome OS Flex to continue the use of devices to perform the same role, whereas the second re-purposes the devices to

transition from desktop computers to thin clients. Additionally, the Standard Life study also includes abatement relating to scope 3 commuting reduction delivered by the new computing solution.

Because of the emergence of the two end user computing solutions enabling remote working and therefore GHG employee emissions abatement, a specific commuting to access information technology case study with Citrix is undertaken as the fourth case study. This is designed to improve upon travel data contextual limitations discovered in the first and third case studies (see chapter 7).

The final case study focuses upon the UK Government and specifically the organisations responsible for forming the Greening Government ICT policy (DEFRA, 2020). This is specifically undertaken to apply the displacement findings generated by the research at scale in relation to scope 3 supply chain GHG emissions and to examine the improvement of scope 2 measurement delivered by the newly developed cTEC method.

The rationale of including both long and short-term case studies is to ensure that the tools produced by the research are capable of being effective in all instances.

Although the method, application and framework are used in all case studies, the approach to achieving each differs.

Where asset profile data collection and retention period data is required this is achieved by using the survey method in case study A, asset management software method in case study B, discussion in case study C and manual asset management compiling in case study E.

For case studies A, B and E how the organisation currently selects devices and whether sustainability already forms part of their operations is discovered by conducting unstructured exploratory interviews with key stakeholders.

In the long-term case study (A), structured and filmed interviews are conducted at the end of the time horizon to determine if the information produced by the research credibly influenced behaviours such as information technology procurement and use policies to abate GHG emissions in the long-term or simply acted as a point in time compliance exercise. In the short-term study, statements are requested from the stakeholders as to whether the research influenced their proposed and actual final outcomes.

The fourth case study D differs from all others in the fact that while again it contributes to the primary research question, the activity also serves to improve commuting to access information technology annual emissions values by collecting primary data rather than relying on secondary national travel statistics. The objective of the research is to actively measure real-life GHG emissions abated by remote working in a large company during two one-year periods before and during the pandemic. Quantifying the values by sum, frequency, transport mode, geography and attitude will enable a discussion related to future impact when the current blanket travel ban is lifted as anticipated in case studies A and C.

Conducted online in accordance with ESOMAR (2020) principles, a survey is generated and completed by employees. The questions are designed to identify how many days per week remote working occurred, the distance travelled during a standard return commuting journey when not remote working, the frequency of this journey, what mode of transport was used, where the commuting occurred and what the individual's attitude is towards the importance of climate change. Ahead of answering the questions, a statement is included to ensure that the respondent understood that the research was to identify scope 3 commuting emissions and not business mileage related to customer external meetings. Additionally, a selection box for miles or kilometres is included as the target employees are international. The five questions asked are:

i.   How many days each week do you normally work from home (before COVID 19 restrictions)?
ii.   How many miles/km would you usually commute to work and back on an average single day (return journey) before the current COVID 19 travel restrictions? Please enter the total miles/km for one return journey.
iii.   What is your predominant commuting mode of transport for commuting?
iv.   What geography, country or region do you work in?
v.   If 10 is the highest importance, how important to you is reducing your carbon footprint?

The questions are worded based upon the circumstance that when the survey was conducted, the software company had recently announced a global lockdown of all office buildings. As such, the approach is to determine the answers for normal behaviour and then compare the results to zero commuting and a future return to work. The company retained the complete commuting ban for 12 months (and more) thus enabling accuracy of comparison. All emissions calculations are undertaken using specific mode of transport carbon intensity conversion factors related to the region in which the commuting was undertaken in line with international GHG accounting protocol.

The first impact case study is suggested to be long-term as involvement with the council occurs at the beginning of the research. Consequently, it is reasonable to suggest that the time horizon for this extends to the full four-year period of the research. It is however noted that interaction was not constant through the period and as such the interviews, asset gathering, calculation, presentation and subsequent publishing of the case study paper (Sutton-Parker, 2022e) consumed approximately one-year of the research period. Comparatively, the second case study was isolated to one period of research and engagement spanning two months towards the end of the research and includes time taken to translate the results into the subsequent case study published by Google (Google, 2022d). The third and fourth case studies occurred between 2020 and spring 2021 with case study C awaiting journal publication. The fifth (HM Gov., 2022b) occurs in 2022 and consumes three months of the research period.

3.2.6   Methodology Time horizon

In total the research period spans four-years between 2019 and 2022 inclusive. While structured to follow the impact value chain model, it was necessary to conduct certain stages in parallel due to the findings and the continued involvement and support of the manufacturers, vendors and participant organisations. In summary, the input stage required four months to gain commitment to resources required to complete the research. The activities stage requires approximately 26 months due to the complexity of the tasks involved whereas the output stage required a total of one year to develop and test the solutions. Finally, the impact stage and completion of the thesis consumes the remaining two years and four months although not consecutively as described.

4. Chapter 4: Activity Results (RQ 1, 2, 3, 4, 5 and 6)

The introduction speculates that organisations wishing to reduce their end user computing carbon footprint by responding to drivers such as new sustainability focused procurement policies may be unsuccessful. As determined by the literature review this is potentially due to existing typical energy consumption and subsequent carbon footprint data being inaccurate and without contextual specificity. The methodology uses the impact value chain model (figure 1) to test the hypothesis during the activity stage. As such, the following section documents the results from the four activities conducted to answer research questions 1-6 and ahead of a discussion as to how the findings influence the subsequent output.

4.1. Activity 1 (RQ1): 'Does the current end user computing use-phase energy consumption methodology accurately reflect device electricity use when subjected to human-interaction?'

As previously discussed, existing research indicates that the human-computer interaction increases the power draw (W) required by a computer to conduct useful work. This is caused by the various hardware components and software interacting and generating a surge in electricity consumption when compared to inactive states such as off, sleep and idle. The time a computer spends experiencing human-computer interaction is known as the active state. As the current methodology used to benchmark the electrical efficiency of computers does not include the measurement of the active state, then it is logical to expect that this exclusion will cause the resulting estimated typical consumption value (eTEC) to be incongruent with electricity consumption experienced in the workplace. As business computers are purchased to conduct useful work they will be subject to regular human-computer interaction thus increasing the power draw for considerable periods of time. It could be argued that if the existing benchmark delivers parity between device results because of the strict test set up and conduct, then the exclusion of the active state does not have an impact in relation to procurement based upon sustainability criteria. This is because selecting the device with the lowest kWh benchmark value will deliver the lowest scope 2 emissions even when the computer experiences the active state. However, since the introduction of the benchmark in 1992, operating system choices have become more abundant rather than being dominated by Microsoft's Windows software as was the case previously. As such, it is speculatively hypothesised that while the low power states of off, sleep and idle may deliver efficiency parity, alternative operating systems may require more or less power draw than Windows when subjected to human-computer interaction. Consequently, if proven to be the case, then organisations purchasing end user computing devices based on the existing benchmark electricity consumption results may be doing so because of unintentionally misleading information.

To test the theory, twenty-seven end user computing devices are measured for both electricity consumption (kWh) and active state power draw values (W), using the Energy Star test set up and conduct practices (see methodology and appendix). The value of capturing the kWh measurement is to compare the results to the published eTEC benchmark results. The rationale is threefold. Firstly, if equivalence between the data sets is coincidentally exhibited, then it is most likely that despite the active state requiring more power draw during the workday, the mode weightings associated with the benchmark and field data counteract the impact of human-computer interaction. Consequently, should equivalence prevail, it may be reasonable to conclude that the currently available benchmark data is sufficient for both sustainable device selection and to calculate scope 2 use-phase emissions as part of a sustainable IT reporting strategy. Secondly, if uniform incongruity is exhibited by a common increase or decrease in annual electricity consumption, then the potential to simply adjust the eTEC value either positively or negatively to acknowledge the active state becomes a possibility. Thirdly, if either equivalence or uniform incongruities are experienced, then due to the wide range of device types measured, the speculative notion that different operating systems react differently in relation to energy consumption is dispelled.

The value of also capturing the active state power draw (W) during the electricity consumption measurement phase is to enable identification of cause should neither equivalence nor uniform incongruence be revealed within the data sets. The rationale is to compare the field captured W values with the highest power draw mode measured during the benchmark test; this being the short idle mode when the computer is ready and waiting for human-interaction. In doing so, the difference in percentage terms between the Energy Star short idle result and the active state measured result can be calculated and the findings may support a trend associated with any given operating system.

As highlighted by table 2, neither equivalence nor uniform incongruence appears when examining the data as a whole. Specifically, examining all end user computing devices, the measured typical energy consumption results differ from the benchmark values by between -60% to +121% causing a disparity maxim of 181% (Sutton-Parker, 2020a). It is noted at this point that the erroneous comparative result of +1,192% is excluded from the discussion as all Energy Star mode and eTEC values published for this device appear as 1.1W within the documentation, which is clearly an error. The conclusion is based upon the fact that when used to complete the eTEC equation, the mode W values do not equal the published estimated typical electricity consumption value. While most certainly exact equivalence is never achieved, three devices or 11% of all devices measured do exhibit results that fall within +/- 10% of the benchmark eTEC value including two notebooks and one tablet. Of these devices, being the Surface Book 2 (+5%), the Latitude 5450 (+6%) and the Surface Go (-8%), all are installed with the Windows operating system meaning that when examined in isolation, 38% of the devices installed with Microsoft software achieved near equivalence.

Table 2. Energy Star eTEC (kWh) and Short Idle (W) compared to field measured results

Device	Operating System	Type	eTEC kWh/y	Watt Meter kWh/y	kWh Difference (%)	Energy Star Short Idle (W)	Watt Meter Active (W)	Watts Difference (%)
Acer CX-12	Chrome OS	Desktop	28.26	10.51	-37%	6.22	6.8	+9.3%
Asus Chromebox 4	Chrome OS	Desktop	26.1	11.14	-58%	5.1	6	+18%
Dell OptiPlex 7010	Windows	Desktop	128.8	64.73	-50%	31.04	34.9	+12%
Lenovo M700	Windows	Desktop	79.5	31.92	-60%	17.7	20.53	+16%
LG 24CN650N	Linux	Int. Thin Client	62.9	34.55	-45%	17.2	20.43	+19%
Acer 14	Chrome OS	Notebook	15.20	11.34	-25%	4.49	6.2	+39%
Acer 311	Chrome OS	Notebook	11.4	7.61	-33%	2.6	4.1	+58%
Acer 513	Chrome OS	Notebook	13.72	10.74	-22%	NA	6	NA
Acer 713	Chrome OS	Notebook	16.6	12.23	-26%	4.7	7.4	+57%
Acer 714	Chrome OS	Notebook	16.2	12.76	-21%	4.5	6.9	+53%
Acer R11	Chrome OS	Notebook	1.1	11.92	+1192	0.1	6.4	+6300%
Acer Spin 13	Chrome OS	Notebook	18.5	12.69	-31%	4.9	6.8	+39%
Apple MacBook Pro	Mac OS	Notebook	9	19.86	+121%	3	10.7	+257%
Asus C436FFA	Chrome OS	Notebook	13.1	9.47	-28%	3.2	5.1	+59%
Asus Flip C434T	Chrome OS	Notebook	15.4	9.56	-38%	4.4	5.15	+17%
Dell Latitude 5450	Windows	Notebook	18.65	19.72	+6%	6.05	10.63	+76%
Dell Latitude 7400	Windows	Notebook	12.6	21.12	+68%	3.7	11.38	+208%
Google Pixelbook C0A	Chrome OS	Notebook	6.1	12.62	+107%	0.1	6.8	+6700%
HP Elitebook 820	Windows	Notebook	15.7	27.38	+75%	4.7	14.75	+214%
HP x360 G1	Chrome OS	Notebook	16.6	11.65	-30%	4.8	6.28	+31%
Microsoft Surface Book 2	Windows	Notebook	21.2	22.32	+5%	6.6	12.02	+82%
Microsoft Surface Laptop 3	Windows	Notebook	11.1	21.2	+91%	3.5	11.42	+226%
Apple IPad Mini	Mac iOS	Tablet	8.6	3.62	-58%	2.3	2.5	+9%
Microsoft Surface Go	Windows	Tablet	12.8	11.74	-8%	3.3	6.33	+92%
Samsung Galaxy Tab S4	Android	Tablet	9.6	7.42	-23%	3.1	4.0	+29%
IGEL UD2	Linux	Thin Client	16.3	8.35	-51%	3.6	4.5	+25%
HP T460	Linux	Thin Client	37.9	17.52	-54%	8.7	9.5	+9%

Table 2 note: eTEC kWh/y and Short Idle (W) values are obtained via the Energy Star certified computer database (Energy Star, 2022). Watt Meter kWh/y and Active (W) are measured by Activity 1 using test set-up, conduct and equipment compliant with Energy Star (Energy Star, 2020). The kWh/y and Watts Difference percentages are generated by comparing the watt meter results with the Energy Star data.

To identify an obvious influence that may be causing the trait, two further field data points are examined. The first being the daily kWh measured values to identify if a specific occurrence, such as inconsistency during the 5-day period, is contributing to the results. As table 3 identifies, no anomaly is detected based upon the average deviance of 8% and the three devices exhibiting no extreme differences from one day to the next. Specifically, the Surface Book 2 registered 4.26% and the Latitude 5450 4.86% electricity consumption fluctuation during the five days, consistent with six further devices that did not achieve near equivalence. Similarly, the Surface Go experienced a 2% fluctuation consistent with a further four devices that did not produce results similar to the eTEC annual value.

Table 3. Daily field measured electricity consumption (kWh) and weekly deviance between results (%)

Device	Day 1 (kWh)	Day 2 (kWh)	Day 3 (kWh)	Day 4 (kWh)	Day 5 (kWh)	Average (kWh)	Deviance (%)
Acer CX-12	0.045	0.046	0.044	0.047	0.045	0.045	5.68%
Asus Chromebox 4	0.050	0.047	0.049	0.048	0.047	0.048	5.53%
Dell OptiPlex 7010	0.280	0.278	0.284	0.277	0.276	0.279	2.90%
Lenovo M700	0.140	0.138	0.137	0.137	0.138	0.138	1.82%
LG 24CN650N	0.150	0.148	0.149	0.147	0.151	0.149	3.07%
Acer 14	0.050	0.049	0.048	0.051	0.047	0.049	8.51%
Acer 311	0.032	0.032	0.031	0.034	0.035	0.033	12.90%
Acer 513	0.046	0.045	0.049	0.046	0.046	0.046	1.11%
Acer 713	0.053	0.052	0.054	0.051	0.053	0.053	5.88%
Acer 714	0.057	0.056	0.053	0.054	0.055	0.055	7.55%
Acer R11	0.054	0.048	0.049	0.052	0.054	0.051	12.50%
Acer Spin 13	0.054	0.053	0.057	0.055	0.053	0.054	7.55%
Apple MacBook Pro	0.083	0.086	0.084	0.086	0.089	0.086	7.23%
Asus C436FFA	0.041	0.043	0.040	0.041	0.039	0.041	10.26%
Asus Flip C434T	0.043	0.039	0.040	0.043	0.041	0.041	10.26%
Dell Latitude 5450	0.085	0.087	0.086	0.084	0.083	0.085	4.82%
Dell Latitude 7400	0.092	0.090	0.093	0.088	0.092	0.091	5.68%
Google Pixelbook C0A	0.056	0.052	0.053	0.055	0.056	0.054	7.69%
HP Elitebook 820	0.137	0.138	0.114	0.100	0.101	0.118	38.00%
HP x360 G1	0.051	0.049	0.052	0.048	0.051	0.050	8.33%
Microsoft Surface Book 2	0.098	0.094	0.096	0.098	0.095	0.096	4.26%
Microsoft Surface Laptop 3	0.091	0.092	0.091	0.091	0.092	0.091	1.10%
Apple IPad Mini	0.015	0.016	0.017	0.015	0.015	0.016	13.33%
Microsoft Surface Go	0.050	0.051	0.051	0.050	0.051	0.051	2.00%
Samsung Galaxy Tab S4	0.030	0.035	0.030	0.030	0.035	0.032	16.67%
IGEL UD2	0.036	0.040	0.034	0.034	0.036	0.036	5.88%
HP T460	0.076	0.077	0.076	0.076	0.073	0.076	5.48%

As near equivalence to the eTEC annual value is not due to coincidence caused by daily changes in electricity consumption the second field data point relating to the active state power draw value is examined. It is at this point that the three devices prove to share a relative commonality. The potential trend is not in relation to the field W value as this is 12.02W for the Surface Book 2, 10.63W for the Latitude 5450 and 6.33W for the Surface Go (table 2) and as such differs by as much as +90%. The similarity is highlighted by the difference between the Energy Star short idle mode value and the active state being 82%, 76% and 92% respectively. This indicates that it is feasible that when measured in standard business environment a device exhibiting an increase in W of approximately 80% when subjected to human-computer interaction will achieve near equivalence with the Energy Star annual estimated typical energy consumption value. Should this be the case then it is reasonable to speculate that achieving incremental increases or decreases to this threshold may deliver similarly consistent results.

To test the concept, the remaining secondary data and primary field measured W values are grouped by data sets depending upon the power draw increase experienced during the active state W measurement. These rise in 25% increments from zero through to the final group of computers exhibiting more than a 100% increase in power draw (table 4). It is noted at this point that the Acer R11 is excluded from the

results due to the previous reasoning. Additionally, the Acer R11 and Google Pixelbook too are excluded as again the short idle value is noted in the published documents to be less than the sleep variant and therefore clearly incorrect and subject to an typing error when uploaded by Energy Star. Examining the influence of the active state percentage increase, it becomes clear that as the active W value rises in percentage when compared to the Energy Star short idle W value a pattern of influence appears. Specifically, the 0-25% increase grouping exhibits a range of annual electricity consumption of between 37-60% below the associated Energy Star eTEC values for each device model. For the 26-50% grouping this reduces the gap between the two annual values to between minus 23-31%. The 51-75% group exhibits a similar range between minus 21-33%, whereas the 75-100% group is a previously described. For those computers producing results in excess of 100%, the influence to the eTEC comparison becomes incremental, raising the value by between 68-121%.

Table 4. Comparison of the active state and short idle mode and the impact upon achieving equivalence with the Energy Star eTEC value

	Operating System	Range 0-25%		Range 26-50%		Range 51-75%		Range 76-100%		Range >101%	
		eTEC %	Watt %	eTEC %	Watt %	eTEC %	Watt %	eTEC %	Watt %	eTEC %	Watt %
Acer CX-12	Chrome OS	-37%	9.30%								
Asus Flip C434T	Chrome OS	-38%	17%								
LG 24CN650N	Linux	-45%	19%								
Dell OptiPlex 7010	Windows	-50%	12%								
Asus Chromebox 4	Chrome OS	-58%	18%								
IGEL UD2	Linux	-51%	25%								
HP T460	Linux	-54%	9%								
Apple IPad Mini	Mac iOS	-58%	9%								
Lenovo M700	Windows	-60%	16%								
Samsung Galaxy Tab S4	Android			-23%	29%						
Acer 14	Chrome OS			-25%	39%						
HP x360 G1	Chrome OS			-30%	31%						
Acer Spin 13	Chrome OS			-31%	39%						
Acer 714	Chrome OS					-21%	53%				
Acer 713	Chrome OS					-26%	57%				
Asus C436FFA	Chrome OS					-28%	59%				
Acer 311	Chrome OS					-33%	58%				
Microsoft Surface Go	Windows							-8%	92%		
Microsoft Surface Book 2	Windows							5%	82%		
Dell Latitude 5450	Windows							6%	76%		
Dell Latitude 7400	Windows									68%	208%
HP Elitebook 820	Windows									75%	214%
Microsoft Surface Laptop 3	Windows									91%	226%
Apple MacBook Pro	Mac OS									121%	257%

Table 4 note: The eTEC % is the difference between the Energy Star (2022) kWh/y value and the field watt measured kWh/y value as indicated in table 2. The Watt % value is the increase in power draw from the Energy Star defined short-idle value (W) and the field measured active-state value (W). The five Range categories are created to group devices by the % increase in watts highlighted by the Watt % value. Organising the data in this manner enables the ability to examine if there is a link between the two outcomes.

The pattern of the increasing active state power draw influencing the annual consumption value arguably meets expectation. The greater the influences of human-computer interaction upon power draw, the greater the disparity will be with the benchmark annual consumption values and as noted, the eTEC calculation does not account for the active state. However, following such logic it was anticipated all field values would exceed the Energy Star benchmark as the active state will always require a higher

wattage than the low energy modes of idle and sleep and may therefore be significant enough to render the impact of the extended off mode weighting irrelevant.

Examining the eTEC and field annual electricity consumption data highlights that in fact only 22%, or six devices, exceeded the benchmark value. As noted, this is because the incremental influence of the active state remained below the discovered threshold of +80% and in some cases exhibiting just a 9% rise in power draw. What is perhaps equally surprising is that the data clearly identifies the majority of field results exhibiting a value lower than the published eTEC are produced by operating systems other than Microsoft Windows. In fact, within the 0-25% grouping 78% of the devices are either Chrome OS, Linux or Mac iOS. Of the two subsequent groups, 88% are Chrome OS and 12% Android with no Windows devices represented. Finally, to further substantiate the finding, it is also noted that five of the 6 devices that exhibit a higher annual electricity consumption value in the field are installed with Windows software, while the sixth has the Mac OS. As such, the data begins to substantiate that alternative operating systems do respond differently in relation to required active state power draw.

Examining energy efficiency in the field in isolation, it is apparent that the Chrome OS devices prove to consume the least electricity when used within the workplace (tables 2 and 3). As an example, of the seventeen notebooks all eleven Chromebooks exhibit a range of between 7.61 to 12.68 kWh/y, creating an average of 11.15 kWh/y. Comparatively, the subsequent five Windows and one Mac OS device consume between 19.72 to 27.38 kWh/y, creating an average of 21.93 kWh/y.

As such, it is reasonable to determine that the notebook devices installed with the Chrome OS operating system consume on average 49% less electricity in a business setting and when compared to legacy operating systems. Similarly, of the five desktop computers measured, the Chrome OS devices produced an electricity consumption average of 10.82 kWh/y compared to Windows devices producing an average of almost five times higher at 48.33 kWh/y. Because of the active state efficiency and the overall efficiency characteristics exhibited by the Chrome OS devices it is worthwhile examining device selection based upon sustainability criterion using both the field and Energy Star data sets. To determine if the outcome using the existing methodology is indeed misleading as speculated.

To achieve this, four of the devices are compared for suitability procurement selection. These include the HP Elitebook 820 representing a legacy device ready for replacement, plus the Microsoft Surface Laptop 3, Apple MacBook Pro and the Asus Chromebook Flip C434T representing potential new devices. To add a concomitant GHG context, the results are also converted into scope 2 emissions values using the UK factor (Dept. BEIS., 2021). According to the published Energy Star eTEC data, the HP Elitebook 820 legacy Windows notebook is indicated to consume 15.7 kWh per device each year (Energy Star, 2022). However, based upon the measured results that include the active state, the value is accurately determined to be 74% higher at 27.38 kWh per device (table 2). From a company scope 2 report perspective, the values would be considered as 3.33 $kgCO_2e$ when using the existing Energy Star methodology and 5.81 $kgCO_2e$ using the measured data.

Drawing the same comparison, a Microsoft Surface Laptop 3 Windows replacement notebook is indicated to consume 11.1 kWh per device each year (Energy Star, 2022) whereas when measured to include the active mode, the device consumes 86% more electricity, using 21.20 kWh per year (table 2). As such, applying the Energy Star data the device is represented to be 28% more efficient than the existing device and 23% improved based upon the findings. In this instance while the difference in efficiency gains is incongruent by only 5%, the reality that the device produces 4.5 $kgCO_2e$ per year when operated in the workplace compared to an anticipated 2.36 $kgCO_2e$ masks the device's true scope 2 environmental impacts.

Also proposed as a replacement device option, the MacBook Pro Mac OS notebook is indicated by Energy Star to typically consume 9.8 kWh per device each year (Energy Star, 2022). However, using the field data the annual electricity consumption value is accurately determined to be 103% higher at 19.86 kWh (table 2). The issue in this example is that the no-user present benchmark indicates the device is 48% more efficient than the existing HP notebook, although when operated in the workplace it is actually only 28% more efficient producing 4.22 $kgCO_2e$ compared to 5.81 $kgCO_2e$ for the legacy device. As such, while the efficiency gains represented by the Energy Star data suggest that the device far outperforms the Microsoft Surface notebook, the reality is that the two are almost identical in both electricity consumption and scope 2 emissions when measured in the field.

While selecting either of the previous devices based upon the Energy Star results would represent an albeit inaccurate but positive occurrence, the issue of excluding the influence of active state power draw when selecting new devices is best emphasised by the results produced by the Asus Chromebook Flip C434T Chrome OS notebook. In this example the published Energy Star eTEC is 15.4 kWh per (Energy Star, 2022). This value suggests to the buyer that the Chromebook is only 2% more efficient than the existing notebook, 39% less efficient than the proposed Microsoft device and 57% less than the Apple device. As such, it is reasonable to suggest the Asus Chromebook device would be excluded from procurement if the decision is based upon the Energy Star eTEC data. However, the field results determine that due to the low incremental power draw experienced during the active state of only +17% compared to +226% for the Microsoft device and +257 for the apple device, the actual annual electricity consumption is 38% lower than the benchmark data at 9.56 kWh (table 2). Consequently, based upon quantifying emissions including human-interaction, the Chromebook is in fact the most energy efficient of all four existing and proposed end user computing devices. Specifically, the resulting annual scope 2 emissions value of 2.08 $kgCO_2e$ is 65% lower than the existing HP notebook, 55% lower that the proposed new Windows notebook and 52% lower than the Mac OS option (figure 3).

Figure 3. Comparing Energy Star data and concomitant scope 2 GHG emissions with Activity 1 results
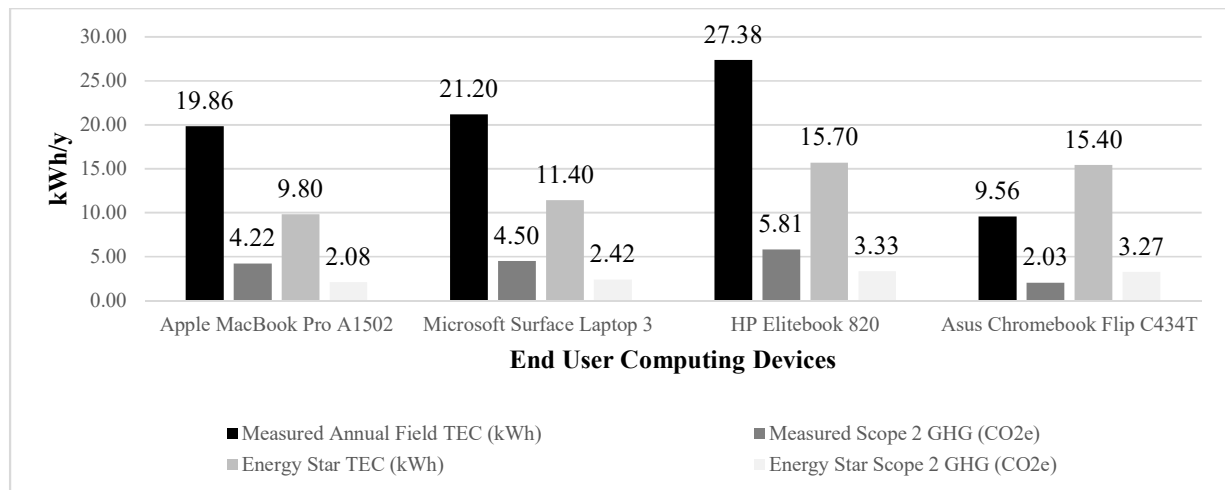
The procurement assessment scenario determines that despite having the highest Energy Star eTEC value of all replacement device options, when measured to include active use in a business environment, the Chromebook is contrarily the most energy efficient device choice of all (table 2) delivering a 65% total electricity consumption and concomitant scope 2 GHG reduction (figure 3). The findings

substantiate that should the Energy Star eTEC figures have been solely relied upon to assess devices for environmental impact criterion, of the three new devices the Chromebook would be determined as the least energy efficient. Consequently, the Apple device would be selected believing that a 48% reduction in scope 2 emissions had been achieved. Although in reality only 28% reduction would be experienced, and a further reduction of 37% dismissed due to the benchmark data.

Returning to the research question addressed by activity one, it is reasonable to conclude that the current end user computing use-phase energy consumption methodology does not accurately reflect device electricity use when subjected to human-interaction. The reality is that in 89% of cases the eTEC value will be inaccurate by a range of between -60% to +121% and in no instance was exact equivalence achieved. The reason for the feasible 181% incongruence is due to the influence of power draw during the active state when compared to low power modes such as short idle. The issue is further compounded by the substantiation that differing operating systems require differing power draw values to conduct useful work. An example is that the top eleven most efficient device results within the notebook category were populated by Chrome OS devices that achieved an average of 49% less energy consumption than similar Microsoft or Apple models.

As such, while a pattern emerges within the active state power draw incremental data, no simplified universal increment or reduction can be applied to the eTEC results to enable a valid or at least credible use-phase annual electricity consumption value that represents device use within the workplace. Because of the findings, activity 2 examines the exact cause of the additional efficiency exhibited by the Chrome OS devices. As highlighted by the Acer 14 achieving a comparative reduction of 25% based upon an active W increment of 39% while the Acer 713 achieves 26% based on an increment of 57%, it is reasonable to speculate the reduction is not attributed to the operating system in isolation. The hypothesis being that common components will also influence energy efficiency. As such, if identified to be the case, rather than ruling out a single universal increment that represents the influence of human-interaction, the answer to the problem may lie within series of rising increments based upon computer attributes such as the operating system and specific components.

4.2. Activity 2 Part 1 (RQ2): Can the influence of computer specifications upon electricity consumption contribute to forming universal active state power draw increments?

The results of activity 1 clearly identify that the alternative operating system is responsible for energy reduction. As not all reductions are equivalent, then further influence, such as component specification may also be contributing to efficiency gains. The value of proving this latter aspect may assist with regards to further refining the impact of the active state upon the idle value dependent upon a device's operating system and specification. Doing so may enable an algorithm to be formed that, while not a simple percentage uplift as anticipated, can be applied to the Energy Star eTEC equation to form an active state power draw value and therefore, with the inclusion of a proposed mode weighting, enable widespread quantification of commercial end user computing electricity consumption. As described in the methodology (Activity 2), the objectives are achieved by firstly re-purposing two of the originally measured Windows OS notebooks, being the HP Elitebook 820 and the Dell Latitude 5450 with Google's Chrome OS Flex software. As neither device has experienced any component changes, then any efficiency gain must be solely attributed to the new software. Secondly, having determined the percentage influence of the software, components included within the Chromebooks measured in activity 1 are documented to determine if a trend appears based upon common or increasing specification attributes. The concept being that an additional incremental efficiency percentage may be applied due to the inclusion of certain components such as low power memory or solid-state hard drives that require less power draw.

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 5). This equates to

5.81 kgCO$_2$e of use-phase GHG 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$_2$e. The Dell Latitude 5450 notebook when installed with a Windows operating system proved 28% more energy efficient than the equivalent HP device, consuming 19.72 kWh of electricity annually in the workplace and producing concomitant emissions of 4.19 kgCO2e. When re-imaged, this value reduced by 18% to 16.24 kWh (table 5) and emissions of 3.45 kgCO2e. 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 5. Device use-phase electricity consumption (kWh), scope 2 and 3 GHG emissions (kgCO$_2$e) results

End User Computing Device	Operating system	Average Daily Energy Consumption (kWh)	Annual Energy Consumption (kWh)	Annual Scope 2 GHG Emissions (kgCO$_2$e)	Supply Chain Scope 3 GHG Emissions (kgCO$_2$e)
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

Note table 5. The scope 3 supply chain emissions (kgCO$_2$e) data is sourced from product carbon footprint reports published by the manufacturer (Dell, 2022; HP, 2022; Microsoft, 2022). The scope 2 electricity emissions are produced using the research field kWh/y values measured in activities 1 and 2 multiplied by the UK GHG conversion factor (2020b). The HP Elitebook and Dell Latitude are shown with two data sets each. This is one data set for the original Windows operating system state and one data set further to being reimaged with Google Chrome OS Flex.

Google describes the efficiency capability, in the context of Chromebooks, as being attributed to the operating system being able to optimise device energy performance by focusing on efficient charging (Google, 2022b) although no further information exists beyond this statement. Examining the data from activity one and comparing energy consumption between new Microsoft and Chrome OS native devices, it is apparent that an average of 46% electricity consumption reduction is achievable by using Chrome OS. As such, it is reasonable to speculate that in line with research such as Boyd's examination of semi-conductor evolution (2012), while 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 activity 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 6). All fourteen devices are examined for key components including screen size, processor, hard drive and memory. Similarities common to all original manufacturer devices may become apparent when aligned with electricity consumption values.

Examining all device specifications clearly indicates 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 6, the additional efficiency is delivered by component differences including reduced thermal design power central processing units (CPU), embedded multi-media card (eMMC) storage and low power double data rate memory. Beyond the impact of the operating system upon the active state power draw (W), it is evident that those devices replacing a solid-state drive (SSD) with an eMMC storage component predominantly exhibit significant energy efficiency gains (table

6). As such, with the exception of the Acer 311, the devices consequently represent the five lowest active state power draw increases. The advantage being that the embedded storage requires approximately 85% less power draw to operate than the SSD drive at just 0.5 W (Samsung, 2022). The low power version of double data rate memory used in the Chromebooks requires a supply voltage of 1.1 V compared to the standard DDR memory used in the repurposed devices that requires up to 1.5 V (Electronic Design, 2015). As such, the impact is minimal in relation to the overall impact on power draw as highlighted by the HP x360 14 G1 Chromebook that experiences the second lowest active state power draw increase of just 31% yet utilises DDR4 memory.

Table 6. Device electricity consumption (kWh) and components comparison for Chromebooks and repurposed Chrome OS Flex devices

End User Computing Device	OS	Screen Size	Processor	Hard drive	Memory	Watt Increase
Microsoft Surface Laptop 3	Win	13.5	Intel® Core™ i5	256GB SSD	16GB LPDDR4	226%
HP Elitebook 820 Windows	Win	12.5"	Intel® Core™ i5	256GB SSD	8GB DDR4	214%
Dell Latitude 7400 Windows	Win	14"	Intel® Core™ i7	256GB SSD	16GB DDR4	208%
Microsoft Surface Go	Win	10"	Intel® Pentium® Gold	128GB SSD	8GB DDR3	92%
Microsoft Surface Book 2	Win	13.5"	Intel® Core™ i5	256GB SSD	8GB LPDDR3	82%
Dell Latitude 5450 Windows	Win	14"	Intel® Core™ i5	500GB SSD	4GB DDR4	76%
Asus C436FFA	Chrome	14"	Intel® Core™ i7	256GB SSD	16GB LPDDR3	59%
Acer 311	Chrome	11.6"	MediaTek MT8183	32GB eMMC	4GB LPDDR4	58%
Acer 713	Chrome	13.5"	Intel® Core™i5	256GB SSD	8GB LPDDR3	57%
Acer 714	Chrome	14"	Intel® Core™ i7	64GB eMMC	16GB DDR4	53%
Acer 14 CP5-471	Chrome	14"	Intel Celeron 3855U	32GB eMMC	8GB LPDDR3	39%
Acer Spin 13	Chrome	13.5"	Intel® Core™ i5	64GB eMMC	8GB LPDDR3	39%
HP x360 14 G1	Chrome	14"	Intel® Core™ i5	64GB eMMC	8GB DDR4	31%
Asus C434T	Chrome	14"	Intel® Core™ m3-8100Y	64GB eMMC	8GB LPDDR3	17%

Note table 6: Device specifications are extracted from the operating system settings>system menu. The Watt Increase % value is from results in Activity 1 comparing the increase between short idle power draw (Energy Star, 2022) and the field watt meter measurement (table 2).

Examining all device specifications clearly indicates 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 6, the additional efficiency is delivered by component differences including reduced thermal design power central processing units (CPU), embedded multi-media card (eMMC) storage and low power double data rate memory. Beyond the impact of the operating system upon the active state power draw (W), it is evident that those devices replacing a solid-state drive (SSD) with an eMMC storage component predominantly exhibit significant energy efficiency gains (table 6). As such, with the exception of the Acer 311, the devices consequently represent the five lowest active state power draw increases. The advantage being that the embedded storage requires approximately 85% less power draw to operate than the SSD drive at just 0.5 W (Samsung, 2022). The low power version of double data rate memory used in the Chromebooks requires a supply voltage of 1.1 V compared to the standard DDR memory used in the repurposed devices that requires up to 1.5 V (Electronic Design, 2015). As such, the impact is minimal in relation to the overall impact on power draw as highlighted by the HP x360 14 G1 Chromebook that experiences the second lowest active state power draw increase of just 31% yet utilises DDR4 memory.

Perhaps the most significant efficiency impact is evident within the Asus C434T device that exhibits the Chrome OS, eMMC storage, LPDDR memory and uniquely the Intel Core m3-8100Y CPU based upon the reduced thermal design. Equivalent in processing power to the non-reduced thermal design Intel Core i5 included in the repurposed devices and many of the other 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 m3-8100Y CPUs, as an example, require only 5W (Passmark, 2022).

While 79% of the devices have similar screen sizes (13.5" or 14"), screen size offered no apparent logical trend to explain power draw percentage increases. As an example, the Microsoft Go has a 10" screen and causes a 92% W increase from short idle to active. Comparatively, both the Microsoft Surface Go and Dell Latitude 5450 Windows devices have 13.5" and 14" screens yet produced 82% and 76% increases respectively (table 6). Similarly, the Chromebook with the smallest screen, the Acer 311 proved to generate the second highest power draw increase within the Chrome OS group at 58%.

It is feasible that should the Chrome OS operating system and common component types such as eMMC storage and reduced thermal design CPUs be identified during the Energy Star low power mode benchmarking process, an incremental percentage increase to the power draw could be applied to the short idle values to create an active state W value. The concept is that the impact of each efficiency component could be calculated to represent an isolated or cumulative increment, depending upon specification. Therefore, it becomes possible to extend the eTEC equation to consider the active state without additional mass testing or alternative field methodologies being required. While it is accepted that mode weightings would require determination based upon a valid percentage of time spent in the active state, the extended equation would resemble the following form:

Commercial Typical Electricity Consumption
$$= 8760/1000 \; x(P_{Off} \, x \, T_{Off} + P_{Sleep} \, x \, T_{Sleep} + P_{LongIdle} \, x \, T_{Lomgidle} + P_{ShortIdle} \, x \, T_{Shortidle} + \; P_{Active} \, x \, T_{Active})$$

In this example 'P active' represents the power draw exhibited when in the active state. The W value being derived by attributing proportional increases by cumulative common attributes. To achieve this in a rudimentary form, the results of activities 1 and 2 are applied to the short idle of each model which represents the baseline. Specifically, the results deduce that a combination of a Windows OS, standard CPU and SSD drive increases active state power draw by 150% as an average (table 6). Comparatively Chrome OS devices with similar specifications create an average increase of 58%. Combining Chrome OS with a standard CPU and an eMMC drive reduces the increment to 40.5% and introducing a TDP CPU reduces this further to an increment of just 17%. Obviously based upon the sample set being limited, to achieve accuracy and validity, further devices would require filed measurement to refine and prove the data. As an example, to provide parity in the process, Microsoft Windows devices with energy efficient components such as eMMC storage and TDP CPU must be measured.

However, returning to the research question posed by activity two, 'Can the influence of computer specifications upon electricity consumption contribute to forming universal active state power draw increments?' the answer is that this cannot be achieved with confidence. The pragmatic conclusion is drawn because although conclusive evidence is generated to substantiate the influence of operating systems upon efficiency, the influence of differing components remains inconsistent. The best example is that while the Windows devices exhibit an average of a 150% increase in active state power draw, the range is actually 78-226% offering limited evidence of congruity. The same applies to the Chrome OS devices with eMMC and standard CPUs ranging from 31-53%. While greater congruity is achieved with the latter devices a feasible error of 22% exists. As such, as the holistic goal of the research is to produce

meaningful data, then producing electricity consumption estimates for devices used in a commercial environment with an error range between 22-150% is arguably as limited in credibility as the existing methodology that utilises only low power mode data to calculate use-phase emissions. Consequently, it is concluded that the decision to test an alternative method of capturing end user electricity consumption data in the field is worthwhile.

4.2.1. Activity 2 Part 2 (RQ3): To what extent can greenhouse gas abatement be delivered by alternative computer operating system displacement strategies?

The objective of this research question is to challenge research suggesting that abatement gains associated with new device energy efficiency will outweigh the environmental value of extended device retention periods (Bakker et al., 2014; Boyd, 2012, Cooper and Gutowski, 2017; Deng et al., 2011; Prakash et al., 2016; Schiscke et al., 2003; Vadenbo et al., 2017; Wolf et al., 2010). This is achieved by the combined embodied emissions and on-going concomitant emissions of two new devices previously measured in Activity 1 being plotted against the continued impact of the scope 2 emissions of the repurposed devices from Activity 2 RQ3.

The new Microsoft Surface Laptop consumed 21.11 kWh of electricity per year (table 2) producing 4.48 kgCO$_2$e of use-phase emissions (table 5). 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. 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 (table 5). With respect to the embodied emissions, Microsoft states that producing the Surface 3 device produces 111 kgCO$_2$e of GHG emissions (Microsoft, 2022). In context of proportionate representation, based upon the measured electricity consumption values and extrapolated to an average retention period of 5-years, this indicates that when operated in the UK the notebook has a total carbon footprint of 133.4 kgCO$_2$e. This is represented by an 83% embodied emissions contribution and a 17% use-phase emissions contribution.

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 (table 2) generating 2.46 kgCO$_2$e of concomitant use-phase emissions (table 5). 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%. While significantly more efficient than the Surface Laptop, it is notable that the HP Chromebook has a 43% higher embodied emissions value of 195 kgCO$_2$e (HP, 2022). In context of proportionate representation, using the same approach as before, the total carbon footprint is therefore 207.3 kgCO$_2$e. This is represented by a 94% embodied emissions contribution and a 6% use-phase emissions contribution.

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 4). The rationale used for this is that annual values for the repurposed devices include only the on-going 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.

Figure 4. Cumulative GHG emissions (kgCO$_2$e) generated by end user computing devices
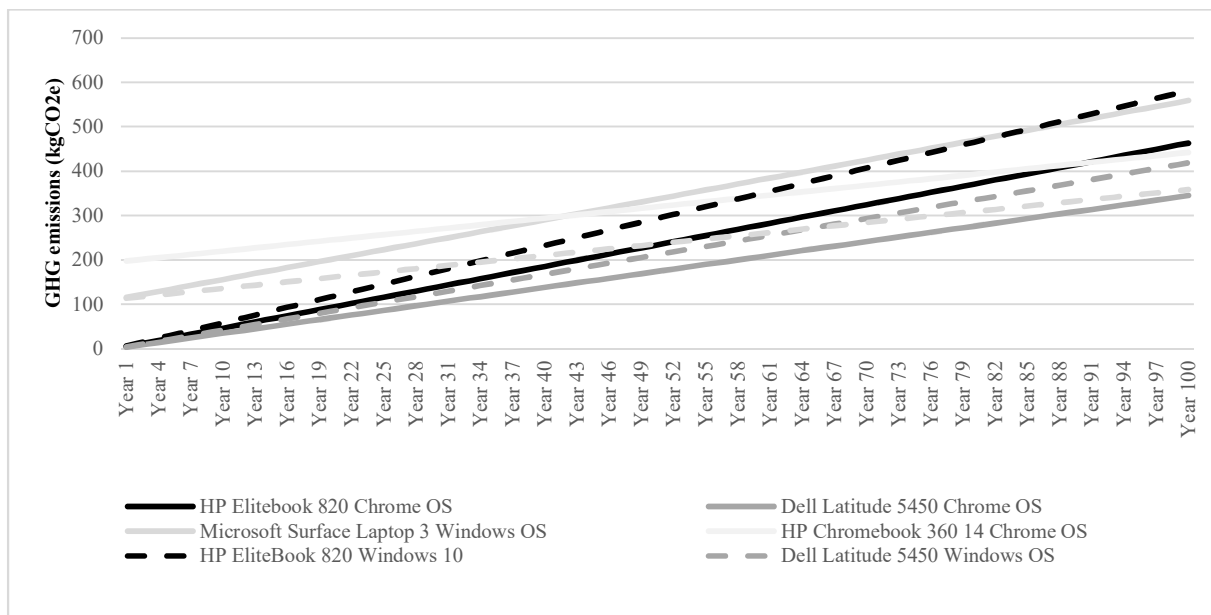
Note figure 4. The scope 3 supply chain emissions (kgCO2e) data is sourced from product carbon footprint reports published by the manufacturer (Dell, 2022; HP, 2022; Microsoft, 2022). The scope 2 electricity emissions are produced using the research field kWh/y values measured in activities 1 and 2 multiplied by the UK GHG conversion factor (2020b).

As highlighted in figure 4, the impact of embodied emissions is sufficiently significant 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, becomes equivalent to the least efficient repurposed device, the HP Elitebook. Notably, such is the improved 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. As such, 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 (Prakash et al., 2016 and Thiébaud et al., 2017) 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 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 on-going use-phase impact of the repurposed Dell device is not equalled in the first one hundred years of use. The exercise determines the existing perception that energy efficiency delivered by new device innovation counteracts abatement driven by extending the

useful device lifespan (Bakker et al., 2014; Boyd, 2012, Cooper and Gutowski, 2017; Deng et al., 2011; Prakash et al., 2016; Schiscke et al., 2003; Vadenbo et al., 2017; Wolf et al., 2010) is unfounded. With embodied emissions being the dominant source, sometimes as high as 96%, then rationally, where feasible the displacement of new procurement cycles is vital to successfully delivering reductions to societal emissions. Additionally, the exercise further emphasises the fact that even devices within the same device type category, such as notebooks, differ considerably in both scope 2 and 3 emissions values and therefore total carbon footprint. Combining the two outcomes further substantiates the importance of identifying devices with the lowest scope 2 and 3 emissions in order to make behavioural changes during both the pre and post purchase stages.

4.3. Activity 3 (RQ4): Can analytics software measure end user computing electricity consumption?

Activities 1 and 2 fail to produce evidence that a standardised incremental uplift can be applied to the idle mode power draw to generate a credible active state value. As such, activity 3 tests the concept of capturing end user computing device electricity consumption in the field using distributed node-based analytics software. The hypothesis is that, if successful, issues of scale and mobility that prevent extensive field measurement (Greenblatt et al., 2013) are overcome. This is because, unlike a watt metre, each node can be deployed and monitored globally from a centralised location and can move with the computer. As discussed in the methodology, activity 3 tests both the capability and accuracy of the software and as such the results are structured to reflect these two attributes.

4.3.1 Asset profile capture - quantity, type, model and user

The analytics software is capable of generating and compiling both computer asset and human use profile data sets required for computer electricity consumption calculation (Kawamoto et al., 2001; Roth et al., 2002). Capturing data from all one hundred and eleven instances it was noted that not all required fields were complete (table 7). All device model descriptions were complete, identifying seven brands, consisting of forty-six different device models. Notably, no categorisation was achieved for 10% of devices by type, with the remainder being made up from 4.5% tablets, 10% desktops and 75.5% notebooks. The user role field identified 17 salespeople, 6 corporate workers, 1 professional services consultant, 7 technical support representatives and 2 technical services engineers. As such, 78 (70%) of employee role types were simply listed as 'not collected'. Location was captured successfully in 90 instances across eight countries with the remaining registered as 'not collected'. Of the captured location data, 43% were based in the USA, 26% in the UK, 10% in India, 2.2% in each of the Netherlands, Poland, and the United Arab Emirates and 0.9% in both Israel and South Africa.

Table 7. Success and error percentages created by asset data collection results from the Systrack software

Data Set	Success Rate	Error margin
Device Model	100%	0%
Device Type	90%	10%
User Role	30%	70%
Device Location	80%	20%

Note table 7. The table highlights the data margin of error caused by the Lakeside Systrack analytics software not collecting specific information relating to the asset profile. .

Further to the findings it is notable that while asset data was captured for 100% of devices, the success rate of each metric suffered omissions. The 10% omission of type was discovered to be due to the

software application programme interface (API) accessing basic meta-information from the Microsoft Windows Management Instrumentation (WMI) database. The WMI stores definitions of products to work in conjunction with the Windows Driver Model (WDM) to allow for update and management of the device by acting as a repository of software drivers, applications and extensions available in the Windows operating system (OS). As the inventory data populates automatically using the WMI data when the analytics agent is installed on the device, then the issue of type omission would require to be addressed within the WMI and is therefore arguably surmountable. The issue of only collecting 30% of job roles was defined as the role based attributed not being defined within the company's active directory. Consequently, to improve accuracy simply updating the employee role details on the domain network would theoretically rectify the issue. Of location, no definite reason for 21% lacking in data although the hypothesis was suggested that users exhibiting this lack of granularity may be using internet protocol (IP) masking software therefore denying the function access to information identifying which country the device is being used in.

While it is anticipated that each omission may be overcome with additional focus, to gauge if the proposed analytics approach used within Lakeside represents an improvement to existing techniques, further asset profiling practices were undertaken at two different organisations using survey and asset management software as described in the methodology.

Specifically, a separate asset profile exercise using a questionnaire technique was undertaken at the University of Sussex. The organisation agreed to assist the research due to an interest in wanting to better understand the environmental impact of the current end user computing estate with regards to use-phase emissions. The technique proved highly time consuming from a creation process as it required sixty-eight specific questions to capture the required data via drop down, sliding scale and free type inputs. As the results were populated manually by the information technology manager, there was no ability to identify location of devices and only hardware supplied by the University could be included. As an example, it was not possible to account for any student owned devices used in the campus.

Further to completion of the comparative asset profile exercise at the University, the results identified 8,927 end user computing devices and 20,000 light-emitting diode (LED) displays. By type the devices were noted as 5,200 desktop computers, 1,840 integrated desktop computers, 960 workstations, 927 notebooks and 20,000 monitors. Excluding the monitors, the devices are dominated by 58% desktops, 21% integrated desktops, 11% fixed workstations and 10% notebooks. Specifically, due to the prominence of monitors within the University estate, the survey technique highlighted that the analytics software failed to capture peripheral devices such as displays. Upon further investigation, it was found that the initial analytics 'hardware' report includes a column indicating the number of monitors detected as connected to the device at any point during the measuring period rather than any associate make, model or size. Further to speaking with the analytics vendor it was explained that as the condensed SQL node requires an operating system to interface and as such reporting asset or power profile data for peripheral devices, such as monitors, was not achievable currently. Considering that 157 monitors are listed as connected to the devices profiled by the analytics software, the impact is significant as the resulting electricity consumption would be excluded from any calculations due to the lack of asset data.

Comparing the two practices, each suffers setbacks. The questionnaire technique lacks the automation of the analytics approach and cannot generate location context. Although from a positive perspective, the ability to include peripheral devices is arguably essential for complete representation of use-phase emissions. From a time to completion perspective, the lack of automation suffered by the survey method is partially passed on to the person tasked to populate the asset profile data as noted by the University IT manager:

'I think the survey was very easy generally. There were a couple of sections I had to go back over because I'd not appreciated the whole breakdown of areas so consolidated initially and then had to separate once I realised, but this wasn't bad and could be addressed by providing a list of the areas in advance. That would probably help anyway to be honest as there is a fair amount of info to gather which I happened to have but I'm guessing not everyone would.' – P. Collier, University of Sussex

The comment highlights however, that unless some form of asset list already exists then, unlike the analytics approach, the process may become unfeasible. Consequently, to offer an automated comparison to the analytics method, a second comparative asset profile process was undertaken using automated asset management software at a prosthetic limb manufacturing company, Ossur. The company is an active participant in the United Nations Global Compact working towards sustainable and socially responsible goals and, similarly to the University, wished to assist the research in testing viable methodologies. As asset management software called Lan Sweeper was already installed at the company, a similar Microsoft Excel file extension spread sheet was extracted using the software report structuring capability. As before, asset profile inputs such as quantity, manufacturer, model and location were generated with the exception of chassis (type) and role. This first exclusion was caused because the type of device, such as notebook, was not available within the report function as a criterion. To overcome this, a look up table was created to compare the captured device brand and model data with type data extracted from the Energy Star (2021) online data base.

With regards to role, it is feasible within the software, although similar to the analytics software the function had not been configured at the active directory level. To overcome this in the short-term, the captured location data was used to create role-based context. Although not conclusive, this was achieved because each Ossur site has a specific function such as manufacturing and clinics. As such, a further lookup was created to generate a 'role' defined by location column, including support, manufacturing and clinician. With the exception of the additionally created functions, unlike the survey method, the data extraction was instantaneous reflecting the time saving capabilities of the analytics solution. More importantly, the asset management software also identified peripheral devices such as monitors excluded by the analytics tool.

Specifically, the asset management software method identified 3,928 end user computing devices. Of these 30% (1,160 units) were desktop computers, 67% (2,643 units) notebooks, 1% (43 units) integrated desktop computers and 2% (82 units) workstations. A further 2,579 monitors were identified ranging from 14" mobile screens to 92" presentation and information displays. From a role perspective, 20% of devices were used by prosthetic, bracing and supports business units, 20% by clinicians, 14% by manufacturing and operations, 5% by research and development with 41% unable to identify a specific role. Location data was captured for 97.5% of the devices with only 95 devices indicating neither region nor country. Proportionately, the devices were located 62% in Europe, 32% in the Americas, and 6% in Asia and Pacifica.

Summarising the asset profile data capture capability of the analytics software it is reasonable to state that when compared to the existing methods of survey and asset management software it is certainly a more efficient approach in terms of time spent. Contrarily, it is also reasonable to suggest that having created the survey and the look up tables, this advantage diminishes when conducted for a second time. Undoubtedly, the survey method would fail if no prior records existed and as such the asset management software perhaps offers the ideal solution to populate the first half of the Kawamoto data flow. With regards to accuracy, to collect the key inputs of type, make, model, user and role analytics again outperforms both options from a granularity perspective by achieving the chassis categorisation and location without intervention. However, the oversight of not specifying peripherals such as monitors causes it to be flawed as such devices consume often higher electricity values annually than notebook devices. Specifically, in both cases of the University and the medical manufacturer monitors constituted

69% and 40% of all end user computing devices respectively. Although arguably not always utilised by mobile device users operating notebooks and tablets within an organisation, considering too that fixed thin clients, desktop and workstations cannot operate without a monitor and represent 14% of all devices manufactured, ignoring this category is not feasible if accuracy is sought.

4.3.2 Use profile data capture – power draw, on time

Unlike the survey methodology and asset management software practice, the analytics software has the ability to collect use profile data required to populate second half of the Kawamoto et al. (2001) data flow. Leveraging a distributed database architecture that is stored on the endpoint, the software captures thousands of end-user data points at five second intervals. The results are transmitted by networking technologies for compilation by a Microsoft SQL database operated by a master server situated either on-premise at the organisation's data centre or in a cloud computing data centre. The graphical user interface offers a configurable dashboard that when configured, enables selected metrics to be displayed either in summary or by detail such as a single user device at any selected time. Among the available metrics, the power reporting function captures power draw (W) per device and OT observed (hours and minutes) to generate the kWh calculation. As discussed in the methodology, this capability is effectively mimicking the actions of a watt metre without the restriction of being bound to a static power source. Consequently, the use profile data captured for the subject organisation's devices is examined for completeness and tested for accuracy. Data quality assessment is achieved by ensuring the use profile data generated by the organisation's workforce is complete and where appropriate the kWh data can be converted to display location specific use-phase GHG emissions. Accuracy is validated using a single user as a control subject measured by both a watt metre and the analytics software's power capability.

Data completeness was high with regards to capturing the use profile values as only 7% of devices were excluded. Examining these exclusions revealed that only the egress IP location had been captured suggesting that the device had been used at some point during the last year but not during the measurement period as this data is retained until refreshed. While not confirmed in this specific case, this may be because the devices are surplus stock awaiting assignment to new employees. Consequently, 103 devices reported power and OT observed metrics required to complete the electricity consumption (kWh) calculation. The power draw is represented as a W average value for the entire period. This ranged from 10W registered by an Apple MacBook Pro notebook to 145W for the HP EliteDesk 800 G5, which is a tower form factor desktop similar to a small server. This created an average power draw of 49W for the entire end user estate. The demand was elevated specifically by the desktop category, as would be anticipated due to the component architecture of the devices. As an example, the desktop power draw ranged from 59W required by a small form factor HP EliteDesk 800 G1, rising to the noted 145W, creating a desktop computer category average of 88W. Comparatively, the notebook estate ranged from the noted 10W value to 93W registered by a Dell Latitude 5285 convertible notebook. As such, the measured notebooks averaged 39.66W and 55% lower than the desktop estate. Examining the data from activity 1, the notebook values, in particular, appear relatively high adding emphasis to the examination of the control data discussed below.

The second metric of 'OT observed' is represented by a percentage of the 30-day period that the software node registers the computer as being used. As such, a 10% OT reading means that the device is used for 72 hours during the available 720-hour measurement period. Consequently, if the average power draw is 10W, such a device would require 0.72 kWh of electricity consumption for one month. As with the W value, all but eight devices registered OT ranging from 2.4% (1 hour 45 minutes) to 100% (720 hours). The average for all devices was 41.42% OT during the thirty-day measurement period. As the month in which the measurement occurred included twenty workdays this result indicated that the employees were either spending an average of almost fifteen hours per working day operating devices or that other factors were influencing use. These include the possibility of shared use, additional leisure use such as streaming, standard power management settings such as sleep being overridden or software inaccuracy. As accuracy is investigated thoroughly by the control device and leisure time and power

management are not tracked, shared use was examined. 10% of the devices exhibited between 90-100% OT raising the average value considerably. Of these devices, it was revealed that 64% were desktops operated by technical support in shifts that according to the organisation enable the support team to action requests twenty-four hours per day.

Applying the power average to the OT in the manner previously discussed produces a total of 1,592 kWh of electricity consumption by the end user computing estate. Specifically, the data determines that eleven desktops representing just 10% of all devices consumed 41% (657 kWh) of the measured energy due to a combination of high W values and extended OT as discussed. Comparatively, one hundred notebooks representing 90% of the estate consumed 59% (935 kWh). By location the UK consumed the highest value of 699 kWh (24 units), followed by the USA 585 kWh (39 units), India 66 kWh (9 units), Netherlands 29 kWh (2 units), Poland 19 kWh (2 units), the United Arab Emirates 23 kWh (2 units), Israel 21 kWh (1 unit) and South Africa 13 kWh (1 unit).

The representation by country as displayed in figure 5 allows for visual comparison as to the importance of location when determining use-phase emissions using national specific electricity conversion factors. The use profile data determines the UK to be the highest consumer of electricity even though it has 14 less devices than the USA operations. However, in terms of actual scope 2 emissions the USA proves to be the highest polluter.

Figure 5. End user computing use-phase electricity consumption (kWh) and GHG emissions (CO_2e) by country
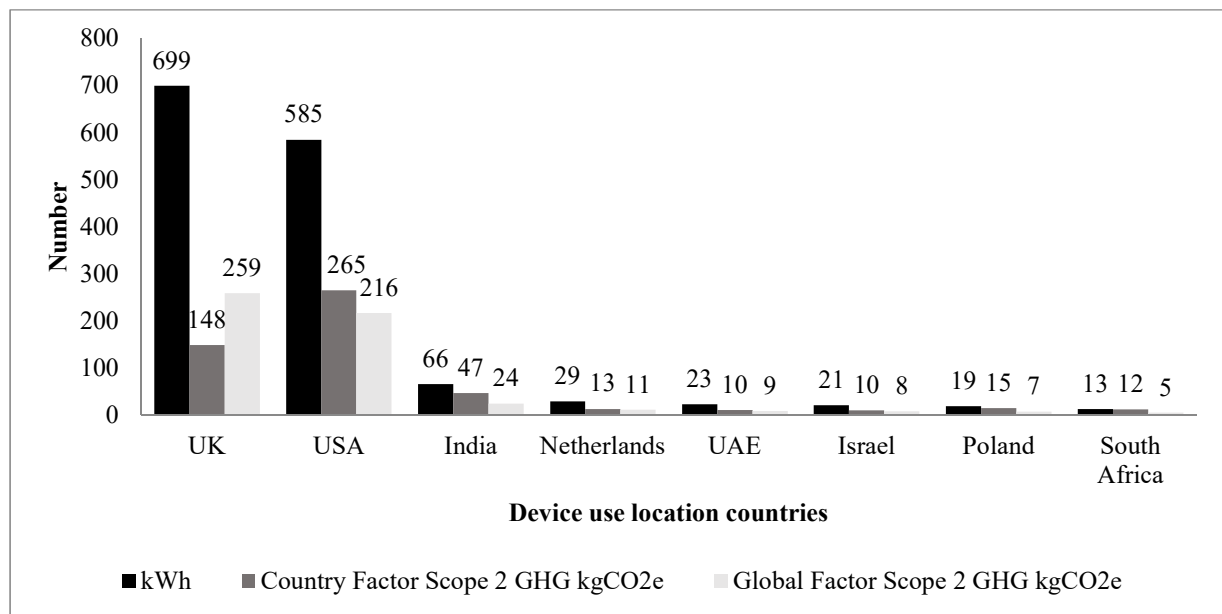
Note figure 5. The y axis is a unit numeric value for both kWh electricity consumed and GHG $kgCO_2e$ scope 2 emissions generated. The country factor scope 2 GHG value is calculated by multiplying the electricity consumption results from activity 3 by each appropriate country's electricity to GHG conversion factor (Carbonfootprint, 2020). The global factor scope 2 GHG value is created by multiplying the electricity consumption results from activity 3 by the global average electricity to GHG conversion factor (Carbonfootprint, 2020).

This is because, international renewable energy adoption is occurring at different rate depending on location. As an example, the global average for electricity production from renewable energy sources is 29% currently (IEA, 2022) and forecast to reach between 35-42% by 2030 (IEA, 2022). Comparatively, Europe has achieved over 38% (IEA, 2022) with 63% diffusion planned for 2030 (IEA, 2022). This is reflected in the recasting of the Renewable Energy Directive 2018/2001/EU (EU, 2018), the agreements

within the European Green Deal and to meet aspirations presented by the REPowerEU report (EC, 2022). To date, the US has achieved 21% renewable electricity supply mix (IEA, 2022) being 8% behind global adoption and 17% behind Europe (IEA, 2022). While an executive order exists stating renewable energy will reach 100% by 2030 (USEPA, 2021), the US Energy Information Administration (2022) indicates a most likely outcome is 44%.

To harmonise the impacts, a global electricity to factor of 0.37002 generated by the average of carbon factors derived from fifty nations currently participating in GHG accounting and reporting (Carbonfootprint, 2020) is applied to the results (figure 4). Consequently, the 699 kWh consumed in the UK rises to 259 $kgCO_2e$ scope 2 emissions. Comparatively, the 585 kWh consumed in the USA declines from 265 kgCO2e to 216 $kgCO_2e$.

4.3.3 Determining the accuracy of analytics software captured use profile data

Following the completion of the 30-day measurement period the control user results indicate that the analytics software overestimates electricity consumption (kWh) by an average of 48%. The range of error is between minus (+) 29% to 58% with minor anomalies of -100% caused by long period of 'off mode'. At a summary level, the accurate watt metre measured 4.25 kWh for the single device whereas the software measured 6.31 kWh of electricity consumed. To determine the source of the disparity, the two measured values used to generate the kWh result are examined for inconsistency. As noted in the use profile capture section, these values are the time spent in operation and the power drawn (W) during that period.

On Time observed

As noted, 'on time' (OT) is defined as the period measured in hours and minutes that the notebook is registered as drawing power and therefore consuming energy. Due to the 30-day duration of the experiment the highest feasible OT would be 720 hours (30 days multiplied by 24 hours). OT represents one of the key values used to calculate a kWh value. The results highlight that the watt meter reported a total OT measurement of 44.3% or 318.95 hours during the 30-day period. Comparatively, the software reported an OT of 40.8% or 293.76 hours. The results deliver an error of OT underreporting by the software of -3.5% or -25.2 hours. Divided by the time horizon, this suggests that the software is not reporting electricity consumption for an average of close to 50 minutes per day. To identify the source of the OT inconsistency, data relating to 'off' and 'sleep' modes were examined.

'Off Mode' is defined (Energy Star, 2020) as when the power consumption level in the lowest power mode which cannot be switched off (influenced) by the user and that may persist for an indefinite time when the appliance is connected to the main electricity supply. In context, off mode is achieved when the user has shut down (not sleep mode) the notebook yet it remains plugged into the power source. In this state no 'OT' should be registered by either the watt meter or the software. The results indicated that the watt meter did not register any OT when the notebook was in off mode. It was however noted that a minimal draw of 0.005 kWh was recorded for a 24-hour period. Reversing the kWh equation indicates that 0.2W 'trickle feed' of electricity occurs when the notebook is in off mode as the battery experiences a minor energy discharge. The standard Energy Star benchmarks are calculated with 'off mode' assumed as 25% of annual use profile. Using this mode weighting and the experiment results, the watt meter measured value would be 0.456kwh per annum. The official Energy Star published benchmark results for the HP Elite Book notebook is 0.2W draw and 0.438kWh. Consequently, the watt meter results confirm that the source is 100% accurate for reporting 'OT' in 'off mode' and 96% accurate with regards to kWh measurement when extrapolated and compared to the typical energy consumed benchmark.

Comparatively, the software also correctly measured no 'OT' when in the 'off mode'. However, it was noted that the software also measured neither power draw nor energy consumed. The impact of the software not reporting 'off mode' electricity consumption creates an underreporting disparity ranging from zero to 2% maximum depending on the duration of 'off mode' weightings. As an example, the maximum off time that could be attributed to the experiment's measured 30-day period is 55.7% or 16.7 days (401 hours). As such, the total energy not measured by the software in this instance is equal to 0.0835 kWh or 1.9% of the total energy consumption measured. However, as the test set up and conduct methodology includes a requirement for the notebook to be placed into sleep by the Energy Star governed power settings, there is no influence on the results of this experiment. In relation to 'Time' reported during off mode, it is reasonable to state that both the software and watt meter are 100% accurate and therefore this metric does not contribute to the 48% kWh disparity.

Having discounted 'off mode' as the source of error, the 'sleep mode' results were examined. 'Sleep Mode' is defined as a low power state the computer enters automatically after a period of inactivity or by manual selection. As determined by the methodology the sleep mode was set to initiate automatically after 20 minutes for the predominant duration of the experiment. Exceptions did occur including setting the notebook to sleep instantly at night and as described below to test the software capability. The results indicated that the watt meter registered 90 minutes of OT during a 24-hour period when the notebook was in sleep mode consuming a maximum of 0.020 kWh per full day. The standard Energy Star eTEC benchmark results are calculated with 'sleep mode' assumed as 35% of annual use profile. Using this mode weighting and the experiment results, the watt meter measured value would be 0.895 kwh per annum. The official Energy Star published benchmark results for the HP Elite Book notebook (the equipment under test) is 0.3W draw and 0.919 kWh.

Consequently, the watt meter results confirm that the source is 97.4% accurate with regards to kWh measurement when extrapolated and compared to the typical energy benchmark and within the accepted 5% error range. Comparatively, the software measured zero 'OT' during sleep mode and no associated power draw or electricity consumption causing it to be determined unresponsive and therefore inaccurate for all periods of time spent in sleep mode. As the OT registered by the software is 40.8% and the methodology dictates no 'off time', this finding indicates that the notebook entered sleep mode for a maximum of 59.2% of the experiment's duration. This period is equal to 426 hours and 14 minutes. The watt meter indicated that for each hour the notebook spent in sleep mode 3.83 minutes were classified as OT as the notebook was drawing a minimal amount of energy. Combining the mode and duration values indicates that 26.64 hours of 'OT' has occurred but not been reported by the software due to sleep mode. Consequently, if the OT measured during sleep mode by the watt meter is added to the software OT reading, the result is 320.16 hours of OT and is correct to within 0.37% of the watt meter 'Time' reading. As such, it is reasonable to state that the time disparity between the two data sources has been identified and explained.

Power Draw

While the difference between 'OT' values was satisfactorily addressed, the finding did not correct the 48% energy consumption (kWh) disparity generated during the experiment. Contrarily, if the additional kWh generated by the extra OT generated by sleep mode (0.1278 kWh) were added to the software results then the disparity would rise a further 3% to 51%. As such, the second key value of power (W) was examined for inconsistency. Having determined that time reporting was consistent between sources to within an error of -7.9%, and that the watt metre was accurate within less than 3% compared to published TEC results, theoretically the over reporting error must be caused by inflated W readings. As figure 5

shows the kWh daily reading from both sources is relatively consistent in its disparity across all 30 days. Both data sets follow one another's peaks and troughs across the experiment's time horizon as content switching fluctuated the power draw as various components worked at varying paces. The only exceptions to this are shown on two weekends (days 21, 22 and 28, 29) when the notebook was used for a very limited (and in some cases not at all) period. In these examples the sleep mode kWh reported by the watt metre exceeded the zero kWh noted by the software as previously validated. Consequently, it is clear that the power draw (W) is being over reported by the software by an average of 51% per day when the four anomalous days were excluded. The full range of error was between +48% and +58%.

As the uniform disparity became obvious from the results generated in the first week a one-day test measure was introduced for the 8th day in the hope that the results generated might indicate to source of the error. As such, specific short-term changes were introduced to the test set up and conduct. Specifically, for the duration of day 8 only (figure 6), the power options on the notebook were altered from those described in the methodology to the following:

- Turn off display when plugged in = Never

- Put the computer to sleep = Never

The rationale for the changes being that the notebook would remain in an apparent active work state for 24 hours even after the user interaction had ceased. The results would list both the power requirements during working hours when content switching occurred and during the time that the screen was left active but resting during non-working hours (when no content switching occurred). Consequently, anomalies during either active or resting OT period may offer clues to the problem.

Figure 6. Energy Consumption (kWh) Measurement by Source (watt metre and software)
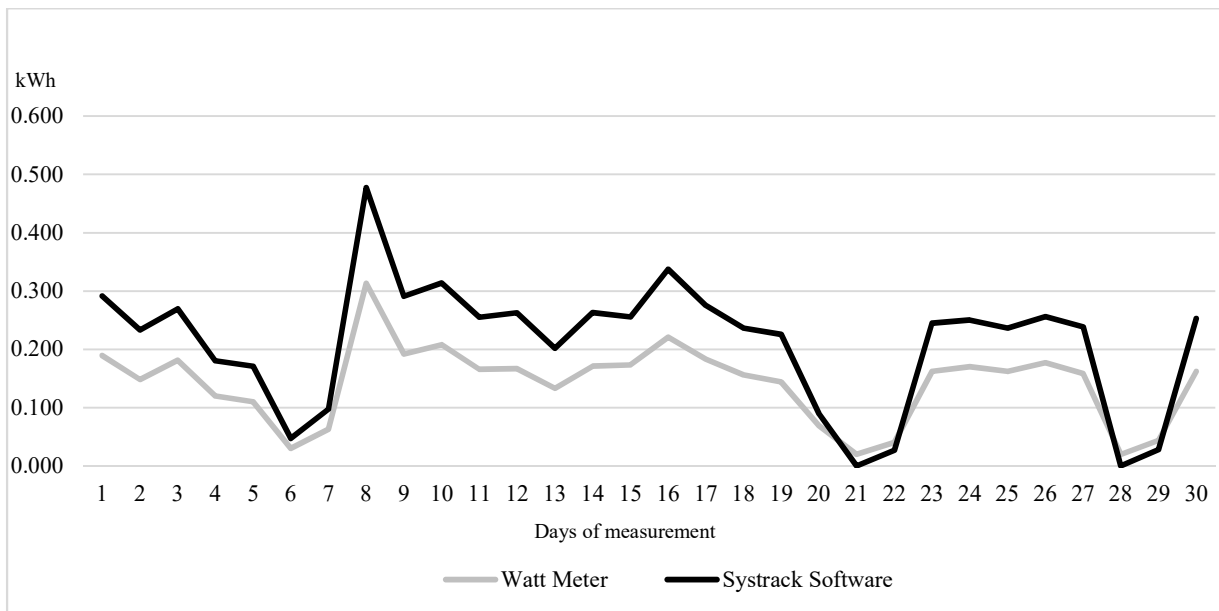
Note figure 6. On day 8 the power management options on the notebook were intentionally altered from those described in the methodology to the following: turn off display when plugged in = Never and Put the computer to sleep = Never.

The results for day 8 highlighted that the as expected the OT reported by both the software and watt metre was exactly 24 hours and therefore correct. This further validated that the software is accurate with

regards to OT measurement. During the 9 hours when the notebook experienced user interaction the kWh inaccuracy rose to 63%. Comparatively, during the remaining 15-hour period of the notebook being active but without user interaction, the kWh inaccuracy was lessened with a disparity of 46% when compared to the watt metre readings. Examining the W results for the inactive period revealed that the software recorded a near constant reading of 19W whereas the watt metre recorded 13W. As such it is reasonable to state that when the notebook is in idle or long idle mode (represented by the inactive period) the software is uniformly inconsistent by 46%. Examining the W results for the active 9-hour period revealed that the software recorded a range of 19W to 26W. Comparatively the watt metre ranged from 13W to 27W. At the lower end, the results reflected the inactive period results as expected.

However, it was notable that the high-end readings became almost equivalent in some instances. This suggested that either the frequency of measurement, changes in user tasks or a combination may be causing the issue. If the watt metre reports in real-time, then the equivalence may only last for one second yet could theoretically be measured by the software for a longer period causing a great disparity. Before examining the method of measurement used by both sources the impact of user tasks on the W readings was examined (figure 6). Both lowest (L) and highest (H) W readings were noted (figure 7) during four tasks including logging on (powering on), resting (with applications open), productivity (email, documents, spread sheets) and video conference calls. The watt meter exhibited as total range of 107% and the software 37% creating a difference of 70% range during the active period. Specifically, the two sources lowest to highest (figure 6) readings ranged across the four tasks as follows:

1. Power On
   a. Watt Metre   32%
   b. Software   24%
2. Resting (Applications running)
   a. Watt Metre   8%
   b. Software   5%
3. Productivity
   a. Watt Metre   57%
   b. Software   37%
4. Video Conference
   a. Watt Metre   93%
   b. Software   9%

The disparity in percentage ranges generated by the W results indicated that the two sources were using different methods of data capture. As an example, the 84% range disparity attributed to video conferencing is a result of two factors. Firstly, the rapidity of content switching driving the W requirement changes, as people interact via audio, video and screen presenter ownership. Secondly, the likelihood that only one of the two methods of measurement is able to keep pace. To substantiate the hypothesis, the method of W data capture was examined for both the watt meter and the software.

As expected, the watt meter updated the change in power draw (W) in real time as the user switched tasks, rising and falling as applications, video calls and web pages were opened, utilised and closed or left to rest.

Figure 7. Task impact of W required showing the lowest and highest measured values (W)
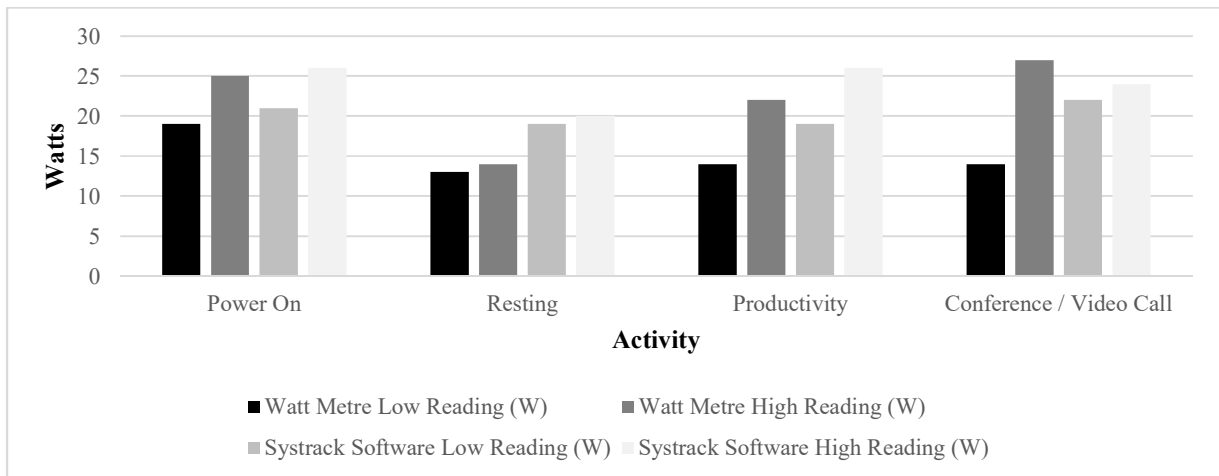
Monitored by filming the changes for two hours during a working day, it was noted that the watt metre W value altered on average every three seconds as content interaction or focus changes. Comparatively, the Lakeside software reports measurements every five seconds obtaining power and energy consumption data by querying the hardware bios counters. The data points are then reported as an average power rating in W and a total energy consumption figure in kWh for consecutive ten-minute periods during 'OT'. As such, it is true to state the following:

- For a single data capture conducted at 5 second intervals by the software, the watt meter will between 1 or 2 power (W) readings. As such the regularity of data snapshot by the watt meter is feasibly 2:1 compared to the software.
- For each ten-minute average W measurement reported by the software, the watt meter will have conducted a minimum of 200 calculations compared to the software's 120 readings

It is reasonable to conclude that the software undertakes approximately 40% less W readings per day than the watt metre and this may cause increased margins of error if the components being measured are subject to content switching. As an example, during the 15-hour non-interactive period this had no effect as the power requirements did not fluctuate during the 3 second watt metre reading internal and the 5 second software interval. However, during the 9-hour active period the rapidity of power fluctuation driven by content switching caused the resulting kWh calculation to increase in disparity by a further 17% when compared to the inactive period. As the 'active OT' period experienced during day 8 represented 37.5% of the 24-hour period, the overall disparity was increased by 7% to +53%, registering energy consumption of 0.478 kWh by the software versus 0.313 kWh. As content switching is random with no day exactly matching another in tasks undertaken or duration it was deemed highly unlikely that examining whether the duration (percentage) of 'OT' would uniformly affect the kWh disparity. As figure 8 highlights this was proven to be the case as the lines generated by the OT and kWh disparity do not track one another and instead often cross over with one value exceeding the other.

As an example, days 23, 27 and 30 all registered 52% OT (figure 8), yet they have an energy consumption disparity between the software and the watt metre of 49%, 51% and 56% accordingly (figure 6). In the first two examples the results appear promising that there is a correlation, however the third day

questions the validity of the statement. Examining the OT results, notes and calendars for the three days, reveal that days 23 and 27 were spent working on research documents for the majority and therefore similar tasks were undertaken explaining the uniformity of the disparity in both OT and energy consumption.

Figure 8. On time (OT) vs. kWh disparity
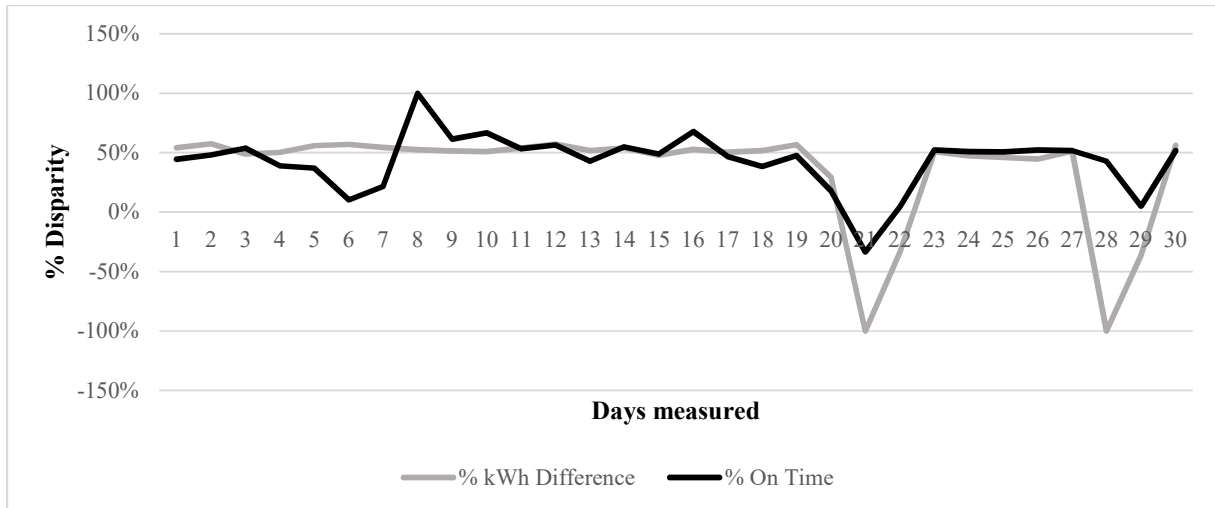
Note figure 8. As previously noted days 21, 22 and 28, 29 are weekends when the notebook was used for a very limited time.

However, day 30 was spent viewing online training videos and participating in conference calls. Consequently, the tasks undertaken were evidently driving up the disparity due to the rapidity of content switching, despite the identical OT. As such, it is fair to state that while the active OT certainly influences the overall kWh measurement it is the duration of time spent during this mode undertaking specific tasks that dictate the range of increased over estimation.

To summarise the findings of the accuracy test, it is clear that the software is with substantial error in relation to measuring notebook energy use. Therefore, without compensatory measures being introduced to the calculations to generate concomitant GHG values for the proposed application, the emissions reporting will also be incorrect.

As the experiment identifies there are four specific factors that are causing the inaccuracy:

- A 46% uniform over reporting of kWh energy consumption during 'OT' (figure 8)
- An average additional 5% over reporting of kWh energy consumption during 'OT' generated by user content switching outpacing the measurement intervals
- A zero kWh value measured during 'off mode'
- Zero OT recording during 'sleep mode' causing minor associated energy consumption to be excluded

These findings were discussed in depth with the analytics software manufacturer by video conference in an attempt to validate the causes suggested by the results. The engineering experts suggested that the uniform over reporting was most likely due to the fact that the software algorithmic tables that are used for component energy consumption had not been updated for several years. They explained that when the analytics software was originally conceived the tables were based upon mechanical hard drives (Sutton-

Parker, 2022b). As the device used in the test had a solid-state hard drive which would require fewer W to power then this would cause the erroneous but uniform disparity. They accepted that the additional 5% over reporting due to content switching causing a lag in results due to the real time reporting of the watt meter and the software would be an issue during active user time. The zero kWh value measurement during off mode and the zero OT during sleep mode were also accepted as a minor issue that could not be overcome. The positive response was that based upon this research, Lakeside would re-examine their algorithms for component parts and bring them up to date to cope with the introduction of solid-state storage and similar modern innovation. Doing so may overcome the main issue of the 46% over reporting although this would require further research.

4.4. Activity 4 (RQ5): Is sufficient carbon footprint information available to make sustainability focused computer procurement strategies meaningful?

As previously discussed, end user computers are already subject to international environmental certification (EPEAT, 2022; EU, 2022a; TCO, 2022; Energy Star 2020) and legislation (EU Law, 2009; CAER, 2021; US Gov., 2021; EC, 2021a; DEFRA, 2020) ensuring both sources of emissions are limited through environmentally conscious design and production. Theoretically, such frameworks reduce the total product carbon footprint of devices purchased by organisations by created a layer of control at the manufacturing level. Associated national and regional level policies also exist to ensure that organisations assess and procure devices with the lowest carbon footprint (US Gov., 2021; EC, 2021a; b; DEFRA, 2020). However, it is noted that as the policies are based upon devices bearing third-party certification (EPEAT, 2022; Energy Star, 2022) then it is entirely feasible for high environmental impact devices to enter the supply chain due to the range of carbon footprint allowed by the programmes. The example given was that the Microsoft Surface Laptop 3 has a published total carbon footprint of 138 kgCO_2e (Microsoft, 2022) compared to 809 kgCO_2e attributed to a Lenovo ThinkPad P51 (Lenovo, 2022). While both meet the labelling criteria, the latter has a carbon footprint six times that of the former. As such, to look beyond the third-party certification schemes and generate meaningful data that may achieve behavioural changes capable of significant abatement, the research question, 'Is sufficient carbon footprint information available to make sustainability focused computer procurement strategies meaningful?' is addressed in activity 4. The value being that if data sources are limited, complex or misleading then comparison may not be conducted with parity and incorrect conclusions made.

To achieve the research objective, as detailed in the methodology, a significant and unbiased data pool of end user computing devices is generated during six asset profile exercises using techniques developed in activity 3. Secondly, it is attempted to locate the associated product carbon footprint reports from manufacturer websites for each unique model discovered. Where reports do exist, information and data points such as the methodology used to produce emissions data, scope 2 and 3 emissions values, number of years included within the use-phase calculations, annual typical energy consumption values and electricity to GHG emissions factors are documented. The outcomes are then discussed in context of availability, methodology and subsequent parity between brands, plus the impact this may have upon realising meaningful sustainability focused computer procurement strategies.

Of the 71,990 end user computing devices profiled (table 8), 56% (40,456 units) are computers and 44% (31,534 units) are displays, meaning that the ratio is 1.3 computers for every monitor (table 8). In total, 42 different brands are represented by 707 unique device models. The variety of manufacturer brands is lower within the computer category, being 11, while the display category includes 36. As explained below this incongruity influences both the number of unique models in each category and the availability of product carbon footprint data. Specifically, 70% (495) of the models are generated by the

displays, indicating that on average each brand is responsible for fourteen variations of monitor. As such, 30% (212) appear within the computer profile data creating an average of nineteen models per brand.

Table 8. Asset profile data captured and available carbon footprint data by computer type

| Computer Type	Units	Unique Brands	Unique Models	% of Total	Available CFP data (%)	Scope 2 Contribution (%)	Scope 3 Contribution (%)	Total CFP Range (kgCO$_2$e)	Feasible Abatement Per Device (kgCO$_2$e)
All devices	71,990	42	707	100%	22%	23%	77%	63-2,867	585
Computers	40,456	11	212	56%	51%	27%	73%	63-2,867	581
Displays	31,534	36	495	44%	10%	18%	82%	290-881	591
Static computers	22,931	8	61	32%	44%	38%	42%	63-2,867	594
Desktops	17,321	6	42	24%	36%	35%	65%	278-782	504
Integrated desktops	3,354	4	8	4.8%	88%	35%	65%	489-878	389
Thin clients	855	2	3	1.2%	33%	53%	47%	63-197	134
Workstations	1,401	3	8	2%	50%	53%	47%	389-2,867	2,478
Mobile computers	17,525	8	151	24.3%	54%	14.2%	85.8%	75-731	565
Laptops	16,923	8	139	23.5%	53%	14%	86%	149-731	582
Tablets	302	2	3	0.4%	100%	23%	77%	75-135	60
Mobile thin clients	150	1	1	0.2%	100%	9%	91%	295-355	60
Mobile workstations	150	3	8	0.2%	50%	23%	77%	390-539	149

Note table 8. Units represent the number of devices identified although the carbon footprint data is available for only 22% of devices as noted. Unique brands and models represent different brands identified during activity 4. The % of the total is the proportional representation of each device type. CFP is an abbreviation for carbon footprint. Scope 2 and 3 are the percentage contribution of each scope to the product's total carbon footprint. Carbon footprint data is retrieved from manufacturer carbon footprint reports as explained in the methodology. The Total CFP Range is the lowest to highest product carbon footprint value identified for each device type. The feasible abatement is the lowest total CFP range deducted from the highest. The rationale being that selecting the same device type with the lowest carbon footprint will abate this value of emissions.

4.4.1 Carbon footprint data availability

The computer category is unsurprisingly dominated by Apple, Dell, HP, Lenovo and Microsoft, considering that the companies collectively supply over 73% of the world's end user computers (Gartner, 2021; Statistica, 2020; 2021). As all five brands produce product carbon footprint reports, the availability of data proved to be 51%. The limiting factors preventing a higher success rate were twofold. Firstly, participating companies focus on publishing data for only the most popular models. As an example of best practice, Apple and Microsoft publish reports for 100% of computer product models while the remainder achieve between 53-74% (figure 9).

Of the 104 Lenovo models, 55 associated reports were located resulting in quantification of 53% of the device variations. In context, Lenovo produces 27% of global personal computers (Gartner, 2021; Statistica, 2020; 2021) and as such has a far wider portfolio than, for example Apple, that supplies 9% of end user computing devices (Gartner, 2021; Statistica, 2020; 2021). As such, the proportionate availability could be judged as reasonable considering the myriad of models produced by Lenovo. To justify this opinion, it is worth comparing the outcome with the second and third placed global suppliers. Attaining 20% of global sales (Gartner, 2021; Statistica, 2020; 2021), a similar outcome is experienced in relation to HP with 12 (57%) of the 21 models quantified. However, Dell with a 17% market share excels by enabling 74% quantification, publishing 29 reports for 39 models. As such, it is reasonable to suggest that while the perfect solution would be to publish 100% of reports as Apple and Microsoft do, an availability benchmark of almost three quarters is achievable even at scale. The second limitation was simply due to non-participation in the production of product carbon footprint reports.

Figure 9. Percentage of available product carbon footprint reports vs. global market share
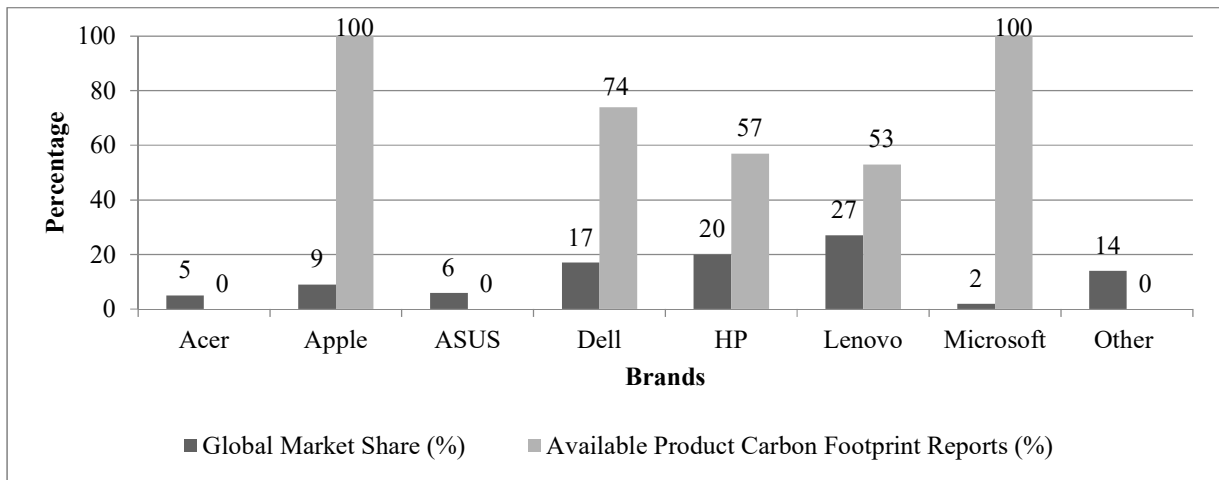
Note figure 9. The figure compares the percentage of available product carbon footprint reports identified by activity 4 together with each manufacturer's global computer sales market share (Gartner, 2021; Statistica, 2020; 2021). 'Other' represents companies that represent less than 1% of market share and do not produce product carbon footprint reports.

Specifically, companies such as Acer and Asus that collectively supply over 11% of the world market do not produce relevant data. This behaviour causes 12% of the profiled computers to be excluded from scope 2 and 3 quantification. Combined, it is therefore reasonable to determine that even before examining data validity and parity, organisations wishing to introduce sustainability as a criterion for computers during the assessment and procurement phase will fail to do so for almost half of all available computer models.

Comparatively, within the display category, the increased number of brands that do not produce product carbon footprint information reduced the available data further to just 10%. Of the thirty-six manufacturers it is determined that only four consistently produce carbon footprint reports including computer companies Dell, HP, Lenovo and electronics manufacturer Philips. However, these manufacturers also limit the number of models included in the process further narrowing available information. As an example, HP produced only 8 (10%) carbon footprint reports of the seventy-eight identified display models. Philips raises the success rate marginally to 13%, producing three reports for twenty-four models. Of the eighty-four Dell models identified, 24 reports were available resulting in 29% quantification, while Lenovo's thirteen reports produced for the thirty-four models generated the highest outcome of 38%. As such, it is reasonable to suggest that participation is higher within companies involved in predominantly computer or joint computer and display manufacturing compared to brands focusing in isolation on producing displays. Specifically, removing Dell, HP and Lenovo from the results based on the fact that these manufacturers also produce displays, it is reasonable to state that, only one display manufacturer, Phillips, produces product carbon footprint reports. Considering that displays represent 44% of the end user computing estates profiled, this indicates that displays not produced by leading computer manufacturers cannot be quantified nor assessed for sustainability criteria.

Consequently, combining the findings it proved feasible to source and quantify the potential carbon footprint for just 22% of all end user computing devices (table 8). Setting aside popular model limitation, the availability issue is predominantly driven by the fact that 86% of the identified manufacturers do not currently produce product carbon footprint reports. These include Acer, AGN, AIC, AOC, Asus, Aures, AVD, Benq, B&R Industrial Automation, Eizo, ELO, Gigabyte, GVT, Hyundai, IGEL, Iiyama, ITE,

Kenowah, Kogan, KVM, LG, Medion, MSI Optix, NEC, Peaq, Planar, Ricoh, Samsung, TCL, Toshiba, Viewsonic, Viglen, Viotek, Vizio, WAC and WDT. As such it is reasonable to state that 78% of end user computing device models captured during the asset profiling exercise do not have available data that would enable identification of computers and displays with a low carbon footprint.

4.4.2 Carbon footprint data parity

Of the six companies publishing product carbon footprint reports, the variety of methodology and representation of data further exacerbates the prospect of valid comparison between brands and even models of the same brand. This is caused by three different approaches used to calculate scope 3 emissions and while scope 2 emissions are all derived from the same electricity consumption source, a lack of uniformity applied to influencing factors and subsequent calculations, causes the data to become incomparable.

Whereby all six companies follow the standardised life cycle assessment (LCA) input and output framework (ISO, 2016), Dell, HP and Lenovo harmonise their approach using the Product Attribute to Impact Algorithm (PAIA) methodology when producing scope 3 emissions data for production and delivery (MIT, 2016). Comparatively, Apple, Microsoft and Philips create values independently using LCA software that accesses a variety of life cycle inventory databases to calculate scope 3 global warming potentials. The lack of uniformity in relation to these methods is subject to review by Andre et al. (2018) concluding that incongruity in results is caused by the lifecycle inventory data sources. While the process is governed by international standards (ISO, 2016), not all databases follow the same methodology to generate GHG impact values for actions such as raw material extraction and production. Consequently, if the life cycle inventory input values differ then so too will the output results, even though each one is substantiated as theoretically accurate (Finnveden et al., 2016; Peters and Weil, 2016; Rigamonti et al., 2016; Rorbech et al., 2014).

The difference in output is highlighted by the fact that where the Apple, Microsoft and Philips product carbon footprint reports offer a precise value for the scope 3 supply chain emissions, Dell, HP and Lenovo offer a mean together with a feasible +/- range. The estimated range is generated by the PAIA tool that seeks to simplify carbon footprint calculation by applying most likely emissions values to common attributes such as a notebook's screen size. As an example, the carbon footprint report for an HP EliteBook 850 G8 laptop states the estimated GHG emissions to range from 210-790 $kgCO_2e$ with a mean of 370 $kgCO_2e$ (HP, 2022). This creates a range of doubt equal to 276% and consequently prospective buyers may misinterpret data points. This is most likely to happen in relation to Lenovo computers as the manufacturer leads with the highest impact value and accounts for the range within subsequent small print (Lenovo, 2022). Comparatively, both Dell and HP take the opposite approach leading with the mean and positioning the range in additional commentary (Dell, 2022; HP, 2022). While certainly a complexity that may create a barrier, for the purposes of this research the mean, together with exact values from the other brands, is used in all discussions involving representation of scope 3 emissions.

In relation to scope 2 emissions generated by electricity consumption during the use-phase, all six manufacturers use the annual typical energy consumption value (kWh) generated by Energy Star (2022) during energy efficiency benchmark testing to calculate concomitant use-phase emissions. However, a lack of uniformity is evident when presenting the final values that causes the total carbon footprint values to again become incomparable. As speculated by the introduction, the problem is caused by the manufacturers including different numbers of years of electricity consumption within the report totals and by using different electricity to GHG emissions factors to calculate the scope 2 emissions results.

Inspecting the available carbon footprint reports it is clear that Dell uses a low carbon intensity factor based upon a European Union blended value. While HP and Apple predominantly apply a higher intensity global value, Lenovo utilises European, USA and global values and Philips alternates between a country specific Netherlands factor and the worldwide variant. As such, scope 2 emissions can be underrepresented by just over 30% if the buyer is not aware of this influencing factor. From an inclusion of years of use perspective, manufacturers range from between 1-year to 6-years. As such, it is apparent that in the extreme, the impact of 5-years (83%) of electricity consumption and concomitant GHG emissions are excluded from what appear to be equivalent carbon footprint reports. Consequently, the lack of harmonisation within the published data causes potentially misleading values against which to judge and procure devices as previously explained.

To overcome the issue and enable data parity, the data can be harmonised by isolating the scope 3 mean and exact data from carbon footprint reports and the Energy Star benchmark data and then applying a single region of use and a uniform number of use-phase years. The effectiveness of such harmonisation upon selection decision making and environmental impact is arguably best highlighted by examining data examples before and prior to creating parity. In the case of the profiled desktop computers, using the published data, the Lenovo ThinkCentre M910q device appears marginally less impactful, generating a 338 kgCO$_2$e total carbon footprint compared to the 350 kgCO$_2$e of the HP device. However, the Lenovo device only includes 3-years of use-phase emissions compared to the HP device data that includes 5-years. Additionally, the HP device applies a worldwide GHG electricity conversion factor that is 18.4% lower than the United States value applied to the Lenovo device.

Consequently, when both are harmonised by the application to the European Union factor value with 5-years of use, the Lenovo device is quantified as 360 kgCO$_2$e and the HP device 328 kgCO$_2$e. In this example, where originally the Lenovo device is portrayed by the published data as being 3.5% lower in carbon footprint than the HP device, the reality is that the HP desktop computer is 9.75% less impactful. The issue is, however, not unique to competing brands. As an example, because Lenovo does not standardise on either input, the Lenovo ThinkCentre M73 model discovered during the profile exercise appears to be a 5% more sustainable choice than the Lenovo M90 model when comparing existing carbon footprint reports. However, after the same harmonisation, the M90 actually has a 12% lower total carbon footprint.

Similar examples appear throughout the computer categories and types. Offering a further example, the product carbon footprint report for the Dell P2717H 27" display indicates a total carbon footprint of 508 kgCO$_2$e compared (Dell, 2022) to the Lenovo L27q-10 at 444 kgCO$_2$e. The difference is caused because 3-years less use-phase emissions are included in the Lenovo report. Consequently, when harmonised, the Dell display has a total carbon footprint of 484 kgCO$_2$e which is 12% lower than the Lenovo device at 540 kgCO$_2$e. The impact of this lack of parity is arguably emphasised by the range of carbon footprint values determined during the research (table 8). Specifically, popular devices such as desktop computers and laptops that combined account for almost half of all devices, exhibit a range of carbon footprint between 278-782 kgCO$_2$e and 149-731 kgCO$_2$e respectively (table 8). As such, it is reasonable to suggest that by enabling comparative data during the assessment and procurement phase, scope 2 and scope 3 emissions could be reduced per device by 504 kgCO$_2$e for desktops and 582 kgCO$_2$e for laptops based upon a 5-year retention period (table 8).

The issue of unintentionally overlooking low carbon footprint computers is particularly relevant within the workplace. Examining the computer category asset profile results reveals that 43% of computers are desktops (table 8). This appears excessively high when compared to annual manufacturing statistics (Gartner, 2020; Statistica, 2021) that include both business and consumer computer shipping statistics. Specifically, the secondary data indicates desktop computers account for only 14% of all manufactured devices (Gartner, 2020; Statistica, 2021). As such it is reasonable to deduce that based on the findings of

activity 4, desktop computers remain significantly more prevalent in business than compared to consumer instances.

As such, because a desktop requires a monitor to function the combined carbon footprint of such devices will be between 568 kgCO$_2$e and 1,663 kgCO$_2$e (table 8). This offers a potential maximum abatement opportunity of 1,095 kgCO$_2$e per desktop computer solution if sustainability selection by carbon footprint criteria is introduced into procurement practices. Similarly, the practice could be taken one step further to ensure businesses switch to notebooks in favour of desktop computers to follow consumer trends (Gartner, 2020; Statistica, 2021). A notebook doesn't require a monitor to operate and the range of product carbon footprint identified in activity 4 is lower than a desktop and monitor combination at 149-731 kgCO$_2$e (table 8). As such, it is feasible to suggest that by simply changing device type as much as 1,514 kgCO$_2$e could be avoided per device.

4.5. Activity 5 (RQ6): 'To what extent is sustainable IT resisted and what barriers to diffusion are key to success?'

Before creating the output, research was undertaken (Sutton-Parker, 2020a) to explore and substantiate barriers experienced by organisations to the adoption of sustainable IT strategies beyond the reviewed policies and literature. The value of doing so is perceived to substantiate that focusing upon the triple bottom line approach would, if presented with meaningful triple bottom line data, create the greatest resonance with stakeholders thus improving the potential success and likely impact of the case studies. To test the hypothesis and gauge the level of resistance, a survey was conducted involving over five hundred service sector managers. Asking ten questions, the data creates what is termed as 'intensity of resistance percentages' generated for the three specific categories of awareness, action and barriers. In the context of a sector and job role level, the results highlight differing responses to the resistance of adopting sustainable IT practices. Conducted as described in the methodology, survey targeted and received responses from 503 people in decision making managerial roles. All worked in commercial companies of 250+ people or the public sector in the UK Service Sector. The questions were designed to document the existing depth of awareness of GHG legislation and consequential policies, what related actions were already in place to deliver against the legislation and what barriers exist from embracing sustainable IT practices.

The demography of the responses created a data set proportionately representative of the UK service sector employee balance almost exactly including 66% commercial (331) and 34% (172) public sector responses (Dept. BEIS, 2018). Categorised and analysed in three major resistance categories of awareness, action and barriers, the survey results indicate that while the board directors were far more aware of legislation, company policies and actions than middle managers, a consistent set of barriers emerged across all variations of job role and sub sector including time, money and belief that IT could deliver impactful abatement (table 9). The following section discusses these results in each of the three focus categories, being awareness, action and barriers.

Table 9. Summary intensity of resistance (%) results table

Intensity of Resistance	Service Sector	Commercial Sector	Public Sector	Board Level
Awareness	25%	24%	25%	8%
Action	28%	30%	26%	17%
Barriers	24%	24%	23%	21%

4.5.1 Awareness

At the service sector level, the data confirmed that 31% (table 9) of managers were unaware of national GHG legislation. Twenty-four percent did not know if consequential company CSR policies included GHG abatement. The same percentage was unaware of any IT sustainability policies. While twenty and twenty-three percent respectively did not know if EUC device electricity consumption was measured or concomitant GHGs reported. As such, the 'intensity of resistance percentage' for the sector is scored at 25% (table 10) derived from the average of 'don't know' responses given to questions 1 to 5 inclusive. Awareness resistance is significant if accelerated IT abatement is to be achieved as it directly decelerates the subsequent action and perceived barrier categories. As an example, if stakeholders determined to be capable of influencing the success of objectives (Freeman, 1984) are not aware of facts, they cannot form an opinion that may eventually result in a positive abatement action. This influencing precedent is substantiated by NRDC (Delforge and Whitney, 2014) research highlighting that IT energy efficiency in data centres was limited due to only twenty percent of IT engineers being aware of energy consumption rises. The reason given was that they did not have knowledge of utility bill costs and as such were unaware that action was required to reduce consumption.

Similar examples are also reflected in the early Energy Star research (Johnson and Zoi, 1992), indicating that despite prior elaborate attempts at efficiency, the greatest results were achieved when users were simply made aware of the fact that they were leaving their PCs switched on at night. By increasing awareness, the companies noted significant reductions in power use associated with IT as users powered down PCs before going home. Koomey (2011) supports awareness as a significant issue and highlights that awareness should be championed by board level executives. In doing so, he indicates that through increased awareness and diffusion comes wider stakeholder responsibility. Consequently, priorities align amongst diverse employee roles and objectives, such as GHG emissions abatement, become part of business culture with results improving rapidly. The survey indicates that in the service sector a gap exists between the awareness levels of the board and other managers, suggesting that Koomey's concept of champions is not being fully exploited. Compared to the 25% (table 9) limited awareness at sector level, board executives are in fact 92% (table 9) aware. As such, it is evident that this executive stakeholder group is not driving awareness throughout the hierarchy of management.

Specifically, the Chief Technology Officers (CTO), responsible for supplying energy and or GHG data generated by IT systems to the executive board, were 100% (table 9) aware of the legislation and 93% aware that IT was being measured for GHG emissions. Comparatively, all other non-board job roles were 59% (table 9) aware of legislation and only 40% (table 10) aware of IT GHG emissions being measured. This indicates that while the legislation GHG measurement and reporting is happening, communications to managers beyond those accountable to the driver of legislation and responsible for the action of measurement, is limited and causing this exaggerated lack of awareness in the wider organisation. Returning to Koomey's point, aligning the executives with the managers may drive better awareness results.

4.5.2 Actions

The difference between 'actions' and 'awareness' is explained as follows. Acknowledging national GHG legislation is awareness, whereas creating and executing a CSR strategy that addresses the legislation is an action. Consequently, awareness, or a lack of, focuses predominately on 'don't know' answers, yet action focuses on 'no' answers. Not knowing about an action doesn't mean it isn't in place. As such, at the service sector level, the data confirmed that 15% (table 10) of organisations did not have a GHG focused CSR strategy, 16% (table 10) were without a sustainable IT policy, 25% (table 10) didn't measure device energy consumption, 23% (table 10) didn't measure IT GHG emissions, 51% (table 10) were unable to influence CSR policy and 40% were not measured and rewarded on CSR success. If, hypothetically, including the 'don't know' answers as an indication of no action being undertaken, then the range could be as high as 38%, 40%, 45%, 49%, 57% and 47% (table 10) created an intensity of

resistance of 46% (table 10). However, to avoid supposition and retain validity, the action intensity of resistance percentage is determined by the survey to be 28%. This indicates that over one quarter of organisations have not undertaken a combination of actions that support GHG abatement related to IT. With specific relation to sustainable IT practices, the actions category can be analysed further by dividing responses into two subcategories of policy actions and physical actions. Focusing on the physical first, these actions are determined as activities undertaken as part of a policy to reduce IT GHG emissions. As such, the survey indicates that the adoption of physical actions such as device energy measurement and IT GHG reporting is arguably less prolific than the resistance intensity suggests at 55% and 50% respectively (table 10).

Policy action measurement enables an understanding of what policies exist that could include physical actions undertaken to reduce GHG emissions. While it could be suggested that one does not exist without the other, separating policy and physical actions removes the assumption that because a sustainable IT policy exists, GHG measurement is being conducted and the focus isn't entirely on other practices such as recycling. Doing so uncovered that while the definitive 'no' answers responding to whether the CSR policy included IT sustainability are low at 16% (table 10), the 'no' answers for whether end user computing electricity consumption was measured are 25% (table 10). This indicates a gap of 9% between the two values, suggesting that this specific action may be influenced by a mixture of awareness and barriers. These may include being unaware that electricity consumption affects GHG emissions, believing that the impact of this is low, or simply not knowing how to accurately measure the energy consumption of devices that are constantly on the move. The concept of further resistance categories affecting the action category is also apparent with regards to the specific CSR actions. This is highlighted in the 'influence over CSR shaping' and 'goal/KPI' action values. In isolation, both values are far higher than the intensity of resistance of 28% at 51% and 40% respectively (table 10). Examining the same responses by job role reveals that these two values reduce considerably at the board level. Amongst the executives, both values halve to 25% and 20% (table 10). This reduced resistance is also reflected consequently in the CSR awareness value. For the board executives, awareness of the existence of a CSR policy that includes GHG abatement is only 93% compared to 61% (table 10).

The disparity in values reveal that as the C-suite has a high level of influence on the crafting of CSR framework and is measured upon its success these employees naturally have a far higher awareness of the policy. In contrast, non-executive employees not influencing or being measured have a far lower awareness. Whether one factor leads the other is not strictly determined although the values do suggest that by including a wider stakeholder group beyond the board to help craft and deliver the CSR policy and objectives would consequently open dialogue as to what actions can reduce GHG emissions. Through this action, amplified appreciation and understanding would become widespread and consequentially, the awareness intensity resistance percentage would decline accordingly. Robalino and Lempert (1999) examined the effectiveness of technology focused incentives and penalties that could overcome barriers to achieving IT energy efficiency. They concluded that while their model showed the approach to be worthwhile, the levels of stick and carrot had to be high enough to deliver significant impact on GHG abatement. Achieving the correct levels as being key to success is supported by and links to the survey results for the specific barrier of 'low company priority', scoring 25% as a sector average (table 9). Comparatively, at a board level the score is significantly more positive at only 10% (table 9). As such, the data confirms that those in executive job roles responsible for CSR content and goaled on success consider the subject of IT sustainability to be far more important than those without input or measures. Consequently, the survey substantiates that many of the barriers indicated are once again interconnected and affected by both awareness and action factors.

4.5.3 Barriers

Barriers represent obstacles that are preventing or delaying adoption of sustainable IT practices. The total resistance intensity percentages from the awareness and action categories are included as barriers. A lack of awareness and a lack of action create barriers to adoption. In total, eleven barriers are measured by

the survey ranging from financial burden to employee impact perception as highlighted in question ten. At a sector level the resistance intensity percentage was 24% suggesting that a quarter of all companies suffer from barriers that prevent them from embracing sustainable IT practices. Perhaps unsurprisingly, the highest scoring barrier is a lack of budget, at 48% (table 10). The concern for profit coming before environmental impact has long been subject to scrutiny, arguably reaching the global stage in the early 1960s (Carson, 1962). Within the text the author describes the impact of chemicals such as DDT on the organic and human environment created by companies chasing high profits while ignoring the death of people, animals and landscapes. Following three decades of subsequent scientific examination of anthropogenic interference, research (Bolin et al., 1986; Flohn, 1970; Granat, 1972; Kellogg, 1977) led to the publication of 'Climate Change' (Houghton et al., 1990). The latter was the combination of over one thousand scientists gathering evidence of humankind's impact on the planet caused by innovations such as electricity and transportation that were also driving economic growth. The data was as comprehensive as it was concerning and influenced the creation of the United Nations Framework Convention on Climate Change (1992). While IPCC reports and UN actions continue today, the original expose caused people beyond the realm of science and politics to deduce ways of assessing how to measure progress versus harm. These include the previously discussed Rees and Wackernagel (1996), Elkington (1997), Carroll (1979) and Spreckley (1987) that led to the concept of suggesting companies could adopt a non-traditional approach to accounting that includes profit, social wealth and environmental performance elements.

Today the theme of overcoming cost barriers by creating self-funding actions continues (HM Gov., 2019b). Gove notes that human health and prosperity depend on the health of the planet quantifying that the annual cost of breathing related illnesses to the UK economy could be reduced by as much as £5.3 billion by reducing emissions. In the context of this research the barrier intensity value of 48% attributed to cost may at first be seen as insurmountable. However, if the awareness that certain EUC devices are more efficient than similarly specified devices as demonstrated in activities 1 and 2, the cumulative monetary value of electricity saved by transitioning to efficient devices may be significant enough to kick-start actions to measure and abate end user computing device GHG emissions. Second to money the survey indicates that a lack of time is considered the second largest resistance barrier at 33%. It is reasonable to state that this is likely driven by negative perception fuelled by limited awareness highlighted in the survey. As an example, 25% (table 10) of managers indicated that IT cannot drive major GHG abatement impact within their organisation despite considerable research existing substantiating the fact (GeSI, 2008; 2012; 2015) and legislation already in place specifically to focus on IT GHG emissions as discussed. If sustainable IT is not seen as a priority due to low impact, then it will not be supported with dedicated human capital, thus becoming a subject that cannot be afforded time.

Time however does not necessarily prevent willing. Understanding that employees may personally wish to prioritise sustainable IT but do not feel supported could deliver higher success in the long term if the barrier is removed. To explain, 47% (table 10) of managers suggested IT sustainability was judged a medium or less priority for the company, while only 16% (table 10) stated it wasn't a personal priority. Notably, this suggests that while company perception is moderate, 84% (table 10) of employees do see it as a priority suggesting willingness could leave staff open to sustainable IT programmes if the impact is evangelised. Theoretically the barrier at a personal level may not even exist as 20% (table 10) believe that employee push back would be heightened if sustainable changes were introduced in IT. While unanswered, the data suggests that all but 4% of people who do not see GHG abatement in IT as a priority, could be the same people opposing the sustainability programmes. Again, this leads back to Koomey's (2011) research that indicates the executive board should lead the conversation to ensure barriers are equal amongst the executive board and non-executive managers. However, in the case of EUC UPE energy consumption being an accelerator of GHG emissions abatement the board too appears conflicted. Specifically, the survey notes that 21% (table 10) of managers believed there is no executive support for sustainable IT programmes. Comparatively, the CEOs consider this to half the resistance intensity at 11% suggesting that there is almost 90% (table 9) support from the executive board. Unlike awareness and actions, with the board delivering harmonised responses, the variation in resistance intensity in barriers is pronounced.

As such, it is noted that the CTO role responsible for delivering sustainable IT responded with a threefold increase of 33% concern that other board executives are not supportive. Evidently pressurised by limited resources, a lack of time is noted as 40% (table 10), superseded only by employee pushback at 47%. This last figure is surprising considering that 84% (table 10) of managers surveyed suggested sustainability was a priority indicating that perhaps the pushback is from non-managerial staff. Consequently, it is fair to suggest the data indicates that on one side the role signing off the information for GHG accounting in company and quarterly reports, the CEO, feels supported by the person supplying the data, the CTO. In contrast, the CTO feels unsupported by both the executive board for not allocating sufficient resources to the task and the company as a whole for not perceiving IT sustainability practices to be worthwhile when compared to interruption to productivity that may arise during technology transformation.

This returns to the concept that awareness of impact of IT (the carrot) is being overshadowed by legislation (the stick), causing not only frustration but also additional, and perhaps unnecessary resistance to the adoption of sustainable IT practices. It is therefore suggested that in light of the data, executive boards need to harmonize with regards to addressing barriers before communicating the policy and expected goals to a wider stakeholder group including both non-executive managers and non-managerial staff. Beyond the obvious savings in electricity consumption and reduction of GHG emissions the move may also align with seemingly unrelated priorities such as human resources. As top HR priorities include prospective employee attraction, current employee experience, engagement and retention sustainable outcomes could be used as an appeal (Cone, 2019).

Table 10. Intensity of resistance (%) expanded results table

Resistance Intensity Percentage		Legislation (National)	Strategy (CSR GHG)	Strategy (Sustainable IT)	Energy (Device Measurement)	GHG (IT Measurement)	Influence (CSR Shaping)	Goaling / KPI	Barriers (Limited Awareness)	Barriers (Limited Action)	Barriers (Low Company Priority)	Barriers (Low Personal Priority)	Barriers (Lack of Budget)	Barriers (Lack of Time)	Barriers (Executive Support)	Barriers (Employee Pushback)	Barriers (Education)	Barriers (Not Suitable)	Barriers (Impact Perception)
Service Sector	Total %	Q1	Q2	Q3	Q4	Q5	Q6	Q7			Q8	Q9	Q9	Q9	Q9	Q9	Q9	Q9	Q10
Awareness	25	32.41	23.5	23.75	19.68	23.4													
Action	28		15.1	16.25	25.25	22.86	50.8	40.4											
Barriers	24								25	28	25.45	16.3	47.91	33	20.87	19.88	13.32	3.98	29.6

Note table 10. Awareness scoring includes responses noting no knowledge of sustainability legislation, strategy, energy and GHG device measurement. Action includes no strategies being in place relating to CSR policies, involvement or gaoling, energy and GHG device measurement. Barriers include the combine limitation of a lack of awareness and action plus positive responses noting existing barriers perceived as sustainable IT being a low company and personal priority, lack of budget, lack of time, lack of executive support, employee pushback, education in the field of sustainability, suitability for their business model and the perceived level of impact delivered by sustainable IT.

5. Chapter 5: Solutions (Output)

5.1. Output 1: Commercial typical energy consumption (cTEC)

The results of activities 1 and 2 substantiate barriers and limitations that prevent the production of meaningful end user computing carbon footprint data. Firstly, the practice of excluding the active state typical energy consumption information causes kWh and therefore concomitant GHG emissions values to be incorrectly estimated by an average of 30% (activity 1). Secondly, current carbon footprint product reports are not only limited in availability, they also rely upon the same typical energy consumption data and therefore carry forward the error. Additionally, use-phase emissions used to populate reports are calculated using capricious GHG conversion factors and therefore lack context. Consequently, organisations assessing end user computers by energy efficiency criteria or reporting concomitant scope 2 emissions have no choice other than to rely upon data that has an error range of -60% to +121% (table 2), masks abatement opportunities of up to 57% (figure 3) and is contextually incongruous when planning sustainability strategies. To overcome these issues, activity 3 explores the concept of node-based analytics software to capture active state electricity consumption at scale. Unfortunately, in doing so it is proven that such an approach achieves one half of the use-profile data required to accurately calculate typical energy consumption values in a business setting. Specifically, while the resulting kWh values proved 46% (figure 6) inaccurate and therefore invalid, the OT measurement was proven to be 100% accurate (figure 8). Consequently, it is reasonable to recommend that measuring all modes of power draw and applying the results to analytics OT data in a structure manner will enable the calculation of meaningful annual business computing electricity consumption. As the Energy Star programme already generates power draw data for off, sleep, long idle and short idle modes, then it is logical to suggest that measurement of the active mode when human interaction is experienced, it to key enabling such calculation.

However, activity 3 highlights that energy draw is not uniform during the active state and differs depending upon the type of computing tasks being undertaken (figure 7). Specifically, the data reveals that productivity tasks such as email and messaging, document creation and review, spread sheet population and review, web-based application interaction and web browsing require relatively equivalent power to conduct. Comparatively, video conferencing is proven to require an average of 20% higher energy draw (figure 7). To account for this varied influence, it is proposed that the two tasks are measured in isolation before being triangulated with both the Energy Star low power mode data and the analytics on time data. For simplicity it is suggested that the new states be called Active 1 for the productivity tasks and Active 2 for video conferencing. In this form, identified values for both can then be applied to form an extended version of the existing eTEC equation. In the new form the calculation produces annual electricity consumption for computers when operated in a business context. As such the proposed name for the new methodology is the commercial typical energy consumption (cTEC) value. Expressed as an equation it is proposed that the following formula is used:

$Commercial\ Typical\ Electricity\ Consumption$
$$= 8760/1000\ x(P_{Off}\ x\ T_{Off} + P_{Sleep}\ x\ T_{Sleep} + P_{LongIdle}\ x\ T_{Lomgidle} + P_{ShortIdle}\ x\ T_{Shortidl} + P_{Active1}\ x\ T_{Active1} + P_{Activ}\ x\ T_{Active2})$$

To enable the formula to be populated, two additional data sets must be generated. The first is the percentage of time in one year a computer will spend in all six modes in a business environment. As the low power mode data already exists as part of the Energy Star benchmark data (Energy Star, 2022), then the second data set required to be generated is the power draw values for proposed new modes. The following sections explain how this is achieved in the context of the impact case study, although it is noted that the same methodology can be applied to commercial organisations holistically. The assumption is based upon the control test conducted to validate the results in activity 3.

5.1.1 Quantifying mode weighting

Activity 3 finds OT data generated by the analytics software to be highly accurate and therefore capable of generating data determining the length of time per working day a computer is being actively used. Therefore, it is logical to suggest that gathering OT data from a sample group larger than the one hundred and thirteen Lakeside employees previously measured will enable the creation of a credible average OT value for business users in general. The recommendations section discusses how this may be achieved at scale and explains why such breadth is beyond the scope of this research time horizon. Consequently, as an alternative and for the purpose of proving the theory of validly including OT data into electricity consumption calculations and to facilitate case studies A, B and C (see impact section) an expanded data set of 1,069 users is generated.

This is facilitated again by Lakeside. Obfuscating all user and machine name data causing the extract to be anonymous and compliant with GDPR (2016), an OT extract from an existing Lakeside Systrack customer is supplied with consent from the organisation. Confirmed as a local council, the data reveals that for each device 4 hours and 7 minutes of active computer on time is experienced per calendar day (figure 10).

Figure 10. OT hours per 30 day period for 1,069 business users
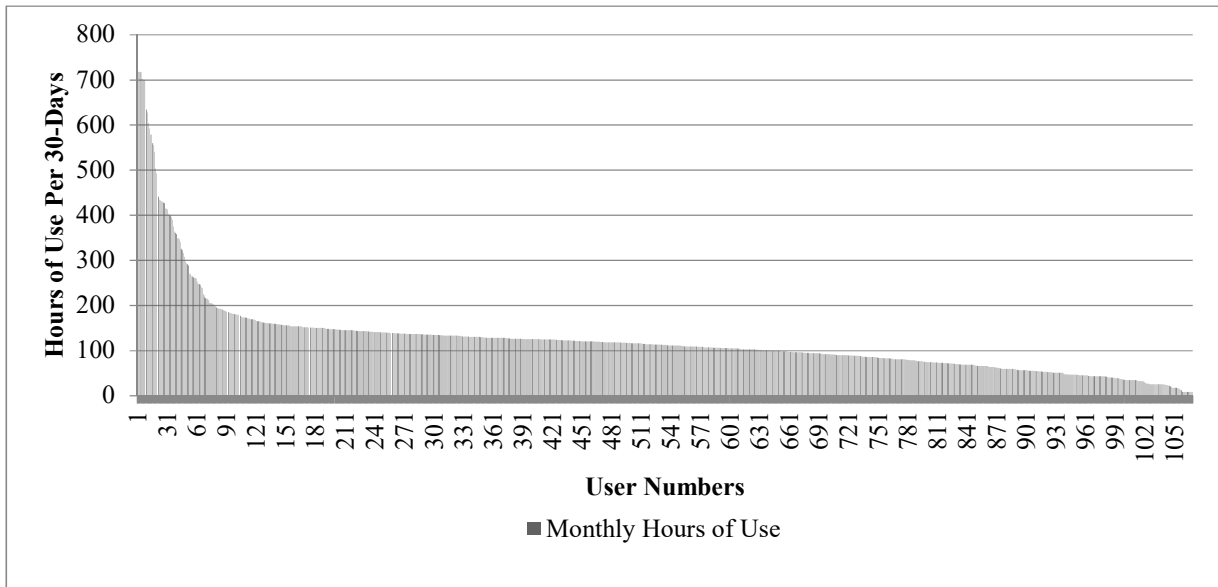
Note figure 10. The OT is generated in hours and minutes by Lakeside Systrack node based analytics software installed on 1,069 computers. The software collects OT daily and therefore the results include non-working periods such as weekend and evenings when devices will not experience human-computer interaction.

The value is speculatively low when compared to secondary data points indicating computer use is between 6-7 hours per day (Data Reportal, 2022; Exploding topics, 2023). However, the primary data extract is based upon a calendar month and therefore includes downtime such as weekends when the business is closed. The opening hours of the organisation measured for OT is are eight hours per day between 9am to 5pm on weekdays only. Therefore, by excluding evenings and weekends the daily duration of the active state can be recalculated to be 6 hours and 30 minutes per day and equivalent to the secondary data points.

In order to extrapolate the OT data to enable annual values that can be applied globally, secondary data points relating to yearly average business days worked were examined (Accace, 2022; Espo, 2023;

Thomson Reuters, 2022; Statistica, 2022). This created an average of 232 days worked per year across forty five countries (figure 11). This means that the proposed total device OT for one year is in this example is 1,508 hours if each working day is multiplied by the daily business use OT hours previously determined (figure 10).

Figure 11. Average number of business days worked annually by country
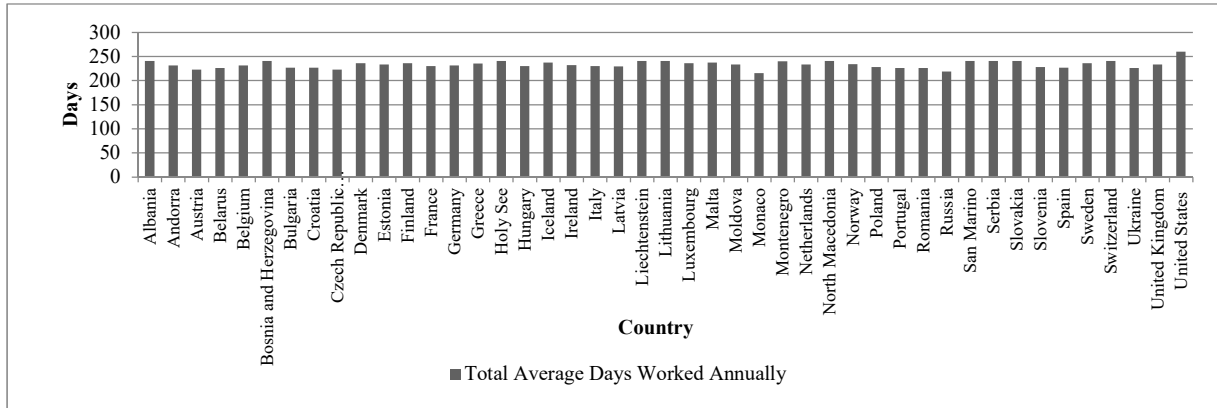
Note figure 11. The average business days worked by employees by country is derived from secondary data sources and allows for weekends and public holidays.

Due to the differences in anticipated power draw for both the proposed Active 1 and 2 modes, time spent in each during one year must be determined. To achieve this, the Lakeside analytics software's primary capability as a user experience measurement tool was investigated. Specifically, the user and machine obfuscated applications and web activity report function was examined at a company level to determine time spent conducting specific activities. The data highlighted that productivity tasks consumed 55% of active state time accounting for 3 hours and 35 minutes of each day. As such a weighting of 9.5% was generated based upon 832 hours spent in this mode each year (figure 12).

Figure 12. Percentage of time spent per device per year in all operational modes
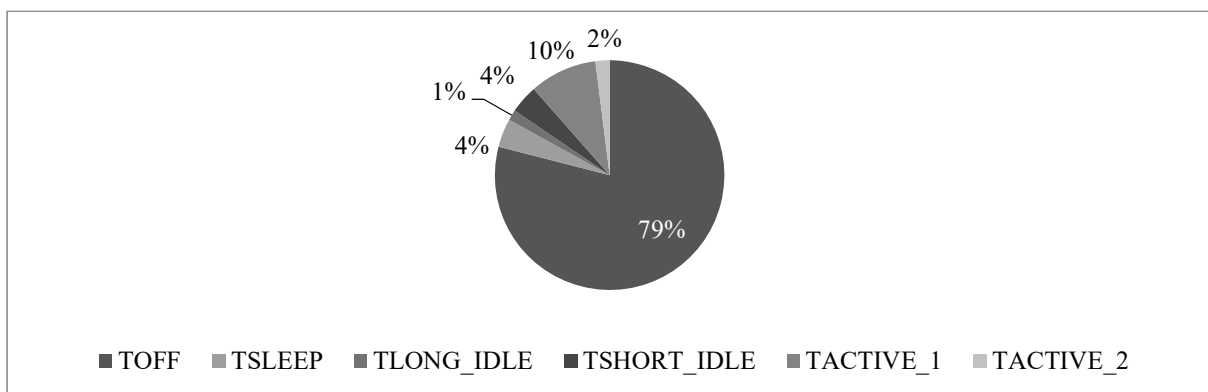
Note figure 12. Time spent in each mode by a device in a business setting is represented by a percentage of total calendar year hours (8,760).

The analytics data created no discernible data specifically related to video conferencing daily use. Consequently secondary data was sought in order to apply an annual time percentage for the proposed active 2 state. Various reports ranged from 30 minutes to 2 hours per day spent video conferencing although the majority indicated that as an average 45 minutes per working day was appropriate when adjusted for period before, during and after the recent pandemic (Dialpad, 2022; HR Magazine, 2022; Leaderonomics, 2022). As such a mode weighting of 2% was assumed for the active 2 state.

Having determined that device OT each working day is 6 hours and 30 minutes, two assumptions are made. Firstly that as the business is operational for 8 hours per day, the device sleep mode duration is logically 1 hour and 30 minutes. Extrapolated by 232 days (figure 11), this determines that 350 hours per year or 4% of computer time is spent in sleep mode (figure 12). The second assumption is that that the computer is switched off by the user at 5pm when the working day concludes. As such, the weighting for off mode is generated by 133 full days switched off due to weekends, vacations and public holidays and for 16 hours during the 232 workdays (from 5pm to 9am). Consequently, as organisations attribute scope 2 emissions to electricity consumed for company operations (and not leisure use) the off-mode weighting is 79% (figure 12).

Due to the percentages of time applied to the active states, 5.5% of one year remained. This was applied to both the long and short idle modes based upon the Energy Star assumption (Energy Star, 2020) that the latter will be three times that of the former. As such the long idle weighting assumed is 1.5% of the calendar year while the short idle is 4% (figure 12). Consequently, the mode weighting for all devices classified as either a notebook or desktop computer are calculated as indicated in table 11 below.

Further to determining the values, two variables are considered. Firstly, it is noted that whereby the current Energy Star eTEC mode weightings (Energy Star, 2020) for desktop and notebook computers differ (table 11) the proposed cTEC percentages will remain uniform for both categories. The analytics data highlighted no discernible difference in on time between device types (figure 11). Secondly, while the proposed cTEC mode weightings are suitable for notebooks and desktop computers, the methodology used for monitors must be adjusted to account for the 'on mode' measured by Energy Star (2020; 2022) being equivalent to both active modes. The power draw of monitors does not deviate in the same way as end user computers (table 12). This is because the device has no moving components nor is it conducting computation and therefore has three modes similar to a television being off, standby (sleep) and on.

Table 11. Mode weightings for proposed and existing typical energy consumption for desktops and notebooks

Mode Weighting	Proposed cTEC %	Proposed cTEC hours per year	Existing Desktop eTEC %	Existing Desktop eTEC hours per year	Existing Notebook eTEC %	Existing Notebook eTEC hours per year
T_{OFF}	79%	6,920	15%	1,314	25%	2,190
T_{SLEEP}	4%	350	45%	3,942	35%	3,066
$T_{LONG\ IDLE}$	1.5%	131	10%	876	10%	87.6
$T_{SHORT\ IDLE}$	4%	350	30%	2,628	30%	2,628
$T_{ACTIVE\ 1}$	9.5%	832	0%	0	0%	0
$T_{ACTIVE\ 2}$	2%	175	0%	0	0%	0

Note table 11. The existing estimated typical energy consumption (eTEC) mode weighting are extracted from the 'Energy Star Program Requirements for Computers version 8.0' (Energy Star, 2020). The proposed commercial typical energy consumption (cTEC) mode weightings are calculated by this research.

Specifically, the off-mode is described as when the device is connected to a power source but cannot produce visual information and cannot be switched into any other mode. The sleep-mode is similar to a television's standby. The difference being, under standard computer power management conditions a desktop or notebook will automatically transition the display to sleep after 15 minutes of no human-interaction. Finally, the on-mode is the when the device has been activated and is conducting its primary function. Because of this Energy Star (2020) applies two weightings of 35% for on mode and 65% for sleep, being expressed as follows:

$$eTEC = 8760/1000 \ x (P_{Sleep} \ x \ T_{Sleep} + P_{On} \ x \ T_{On})$$

Source: Energy Star (2020)

Table 12. Mode weightings for proposed and existing typical energy consumption for displays

Mode Weighting	Proposed cTEC %	Proposed cTEC hours per year	Existing Display eTEC %	Existing Display eTEC hours per year
T_{OFF}	79%	6,920	0%	0
T_{SLEEP}	5.5%	482	65%	5,694
T_{ON}	15.5%	1,358	35%	3,066

Note table 12. The existing eTEC mode weighting are extracted from the 'Energy Star Program Requirements for Computers version 8.0' (Energy Star, 2020). The proposed cTEC mode weightings are calculated by this research.

It is noted that this equation does not account for the impact of the off mode upon consumption. Examining Energy Star data reveals that during the display test set up and conduct the off mode is measured. Consequently, for the proposed cTEC methodology the following approach is suggested. The off-mode weighting will logically reflect the value previously determined of 79%. The sleep percentage will now include the long idle time value as when a computer enters this mode then the associated display will be transitioned to sleep. As such, the sleep mode weighting rises to 5.5%. Finally, as displays do not experience changes to power draw when conducting their primary function, the short idle, active 1 and 2 values will be combined to represent the on mode at 15.5%.

5.1.2 Quantifying Active 1 and 2 Power (W)

To populate the proposed cTEC equation, power draw data for the active modes must be sourced or generated. For displays, the W value is represented by the Energy Star on mode as previously determined. As such, no further display power draw measurement is required as the values required exist within the current practice and can be sourced via the Energy Star online database. However, as described, active modes are not currently measured by existing energy efficiency programmes for all desktop and notebook computer categories and therefore a methodology must be created to enable the generation of the required power draw data. To ensure accuracy equivalent to the existing and accepted Energy Star practices, it is proposed that existing test set up methods be adopted. Doing so will also potentially enable the new practice to represent an extension to the Energy Star programme as opposed to representing an alternative. As such, when conducting active mode power draw measurement, it is determined that the International Electrotechnical Commission (IEC) 62301:2011 household electrical appliances measurement of standby power and IEC 62623:2012 desktop and notebook computers measurement of energy consumption standards be adhered to (IEC, 2011 and 2012). This includes ensuring three key stipulations. Firstly, that, as with activity 1, instrumentation used to meter active power draw (W) is proven to be accurate to within 0.2%. Secondly, 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 to be switched to 100% on all devices to ensure parity between differing models and brands and Bluetooth capability is switched off as standard.

Having determined an appropriate test set up, the newly proposed active state test conduct is designed to produce highly accurate data for the energy performance of each measured device while being subjected to human interaction categorised as active states 1 and 2. The naming convention is based upon the existing description applied by Energy Star and related standards to the active state. Specifically, it is defined as the power state in which the computer is carrying out useful work in response to prior or concurrent user input and includes active processing, seeking data from storage, memory, or cache. As such, it is considered suitable in context. To enable parity between differing device types, brands and models, two structured active mode tests are suggested depending upon device type. Each test will be identical in format regardless of the device type or specification. The structured tests include:

- Productivity: While subject to the test set-up conditions the computer is operated for eight one-hour periods while undertaking productivity tasks. These include email and messaging, document creation and review, spread sheet population and review, web-based application interaction and web browsing. Specifically, in the tests conducted to produce the impact case study Microsoft Office 365 and a Google Chrome browser were used in each instance.

- Video Conferencing: While subject to the test set-up conditions the computer is operated for eight one-hour periods while undertaking video conferencing. Where a camera is present, the test is conducted firstly with the camera on and secondly with the camera off as the minor additional power draw created by the camera operation may influence the results. For this purpose, several platforms are utilised including Google Meet and Microsoft Teams although no discernible difference in power draw were documented.

During each 60-minute measurement periods four values are captured including the lowest and highest power draw (W), the average power draw and the measured kWh results. From this two metrics are generated including the total average power draw and the total average. The rationale for the eight one-hour tests is to examine for fluctuation that may affect the overall results. As the highlighted below very little deviation was experienced in relation to both sets of results and it is feasible that the number of hours measured could be reduced to improve practicality. Doing so may also achieve wider diffusion within Energy Star accredited testing laboratories should the methodology be considered as appropriate.

5.1.3   Quantifying Active 1 and 2 Power (W)

The primary objective of creating the cTEC methodology is to enable meaningful quantification of end user computing use-phase emissions to facilitate the planned impact case studies. To demonstrate the calculation compared to the existing Energy Star (2020) methodology, two of the notebooks from case study A are highlighted in table 13.

Table 13. Device eTEC and cTEC calculations and comparisons

| Device	Off Mode Power (W)	Off Time (Hours)	Off Mode kWh/y	Sleep Mode Power (W)	Sleep Mode Time (Hours)	Sleep Mode kWh/y	Long Idle Mode Power (W)	Long Idle Mode Time (Hours)	Long Idle Mode kWh/y	Short Idle Mode Power (W)	Short Idle State Time (Hours)	Short Idle State kWh/y	Active 1 State Power (W)	Active 1 State Time (Hours)	Active 1 State kWh/y	Active 2 State Power (W)	Active 2 State Time (Hours)	Active 2 State kWh/y	Energy Star eTEC kWh/y	Proposed cTEC kWh/y	Difference
Latitude 5450	0.32	2190	0.70	1.19	3066	3.65	6.05	876	5.30	6.05	2628	15.90							25.50		
Latitude 5450	0.32	6920	2.21	1.19	350	0.42	6.05	131	0.79	6.05	350	2.12	12.80	832	10.65	15.60	175	2.73		18.92	74%
Optiplex 7010	0.43	1314	0.57	3.34	3942	13.17	33.40	876	29.26	33.40	2628	87.78							130.80		
Optiplex 7010	0.43	6920	2.98	3.34	350	1.17	33.40	131	4.38	33.40	350	11.69	43.67	832	36.33	46.80	175	8.19		64.73	49%

Note table 13. The eTEC calculations are derived from the low power mode data published by Energy Star (2022) using the Energy Star defined mode weightings (Energy Star, 2020). The cTEC calculations are derived from the low power mode data published by Energy Star (2022) and the Active 1 and 2 measured power draw (W) as described by the research using the mode weighting defined by the proposed cTEC methodology. The difference is the cTEC value represented as a percentage of the original published Energy Star eTEC value for each device.

5.1.4   Validating the new method

To validate the newly proposed method an extended version of the field electricity consumption experiment conducted in activity 1 was undertaken. Designed as a control test to determine if the cTEC values represented real life business energy consumption, both the Dell Latitude 5450 notebook and Dell 7010 desktop computers subjected to the cTEC calculation were connected to a watt metre and measured for energy consumption for 60 days. Producing energy data for the equivalent of 3 working months in a business setting allows for precise extrapolation to one full year. The results of the control test determined that the cTEC results produced accuracy within a range of -4% to -1%. Specifically, the Dell Latitude

5450 measured 19.72 kWh (figure 13) over 60 days (Sutton-Parker, 2022c) meaning that the cTEC method under quantified the electricity consumption by 4% by generating a value of 18.93 kWh (table 13). While the Dell OptiPlex 7010 desktop consumed 65.1 kWh/y (figure 13) over 60 days (Sutton-Parker, 2023) and the cTEC calculation produced 64.73 kWh/y (table 13). Similar to activity 1 (table 2) it is noted that the cTEC value represents 74% of the equivalent Energy Star eTEC value (Energy Star, 2022) for the notebook and 49% for the desktop. The increased difference in relation to the desktop is due to the mode weightings as noted in table 11 with desktop sleep time being higher than notebooks for the eTEC calculation (Energy Star, 2020).

Figure 13. 60 day field measurement of electricity consumption vs. cTEC daily average kWh value
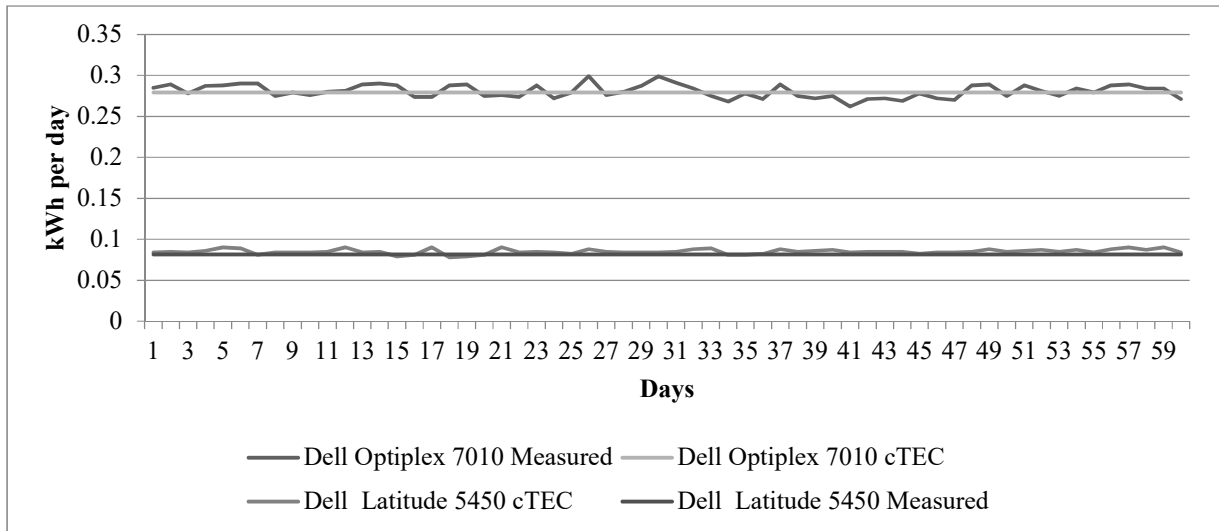
Note figure 13. The measured values show electricity consumption per day (kWh) for the OptiPlex 7010 desktop and the Latitude 5450 notebook when connected to a watt meter during a 60 day period in a business working environment. The cTEC straight line values are the average daily kWh consumption.

As such, while it is discussed in the recommendation that further field testing be undertaken to test accuracy, the methodology is validated as accurate in the context of the case studies by this control experiment. Additionally, it is reasonable to suggest that in the wider context, the results act as an indication that the proposed cTEC weightings, active power draw measurement and calculation methods offer parity between results. The concept is that if the same approach is used for all devices then energy efficiency comparison between brands and models of the same type can be undertaken as it is with the existing Energy Star approach (Energy Star, 2020; 2022). The difference being that the active state when human-computer interaction occurs is now accounted for to generate real world typical energy consumption values against which concomitant scope 2 GHG emissions can be calculated.

5.2. Output 2: Dynamic carbon footprint application

Activity 4 determines that only 22% of end user computing devices have associated product carbon footprint reports available to the public. This is due to only 14% of major manufacturers currently participating in lifecycle assessment quantification and publication. Of the available information, all six participating manufacturers use different retention periods and electricity to GHG conversion factors. This means that the use-phase contribution to each product's total carbon footprint is not uniformly represented. Consequently, the total carbon footprint value included within each published report does not exhibit parity between models and brands and therefore cannot be meaningfully compared when assessing devices based upon sustainability criterion.

To overcome these issues, an application called the 'Dynamic Carbon Footprint' (Sutton-Parker, 2022c; d) is developed and published for access online by this research. The application is 'dynamic' as, unlike current published reports, the application is characterised by constant change. This is represented by each product carbon footprint report being defined by the user to reflect the location of use and the number of years a device will be used.

With a database initially populated with the carbon footprint details of over two hundred and fifty end user computing devices, the main objective of the application is to the harmonisation of data found to be lacking in activity 4. Specifically, the use-phase scope 2 GHG emissions data is manipulated to ensure that the same number of years of use is included within the resulting dynamic carbon footprint report and that the electricity consumed during this time frame is converted to GHG emissions using a uniform conversion factor. The carbon footprint data for all devices achieves parity due to this re-calculation. The value of doing so is twofold. Firstly, employees responsible for assessing, selecting and procuring end user computing devices can search beyond the third-party certification level in confidence as the unintentional misrepresentation of the use-phase contribution substantiated during activity 4 is removed. Secondly, the application enables digital downloads of a comparative table showing devices ranked by total carbon footprint plus a dynamic carbon footprint report specific to the device selected based upon sustainability criteria. As such, compliance with the discussed procurement legislation can be achieved in the fact that IT and procurement teams within organisations subject to the policies will be able to present documentation proving that the device selected contributes to wider net zero company and national strategies. As a device with the lowest total carbon footprint has been identified using credible and comparable data.

The application design is based upon the research findings during the prior stages and existing accepted standards. Firstly, as with the asset profiling undertaken in activities 3 and 4, device type categorisation used for the first drop down option (figure 14) is based upon the Energy Star approach (2020 and 2022). Specifically, for benchmark test set-up and conduct plus online eTEC results, Energy Star creates nine distinct end user computing device types including desktop, integrated desktop, mobile workstation, monitor, notebook, slate / tablet, thin client, two-in-one notebook, workstation. During the unstructured interviews conducted with the seven organisations participating in activity 3, the two impact case studies (Sutton-Parker, 2022e; Google, 2022a), plus surveys involving five hundred service sector managers (Sutton-Parker, 2020a) used to contribute to output 3 (see below) and two hundred organisations subject to the procurement legislation (Sutton-Parker, 2022a), over 74% of all respondents confirmed they used and were familiar with the Energy Star format. Consequently, following this categorisation model enables familiarity and ease of use; a point emphasised within the results of the user feedback survey discussed below.

The second drop down requests the user to set a retention period. The optional range is set between one-year and eight years. As previously discussed, research concurs that an average retention period is between three and five years (Hart, 2016; Prakash et al., 2016; Thiébaud et al., 2017; Teehan and Kandliker, 2012; Williams and Hatanaka, 2005) while activity 2 and prevailing research (Prakash et al., 2016; Thiébaud et al., 2017) substantiates that extending this to 8-years is viable. Selecting a timeframe for the device's potential useful lifespan enables two meaningful outcomes. Firstly, the use-phase duration, and therefore the contribution of scope 2 concomitant GHG emissions is harmonised regardless of the value originally included within the manufacturer product carbon footprint report. The ability to achieve this initial step towards parity between models and brands is enabled by the standards governing the calculation and presentation of computer carbon footprint data (ISO, 2006).

Figure 14. The Dynamic Carbon Footprint home screen

Specifically, the lifecycle phases of a product are required to be presented as a percentage of the whole carbon footprint to ensure emissions sources, such as electricity or materials, are accounted for in isolation (WBCSD and WRI, 2004). As such, the use-phase contribution can be quantified with ease and removed from the total carbon footprint value proposed by the existing report. To reapply the scope 2 value and reflect this in the application results, the Energy Star eTEC value in kWh/yr is identified via either the manufacturer report (Dell, 2022; HP, 2022; Microsoft, 2022) or via the Energy Star benchmark database application programming interface (API) discussed in detail in output 3 where reports do not include electricity data (Apple, 2022 and Lenovo, 2022). The resulting value is then multiplied by the dynamically selected retention period to generate the total typical energy consumption for the lifespan of the devices. This value is then multiplied by the relevant electricity to GHG emissions factor, also selected by the user as explained below, to generate the new and harmonise use-phase emissions value. As the retention selection is made via one of four main drop-down selections the parameter is applied to all devices held in the application database. As such the user can be confident that devices are being assessed on an equivalent basis. The second meaningful outcome is that the retention period is set by the user to reflect the unique policies specific to each organisation meaning the user is able to determine the typical total carbon footprint that will be experienced during ownership of the device rather than a manufacturer assumption that pre-defines the use-phase contribution.

Further to an additional option to select a specific brand, the application also allows for the location of use to be set. Fifty-eight options are offered, consisting of forty-nine countries, one global setting for organisations operating internationally, eight regional options including the populated continents and two cultural and political groupings being the Nordics and the European Union. Enabling the user to determine where the device is most likely to be used overcomes the final issue of parity caused by variations in

electricity to GHG emissions factors included in the manufacturer product carbon footprint reports as identified by activity 4.

Conversion factor source data is populated within a table located in the application database and updated annually as each country or region refreshes the factor based upon changes to the associated power supply network (AGDISR, 2021; AIB, 2022; Climate Transparency, 2020; Dep. of BEIS, 2022; EEA, 2021; UNFCCC, 2021; USEPA, 2022b). As such, by selecting a specific location the user can be confident that the resulting scope 2 emissions contributions calculated are equivalent across all options. Additionally, the results will now be relevant to their organisation's operational model and accurate for the year of purchase. Product manufacturer reports will remain as calculated in the specific year of publication and the use-phase emissions contribution generated using either USA, European or Global blended factors used in manufacturer reports. While a prior example is given relating to a UK to USA comparison, the difference becomes extreme when calculating the carbon footprint for countries where almost all electricity production is based upon low carbon sources. This is emphasised in the second impact case study (case study B) conducted in the Nordics where emissions factors are as much as 98% lower (UNFCCC, 2021) than those experienced in the USA (USEPA, 2022b).

Having created dynamic filters to recalculate the scope 2 use-phase GHG emissions contribution to the total product carbon footprint, the barriers of limited parity between devices identified in activity 4 are overcome. To remove the further issue of complexity, ranking and comparative abilities, together with third-party certification labelling information are also included within the application output. Without the tool, should a prospective buyer previously wish to compare the carbon footprint of just one notebook from each of the five manufacturers participating in carbon footprint reporting, the individual would have to visit a minimum of seven websites.

Furthermore, a minimum of five data points per device including scope 2, scope 3 and total emissions values, plus energy and raw material and processes third-party certification, would require subsequent manual cross referencing. Even then the prospective buyer will not be guaranteed to have found the notebook with the lowest available carbon footprint, but simply a notebook from a small cross section of widely available devices. Research confirms that the complexity of attempting to achieve meaningful comparison creates a barrier of time versus perceived environmental impact (Sutton-Parker, 2020a). In simple terms if the task is too difficult to complete and consumes valuable resources, then a cost is associated to the process and inevitably profit is prioritised over planet. Consequently, the results delivered by the application are ranked by the total carbon footprint as a default and can be, if required, sorted by energy scope 2 or scope 3 emissions in isolation. Displaying one-hundred devices per page, up to six devices can be selected for side-by-side comparison. This is because the additional attribute data may cause the selection of a device currently ranking below the top placing as the contextual information includes each device's EPEAT rating plus chassis / screen sizing and operating system. As such, whereby if the top device has a silver EPEAT rating and the second device a gold rating, it may be that the buyer will decide to select the notebook with a slightly higher carbon footprint in the understanding that it contains a greater percentage of recycled materials as an example. In the context of delivering simplicity, conducting the same comparison of several hundred notebooks may take several days as was experienced in activity 4. Using the application, the process is completed in less than one second ensuring that the barrier of time and money required to achieve the task is entirely overcome.

The influence of selecting contextual influences such as location of use and the number of years the device is used is highlighted in figure 15. Results for the same notebook are shown using three use locations of Europe, USA and worldwide plus three retention periods of 3, 5 and 8 years. The impact of carbon intensity of regional electricity grids is highlighted by the identical device producing higher scope 2 emissions in the USA compared to Europe and worldwide. This is emphasised when examined cumulatively. The 8-year retention period causes the total scope 2 GHG emissions to be 61.4 kgCO$_2$e for Europe, 92.2 kgCO$_2$e for USA and 75.8 kgCO$_2$e for worldwide use. Meaning that during the 8-year device lifespan, each user will generate as much as 50% more use-phase emissions.

Keeping a device for extended lifespans will add additional years of scope 2 emissions to the total carbon footprint. In this example the device purchased and used in Europe for 3-years will generate a lifespan carbon footprint of 308 kgCO$_2$e (figure 15). Comparatively, extending the lifespan by a further 5-year period to 8-years will increase this to 364 kgCO$_2$e (figure 15). However, as demonstrated by activity 2, keeping the device for longer drives displacement and therefore lowers to total carbon footprint attributes to each year the device is kept. In this example, the device scope 3 emissions remain equivalent at 285kgCO$_2$e (figure 15) as they are not influenced by electricity factors. However, when annualised to highlight supply chain emissions attributed for each year of retention, the total carbon footprint value decreases from 103 kgCO$_2$e annually to 43 kgCO$_2$e annually (figure 15).

Figure 15. Comparing the influence of location of use and retention period for one notebook upon GHG emissions results using the Dynamic Carbon Footprint application
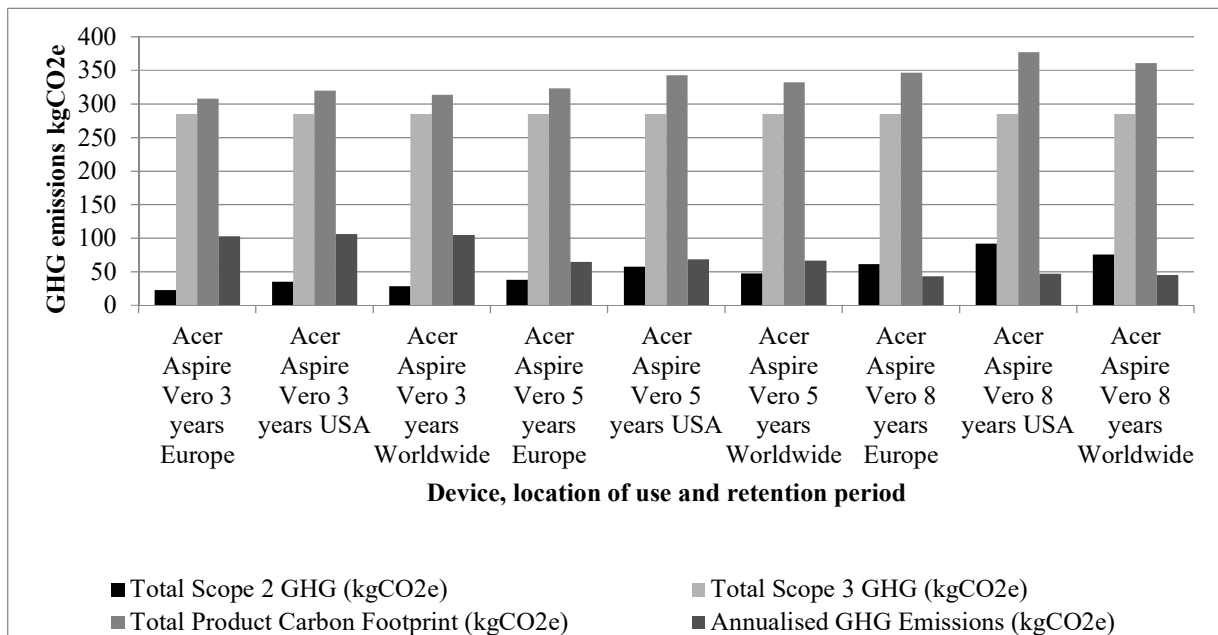
Note figure 15. The notebook selected at random is the Acer Vero AV15-52. The location of use was set and reset to reflect Europe, USA and worldwide regions and therefore the carbon intensity experience in the supply grids. Retention periods were selected to include 3, 5 and 8-year scenarios. The annualised GHG emissions value is the combined scope 2 and 3 emissions divided by the number of years the device is retained.

To ensure that sustainability data relating to the device selected for procurement can be shared, exhibited and retained in order to achieve compliance with procurement legislation, a device specific dynamic carbon footprint report can be generated (figure 16). Containing the scope 2 data defined by the retention period, location of use and device eTEC data, the scope 3 emissions data generated during the original manufacturer's life cycle assessment process, plus attribute data including the EPEAT rating, the document can be shared via a link generation process or as a portable document file (PDF).

5.2.1. Technical construction

As per standard web design practices, the graphical user interface is generated using frames created with a combination of the Laravel hypertext pre-processor framework and Vue java script. This allows for the application to be used dynamically on all formats of device including notebooks, desktops tablets and smart phones. The data base has three specific tables and is hosted within the Google cloud. All are organised by structured query language and defined by relevant categorisations depending on the role of each data set. As an example, the primary table includes asset profile data as defined in activity 3, use-

phase energy values in kWh, plus environmental certification tier information and supply chain carbon footprint data. The secondary table defines current carbon conversion factors by country and region while the tertiary defines the initial main screen drop down selection criteria.

Figure 16. The Dynamic Carbon Footprint report screen (Sutton-Parker, 2022f)
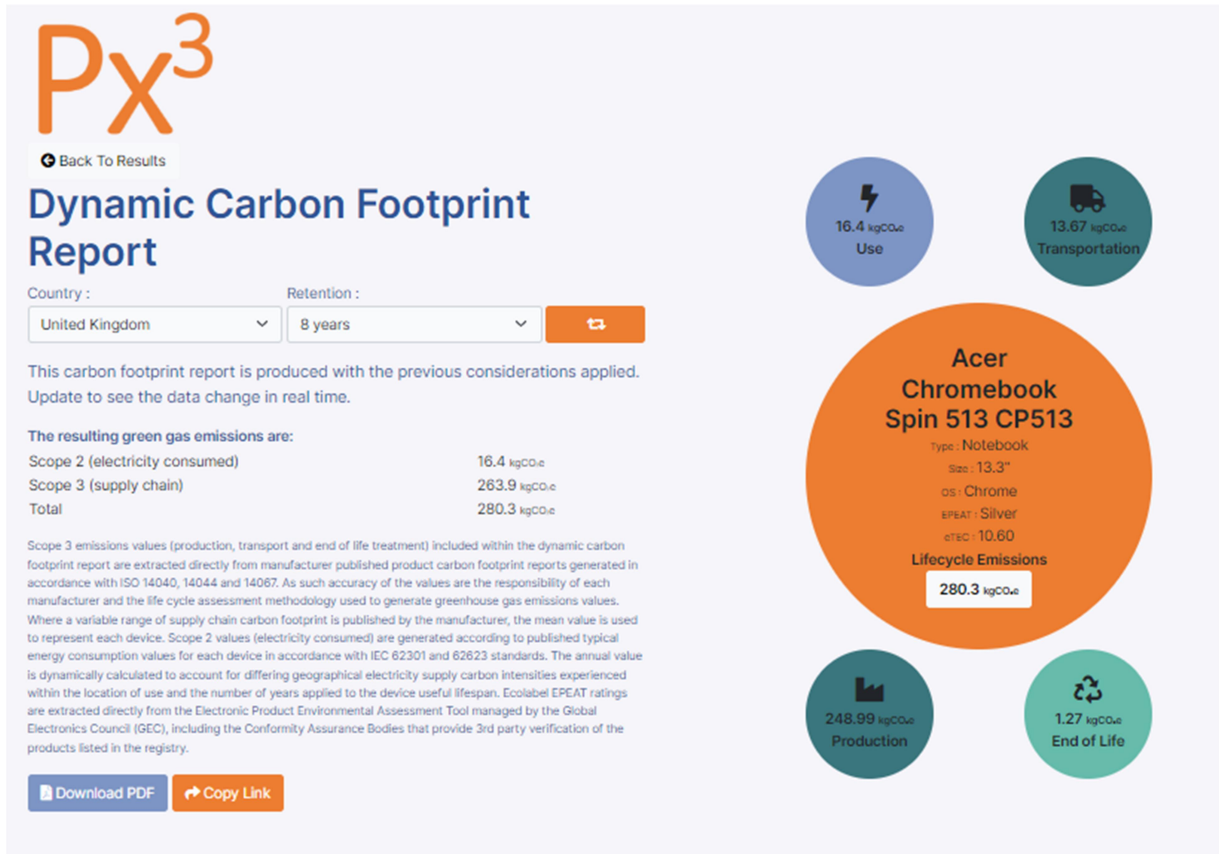
Note figure 16: The dynamic carbon footprint (Sutton-Parker, 2022f) report screen is located online at https://dcf.px3.org.uk

Population and management is achieved via hypertext pre-processor administration tools accessed via a secure browser. The approach allows for constant updates as manufacturers produce new devices and associated carbon footprint data plus third-party certification updates. Additionally, should future user feedback or legislation indicate additional data should be included or additional manufacturers begin to produce environmental data for the first time, the tool can be expanded accordingly. While the tool will be publicly accessible and free of charge, a registration and authentication facility is built into the initial screen to capture user data to enable diffusion to be judged. Individual organisation instances and frequency of use can be monitored with consent.

5.2.2. Pilot phase and user feedback

While the application is designed to overcome the issues identified in activity 4, the usability and value of such a tool will remain theoretical unless subjected to user testing and feedback. As such, twenty people responsible for ICT assessment and procurement for approximately 240,000 users (ONS, 2022) within both the public and commercial sectors were asked to participate in a six-week trial of the application followed by a feedback survey. Selected due to their organisations being subject to procurement legislation, the organisations included in the pilot are the two impact case study

organisations, two of the six organisations involved in activity 4 (the University of Sussex and the Royal Society for the Protection of Birds), plus further UK government organisations that became aware of the application via the research conducted with the Royal Borough of Kingston and Sutton Council. Specifically, this includes the HM Government body responsible for ICT procurement and use policy formation and definition, being the department for the environment, food and rural affairs (DEFRA). The department for education (DfE), the department for work and pensions (DWP), the ministry of defence (MOD), the national health service (NHS), the UK Parliament and Lancashire Council.

Further to acceptance to participate, the group was given a 30-minute online demonstration explaining how to request access and how to use the application. Following the six-week period of use each participant was contacted individually by email and requested to complete the satisfaction and feedback survey detailed in the methodology. From an awareness perspective, 25% of the participants were not aware of the legislation governing procurement prior to involvement in the research.

This concurs with the expansive survey conducted for the Px3 application design (Sutton-Parker, 2020a) suggesting that awareness may be a barrier to diffusion of procurement strategies that include sustainability criteria. In relation to the lack of parity within product carbon footprint reports, 62.5% noted that they were aware of issues before participation, while the remainder noted they were not. When asked if they were historically able to credibly identify, assess and select end user computing devices based upon scope 2 (electricity consumption) and scope 3 (supply chain) GHG emissions the impact of an awareness of inaccuracy of data is emphasised. Specifically, 37.5% noted they were not able to credibly assess and compare devices, while a further 50% indicated it was partially achievable. This indicates that while 87.5% retained doubt as to the validity of the practice based upon current approaches and data, 12.5% believed they had achieved the goal previously.

Asked whether the application enables this capability, 100% of participants believed that the tool does enable meaningful and credible identification, assessment and comparison of end use computers based upon sustainability criteria. In context of the combined computer user install base supplied by the participants, the combined responses suggest that while a potential 30,000 users (12.5%) are already being supplied low carbon footprint hardware, the tool increases this possibility by a further 210,000 users (87.5%). To show the impact of such a behavioural change an exercise is undertaken to calculate the difference in emissions between selecting average carbon footprint devices and low carbon footprint devices for the 201,000 additional users. To achieve this, an average carbon footprint for each device type is determined using the product carbon footprint data compiled in activity 4 (table 8). This data is then triangulated (table 14) with emissions data from devices exhibiting the lowest carbon footprint by type as identified by the dynamic carbon footprint application when set to UK as a location of use. Applying the proportional representation of devices by type (table 14) as determined in case study E (HM Gov., 2022b) during the UK government end user computing scope 3 quantification (table 21) an approximate impact delivered by using the new tool to introduce sustainability as a criterion during procurement can be estimated (table 14).

Table 14. Feasible abatement impact upon the pilot participants

Device Type	Proportional Representation	Units	Average Carbon Footprint (kgCO$_2$e)	Lowest Available Carbon Footprint (kgCO$_2$e)	Feasible Abatement per unit (kgCO$_2$e)	Abatement %	Total Abatement (kgCO$_2$e)
Desktops	31%	65,100	293	184	109	37%	7,095,900
Notebooks	59%	123,900	285	137	148	52%	18,337,200
Tablets	6%	12,600	114	70	44	39%	554,400
Thin clients	4%	8,400	154	160	6	4%	50,400
Monitors	81% of devices	170,100	385	187	198	51%	33,679,800
Total		**380,100**					**59,717,700**

Specifically, based upon a retention period of 5-years, the additional users would abate 59,717,700 $kgCO_2e$ of combined scope 2 and 3 GHG emissions by using the tool to accurately identify devices with the lowest available carbon footprint. This is equivalent to avoiding the pollution created by 216,399,840 car miles and releases the sequestration capacity of 71,661 acres of forest. In relation to likelihood of adoption, the barrier of complexity previously indicated and examined in output 3 is overcome within the group potentially improving the possibility of future use. All users noted that the application was simple to use with the ability to identify and rank products by the total carbon footprint as being the most valuable feature. This was followed in popularity by the ability to compare devices alongside one another and then the third most valuable feature was the ability to generate a carbon footprint report specific to location and retention periods.

All three results arguably substantiate the need for such an application in order not only harmonise data but also to add the context of each organisation's specific operational parameters and generate data that can enable procurement legislation compliance. When asked whether the users believe they will use the tool to assist in the future to identify end user computing devices with the lowest carbon footprint, adoption proved most likely with 100% confirming they would. Specifically, 75% believed the application would directly enable them to create and support sustainability strategies that will abate future end user computing GHG emissions, while 25% suggested the application would somewhat assist. Examining the free text responses, it is clear that all users found value in the tool and enjoyed the simplicity. Many comments included a want to expand beyond the two hundred and fifty devices currently loaded in the database. One comment requested a free text search facility so that the procurement team could locate the device they were buying and print the carbon footprint report. This was directly challenged suggesting this would create an opportunity for buyers to undertake exactly the described activity and therefore avoid comparison and identification of more sustainable options. The participant accepted the point and conceded that the search concept was flawed.

In summary, the tool proved to be well received by all participants and improved the capability to respond to end user computing device assessment and therefore procurement based upon sustainability criteria. The key value being that creating a simple to use interface that delivers organisation specific context together with data parity caused a previously complex task to be achievable within seconds. As such, combined with the ability to create carbon footprint reports to confirm the task has been credibly undertaken ahead of purchase, the application both enables procurement strategies to become meaningful and comply with ever tightening legislation.

Beyond the utilisation of the tool in the case studies, it was identified that all parties would continue to use the tool and indications of further diffusion have since been exhibited. Specifically, the council participant contacted the Society for innovation, technology and modernisation (SOCITM) to recommend the approach. The society has over 2,500 members helping shape and deliver public services. This includes in excess of 250 councils that will now be made aware of and invited to use the tool starting in Spring 2023. Equally, DEFRA confirmed that all government departments and bodies are free to adopt the tool should they see benefit in using it. Specifically, the department also initiated a full scope 3 audit using the tool (see outcomes). Involving just over 3.1m ICT devices, the intention is to leverage the results to lower the government's current and future cumulative ICT hardware carbon footprint via the achievement of procurement based upon sustainability criteria.

5.3. Output 3: Px3 Planet, People, Profit Framework

The activities stage substantiates that inaccuracies and a lack of both availability and parity exist with regards to the measurement of end user computing electricity consumption and product carbon footprint values in general. To overcome such barriers, output 1 builds upon the findings, producing the cTEC methodology used to calculate active phase energy consumption. Similarly, output 2 creates the dynamic carbon footprint application to generate parity for existing carbon footprint data. As such, the objective of

the third and final output is to create a framework and spread sheet driven application capable of generating and presenting meaningful information specific to an organisation's information technology operations. In doing so, practices such as asset profiling developed during the activities stage and the previously discussed outputs are triangulated to create a representation of both the existing and proposed impact. Understanding both actual and potential results may drive behavioural changes that ultimately abate GHG emissions. The following sections discuss the concept and production in detail.

5.3.1. Px3 framework

The framework or more precisely a method of presentation, produced by output 3 is called 'Px3' representing the triangulation of metrics related to Planet, People and Profit (Elkington, 1997). In context, the first metric relates to simplified quantification of existing and abated information technology environmental impacts. This specifically overcomes two barriers to the diffusion of sustainable IT practices discovered to exist within businesses in activity 5 (Sutton-Parker, 2020a). The first is the barrier of time (complexity) associated with quantifying and planning for sustainable IT. The second is the limited perceived impact that sustainable IT can deliver (Sutton-Parker, 2020a). The second metric diverges away from Elkinton's (1997) original example of 'people' and the improvement of social wellbeing and local economic growth caused by corporate activities. The metric is instead represented by abatement achieved via employee working behavioural changes that influence overall GHG emissions. This is intentional to again leverage the finding of activity 5 that beyond the board level and manager stakeholders, employees without environmental key performance indicators will not be encouraged or able to participate in positive environmental actions unless they have a measurement appealing to personal interests. Whereas the third metric of profit, represents cost reductions related to lowered utility and supply chain costs delivered by new strategies such as low energy device adoption, hardware displacement and remote working. This specifically overcomes the key barrier discovered in activity 5 (Sutton-Parker, 2020a) that adopting sustainable IT is perceived to be cost prohibitive and therefore no budget exists for such activities.

The name is derived from the influence of two publications already discussed within the literature review Rees and Wackernagel (1996) addresses humankind's material impact on Earth and sets the tone for quantifying specific impacts, represented in this instance as information technology production and use. Elkington (1997) discusses the idea that profit retention does not automatically result in environmental damage, expanding considerably upon corporate social responsibility (CSR) works such as Carroll (1979) and Spreckley (1987) by suggesting companies could adopt a non-traditional approach to accounting that includes profit, social wealth and environmental performance elements. This approach is appropriate for the application as it is designed to appeal to multiple stakeholders based upon their role or personal needs and interests. Costs, resources and perceived impact all act as barriers to the diffusion of sustainable information technology strategies. Consequently, if a framework and application can be developed to deliver information that is sufficiently meaningful to all stakeholders then the likelihood of success is arguably increased.

Having satisfied the prospective design approach for the Px3 framework, the subsequent phase was to structure the data flow. As highlighted in figure 17, both secondary and primary inputs are required to calculate the results. The majority of sources of each data set are described previously in activities and initial output phases. However, each input and output is discussed to clarify exceptions and to offer specific explanation of functions attributed to the Px3 framework.

Figure 17. Px3 'Inputs and Outputs'
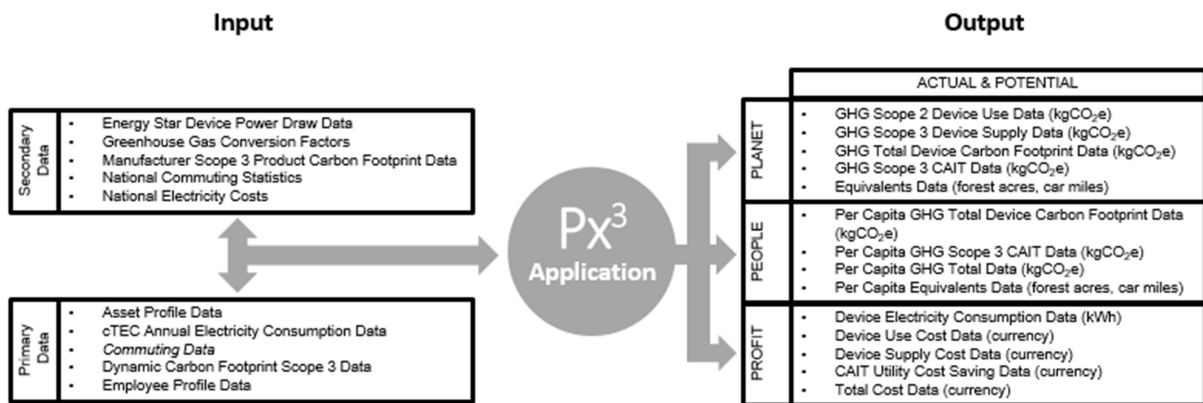
5.3.1.1.   Secondary data inputs

As described in output 1, Energy Star power draw data is required to calculate the annual commercial energy consumption (cTEC) value for each device identified during the asset profiling exercise and suggested for the potential environment output (see below). The data is reported in W and for the purposes of the Px3 framework, captured using two methods in two ways. The first involves extraction directly from the Energy Star web site using the publicly available application programming link. Communication with the secondary data source is automated using a hypertext transfer protocol secure (HTTPS) to enable identification and authentication. Specifically, this is achieved using a unique app token supplied by Energy Star. The response uses extensible mark-up language (XML) to ensure that the data can be structured to match both the asset profile and mode data requirements. As each column in the data set includes multiple fields that are not relevant to the Px3 requirements, simple filters are applied to the data request. These include brand_name, model_name, model_number, type plus category 1 and 2 filters for off_mode_watts, sleep_mode_watts, long_idle_watts, short_idle_watts and tec_of_model_kwh. The resulting data is stored in a structured query language (SQL) table hosted in the Google Cloud Platform and administered using a secure hypertext pre-processor (PHP) portal. This approach is taken to ensure that the secondary energy data is automatically updated as and when new devices are tested and become Energy star certified. Should the cTEC lookup and matching process (explained below) fail to find a result, due to issues such as device age, then the second variation of data sourcing is undertaken. This involves manually searching repositories including manufacturer environmental compliance and Eco-Declaration documentation.

The relevance of the GHG emissions conversion factors is explained in detail in both the activities stage and outputs 1 and 2 and as noted, is essential to ensuring the use-phase emissions reflect the carbon intensity of the country or region where each device is operated. To enable the multiplication of the cTEC value by the factor to produce the scope 2 emissions values, an SQL data table is created listing the relevant country and the associated factor. Where regional values are required the relevant factors for countries within an area, such as Europe, are combined and an average created. The factor data used to populate the table is extracted manually from a variety of sources including European residual mixes data published by the Association of Issuing Bodies, the United States Environmental Protection Agency eGrid Database and national inventory reports. As before, the 'factors database' is maintained and managed via the same PHP portal. It is noted that the same table is used for both the Px3 framework and

the Dynamic Carbon Footprint (Sutton-Parker, 2002c; d) tool and updated annually to reflect the international reporting cycle as governed by the United Nations Framework Convention on Climate Change (UN, 11992) national inventory submissions policy.

The manufacturing scope 3 carbon footprint data is extracted directly from the database created during output 2. Specifically, a lookup and match query is executed using the data defined during the primary data asset profile input. Where a value is not generated due to the model data not being available, an average kgCO$_2$e value is used to populate the results. This is necessary as activity three substantiates only 22% of devices are currently quantifiable for scope 3 emissions. Specifically, the average is created by filtering the available scope 3 data by the 'type' field to match the device in question (e.g. notebook). This is to ensure that the calculated impact is specific to each style of end user computer devices as this varies considerable as defined in activity 3.

The relevance of the national commuting statistics is to determine the number of miles travelled on average by computers users each time they commute to an office to access information technology (CAIT). This enables the representation of scope 3 commuting GHG emissions generated annually by the inspected workforce. As explained in the case study, the value is currently restricted to the impact of car use based upon the concept that other services such as public transport will operate regardless of individual remote working patterns and therefore not deliver a pollution reduction. The importance of including this value within strategies to reduce IT related GHG emissions are explored in associated research (Sutton-Parker, 2021). Specifically, the research indicates that reduced commuting (Gartner, 2020a; b) in 2020 significantly lowered GHG emissions (ESA, 2020). As transportation generates 14% of global GHG emissions by economic sector (USEPA, 2020; Dept. for BEIS, 2019), reducing commuter emissions is key to a sustainable future and achieving international GHG abatement targets (CCC, 2020).

As such, in the spirit of the UNEP (2019) bridging strategy, remote working enabled by end user computing solutions is suggested to be capable of delivering innovation and behavioural changes that will contribute to the reduction of societal emissions. To determine the percentage of GHG emissions abatement achieved by remote working, the research measures 815 employees across a 2-year time horizon, spanning both pre and COVID-19 periods (see case study D). The results indicate remote working reduced commuting emissions by 43% in 2019 and 97% in 2020, generating a per capita abatement value of 1.9 tCO$_2$e. Examining the commuting data generated by the employees in twenty-four countries using twelve forms of transport, the research also quantifies the impact of returning to a 'new normal' when commuting recommences. The results indicate that now the question of whether remote working is feasible for a wider audience has been proven by enforced business continuity in 2020, three key factors must be examined to ensure commuter emissions do not revert or exceed 2019 values. These include leveraging the benefits of work life balance delivered by remote working, awareness of the environmental impact of commuting and adoption of zero carbon transportation. In doing so, the statistics indicate that while employees will return to the office, future abatement of 60% is achievable in the 'new normal'.

To address this feasible environmental gain, the secondary data used to populate the CAIT input is currently done so to enable the case study section. Specifically, UK Department for Transport statistics (DfT, 2021) related to the percentage of journeys undertaken for commuting purposes and the average miles travelled per journey is triangulated with a scope 3 GHG conversion value for an average car published by Department for Business, Energy and Industrial Strategy (Dept. for BEIS, 2021c). As the associated research (Sutton-Parker, 2021) determines that the impact of car travel changes in intensity depending upon countries due to engine efficiencies and average miles travelled, then future versions of

the application must be developed to include a more extensive CAIT data table to reflect location data captured during the asset profile exercise.

The national electricity costs database is essential to enable the profit output. Reductions in kWh electricity consumption will vary by geography due to the local cost of energy. As such, an average cost for commercial electricity within each nation must be applied to the 'profit' output calculation based upon the location data captured during the asset profile exercise. To enable this a fifth data base called, 'Electricity Costs' is generated by accessing government electricity prices attributed to each nation where available. As an example, the UK costs located in the Department for Business, Energy and Industrial Strategy 'UK Commercial Energy Costs Table' (Dept. for BEIS, 2021d) is utilised to populate the relevant year of assessment for the case study. The result is matched using the standard visual basic for applications 'xlookup' function. The data base is again hosted and managed in the same manner as previously described.

5.3.1.2.   Primary data inputs

The asset profile data is specific to each organisation and as such a data table called 'Asset Profile [Insert Organisation Name] is populated for each new assessment. The table is structured by the fields determined during activity 2 and output 2, in line with the Kawamoto et al. framework and the naming conventions used by Energy Star. In summary, these include type (e.g. desktop), brand_name (e.g. HP), model (e.g. HP Elite Dragonfly G2) and location (e.g. UK). The data is populated using the capture process described during the analytics software testing activity. As such, this includes extracting data from XLS spreadsheets generated by either asset management or analytics software, plus the previously developed survey technique.

The commercial typical energy consumption (cTEC) data is calculated using the approach described in output 1. For models that have been measured for active power draw (see case study and outcomes) and displays, a cTEC data base exists. This is structured using the asset profile fields with the unit value set to 1, plus additional energy focused fields. Specifically, these include the low power modes populated by the Energy Star data, being off_mode_watts, sleep_mode_watts, long_idle_watts, short_idle_watts, plus the newly proposed active_one and active_two modes.

The dynamic carbon footprint data is populated using the existing data table created during output 2 to enable the calculation of scope 3 emissions as previously described. As before the xlookup function is used to match the asset profile data to the scope 3 records.

The employee profile data is captured during the asset profile survey stage and simply consists of an input documenting the number of computer users. The value is required to enable the per capita ratio described below.

5.3.2. Data outputs

The three Px3 outputs include both actual and potential representations of information technology related emissions and associated data. The subject organisation is presented with impact information associated with the current status as well as a future improved value that could be achieved by adopting sustainable information technology best practices automatically suggested by the application. As noted previously, this includes transitioning to low carbon footprint devices as the need to procure arises, by extending retention periods to displace new purchases and promoting an increase in remote working days enabled by computer solutions to lower commuting to access IT emissions. The values used within each output reflect the focus of the theme.

For the 'planet' information two categories of quantification are represented. The first uses GHG emissions accounting and protocol compliant units measured in $kgCO_2e$. Doing so ensures that international standards are met and the results can be used to add context to mandatory company reporting. In this instance, the results can be used, if required, to determine what percentage of the organisation's total operational carbon footprint is generated by information technology. The value of this being that improvements delivered by potential behavioural changes in relation to IT operations will also reflect as a decline in contribution to environmental impact. As such, the perception that IT is contributing to organisational wide net zero strategies and targets is increased among stakeholders that would otherwise be unaware. The second value category is described as 'equivalents'. This consists of converting the arguably intangible $kgCO_2e$ accounting values to familiar analogous measurements. These include the number of car miles travelled to create the equivalent pollution or the area of forest required to remove the pollution from our atmosphere via photosynthesis. The decision to include equivalents is to achieve the consumer psychology 'aha' moment via familiarity. Specifically, this is to appeal to stakeholders that are not experienced in GHG accounting and will not therefore know if 1,000 $kgCO_2e$ is good, bad or indifferent. The concept is not new, having been evident in the EPA's Greenhouse Gas Equivalencies Calculator since 2008 (USEPA, 2022a) and as such may prove, as it has for the EPA, to increase or at least expedite resonance.

For the 'people' information a similar approach is repeated with regards to accounting and equivalent values used to represent the impact of employee behaviours driven by device selection and remote working behaviours. However, the exception is that the forest area equivalent is replaced by a per-capita value called the equivalent value per employee (EVE) ratio (Sutton-Parker, 2020c). The result is derived from two elements. The first is the total IT related carbon footprint represented in car miles (see planet output) and the second, the number of computer users determined during the asset profile exercise. The ratio expressed as follows:

$$1 = Total\ IT\ related\ vehicle\ miles\ equivalent\ /\ Number\ of\ IT\ users$$

As an example, if the vehicle mile equivalent is 400,000 and the number of employees 1,000 then the result is 1:400. This means that for every user the equivalent of 400 miles of vehicle pollution is generated by end user computing operations. The rationale of using the value is to create a standardised ratio that can be used to compare organisations regardless of size and to judge internal annual improvement in the same way that Power Usage Effectiveness (PUE) achieves with regards to data centres (Belady and Malone, 2006). While not currently developed fully, the future concept is to use the ratio to engage individual employees via a mobile application that ensures they are offered an ability to participate in net zero strategies. This would be achieved by inputting commuting and device selection data that if selected using sustainability criteria via tools such as the dynamic carbon footprint the choices will lower their personal impact and improve the company EVE ratio. This is arguably important as related research indicates that employees not involved with environmental accounting, sustainability strategy setting or subject to related key performance indicators struggle to connect with environmentally focused initiatives.

The 'profit' output is quantified in currency to reflect operational and capital expenditure reductions delivered by reduced energy consumption and displaced device purchases. The currency value reflects the country or region in which the budget is assigned or accounted for. The rationale for the inclusion of a financial value is to substantiate that sustainable information technology strategy will in most case reduce cost. The value of this is that associated research determines the greatest barrier to the diffusion of such strategies is money. As such, if sustainability strategies are proven to reduce costs and therefore become self-funding, then the barrier to success is removed by appealing to the role-based interests of

stakeholders such as the chief financial officer. As such, the following sections explain each output category in detail from both a before and after context.

5.3.2.1. Planet

The end user computing device emissions output enables the presentation of the carbon footprint generated by all variations of displays, desktops, tablets, thin clients and workstations used or potentially adopted in the future by an organisation. The values are presented to include a total carbon footprint and the isolated scope 2 electricity and scope 3 supply chain emissions contributions. The two scopes are accounted for separately as part of international reporting protocols and frameworks.

The 'actual' GHG scope 2 emissions values are generated by multiplying the matched asset profile and cTEC kWh data by the relevant location-based carbon conversion factor. The Px3 framework achieves this using a combination of complex wildcard match between the 'Asset Profile' and 'cTEC' data tables plus an 'xlookup' function between the asset and 'Carbon Factor' data tables. The results are represented by a total scope 2 annual value for all devices although this can be dynamically mined using filters based upon the combined asset profile and newly produced emissions results. As an example, the 'type' field can be used to compare combined display and desktop computer electricity emissions to notebook emissions to assess whether a wholesale move to mobile computing strategies will lower end user computing emissions. Additionally, devices can be sorted by individual high to low emissions values to determine if certain models of device are producing excessive amounts of concomitant emissions. Comparatively, the 'potential' values are generated by multiplying the number of units by type (e.g. notebook) captured during the asset profile exercise by the scope 2 emissions generated by a 'best in class' device. Such a device is defined as being a notebook, desktop, display or tablet exhibiting the lowest total carbon footprint. The focus upon the combined emissions value is because as highlighted in activity 2, scope 3 emissions remain dominant. Therefore, a device with the lowest scope 2 emissions may not deliver the lowest total environmental impact in the longer term. As such, by considering the proportionate contribution to an assumed lifespan of 5-years enables the mistaken recommendation of a total carbon footprint increase to be avoided. The potential device is identified using the 'type' filter and sort by 'carbon footprint' functions within the Dynamic Carbon Footprint tool (see output 2). The resulting data is then matched using the wildcard and 'xlookup' function to apply the relevant cTEC and location-based scope 2 emissions.

The actual scope 3 emissions are generated using the same wildcard function to match each device captured during the asset profile exercise with the total supply chain emissions field in the Dynamic Carbon Footprint database and then multiplying the results by the asset profile unit field. The values are then divided by the number of retention years declared by the subject organisation and the supply chain impact is spread across this period to form an annual impact. This action allows for the potential improvement to be represented by a combination of an extension retention periods and a transition to 'best in class' devices identified during the scope 2 calculation exercise. In each instance the new calculation is based upon harmonising retention periods to 8 years for computers and 10 years for displays based upon related extended use research and operating system software support durations operated by major vendors. The findings are presented in the same top level and dynamic and minable variations as the scope 2 emissions results.

As to be expected, the total GHG emissions values for both actual and potential scenarios are simply a combination of the previously determined results and the difference between the two before and after

values is displayed to ensure the organisation is aware of the abatement achievable further to the adoption of low carbon footprint devices.

The Commuting to Access IT (CAIT) or remote working GHG value is produced by triangulating several inputs as discussed in the secondary data section. In summary, using the case study as an example, this is achieved by determining the number of computer users that most likely drive a car to work and multiplying the results by an average number of miles travelled. This value is then multiplied by the relevant vehicle emissions to GHG emissions conversion factor. The inputs required to achieve this are supplied by both the primary and secondary data inputs. Specifically, the asset profile data input and the statistics from the secondary data commuting input. The actual and potential scope 3 IT related commuting emissions presented by the application are used to highlight abatement that could be achieved by increasing remote working days enabled by information technology solutions. Increasing from zero to two days, as an example, would immediately reduce car generated emissions by 40% based upon a five-day working week. As previously noted the case study is undertaken in the UK and therefore enables a relatively simple approach to calculation using an XL SUM script. However, associated research conducted to support the development of a more sophisticated approach will enable variations in the future. These will include the ability to capture employee data including preferred mode of transport, country of travel and return journey miles travelled. Specifically, the research objective of capturing and quantifying commuting to access information technology behaviours among eight hundred and fifteen employees, working in twenty-four countries and experiencing over ten modes of transport is achieved proving that the development is feasible.

As previously noted, planet GHG accounting values are translated to equivalent values including car miles and forest acres. Specifically, the car mile equivalents are based upon car emissions reporting factors published by participating countries as described within the input section. The forest acre value is based upon the EPA conversion tool (USEPA, 2022).

5.3.2.2. People

As discussed, the focus of the people output is to express the already generated planet results as a per-capita ratio called EVE. The data points required to achieve this are based upon the computer user number input created during the asset profile exercise and the equivalent car mile value generated by the associated planet output. As noted, the ratio is generated by simply dividing the later by the former. By including the people aspect, the concept is not to shift the commercial carbon footprint responsibility from the business to the individual, but to appeal to a wider audience by reaching outside the managerial corporate social responsibility key performance indicators of compliance and accounting. Ultimately, it is designed for human resources leaders and individuals who want to measure environmental progress at both an individual and organisational level, but to do so without complexity. In addition to making the measurement of personal environmental success feasible, EVE also sets a baseline for improvement. As the EVE reduces because of IT selection and operational behaviours, the attainment of success becomes tangible.

5.3.2.3. Profit

The 'profit' output focuses on the same pillars as the planet results including device use and supply plus remote working. However, the GHG emissions and equivalent units are replaced as discussed by currency. The actual and potential values generated represent the current costs of electricity consumption and annual device supply: both can be reduced by improving energy efficiency, lowering the number of days per year devices are powered within the office and extending the number of years attributed to

device depreciation. The device use calculation is determined by the total kWh value generated during the planet scope 2 device calculations minus the number of days operated outside of the office. As an example, if the current actual remote working days value is 1 day per week, then 20% of the electricity cost is removed based on the rationale that the utility cost is met by the user. This is approached differently to the environmental values as regardless of whether the device is used within or beyond the office scope 2 emissions are emitted and therefore do not change. Comparatively, if the potential remote working policy transitions to 2 days per week, then 40% energy consumption is reflected with an incremental 20% minus figure calculated as per below. Retaining the location specific field, a simple XL SUM subtracts the improved potential value from the actual value to quantify the number of kWh units saved per country should new energy efficient devices be adopted. Using the xlookup function based upon the location field, this value is then multiplied by the relevant cost per kWh stored within the 'National Electricity Costs' data table. The results table is then compiled to produce an annual savings value converted back to the currency used by the organisation's headquarters.

The device supply financial saving is calculated by multiplying the average cost of purchase per device type supplied by the subject organisation during the asset profile exercise by the number of units by type. This is then divided by the number of years included in the relevant retention period to produce an actual annual supply cost for all computers. The same calculation is then undertaken with the exception of applying the extended retention periods of 8 and 10 years to the computers and displays to produce the now proportionately lower potential value. This is then subtracted from the actual value to produce a yearly cost saving generated by a change in policy relating to retention periods.

The final remote working calculation determines the costs saved by operating devices beyond the office. This is achieved by simply calculating the reduction caused by additional days when devices are operated remotely. As explained previously, moving to 2 days per week remote working from 1 day enables an additional 20% utility saving per year. As such, the saving is generated with a XL SUM capable of applying the percentage reduction to the potential energy consumption cost value.

5.3.3. Presentation

To enable dynamic presentation of the meaningful data, the framework is designed similarly to the dynamic carbon footprint report. The organisation can access the results online and share the content should this be required. The home page acts as a summary of the organisation's policy decisions relating to influences such as user numbers, device retention periods, remote working days and location plus the results structured by the three planet, people and profit headings (figure 18). The outputs previously discussed are listed within each relevant section together with the potential reduction available should the organisation adopt further sustainable information.

Each result acts as a link to enable the data mining screens to be accessed. As an example, clicking on the Device Scope 2 (Electricity Consumed) displays a page highlighting quantitative data including the percentage of devices by type and units per country (if relevant) plus scope 2 emissions percentages by device type and country (figure 19). These graphs are again dynamic and when selected mine down one level to show the specific device data tables. These include the asset profile and results relating specifically to energy consumption and the total carbon footprint. The potential abatement and reduction link highlighted in orange (figure 19) in each section link to the potential screen. This is a similar version of the 'actual' home screen although in this instance the potential values are displayed in place of the 'actual values'. For ease, the screen can also be accessed via the 'view' option that is dynamic and toggles between the actual and potential results.

Figure 18. Px3 framework output interface
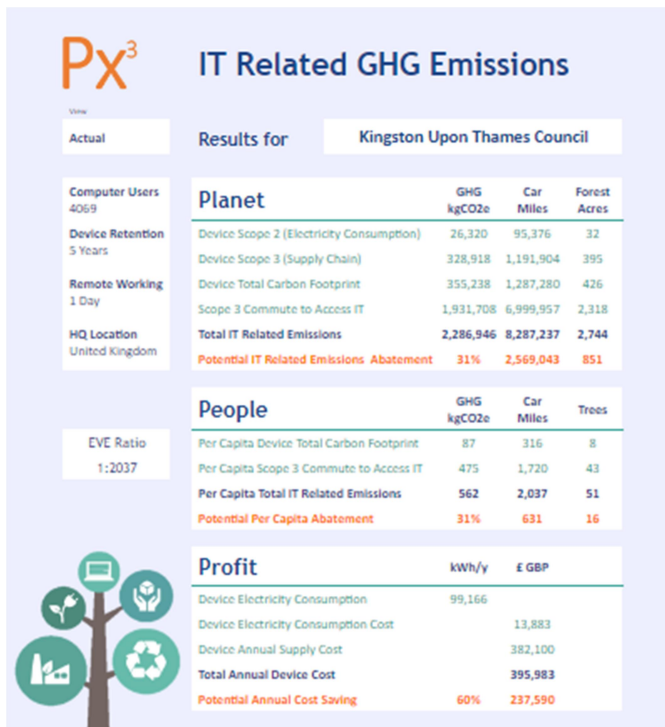
Note figure 18: The Px3 framework interface is located online at https://itcf.px3.org.uk

As with the Dynamic Carbon Footprint tool, the Px3 framework allows the results to be shared by either download of email of the relevant portable document file. The data can be used for compliant emissions reporting purposes or to populate an environmental business case that can be justified by further metrics such as cost savings as previously discussed. The success of this and the data presentation is tested within the impact case study. The intention being that if effective, the application can be used in further instances to promote the representation of meaningful information to drive behaviour changes that will drive the adoption of sustainable information technology strategies.

Figure 19. Px3 framework device proportionate representation page
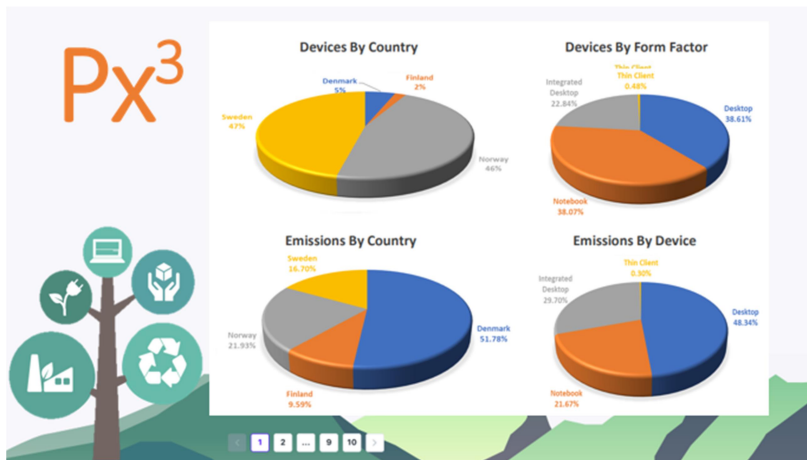
Note figure 19: The Px3 framework interface is located online at https://itcf.px3.org.uk

6. Chapter 6: Influence (Outcomes)

The final impact case study stage tests the three solutions for effectiveness. In doing so, both the primary research question, 'Can meaningful end user computing carbon footprint information drive human behavioural changes to abate greenhouse gas emissions?' and the 'responsible consumption' aspect of UNSDG 12 (UN, 2015) are addressed.

However, ahead of this exists the penultimate stage of the impact value model used to frame the research; the outcome stage. Described as a stage used to highlight influence, change and effects experienced by individuals and organisations that have been involved in the research, the section examines the research's impact upon the 'responsible production' aspect of UNSDG 12 (UN, 2015).

This is achieved by identifying changes to business practices adopted by major manufacturers identified in the initial 'input' stage of the research model. Whilst not conclusive or metrics based, the value of doing so indicates that the evolving research has caused organisations involved in manufacturing computers to re-think business practices by including sustainability as a key criterion.

6.1. Outcome 1: Google

As the input stage notes, Michael Wheeler-Wyatt, Head of Google Chrome, EMEA became aware of the research in autumn 2019 further to agreeing to supply Chromebooks for the testing in activity 1. The findings of this field experiment revealed that devices installed with the Chrome OS operating system proved to be 46% more energy efficient during the active stage than notebooks with alternative software such as Microsoft Windows 10 (Sutton-Parker, 2020b). Wheeler-Wyatt facilitated a meeting with further Google stakeholders leading both sustainability and marketing strategies. The intention was to validate the findings with a view to using the results as the foundation for a new global Chrome OS sustainability strategy based upon energy efficiency. Further to peer review by both the scientific journal and an independent academic appointed by Google, Professor Erinn Ryen, the capability of Chromebooks to reduce scope 2 GHG emissions was accepted.

In winter 2020, Google produced the first strategic illustration called, 'Create a better tomorrow with Chrome OS'. The content notes that Google, in relation to Chromebooks, is a, *'company, hardware and an ecosystem built to protect the planet and its future.'* Specifically, it is announced that, *'Chrome OS is a cloud first software, resulting in an overall device carbon footprint'.* It is noted that responsible energy conversation delivers the 46% electricity consumption value as determined by the research.

Encouraged by the findings and the impact delivered at the local council case study used in the impact section, Wheeler-Wyatt engaged his Europe, Middle East and Africa regional customer and channel facing sales teams. Further to presentations explaining the findings, several members of the team began to voluntarily include the sustainability gain within their sales and marketing strategies; an action that would result in a second case study with a hotel group discussed below. Additionally, during this period, two further outcomes accelerated the changes in approach directed by Wheeler-Wyatt. The first was the production of a video case study (YouTube, 2022a) to showcase the findings of the impact case study conducted with the Royal Borough of Kingston upon Thames and Sutton Council (see case study A). The filming was undertaken to link back to the initial positioning of an ecosystem approach and to offer a real-life illustrative example of how lowering energy consumption in the workplace can reduce scope 2 emissions. Included within the filming are both Acer and Citrix based upon the former being the device provider and the latter enabling secure remote working access to legacy applications. The resulting short

film appears on YouTube (2022a) and is used within customer and internal sustainability presentations and training for all three technology companies.

The second event was the completion of activity 2 conducted to determine the proportionate contribution of the Chrome OS software and components to the substantiated device energy reduction. As discussed, this was achieved using Chrome OS Flex and determined that the software in isolation is responsible for approximately half of the environmental gain. As such, the potential of the replacement operating system to enable re-purposing, support displacement and reduce legacy device energy consumption was recognised by Google. This research, subsequently published by Procedia Computer Science (Sutton-Parker, 2022c) formed the second foundation for the Google Chrome OS sustainability campaign.

Specifically, in Spring 2022, several activities were undertaken by a growing collective of Google sustainability stakeholders led by Wheeler-Wyatt and advised by this research. The first involved using the cTEC methodology to measure further Acer, Lenovo, Dell and HP Chrome OS devices. The energy consumption data, in conjunction with the original research findings, was used to produce two sustainability sales and marketing tools. These included an extension to the existing spread sheet-based Google Chrome OS return on investment calculator used in sales engagements. The original tool specifies productivity gains delivered by the software when organisations move from alternative solutions such as Windows 10 to encourage purchases of Chrome OS. Alternatively, in this new instance, a less complex version of the Px3 approach was incorporated to leverage averages generated by both the cTEC results and the dynamic carbon footprint tool to highlight sustainability gains, such as scope 2 and 3 emissions reductions achieved by making the transition.

Additionally, a mobile application based upon the same findings was created to enable organisations to estimate themselves the environmental gains when moving to Chrome OS. Customers are asked to input data such as the total number of end user computing devices, the percentage replaced annually and the main location of operation. The responses are then interpreted by an algorithm written by this research to produce an estimate of scope 2 and 3 emissions avoided.

This is represented as follows:

$$1 \; year \; kgCO2e \; scope \; 2 \; abatement$$

$$= \left(\left(\left(\frac{C4}{2} \right) * (C5 - C6) + \left(\frac{C4}{2} \right) * \left(\left(\frac{C5}{100} \right) * C11 \right) \right) \right.$$

$$\left. + \left(\left(\frac{D4}{2} \right) * (C7 - C8) + \left(\frac{D4}{2} \right) * \left(\left(\frac{C7}{100} \right) * C11 \right) \right) \right) * B2$$

Whereas:

$$1 \; year \; kgCO2e \; scope \; 3 \; abatement = \left(\left(\frac{C4}{2} \right) * C9 \right) + \left(\left(\frac{D4}{2} \right) * C10 \right)$$

For simplicity, the calculation assumes that 50% of the replacement units will be renewed with Chrome OS new devices and 50% will be retained and converted to Chrome OS Flex. This percentage value is simply indicative.

As such the algebraic representations are interpreted as follows:

B2 = the relevant national carbon conversion factor
C4 = the number of desktop computers usually replaced each year
C5 = the average annual Windows desktop electricity consumption
C6 = the average annual Chromebox desktop electricity consumption
C7 = the average annual Windows notebook electricity consumption
C8 = the average annual Chromebook notebook electricity consumption
C9 = the average desktop embodied emissions
C10 = the average notebook embodied emissions
C11 = the electricity reduction caused by Chrome OS Flex
D4 = the number of notebook computers usually replaced each year

The second activity involved using the cTEC methodology and Px3 framework to quantify meaningful emissions with a second Google customer generated by a growing interest from the Google sales team as previously alluded to. Specifically, Nordic Choice hotels, a company that operates more than 200 hotels in five different countries across the Nordic region, was analysed to determine the sustainability benefits of transitioning 4,800 devices from Windows 10 to Chrome OS via replacement and displacement strategies. As such, this short impact case study is discussed in detail below (case study B) based upon the considerable behavioural change exhibited by the Nordic Choice Hotels and the abatement delivered by the change in strategy caused by the research. This summary outcome is also published by Google as an international sustainability case study / white paper (Google, 2022a) and used in conjunction with the two previously discussed tools and the council case study to conduct an Earth Day event in April 2022. Broadcast simultaneously in London, France and Germany, the event enabled over six-hundred attendees to understand the research behind the sustainability strategy, use the mobile application via a quick response (QR) code and for those attending in-person, to partake in a sensory zone portraying impact of computer manufacturing and use upon the environment. Specifically, during four hours, the overall research was utilised as a key-note speech together with panel conversations involving the two case study organisations. Wheeler-Wyatt acted as host and explained how meaningful end user computing carbon footprint information has enabled all parties involved to realise the impact information technology has on climate change and how their collective behaviours are now enabled to conduct climate action on a daily basis. A short film highlighting the content also appears on YouTube (2022b).

In July 2022, Google will also launch a global campaign promoting the energy reduction capabilities of Chrome OS Flex as identified in activity one and validated by activity 2. All media and technical content produced by Google will reference the research findings directly (Google, 2022b).

Reflecting up the entire effect and influence of the research, Wheeler-Wyatt (2022) noted, *'Prior to being involved in the research, I knew that end user computing obviously has a carbon footprint. What I didn't appreciate is its significant contribution to annual global emissions and the positive impact stainable IT strategies can have when approached in a meaningful way. The research has identified unique energy efficiency qualities attributed to the Chrome OS and Chrome OS flex operating systems and enabled us to substantiate how this enables climate action. Because of the engagement and the effect upon my team and I, Google now uses the research findings and methodologies to drive end user computing emissions abatement activities. These include using the Px3 information to quantify the impact from customer deployments of Chrome OS software and devices and to help our teams compute the sustainability impact of our product. Simply put, the research and contribution has changed my outlook and business behaviour and helped to shape our approach to sustainability at a global level.'*

Subsequently, Google Chrome OS now has a specific micro website (Google, 2022b) dedicated to sustainability highlighting findings and real-world impacts driven by this research. Wheeler-Wyatt has

since officially included sustainability key performance goals for his sales staff to ensure that environmental impact leads the conversation when engaging with customers. From an ecosystem perspective, the EMEA leader has encouraged one of Google's main distribution partners, Techdata, to also facilitate sustainability events and sales campaigns that allow resellers such as Getech to promote the sustainability benefits of Chrome OS to their customers, thus widening the diffusion of environmental messaging to organisations across Europe, the Middle East and Africa.

6.2. Outcome 2: Citrix

Citrix became aware of the research at a corporate level in winter 2019 via the case study examined in the impact section. Having worked personally with the global digital workspace software company for several years promoting sustainability messaging since 2016, resonance had remained incredibly limited, mainly based upon individual interest rather than role-based needs. However, in December 2019 public sector sales director Chris Oldham recalled conversations about this research and responded to the council's sustainability inquiry by organising a meeting, as described within the impact study, to potentially quantify the impact of emissions. Interested by the concept of end user computing delivering sustainability, an executive stakeholder group was gathered at Citrix to formalise a sales and marketing strategy that could use the research as a foundation for a companywide customer facing sustainability strategy.

Specifically, from a corporate strategy perspective, Tim Minahan, Executive Vice President for Strategy and Marketing, agreed to the publication of a globally available sustainable information e-book called, 'The Sustainability Era' (Citrix, 2020). Based entirely upon the Px3 framework theory and quoting directly from the research, the publication outlines the feasible abatement delivered by low energy devices and remote working.

Minahan (Citrix, 2020) notes, *'As this research makes clear, the choices we make as individuals and businesses can have immediate, cumulative effects and deliver environmental, economic and social benefits that can lead to a more sustainable planet. It's also clear that by using digital virtualisation and workspace technologies to empower flexible and remote work models, companies can positively impact sustainability.'*

As the results of the initial case study asset profile exercise began to emerge in early 2020, Citrix sales effort too began in earnest to apply the findings to further customer interactions. Sutton-Parker was requested to write scripts for training and marketing videos, plus presentational decks explaining the context of the output and anticipated impact. Participants in the subsequent filming included founder of the ethics and sustainability magazine My Green Pod, Jarvis Smith. Then Area Vice President of Northern Europe, Michelle Senecal de Fonseca, organised a structured sales campaign with sustainability focused key performance indicators for all sales staff to accelerate diffusion. These included a requirement to complete the training material and identification of sustainability focused sales opportunities. As further engagements emerged, the developing Px3 framework was utilised with several commercial and public sector organisations to identify customers indicating a wish to prove sustainable outcomes as they transitioned to reduced commuting and low energy end point devices such as thin clients. Specifically, the Universities of Sussex and Northumbria, Ossur and the RSPB underwent asset profile assessment and emissions quantification to enable a meaningful picture of current end user computing impacts to be formed.

The impact of the research is recounted by Senecal de Fonseca (Guardian, 2020), *'What we struggled to understand was how we could involve over 100 million customers in our efforts. Essentially, we*

learned that what Citrix delivers to its customers can be a sustainability solution in and of itself. Currently, my sales, engineering, channel and marketing teams in Northern Europe are being trained on the science and the impact of sustainable workspaces in order to help them take the message to existing and new customers. Yes, this is a marketing message – but the research supporting it validates the environmental gains.'

Today, Citrix continues to use the Px3 framework to quantify both current and potential information technology related GHG emissions. Having set a goal in 2020 to transform 65,000 users in Northern Europe towards sustainable work styles, the software company has in fact achieved 160,000 users already with quantities continuing to rise. Consequently, together with further corporate schemes such as the promotion of sustainable employee commuting, Citrix recently achieved a 58th place within the Corporate Knights 100 Most Sustainable Companies having never previously featured. Currently a micro QR enabled application version of the Px3 framework similar to the Google offering is being produced by this research. The difference being in this example that the focus is upon scope 2 device and data centre abatement plus scope 3 device and commuting to access IT (CAIT) emissions.

Gerry Lavin (2022), Field CTO for EMEA who has adopted leadership of the sustainability focus notes, *'I was introduced to Justin's research in late 2019. I was part of Citrix's emerging Sustainability team, and my focus was on aligning our product portfolio to his research. I immediately found his work engaging and informative. I had been aware, in a general sense, of the huge amount of electricity consumed by IT and the resultant environmental impact, but it was Justin's research that clearly demonstrated this interconnectivity and laid out the impact of ICT on climate change in stark detail. Like all great research and great writing in general, Justin provided answers, but his work also encouraged his readers to ask questions. His research provided the impetus for me to develop my own understanding of this very important topic. The more I learned from Justin and others the more passionate and engaged I became on the subject. Justin's work has had a direct positive impact on how I think about IT and sustainability. This has in no small part led to me becoming an advocate for more sustainable IT and actively engaging with Citrix's employees, partners and customers around the subject.'*

6.3. Outcome 3: Acer

Acer became aware of the research in winter 2020 following Jason Sam-Fat of Kingston and Sutton Council sharing the initial results of the case study. His rationale was that while abatement had evidently been achieved, if the sustainable information technology strategy was to be adopted on a permanent basis and future reductions realised, suppliers of computer equipment to the council ought to be involved at every stage. Consequently, an introduction to Nick Walter, Head of Commercial at Acer UK was made. During a series of initial meetings two specific findings from the research were explained. The first being that Acer notebooks and desktops installed with Google's Chrome OS enabled annual electricity consumption reductions compared to the legacy Dell equipment and therefore concomitant scope 2 emissions abatement. Secondly, as defined in activity 4, Acer did not at the time publish product carbon footprint data and therefore could not meaningfully contribute to supply chain reductions unless this changed.

As the world's third largest manufacturer of Chromebooks, supplying 15.6% of the market, the research was agreed as key to complementing existing commitment to sustainable manufacturing and supply. This includes membership of RE100, a scheme designed to ensure the world's leading businesses are dedicated to the adoption of renewable energy. Plus, responsible resource consumption reflected in recycled paper for packaging and increasing percentages of post-consumer recycled (PCR) plastic used in

notebook chassis. In early spring 2021, it was decided that Acer would adopt the cTEC energy consumption quantification methodology to support   a sustainable device campaign targeting the UK service sector. The rationale is twofold. Firstly, the findings of activity one indicated that the company is most likely at a disadvantage during procurement assessment phases when comparing eTEC results for Acer Chromebooks against competitive Microsoft Windows notebooks when in fact the inclusion of the active state values may prove the devices to be once again more energy efficient in the field. Secondly, if the impact of the use-phase measurement could be further substantiated across the Chromebook portfolio to create a market outpacing strategy, then the leadership team in EMEA and Taipei may be persuaded of the importance of publishing product carbon footprint reports. As such, the Acer Spin 513, Spin 71 and 311 Chromebooks were tested using the cTEC test set up, conduct and calculation methodology (Acer, 2022c).

The results were published by Acer in two subsequent research-based marketing documents. The first is called Sustainability as a key factor in making IT decisions – where are organisations today? Quoting findings from the wider research to position why the reduction of scope 2 emissions is important, the report specifically determines transitioning to devices such as the 513 can reduce emissions by as much as 70% within a mixed end user computing environment. This is feasible as the device was found to consume 10.74 kWh/y in a commercial setting compared to the published eTEC value of 14.36 kWh and 25% higher per device each year (Acer, 2022c).

The second publication relates to the use of the Chromebook 311 within the higher education sector. With a smaller 11" screen the device proved to be the lowest notebook measured of all consuming 7.61 kWh/yr compared to the almost double value derived from the eTEC results at 14 kWh (Acer, 2022d).

Further to the findings, Acer adopted a combination of the Px3 framework and Dynamic Carbon Footprint tool to act as the calculator for a newly proposed online trade-in scheme. Called 'Green Rewards' (Acer, 2022b) the tool is a 'world first' offering companies wishing to refresh end user computing equipment the ability to quantify how doing so will reduce on-going scope 2 emissions by transitioning to low energy Chromebooks. However, despite these positive adoptions, the issue of scope 3 quantification remained creating a barrier to both enhancing future reports and the trade-in tool plus meaningful contribution to the council's procurement strategy.

In autumn 2021, to encourage progress within this area an indicative carbon footprint report was using life cycle assessment and inventory database tools. To enable management to visualise the impact of publication and enable an interim response to European computer procurement frameworks requiring an indication that such documentation is imminent. The report encouraged a subsequent chain of events that resulted in the publication of Acer's first official carbon footprint report in February 2022 (Acer, 2022e). Specifically, the Acer Chromebook Spin 713 measured using the cTEC methodology was first to be subject to life cycle assessment using the PAIA tool preferred by Dell, HP and Lenovo. Consequently, the product generates 403 kgCO2e with 16.4% associated with use based upon a four-year retention period. Acer has subsequently to date produced a total of thirteen reports and committed to creating carbon footprint reports for selected new end user computing products. The result in context being that the world's 5th largest manufacturer responsible for 6% of all products is now participating in product carbon footprint report publication as a direct influence of this research.

Nick Walter (2022) of Acer noted in relation to the impact of the research on sustainability, understanding and behaviours both personally and within Acer, *'The research carried out within the Royal Borough of Kingston really highlighted to us the impact that independent and scientific data could have to help organisations towards Net Zero. Integrating carbon footprint and energy efficiency*

reporting within the decision making process was a key element that we wanted to be able to provide all our customers with. As such we worked closely with the research to develop programmes that ensured Acer was providing the right information now and for the future. The research and workings have meant significant changes to how we create and communicate our energy efficiency and carbon impact on our products. We are currently building local and regional based tools to better support customers to make the right choice and a greener choice. Commercially it's providing Acer with new initiatives within the business and public sectors and fundamentally providing Acer with a unique proposition. Critically the additional value our customers receive by accessing the data within the purchasing process and engaging with our programmes means a positive impact on reducing carbon in the environment.'

7. Chapter 7: Impact Case Studies

The concluding stage of the impact value chain model is, as described in the methodology, represented by five case studies that test the impact of the developed solutions. Doing so, the research question, 'Can meaningful end user computing carbon footprint information drive human behavioural changes to abate GHG emissions?' is answered. It is anticipated that each case study conducted will not include all elements of sustainable IT strategies tested and developed; hence the reason for including several varied examples. As such, the case studies collectively address one or more of the key research elements including low carbon footprint device selection and use, displacement through either extended original function or repurposing and reductions to commuting to access IT. Additionally, each represents different lengths of time required to complete the interaction and is conducted in different business sectors including the public sector, travel, finance and technology. This variation allows for the concept that impact can be delivered in both the long and short term and across sectors therefore improving the likelihood of diffusion of the solutions. As such the following sections detail impact case studies conducted within the Royal Borough of Kingston and Sutton Councils (Sutton-Parker, 2022e), Nordic Choice Hotels (Google, 2022a), Standard Life (Procter and Sutton-Parker, 2023), Citrix (Sutton-Parker, 2021) and the UK government (HM Gov., 2022b).

7.1. Impact case study A: Determining the impact of information technology greenhouse gas abatement at the Royal Borough of Kingston and Sutton Council

Joining a total of two hundred and eighty-two UK councils (Climate Emergency, 2020a), the Royal Borough of Kingston upon Thames and Sutton Council declared a climate emergency in June 2019 (RBKSC, 2019). Already subject to the public sector specific collective greening government commitments (DEFRA, 2011 2016 and 2017 and HM Gov., 2018b and d) designed to recognise the environmental, social and financial benefits from greener operations, estate management and procurement, the council were more recently subjected to the Companies Act 2013 amendment (HM Gov., 2013). Specifically, from April 2019 all public sector organisations were included alongside large commercial organisations already required to report and abate organisational GHG emissions. Consequently, the new climate emergency strategy was designed to examine areas of potential improvement including energy reduction, waste, sustainable transport and ultimately improving air quality in the surrounding area. Speculating that IT may be able to contribute to the new strategy but unable to prove it, the council contacted technology suppliers to explore possibilities. Via a mutual connection it was indicated that this research thesis may be capable of determining the impact of information technology GHG abatement at the council. As such, the following sections discuss the summary methodology and results from the resulting impact case study spanning a time horizon of 3-years from late 2019 to early 2022.

Structured to answer the research question, 'Can meaningful end user computing carbon footprint information drive human behavioural changes to abate greenhouse gas emissions?' the objective of the case study is twofold. Firstly, to determine the abatement impact delivered by recent changes made to the IT estate within the council that may already be contributing to the climate emergency imperatives. Secondly to determine if presenting these results in a meaningful way together with further suggested improvements influences future policies such as IT procurement and operations. The goal being that sustainable IT becomes substantiated to both significantly support wider public sector net zero aspirations (Dept. for BEIS, 2021e) and capable of the long-term behavioural changes that will help to reduce societal emissions (UNEP, 2019). To achieve this, the methodology involves both qualitative and quantitative research techniques and consists of five key stages.

The first is to document a baseline of how IT is currently selected, purchased and used to discover if sustainability already exists as a key criterion in the process and to explore if existing or potential

behaviours may be expanded or improved upon. This is achieved by conducting an unstructured exploratory interview with key council stakeholders at the beginning of the study. The second stage uses a survey methodology developed in activity 3 to capture asset profile data relating to the council's end user computing devices including type, make, model and quantity values. Doing so enables the third stage that uses the commercial typical energy consumption (cTEC) algorithm from output 1 to produce valid electricity consumption data for the devices, measured in kWh. The fourth stage utilises the interview information and profiling data to produce the meaningful information that determines the impact of sustainable IT in both before and after scenarios.

The metrics generated include scope 2 use-phase, scope 3 supply chain and employee commuting to access IT emissions values in both GHG accounting units and analogous equivalents, plus financial savings delivered by reduced energy consumption and displaced device purchasing cycles. This is achieved by using the previously developed Px3 framework and the dynamic carbon footprint embodied emissions database from outputs 2 and 3 respectively. Presented to the original and further organisation stakeholders within the first three months of the study, the format reflects the triple bottom line of corporate social responsibility accounting (WBCSD and WRI, 2004). Specifically, the planet, people and profit values are defined to resonate with stakeholder role based needs and interests regardless of opinions related to climate change as discussed in output 3. The final stage involves a structured and filmed interview conducted at the end of the time horizon to determine if the information produced influenced IT procurement and use policies in the long term or simply acted as a compliance exercise. By conducting these five stages, determination of the impact of IT greenhouse gas abatement at the Royal Borough of Kingston and Sutton Council is made feasible and the research question answered.

Located in southwest London, the Royal Borough of Kingston upon Thames and Sutton Council is one of thirty-two Greater London Borough Councils (LCA, 2020). Representing local government as part of the nation's public sector, the council employs 4,069 staff. Identified as key stakeholders, David Grasty, Corporate Head of Digital Strategy & Portfolio and Jason Sam-Fat, Digital and IT Commercial Manager participated in the initial exploratory interview and remained engaged throughout the case study. Aspirations to improve energy, waste and sustainable transport approaches as part of the climate emergency strategy were confirmed. However, it was agreed that beyond existing facilities and vehicle schemes, no formal sustainability policy had yet been applied directly to IT. The team speculated that computing may have an ability to reduce GHG emissions, although it was deemed not feasible to substantiate the notion due to limited available product carbon footprint data.

Discussions identified that current computer procurement was led by technical specification, user requirement and budget, followed by procurement teams being offered a number of models to proceed with. While trying to limit the receipt of excess packaging to address unnecessary waste, the only other element of environmental efficiency undertaken was to ensure selected computers are Energy Star certified. When asked if IT emissions were quantified annually to assist with compliance reporting, it was confirmed that they were not. When asked specifically how the greening government policies (DEFRA, 2020) are responded to, the team referred back to the Energy Star initiative confirming that meaningful sustainability criteria did not currently influence IT procurement or operational behaviour. During the meeting metrics such as device retention and remote working capabilities were explored to identify further areas of improvement. The council confirmed that computers were retained for 5-years years and displays for 7-years, whereas despite a virtual desktop solution being in place to accommodate legacy applications, little or no remote working was currently exercised.

7.1.1. Asset and use profiling

During the initial interview it was explained that the end user computer estate had recently been transitioned from predominantly Microsoft Windows devices to Chrome OS devices. As activities 1 and 2

identifies Chrome OS devices as being more energy efficient in the field and the majority of the new computing estate was not due for replacement for several years, the council requested that the current energy saving compared to the old computers be established. The on-going annual utility saving and concomitant emissions reduction will contribute to the energy reduction objective of the climate emergency and may influence changes in procurement behaviour for the future if emphasised. As detailed in table 15, the summary changes between the two estates include 3,880 Windows notebooks becoming 3,700 Chromebooks and 180 Windows notebooks. While 800 Windows desktops become the equivalent number of Chromeboxes. As such, the Microsoft operating system is reduced from 100% presence to 4% following the transition. Notably, the 3,584 peripheral displays remain unchanged in both instances.

Table 15. Asset profile, use profile (kWh/y) and scope 2 GHG emissions (kgCO$_2$e) for legacy and current computer estates

	Description	Quantity	Per Unit kWh/y	Total kWh/y	Per Unit kgCO$_2$e	Total kgCO$_2$e
Legacy Estate	Dell Latitude 5450 Windows notebook	3,880	19	72,634	4	15,422
	Dell OptiPlex 7010 Windows desktop	800	64.73	51,784	13.7	10,995
	Acer B246WL 24" monitor	2,640	21.65	57,156	4.6	12,136
	HP 24uh 24" monitor	900	17.7	15,930	3.8	3,382
	LG 29UB67 29" monitor	44	24.08	1,060	5.1	225
	Legacy Total			198,563		42,161
Current Estate	Acer 14 CP5-471 Chromebook	3,700	11.34	41,958	2.41	8,909
	Acer CX12 Chromebox desktop	800	10.58	8,464	2.25	1,797
	Dell Latitude 7400 Windows notebook	180	21.12	3,802	4.48	807
	Acer B246WL 24" monitor (Chrome OS)	2,460	20.29	49,913	4.31	10,598
	Acer B246WL 24" monitor	180	21.65	3,897	4.6	827
	HP 24uh 24" monitor	900	16.59	14,931	3.52	3,170
	LG 29UB67 29" monitor	44	22.57	993	4.79	211
	Current Total			123,958		26,320

Note table 15. The device asset profile is captured using the asset survey technique developed in activity 3. The per unit kWh/y values represent the electricity consumption per year as determined by the cTEC methodology. The per unit kgCO$_2$e values represent scope 2 GHG emissions and are generated using the UK electricity to GHG emissions conversion factor (BEIS, 2021c).

The current end user computing estate consumes 37.6% less energy per year than the legacy estate (table 15). As anticipated and congruent with the findings of activities 1 and 2 (table 2 and 6), this is caused by new Chrome OS devices being more energy efficient. Specifically, the Chromebooks are 40% more energy efficient than the previous Windows notebooks. Additionally, the new Chromeboxes are 84% more efficient than the legacy desktops. While the displays remain identical in both instances, a further 6.3% reduction is also achieved within this device type due to the Chrome OS power management settings. The reason being that the standard display transition to sleep for Windows operating systems is 15 minutes compared to Chrome OS being 8 minutes. The least efficient computer within the current estate is the new Dell Latitude 7400 notebook consuming 46% more electricity than the Acer Chromebook 14 that replaces the Latitude 5450. Representing 180 units, this device generates 3% of the current estate electricity consumption despite being only 2% of the total unit quantity.

Consequently, had the council migrated entirely to Chrome OS devices a further 1% energy saving would have been achieved. Ensuring the most energy efficient computers are identified is important as IT is now the second largest consumer of commercial electricity (Dept., of BEIS, 2021b). Based upon the council's current procurement practice, had the devices been evaluated for sustainability criteria using only the Energy Star typical energy consumption data then it is feasible the Dell Latitude 7400 would have been purchased in favour of the Acer Chromebook 14 as the Dell device has a published electricity consumption value of 12.6 kWh/y. Compared to the Acer device at 15.2 kWh/y and being 21% higher

(Energy star, 2022). However, in reality due to the operating system requiring less power draw during active use, the Chromebook consumes almost 50% less energy than the new Windows notebook. Consequently, the necessity to examine beyond the Energy Star certification is emphasised if the true impact of sustainable IT is to be determined.

7.1.2. GHG emissions

The study quantifies three sources of GHG emissions to determine current and potential abatement impact. Scope 2 relates to use-phase emissions and contributes directly to the council's focus on energy reduction. In context, adopting more energy efficient devices will reduce concomitant emissions. Scope 3 supply chain emissions focus upon the carbon footprint created by device manufacturing. Retaining devices for longer periods displaces and reduces scope 3 emissions by extending the period between purchasing a new device. Additionally, selected new devices with the lowest embodied carbon footprint will also contribute to supply chain emissions abatement and ultimately the imperative of achieving waste reduction. Scope 3 commuting emissions are related to IT by computer services enabling increased levels of remote working. In doing so, the objective of sustainable transport adoption is supported by means of reduced car travel.

Scope 2 emissions are calculated by multiplying the previously determined kWh/y value (table 15) by a government published conversion factor that represents the carbon intensity of the associated national grid (Dept. for BEIS, 2021c). As such, the scope 2 use-phase energy emissions are reduced by the same percentage as the energy results (37.5%) from 42,161 $kgCO_2e$ to 26,320 $kgCO_2e$ creating an abatement of 15,841 $kgCO_2e$ per year (table 15).

Table 16. Scope 3 supply chain GHG emissions ($kgCO_2e$) abatement delivered by displacement and sustainable selection

Description	Quantity	Current Per Unit Scope 3 kgCO2e	Current Total Scope 3 kgCO2e	Total Displace Saving kgCO2e	Lowest Unit Scope 3 Available kgCO2e	Feasible Selection Saving kgCO2e
Acer 14 CP5-471 Chromebook	3,700	300	1,110,000	416,250	102	732,600
Acer CX12 Chromebox desktop	800	341	272,800	102,300	140	160,800
Dell Latitude 7400 Windows notebook	180	294	52,920	19,845	102	34,560
Acer B246WL 24" monitor	2,640	417	1,100,880	330,264	253	432,960
HP 24uh 24" monitor	900	417	375,300	112,590	253	147,600
LG 29UB67 29" monitor	44	417	18,348	5,504	300	5,148
Scope 3 Supply Chain Total			2,930,248	986,753		1,513,668

Note table 16. The scope 3 GHG emissions values are derived using the dynamic carbon footprint application. The model specific data represents the value produced during LCA calculation by the relevant manufacturer where available. For Acer products a device equivalent in model and size is used to represent the scope 3 data as Acer did not produce data at the time of the case study. The lowest unit available value is represented by the comparable device type with the lowest carbon footprint within dynamic carbon footprint database.

Examining computers as a source of abatement is important as IT hardware contributes to 14% of all European waste electrical and electronic waste (European Parliament, 2020). To enable the calculation of both strategies, manufacturing, delivery and end of life management GHG emissions data must be available via product carbon footprint reports. As highlighted by activity 4 Acer, the brand predominantly chosen by the council, did not at the time of the assessment produce product carbon footprint reports. This omission was pointed out to the case study stakeholders and a gap analysis conducted to overcome the issue. In the short term, the potential of extending device retention was conducted using averages generated by the earlier research (Sutton-Parker, 2022d) with the exception of the Dell notebook that has an available report (Dell, 2022). In relation to the initial displacement theory, the council confirmed that

the standard current retention period for computers was 5-years and 7-years for displays. Based upon existing research suggesting longer periods of ownership are feasible (Prakash et al., 2016; Thiébaud et al., 2017) and substantiated by activity 2, an extension of 3-years was suggested for all devices. This is because as the new operating system provider Google offers software updates for a minimum of 8-years and most applications have transitioned to being browser based then, issues of future incompatibility would be reduced causing the strategy to be viable. As highlighted in table 16, the strategy is applied to the current estate and determines that 986,735 kgCO$_2$e or 34% of scope 3 supply chain emissions are avoidable by adopting the displacement scheme as the embodied emissions are spread across additional years and new emissions are not required for a further 36-months.

In relation to potential future reductions to supply chain emissions achieved by selecting devices with low embodied emissions, activity 4 and the dynamic carbon footprint application were again utilised where Acer data was not available. Specifically, the lowest embodied carbon footprint value for each device type was compared to the averages used in the displacement representation. As highlighted in table 16, the feasible scope 3 emissions avoidable if the council were to replace the entire estate in the future is 52% or 1,513,668 kgCO$_2$e. The reduction is predominantly delivered by the notebook selection based upon the Microsoft Surface Laptop 3 that has an embodied value of 102 kgCO$_2$e (Microsoft, 2022) compared to the average used in the prior example of 300 kgCO$_2$e. This highlights that examining beyond the compliant certification level within device types (EPEAT, 2022 and TCO, 2022) can reduce emission by as much as 66%.

Focusing on sustainable strategies for transport is important as the pollution source is responsible for 14% of annual global emissions (USEPA, 2020). Specifically, commuting is a considerable contributor in the UK, being responsible for 27% of all journeys with 68% conducted by car (DfT, 2021). In the context of the council and end user computing, creating a flexible working policy for users supports the concept of reduced commuting. It was noted during the interview and asset profiling exercise that the council already used a Citrix virtual desktop solution to manage legacy application incompatibility. It was discussed that the stakeholders would like to investigate the impact of expanding this solution to enable remote working. As such it was agreed that the concept would be included in the research to highlight the feasible contribution to the council's sustainable transport element of the climate emergency strategy. To examine the environmental impact, emissions relating to employees driving to work are calculated as alternative methods of transport such as buses and trains will operate regardless and as such will not deliver pollution reduction caused by the council's remote working policy.

As no specific data is available relating to council employee commuting, it is assumed that each employee will complete a return journey of 18.2 miles per day (DfT, 2021) and work 232 days as per national statistics (HM Gov., 2019a and 2020a). Vehicle carbon intensity is based upon an average car as published by the UK Government (Dept. for BEIS, 2021c). The council employs 4,069 people, meaning that 2,767 (68%) travel to work by car (DfT, 2021) five days per week. Therefore, annual employee car commuting mileage is calculated as 11,683,38 and creates 3,224,146 kgCO$_2$e of emissions. Using the end user computing remote working solution to enable employees to work from home for two days per week compared to the current 5-days working from the council offices, reduced this value by 40% to 1,931,708 kgCO$_2$e avoiding 1,292,438 kgCO$_2$e.

7.1.3. Meaningful representation of end user computing carbon footprint data

The survey conducted during output (solution) 3 (Sutton-Parker, 2020a) determines that barriers such as cost and perceived impact are limiting the diffusion of sustainable IT practices within the UK service sector. As such, it is important that the data generated by the study is presented to council stakeholders in a meaningful way that will appeal to role-based needs to help overcome these barriers and justify adoption. From a planet perspective, the electricity consumption, supply chain and commuting GHG units

are presented in two forms. The first is the kgCO$_2$e unit measurement required by international accounting and reporting protocol (WBCSD and WRI, 2004). In this format, the results will appeal to those managers and executives tasked with compiling the now mandatory emissions values for annual company reports (HM Gov., 2013) and planning abatement strategies. The second representation uses the equivalent values discussed in output 3 to ensure the impact of emissions figures immediately resonate. From a people perspective, the EVE ratio is included (Sutton-Parker, 2020c). Primarily, this is designed to express a direct correlation between changes in behaviour in relation to an employee's IT related carbon footprint and pollution. Specifically, as previously described (output 3) EVE is a per capita ratio based upon the number of equivalent polluting car miles associated with a computer single user. Calculated by determining the annual combined emissions from scope 2 device electricity consumption, scope 3 embodied device emissions and scope 3 commuting to access IT emissions, the individual and collective result can increase or decrease depending upon variables such as device choice, retention and remote working frequency.

As the survey research highlights that those employees not subject to sustainability strategy formation or related key performance indicators are disengaged with climate emergency strategies (Sutton-Parker, 2020a), the concept is twofold. Firstly, to offer all employees an opportunity to participate in the impact of sustainable IT practices. Secondly, to enable human resources and IT teams an additional way in which to engage with a group that is effectively the largest stakeholder of all and often overlooked in relation to sustainability participation. From a profit perspective, the application produces two financial metrics in order to assist organisations to justify sustainable IT practices from a cost perspective. The first is the annual utility saving caused by both the adoption of energy efficient computing devices and the reduction of office-based device electricity consumption as a result of increased remote working. The second financial metric is the annual reduction in hardware costs delivered by the extension of device retention periods. These two outputs are designed to appeal to stakeholders in operational and financial roles, emphasising that while the climate emergency is being responded to effectively, costs are lowered therefore causing the long term practice of sustainable IT adoption to be viable.

Planet: The new low energy devices reduce Scope 2 emissions by 37.5% creating an annual abatement of 15,841 kgCO$_2$e (table 15). Extending device useful lifespans by 3-years reduces scope 3 supply chain emissions by 34% creating an annual displacement of 328,917 kgCO$_2$e (table 16). Increasing remote working from zero days to 2 days per week reduces scope 3 commuting emissions by 40%, creating an annual abatement of 1,292,438 kgCO$_2$e. In total, should the council continue with the selected devices and adopt the proposed sustainable IT practises of displacement and remote working, a combined annual direct and indirect emissions reduction of 1,637,196 kgCO$_2$e is feasible. In relation to the impact to the climate emergency overall objective of cleaner air for the borough, this is equivalent to avoiding pollution created by driving a car for 5,932,725 miles and releases the sequestration capacity of 1,964 acres of mature forest.

People: As previously described the people element of the results utilises the 'planet' GHG and equivalent emissions to create an environmental per capita ratio. Based upon the IT environmental impact of the current strategy the combined scope 2 and 3 annual emissions are 3,751,114 kgCO$_2$e (table 15 and 16 and accounting for 5 and 7-year retention periods), equivalent to 13,592,962 car miles. This produces an EVE ratio of 1:3341 based upon 4,069 employees. Should the council adopt the suggested retention period extensions and the remote working scheme then annual IT related emissions can be reduced by 39% to 2,286,946 kgCO$_2$e. Equivalent to 8,287,237 miles, this reduces the EVE ratio to 1:2037. During the presentation stage, it was also indicated that by additionally introducing sustainability as a criterion during selection and purchasing processes in the long term, then this value could be reduced further to 2,112,380 kgCO$_2$e per year. Equivalent to 7,654,660 miles the EVE ratio becomes 1:1881, meaning that for every employee it is feasible to reduce pollution equivalent by 1,460 miles annually.

Profit: The annual 74,605 kWh/y device electricity consumption reduction delivered by the new devices saves the council £8,721 per year in utility costs. Additionally, extending all device useful lifespan by an additional 3-year period spreads procurement costs by delaying future purchases. The impact of this is a further annual operational saving of £213,900 via displaced procurement. Finally, should the council decide to proceed with remote working, the effect would be 40% less end user computing electricity consumption within council premises delivering a further utility cost reduction of £5,796. Consequently, it is reasonable to suggest that the concept of cost being a barrier to sustainable IT practices as defined in output 3 is counterintuitive. A combined annual saving of £228,418 is feasible by responding to the key objectives of the climate emergency via the medium of environmentally conscious end user computing decisions.

7.1.4. Behavioural Change

As discussed, the objective of the research is to determine IT related abatement and to document whether longer term behavioural changes were caused by the information being made available in a meaningful format. From a council perspective, Jason Sam-Fat initially noted that, *'The sustainability report was helpful to underpin benefits in our business case to go to Chrome, to say what we would achieve in terms of energy reduction.'* Noting the viable influence on stakeholders, the results were presented to the wider community at a Commissioners Network event and during climate emergency meetings, *'It was the first time we'd had such detailed information about our carbon footprint and it was really good that IT had significantly more information about emissions than any other department and a clear roadmap for the future'.* Grasty agreed, '*We knew at the time that the devices we were deploying were far more efficient and that the infrastructure would deliver sustainability goals but we couldn't quantify it.'* On receiving the research results, he added, *'It's been fantastic having that benchmark and actually quantifying what impact IT has had on the overall Council's goals.'* Alluding to the council's climate emergency key objective of energy consumption reduction he commented, *'The figures have shown that we've made a tremendous difference in our carbon footprint which is something that we didn't know before. Actual quantifiable evidence to be able to say that this is what we've done has shown us that moving from a desktop Windows environment to an Acer/Chrome environment has reduced our energy consumption by a third and taking carbon out of the atmosphere every year, which is a fantastic result in itself.'*

Within two weeks of the initial presentation and subsequent feedback, the influence of the information upon behaviour became more definitive. Grasty, having accepted that it was feasible to utilise remote working to reduce employee commuting emissions, created a five-year business case justified by the data. Clearly identifying that a two day per week home working strategy would directly support the council's key climate emergency strategy of reduced transport emissions the stakeholder looked beyond the exhausted computing budget for funding. Successfully applying for financial investment from an associated climate emergency budget, an expanded Citrix remote working solution was purchased and implemented for all computer users. Anticipating the planned abatement, the results were actually far higher than expected. As the pandemic struck two months later the council were already prepared to respond. Subsequently interviewed (Computing, 2020) Grasty commented, *'the remote working solution enabled us to move seamlessly to more than 95% of our staff working remotely without any changes to our infrastructure, which was fantastic. The majority of our staff just took kit home and worked from home, or worked at home on their own kit until we could provision out a Council Chromebook for them.'* From an impact perspective, during the full year that the council maintained a 5-day a week remote working policy, it is determined that commuting emissions avoided during the subsequent 12-month period was 3,224,146 kgCO$_2$e. This is equivalent to the pollution created by 11,683,381 car miles.

Grasty also confirmed that with a near return to normal working conditions, the original 2-day per week plan is now permanently adopted. Similarly, the council has adopted the extended retention periods

and are now realising the associated abatements in line with the climate emergency objective of reduced waste. Enthused by the prospect, the council is taking additional steps to also adopt the more granular examination of device embodied emissions suggested by the research. The impact is reflected in the new device selection and procurement process now including sustainability as key criteria.

Interviewed in the Autumn, 2021 (YouTube, 2022a) Sam-Fat confirmed, *'For Kingston and Sutton the IT procurement function sits within IT, so we work very closely with the Technical Team to look at the actual best specification and then the sustainability drivers. Looking at the whole lifecycle, it's important to have all of these conversations at the start and understand how you want to procure it, lend it, and at the end of it, what do you do with that as well. So it's a cradle to grave approach and that comes down to the performance and benchmarking.'* Sam-Fat concludes that to achieve this 'walled gardens' must be removed, '*It's about taking stock of where we are and should we be doing something different. And if we are, how can we do that collectively different. For me that's what good sustainability looks like: it's to have partners I can actually equally input and be very open and honest and recognising weaknesses and strengths and actually how can we work together towards a common outcome and a goal'.*

The common goal to address scope 3 supply chain emissions reduction will be realised by examining product carbon footprint data during the selection process. Key to this is having data that is available, accurate and importantly, equivalent. Activity 4 and output 2 produce the dynamic carbon footprint application designed to enable this by overcoming the lack of uniformity associated with published product carbon footprint data and harmonises the results to accurately reflect variable criteria such as location of use and retention periods. Such a capability will enable the council's IT and procurement teams to assess and compare end user computing devices based upon sustainability criteria while ensuring parity is achieved. However, as Acer does not currently publish product environmental data both Google and Acer would not be able to participate in the council's future strategy. Fortunately, based upon the council's intention to evaluate the new tool and coupled with Google's independent verification of the findings from activity 1 (Google, 2021) a behavioural change has also been experienced within the world's fifth largest computer manufacturer. Specifically, and as discussed in the output section, Acer has since utilised the cTEC methodology to create a world first end-of-life trade in scheme called Green Rewards (Acer, 2022b) and has begun to produce product carbon footprint reports and information from 2022 onwards incorporating the methodology developed by the impact value chain research (Acer, 2022c).

7.2. Impact case study B: Determining the impact of information technology greenhouse gas abatement at Nordic Choice Hotels

Impact case study A represents a developing engagement stretching across 3 years and includes behavioural changes related to sustainable device procurement and use plus commuting emissions reduction. Logically, for the methodologies, frameworks and applications proposed by this research to achieve rapid diffusion and drive widespread sustainable IT behavioural changes, it is reasonable to suggest the process be proven to undertaken within a shorter time frame. As indicated by the survey conducted in outcome 3, complexity associated with time and money represents a significant barrier and therefore simplicity and impact must be delivered upon a more immediate basis. The opportunity to prove this is and define the impact of one of the two end user computing displacement strategies is represented by case study B.

In spring 2022 Nordic Choice Hotels began to review over 4,000 end user computing devices. A recent computer security breach (WSJ, 2022) had caused a denial of service instance creating doubt as to the validity of Windows 10 based devices moving forward. The initial reaction to the problem was to simply replace the Windows estate with new Chrome OS devices to leverage the highly secure capability of the Chrome OS. At this juncture, Google shared the results of activity 1 (Sutton-Parker, 2020b) and activity 2 (Sutton-Parker, 2022c) with the Nordic Choice Hotels IT team. It was proposed that as a hotel

chain with more than two hundred premises across the Nordic region and renown for sustainable operations relating to accommodation, consumables and laundry, the concept of environmental stewardship could also be applied to the end user computing estate. Subsequently, the organisation agreed to participate in the research to assess any forthcoming data and decide the appropriate actions based upon the findings.

7.2.1. Asset and use profiling and greenhouse gas emissions

Utilising the organisations existing asset management software and compiling the data as per the methods used in activity 3, it was quickly determined that the estate consisted of 2,970 desktop computers and 1,548 notebooks. While energy efficiency gains experienced during repurposing of notebooks with Chrome OS Flex, it was recognised that this had not yet been validated for desktop computers. As 99.6% of the desktop computer estate was represented by a single model, the Lenovo ThinkCentre M700, the same field experiment as conducted in activity 2 was undertaken for this device. As highlighted by table 19, the results proved congruent with the notebook reduction, being in this instance 18% and 1% lower than the mobile devices. The results from this enabled the calculation of energy consumption reduction for the desktop estate should the hotel chain decide to retain the hardware and extend the useful lifespan by a further three years by repurposing with Chrome OS Flex. Comparatively, the 94% of the existing notebook estate consisted of three models, being the Lenovo ThinkPad X1, L and T. As such, all three models were measured for electricity consumption using the methodology detailed in output 1 (table 17). As activity 2 already defines the average energy consumption reduction as being 19%, this is applied to enable a before and after repurposing state. To generate the scope 2 emissions per device, the cTEC results are multiplied using the Px3 framework to create values for Denmark, Finland, Norway and Sweden. This aspect arguably highlights the impact of low carbon intensity electricity supply upon the contribution of the use-phase. As an example, by extracting the scope 3 emissions value via the dynamic carbon footprint data base (table 17), it is clear the desktop Windows device exhibits a total carbon footprint consisting of 98.7% scope 3 and just 1.3% scope 2 in Demark due to the country's high adoption of renewable energy.

Table 17. Commercial typical energy consumption (kWh/y), Scope 2 and 3 GHG (kgCO$_2$e) results

Description	cTEC kWh/y	Current Per Unit Scope 3 kgCO$_2$e	Denmark Scope 2 kgCO$_2$e/y	Finland Scope 2 kgCO$_2$e/y	Norway Scope 2 kgCO$_2$e/y	Sweden Scope 2 kgCO$_2$e/y
Lenovo ThinkCentre M700 Windows	37.5	380	5.35	3.57	0.29	0.21
Lenovo ThinkCentre M700 Chrome	30.77	380	4.39	2.93	0.23	0.17
Lenovo ThinkPad X1 Windows	15.6	264	2.22	1.49	0.12	0.09
Lenovo ThinkPad X1 Chrome OS	12.65	264	1.80	1.21	0.1	0.07
Lenovo ThinkPad L Windows	21.9	293	3.12	2.09	0.17	0.12
Lenovo ThinkPad L Chrome OS	17.71	293	2.52	1.69	0.14	0.1
Lenovo ThinkPad T Windows	20.7	394	2.95	1.97	0.16	0.12
Lenovo ThinkPad T Chrome OS	16.79	394	2.39	1.6	0.13	0.1

Note table 17. cTEC kWh/y represent the annual electricity consumption for each device. Scope 2 emissions are calculated using electricity to GHG emissions factors for the relevant country (Carbonfootprint, 2020). Scope 3 emissions values are derived from each model's supply chain data stored in the dynamic carbon footprint application data base.

7.2.2. Meaningful representation of end user computing carbon footprint data

Further to conducting the quantification of scope 2 and 3 emissions at a device level, Nordic Choice confirmed that of the profiled devices 53% were immediately due for replacement with an anticipated retirement of 90% of existing devices within 3-years due to the security issue. Based upon this strategy,

the supply chain scope 3 GHG emissions values delivered by a proposed alternative displacement strategy for these devices and subsequent energy consumption reduction values for all devices repurposed with Chrome OS Flex were calculated using the Px3 framework. From an environmental perspective the impact of the reduced electricity consumption was minimal due to the low carbon intensity of the Nordic grids.

Specifically, 36,000 kWh of energy consumption could be avoided, equivalent to a reduction of 26% in energy use with 74% of the total reduction being delivered by a transition to Chrome OS Flex. Although, comparatively only 2,260 kgCO₂e of scope 2 emissions would be abated based upon the carbon conversion factors of the four operating countries (Carbonfootprint, 2020). Significant scope 3 supply chain savings could be realised by successfully converting more than 90% of existing devices to Chrome OS Flex and giving a new lease of life to notebooks and desktops that were due to be replaced. Specifically, by employing the repurposing and displacement strategy just over 1,500,000 kgCO₂e of scope 3 supply chain emissions could be avoided by not replacing the current devices and those additional devices due for replacement during the subsequent 3-year period. The positive impact is equivalent to preventing the emissions of 5,400,000 fossil fuel car miles and would mean that 1,800 acres of mature forest will no longer be required to remove the pollution from Earth's atmosphere. Additionally, from a profit perspective, the resulting savings in combined reduced operational and capital expenditure would amount to 60 million NOK (€6 million / £5 million), undoubtedly substantiating that contrary to the barriers identified in output 3, sustainability strategies are once again evidently substantiated as self-funding.

7.2.3. Behavioural change

Further to receipt of the meaningful information, the Nordic Choice Hotels senior management team decided to change their expected behaviour and cancelled the device replacement strategy. Proceeding instead with the new end user computing sustainability strategy within four weeks of the initial engagement, Torgeir Silseth, CEO of Nordic Choice Hotels noted:

"This is the perfect project. It was an easy decision to make when we learned how much we would save both financially and in greenhouse gas emissions." (May, 2022)

With the project now complete Kjetil Berg Neergaard, Sustainability Manager, Nordic Choice Hotels echoed his words stating that:

"I read the IT sustainability assessment with much joy. It makes me proud seeing these numbers for us having pushed this project through. Our business case for transforming our end-user computing was underpinned by the major sustainability, financial and security benefits so it's great to see the figures confirming the environmental benefits."(May, 2022)

Additionally, the manager noted that having participated in the research the dynamic carbon footprint tool would be adopted by the organisation moving forward. Doing so will enable Nordic Choice Hotels to assess and select end user computing devices based upon sustainability criterion. Specifically, Neergard notes:

"We're already using the Dynamic Carbon Footprint tool and it is golden. As far as I know there's nothing like it out there and as the list of devices grows I can't imagine why companies would go anywhere else to get CO₂e information for their hardware inventory and purchasing decisions." (May, 2020)

7.3. Impact case study C: Determining greenhouse gas abatement achieved by repurposing end user computing devices at Standard Life

While activity 2 and case study B test and prove the viability and impact of displacement achieved by alternative operating systems, both examples focus upon devices continuing their original function as a standard mobile or desktop computing device. As such, neither tests the impact of repurposing. This strategy is when a device no longer performs its initial function and, via modification, assumes a new purpose. The value of substantiating the positive impact of such strategies is to enable companies to have multiple options to extend device lifespans to at least 8-years when faced with device obsolescence. The necessity to replace a device is often caused by the operating system becoming unsupported by the software vendor. 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. The reason is that while Apple will supply security patch updates for 3-years after each new release, the software is being 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 (Teehan and Kandlikar, 2012; Prakash et al., 2016; Thiebaud et al., 2017).

In the wider context of the research, extending useful lifespan is imperative if the current 1% contribution to global GHG emissions is to be reduced. Activity 4 determines the average contribution of scope 3 emissions to the end user computing device total carbon footprint is 73% (table 8). As such, as more than 460m devices are produced annually with 10% growth anticipated during the next decade, the strategy 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 highlighted by the use-phase results in case study B. As an example, the UK's national electricity grid currently creates 212 gCO_2e of scope 2 GHG emissions per 1 kWh of electricity (BEIS, 2021c). As such, a standard notebook such as the Microsoft Surface Laptop 3 consuming 21 kWh/y (table 2) of electricity will generate 4.5 $kgCO_2e$ (BEIS, 2022) of scope 2 emissions in 2022. However, as the government strategy is to adopt 100% renewable energy by 2035 (HM Gov., 2021b), it is feasible for this value to reduce to 0.38 $kgCO_2e$ annually based upon the suggested sources of future electricity production (HM Gov. 2021b). Consequently, whereby the use-phase was previously responsible for 27% (table 8) of the product's total carbon footprint, based upon government projections (HM Gov., 2021b) in 2035 this proportional contribution will potentially decline to just 1.4%.

7.3.1. Asset and use profiling and GHG emissions

The opportunity to prove that repurposing will contribute to GHG abatement arose in 2020. Further to the Corona virus pandemic emerging in the UK, the financial institute Standard Life faced an issue of limited secure remote working capability among its 3,645 computer users. Specifically, 3,150 or 86% of workers did not have the ability to work beyond offices situated in Edinburgh and Dublin. Considering these offices were inaccessible from March 2020 with only a small number of workers returning to premises 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 specific thin client hardware could be purchased or the opportunity to repurpose existing legacy hardware that was due

to be recycled was feasible. The latter option appealed to the organisation to complement 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 (table 18) 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 interface for the user while application processing and data storage occurred within the company's data centres. Having enabled employees to continue to work throughout the travel restrictions experienced in 2020, the company and IGEL agreed to facilitate field experiments to determine the positive environmental impact generated by the repurposing strategy. GHG emissions avoided by repurposing including both displaced scope 3 supply chain emissions and on-going scope 2 emissions comparative efficiencies are quantified using the developed cTEC method. The results and further metrics relating to commuting emissions reductions and financial savings are also calculated using the Px3 application also developed during the output stage.

The scope 3 emissions data are identified via the relevant carbon footprint data published by each respective manufacturer (table 18). In this example, both Dell (2022) and HP (2022) employ the Product Attributes to Impact Algorithm lifecycle assessment methodology (MIT, 2016) 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 as noted in activity 4. 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 (Apple, 2022; Dell, 2022; HP, 2022; Lenovo, 2022). The lack of available data from two of the world's largest electronics manufacturers reflects limitations experienced in activity 4, finding that only 22% (table 8) of end user computing products have published emissions information. The proposed thin client desktop computer, the HP T640 thin client has a supply chain value of 115 kCO_2e per device (table 18). As highlighted by activity 4, this value is two thirds lower than a standard desktop computer exhibiting an average scope 3 emissions value of 342 kCO_2e (table 8) due to fewer components enabled by remote data centre processing.

As such, the environmental impact caused by manufacturing is lessened in this example when compared to a standard desktop like for like replacement as proven exhibited in case study B. However, even in this reduced state, should the financial services company have proceeded with the purchase of 3,150 new thin client devices in favour of displacement, then 362,250 $kgCO_2e$ of scope 3 supply chain GHG emissions would have been generated (table 18). In relation to the legacy computer, it is identified that 1.1% of the Dell OptiPlex 7010's 218$kgCO_2e$ total carbon footprint (table 18) is attributed to end of life treatment equal to 2.4 $kgCO_2e$ per unit (Dell, 2022). As such, should repurposing not have occurred, 7,553 $kgCO_2e$ would also have been realised during recycling and disposal. Consequently, combining both sources of supply chain pollution, it is logical to determine that by adopting a displacement strategy, 369,803 $kgCO_2e$ scope 3 emissions has been avoided due to the temporary repurposing of the desktops. Comparatively, the second AiO thin client option has a notably higher scope 3 value of 459 $kgCO_2e$ (table 18) caused by the display being integrated into the product. As such, 1,453,403 $kgCO_2e$ of supply chain emissions is avoided by continuing with the legacy product rather than adopting the new AiO product. For the purposes of comparison between strategies, 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.

Table 18. Single unit GHG missions (kgCO$_2$e) and energy (kWh) data for the repurposed and potential new end user computing devices

Device / Operation	Operating System	kWh/y	Scope 2 (kgCO$_2$e/y)	Scope 3 Supply Chain (kgCO$_2$e)	Scope 3 EOL (kgCO$_2$e)
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	

Note table 18. kWh/y represents annual electricity consumption for each device. Scope 2 emissions are determined by using the UK electricity to GHG conversion factor (BEIS, 2020b). Scope 3 supply chain and end of life (EOL) emissions are derived from the dynamic carbon footprint application.

To determine the scope 2 electricity generated GHG emissions a combination of further obfuscated Lakeside analytics data and field metering using the process described in output 1 and used in activities 1 and 2 was undertaken. The value of doing so was to expand upon the recommendation that various sector may have differing active use hours. Using analytics data for a sample set of twenty devices for 30 days it is determined 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 (figure 20).

Figure 20. Analytics OT data for 20 devices.
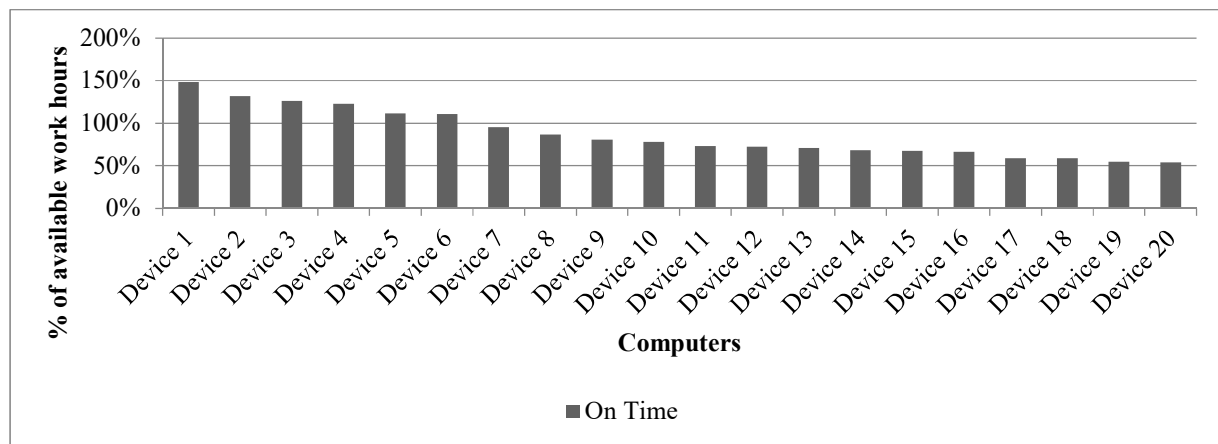
Note figure 20. The OT is the percentage of time the computer is in use per working day. The working day is determined as 10 hours from 8am to 8pm. As such values exceeding 100% confirm extended working times beyond the business operating hours.

The duration is increased compared to the council computer user OT determined in case study A as 70% (figure 10). Therefore, the results validate the Kawamoto et al. (2001) and Roth (2022) finding that job role will influence the annual energy consumption of the computers due to differing use profiles. 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 efficiency design innovation (Boyd, 2012). The finding does not affect the cTEC approach as it is devised primarily to create parity between electricity consumption results that include the active state to enable realistic scope 2 emissions value and facilitate meaning device selection based upon sustainability criteria. However, if the practice is to be used for scope 2 reporting for company reports (HM Gov., 2016) then further research associated with OT in differing business environments is recommended.

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 (table 18). Triangulated with the analytics data (figure 20) and extrapolation to one-year, the legacy desktop in its original format consumes 70.44 kWh/y (table 18). When repurposed with the IGEL OS, the device consumed 0.0274 kW and 54.99 kWh/y (table 18), exhibiting a reduction of 22%. From a device energy consumption perspective the results concur with activity 2 findings determining that alternative Linux based operating systems are capable of reduced electricity consumption between 18-20% (table 6) when subject to human-computer interaction. However, during activity 2 and case study B, Chrome OS Flex software is used to extend device lifespan by continuing with a device's original function. The change of use from a desktop to a thin client in this case study means that some of the reduction experienced by the device is most likely due to offloading the computational and storage activities to the data centre as part of a virtual infrastructure.

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 required to enable the thin client approach diminishes the efficiency gain as an average 1,000 user virtual infrastructure data centre server environment will consume in the region of 17,660 kWh/y (Sutton-Parker, 2015). Therefore, for the purpose of GHG emissions calculation it is reasonable to add approximately 18 kWh/y (Sutton-Parker, 2015) to the electricity consumption value for both the legacy and proposed new thin client devices. Consequently, in realistic terms, the energy efficiency gain related to the legacy device is reversed when compared to the original desktop function to represent a 3.6% increase to 72.99 kWh/y when adding this incremental value to the measured value (table 18).

Comparatively, setting aside the data centre consumption overhead, the repurposed device remains 191% more energy intensive than the proposed HP T640 device measuring 18.86 kWh/y (table 18). 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. Activity 2 identifies that three key common components will reduce power draw. These include reduced thermal design power central processing units, embedded multi-media card storage and low power double data rate memory. The legacy device includes none of these features whereas the new HP thin client includes two. As an example, the thermal design power of the Dell device is 60W (Passmark, 2022) compared to 15W (Passmark, 2022) enabled by the Ryzen R1505G chipset present in the HP device. Additionally, the storage device of the legacy device is a serial advanced technology attachment hard disc drive, whereas the new devices utilise low power flash storage. Consequently, for each retained legacy unit 36.13 kWh/y (table 18) of additional electricity is consumed. From a concomitant scope 2 emissions perspective, this means that 26,534 kgCO$_2$e (figure 21) of additional use-phase emissions are generated during one year by repurposing the devices. As such, the 369,803 kgCO$_2$e already avoided by displacement is reduced creating a total emissions abatement of 343,269 kgCO$_2$e (figure 21).

As the LG device has an integrated display, then 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 (table 18) creating a combined display and repurposed thin client value of 77.67 kWh/y (table 18). Comparatively, the LG 24CN650N integrated desktop consumes only 48% of this value at 37.33 kWh/y (table 18). Consequently, retaining the legacy device consumes 40.34 kWh/y (table 18) more energy per device than transitioning to the new AiO. This equates to an increase in scope 2 emissions during 2020 of 29,625 kgCO$_2$e that could have been avoided via innovation delivered energy efficiency.

Figure 21. Scope 2 and 3 GHG emissions (kgCO$_2$e) comparison between repurposed and potential end user computing devices
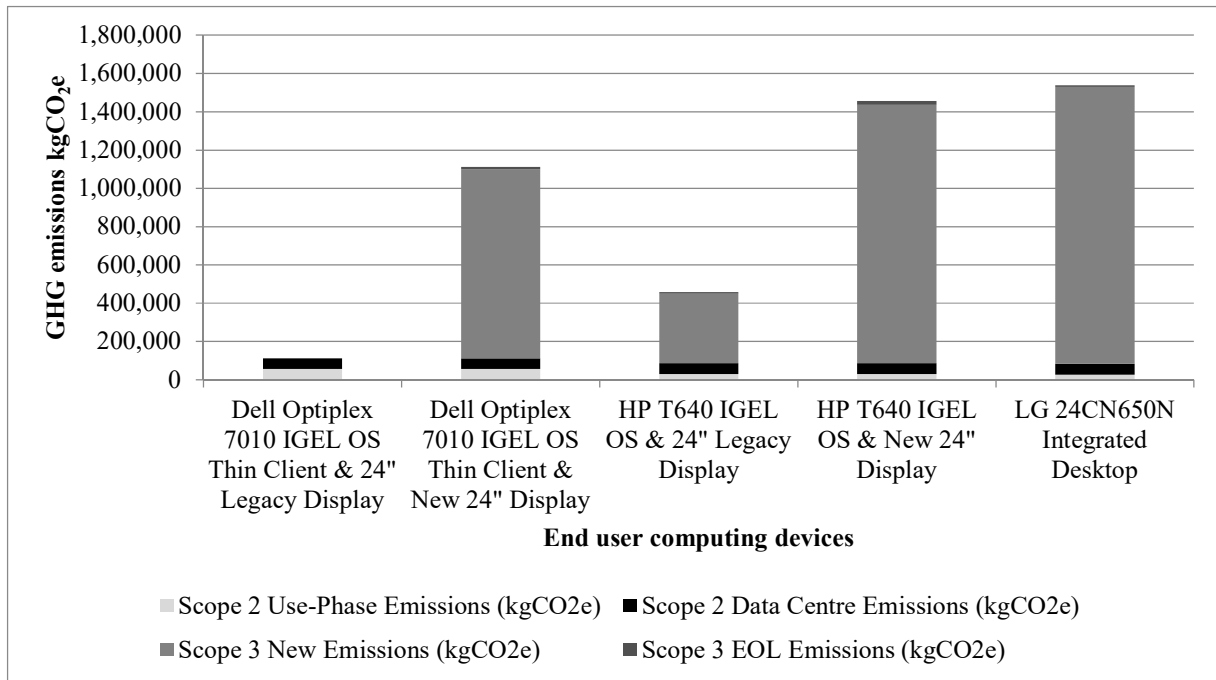

Note figure 21. Scope 2 GHG emissions are derived from combining measured watt meter and OT data used to generate electricity consumption values (kWh/y) that are converted to kgCO2e using the UK conversion factor (BEIS, 2020b). Scope 3 new emissions represent those facilitated by purchasing new equipment. Scope 3 end of life (EOL) emissions are determined by data from the dynamic carbon footprint application. Data centre scope 2 emissions are estimated based upon prior research findings for the kWh/y value (Sutton-Parker, 2015) and converting using the UK conversion factor (BEIS, 2020b).

However, in context of the total carbon footprint, as indicated in figure 21, it is clear that the scope 3 emissions impact of new purchases far outweighs the 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 constructed of only scope 2 emissions generating 113,661 kgCO$_2$e (figure 21) GHG emissions during the one-year period. Purchasing the new HP hardware yet retaining the legacy monitors raises the value by 302% to 456,941 kgCO$_2$e (figure 21) 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$_2$e (figure 21). In this example, 90% of the total footprint is attributed to scope 3 emissions. Replacing the legacy computers and displays entirely with new equipment raises this again by 1,180% to 1,455,491 kgCO$_2$e (figure 21) in the case of the HP product and 1,252% to 1,537,522 kgCO$_2$e (figure 21) in the case of the LG product. 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$_2$e and 1,423,861 kgCO$_2$e (figure 21) of GHG emissions by repurposing existing devices and retaining the existing displays.

The finding concurs with the additional exercise conducted in activity 2 determining that the high proportionate contribution of supply chain emissions to the product total carbon footprint causes on-going abatement gains achieved by energy efficiency innovation to become less significant (figure 4). As such, 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 (Hart, 2016; Prakash et al., 2016; Teehan and Kandliker, 2012; Thiébaud et al., 2017; Williams and Hatanaka, 2005).

Using the same approach as activity 2, the supply chain and continued generation of annual use-phase emissions are projected for the repurposed device and the new HP thin client, both with an existing display, and the new LG AiO computer (figure 22). As highlighted by figure 22, fourteen years of theoretical use 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 intersection until the 49th year (figure 22) due to the raised scope 3 value caused by the embodied value of the integrated 24" display.

Figure 22. Cumulative carbon footprint (kgCO$_2$e) comparison between repurposed and new devices
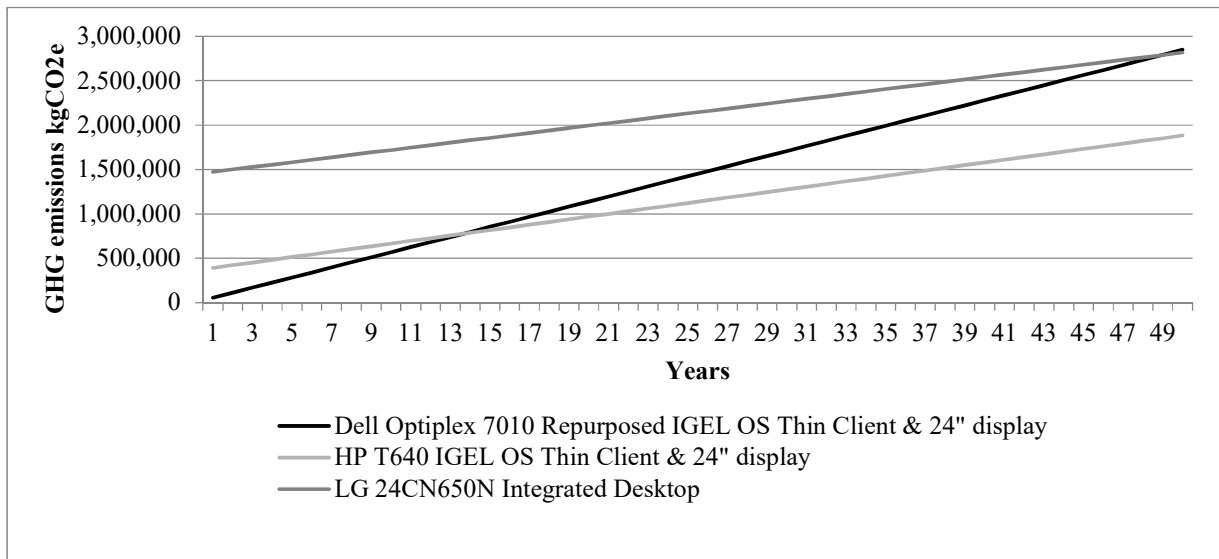
Note figure 22. The repurposed device continues to accumulate scope 2 emissions while the new devices include the initial scope 3 emissions value due to the new supply chain impact plus the on-going scope 2 emissions caused by use-phase electricity consumption.

In both cases, the point when energy efficiency finally offsets the manufacturing and distribution impact is far sooner than in activity 2, occurring in the 91st year (figure 4). 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. As an example, in the prior research a difference of 10.16 kWh/y (table 6) was experienced between the converted 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 (table 18). Consequently, 36.13 kWh/y of electricity consumption and 8.4 kgCO$_2$e concomitant emissions is avoided annually (table 18 and figure 21). Secondly, the scope 3 carbon footprint of the HP thin client device is 41% smaller than that of the Chromebook being 115 kgCO$_2$e (table 18) and 195 kgCO$_2$e (table 18) respectively. As such, the HP device has less initial supply chain emissions to offset than the device used inactivity 2.

However, while carbon intensity data relating to future energy supply cannot be applied with confidence due to lack of certainty, 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 (HM Gov., 2021b). Based upon historical reductions in electricity to GHG conversion factors (BEIS, 2017; 2018b; 2019b; 2020b; 2021c; 2022) highlighting rates of renewable energy adoption, this is potentially feasible. As figure 23 highlights, the conversion factor for 2035 will potentially reach 0.01792 if the already achieved carbon factor percentage reduction is projected. As such, re-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.

Figure 23. UK projected electricity to GHG emissions (kgCO$_2$e) conversion factors
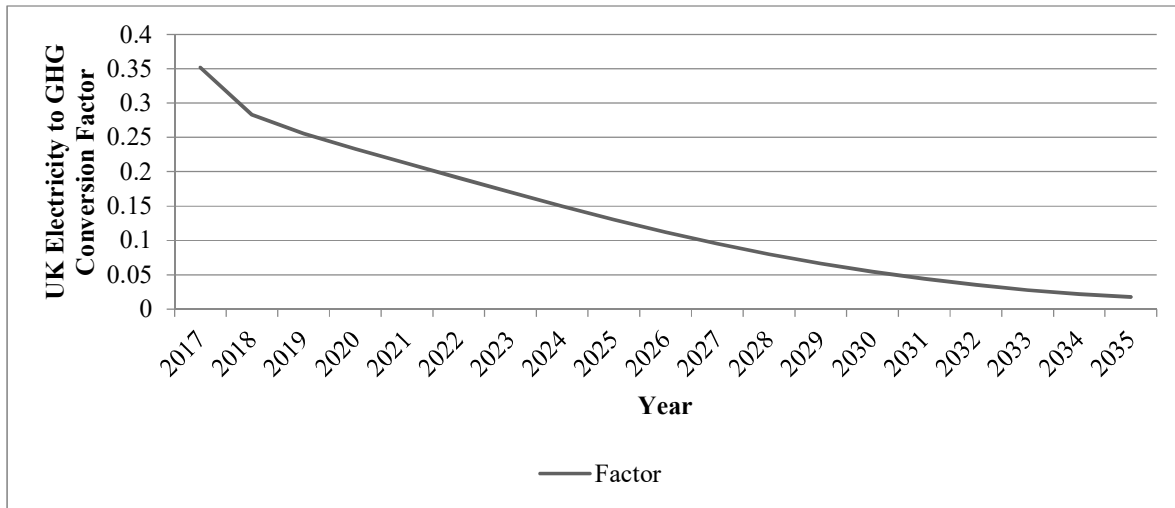
Note figure 23. The projected electricity to GHG emissions factor is based upon reduction experienced to date in UK historical factors published by the government (BEIS, 2017; 2018b; 2019b; 2020b; 2021c; 2022) and a national intent to operate 100% renewable energy by 2035 (HM Gov., 2021b).

Having substantiated the environmental value of computer repurposing, the strategy's impact upon profitability is examined to address the cost barrier to the adoption of sustainable IT strategies determined in activity 5. If the financial expenditure related to the repurposing strategy proves lower than the new device strategy, then this perception is again 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 19, the total avoided costs associated with the most likely replacement solution, the HP device is £1,304,100 (based upon device costs supplied by Computacenter). Ninety-seven percent of the capital expenditure is related to the procurement of the new device with 3% attributed to collection and processing of the legacy devices (table 19). Incurred costs total £330,933 including £100 per legacy device spent on the new IGEL OS software (costs supplied by IGEL) plus an additional cost of £15,933 (table 19) attributed to higher electricity consumption (BEIS, 2021d) exhibited by the repurposed devices when compared to the new alternative. It is noted that this latter cost could be considered irrelevant as payment would be made by the company employee as the devices are operated at home and not in the office. 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 the displacement solution reduces cost for the remote working period by £973,167 (table 19). Had the company selected the AiO device the avoided costs increase to £1,719,900 (table 19) caused by the higher procurement value of £1,764,000.

Comparatively, incurred costs also rise to £332,746 caused by the increased difference in energy efficiency delivered by the integrated desktop resulting in an annual utility cost of £17,746. As such, it is feasible that the overall saving delivered by the sustainable IT solution is £1,431,254 (table 19). In both eventualities, the results concur with similar impact case studies and undermine the cost versus impact perception by further substantiating that displacement strategies using repurposing do reduce capital and operational costs while avoiding GHG emissions as previously determined.

Table 19. Single unit GHG missions (kgCO$_2$e) 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

Note table 19. The avoided cost example is cause by not purchasing new devices and continuing with the repurposed desktops plus avoiding disposal costs in the process. The value of each device and disposal costs is in £GBP and supplied by Computacenter UK as the company both sells and recycles corporate devices. The cost of the IGEL license is supplied by IGEL. Incurred electricity costs are derived by multiplying the kWh/y values from table 18 by the cost of non-domestic electricity in £GBP (BEIS, 2021d).

While the key focus of the case study is to determine the environmental benefit delivered by the displacement strategy, it is reasonable to suggest that remote working will also reduce GHG commuting emissions similar to those calculated in case study A. While, the government enforced travel restrictions requirements during the pandemic will have avoided such emissions whether or not the remote working solution was adopted, it is valuable to determine the scope 3 commuting emission avoided during the period. Doing so will substantiate that a continuation of the practice whether 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 from operations. In order to estimate the most likely impact, the same secondary national transport statistics and data used in case study A. However, having learned from the previous process, an extra level of granularity is applied by addressing all modes of transport, including bicycles, walking, motorcycles and taxis. This is achieved by using proportional travel statistics by mode of transport and frequency (table 20) published by the UK government (DfT, 2019).

To ensure that the positive impact is not subject to exaggeration, as before modes of transport such as public transport that would operate whether employees travelled or not are removed from the calculation. Consequently, it is reasonable to suggest that 1,260,841 kgCO$_2$e (table 20) (400 kgCO$_2$e per employee) of commuting emissions was avoided in 2020 due to the creation of the remote working solution. As the results indicate, almost 99% (table 20) of the pollution is generated by car travel concurring with associated research (Sutton-Parker, 2021) that alternative sustainable transportation modes must be prioritised if companies are to reduce commuting carbon footprints. 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$_2$e (table 20).

Table 20. Commuting avoided scope 3 GHG missions (kgCO$_2$e) estimate

Mode	% of Total	Employees per mode	Average Distance (miles)	Commuting Days	Total Distance (miles)	2020 Scope 3 kgCO$_2$e
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

Note table 20. The percentage of total represents the % of people that use this mode of transport (DfT, 2019) for business travel. The 'employees per mode' value is determined by applying this % to the number of employees included in the case study. The average distance travelled is determined by national statistics (DfT, 2019). Commuting days is determined by the average number of days worked in the UK (figure 11). The scope 3 GHG emissions values are determined using the transport GHG conversion factors published by the UK government (BEIS, 2020b).

7.4. Impact case study D: Can commuting greenhouse gas abatement be delivered by information technology enabled remote working?

The three previous case studies address all strategies now proven to be capable of driving behavioural changes and abating end user computing emissions. Specifically, case studies A and C include commuting emissions reduction enabled by IT. It is recognised in these examples rather than using primary data, the mileage calculations rely upon secondary data in the form of national survey statistics. To ensure results become increasingly meaningful in relation to commuting to access IT emissions reduction, it is reasonable to suggest that primary data be generated in each instance to create context. This would then mean that the scope 3 emissions abatement is derived from travel behaviours specific to each organisation.

To achieve this, case study D creates a method of data capture to both document commuting habits within a large organisation and, using the Px3 application, generates meaningful information to calculate emissions metrics. Using the survey technique detailed in the methodology, the commuting activities of employees of an international cloud technology company are measured. The time horizon includes business-as-usual travel in 2019 and a one-year period during the pandemic covering 2020 and early 2021. The period offers a unique opportunity to assess feasible standard-working practices abatement opportunities and total remote working impact. The results track 815 employees working in four continents, monitoring a variety of commuting modes. Key topics are examined including miles travelled and abated, preferred transportation modes and their differing impact on pollution, attitudes towards climate change, remote working behaviours and the related reduction in GHG emissions created by remote working.

7.4.1. Employee travel and GHG emissions

The technology company operates globally and is organised into three geographic regions. Eight hundred and fifteen employees from twenty-four countries responded to the survey during April 2020; represented by 62% from the Americas, 13.5% Asia Pacific and 24.5% from Europe, the Middle East and Africa (EMEA). Globally, 72% of employees included remote working as part of their routine, spending an average of 2 days per week away from the office before coronavirus travel restrictions were introduced. The remaining 227 employees worked permanently from company offices. Eighty-seven percent of employees (705 people) indicated that they commute, travelling an average of 71km per day, while 13% (110 people) worked remotely at all times (figure 24). Employee transportation modes included 74% by combustion propelled car, 8% train, 5% hybrid car, 4% electric car, 2% taxi, 2% motorbike, 2% bicycle, 2% walking, 1% bus and less than 1% on aircraft (figure 24).

Figure 24. Employee commuting preferred mode of transport
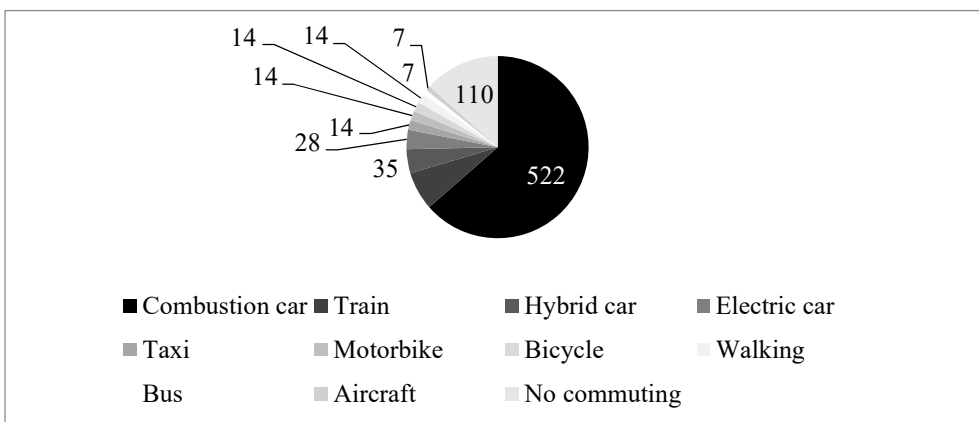
Note figure 24. The pie chart shows the commuting mode of transport for 815 people.

Consequently, in 2019 employees collectively commuted 6,845,821km to access IT. Applying national transport to GHG conversion factors (BEIS, 2019b; Carbonfootprint, 2020; USEPA, 2019) this generates 1,025,072 kgCO$_2$e of scope 3 commuting GHG emissions and an average per capita value of 1,258 kgCO$_2$e. The total emissions require an estimated 1,230 acres (USEPA, 2022a) of forest to sequester the pollution, indicating that for each employee 1.51 acres is required annually to offset commuter emissions.

Figure 25. Global Per Capita Commuting Emissions 2019
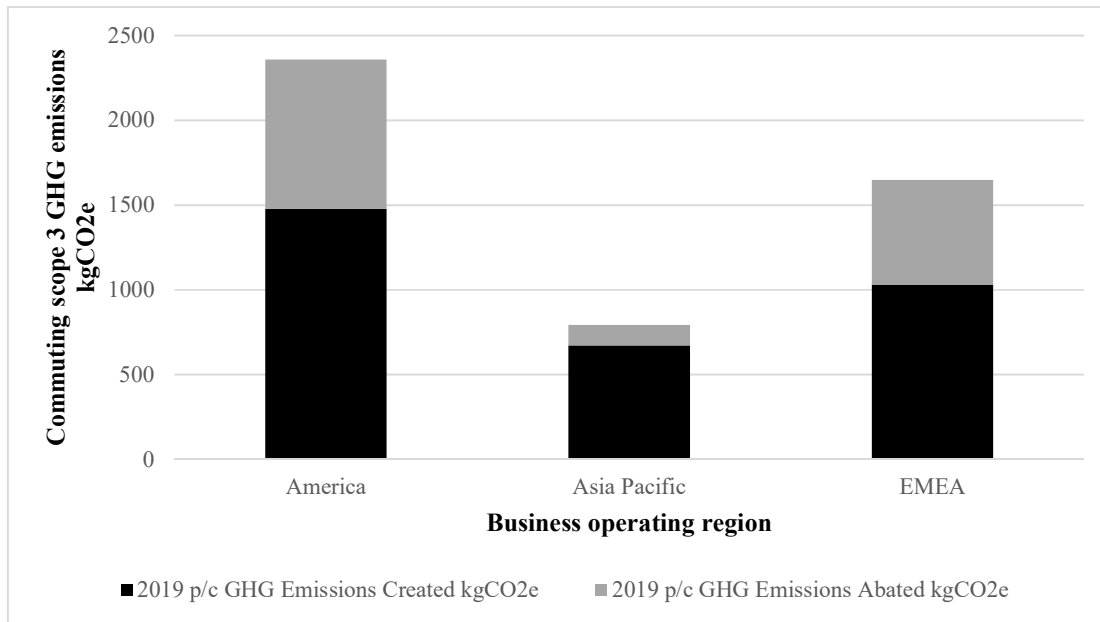
Note figure 25. The 2019 per capita (p/c) GHG emissions created reflect the average scope 3 commuting emissions generated by those employees who travel to work. The 2019 per capita abated emissions highlight the average per capita scope 3 commuting emissions avoided by employees choosing to work remotely or use sustainable modes of transport such as bicycles

In the Americas, the number of remote working days matched the global value as previously noted. Eighty-five percent of employees (426 people) indicated that they commute, travelling an average of 80km per day representing a 13% increase on global averages. While 15% (78 people) worked remotely at all times, 27% indicated that they worked permanently from a company office. Employee transportation modes included 87% by combustion propelled car, 6% hybrid car, 4% electric car, 1% aircraft. 1% walking and 1% train. Consequently, in 2019 employees in the Americas commuted 4,509,411km, representing 66% of global kilometres travelled. This generated 744,558 kgCO$_2$e GHG emissions, representing 73% of global commuting emissions, creating a per capita value of 1,477 kgCO$_2$e (figure 25). The total emissions require an estimated 893 acres of forest to sequester the pollution, indicating that for each employee 1.77 acres is required annually to offset commuter emissions.

The Americas per capita pollution proved to be the highest of all three regions, exceeding Asia Pacific by 119% and EMEA by 43% (figure 25). This was arguably surprising as Asia Pacific employees commuted on average for one extra day per week with twice the number of staff working from an office permanently. The cause was due to three key factors of distance, mode of transport and localised transport inefficiency. Firstly, in the Americas the average commuting distance was 64% higher than in Asia Pacific. Secondly, nine out of ten commuters opted for combustion propelled cars compared to Asia Pacific's five out of ten. Thirdly, the excessive reliance on car transportation was exacerbated by cars in

the Americas being 40% less fuel efficient than European and Asian vehicles, thus increasing the carbon intensity per kilometre.

In Asia Pacific, the number of remote working days was half the global value at one day per week. Ninety percent of employees (99 people) indicated that they commute, travelling an average of only 29km per day representing a 59% reduction on global averages. While 10% (11 people) worked remotely at all times, 54% worked permanently from a company office. Employee transportation modes included 54% by combustion propelled car, 13% by train, 12% by taxi, 7% motorbike, 6% electric car, 5% bus, 1% bicycle and 1% walking. Consequently, even with an additional day of commuting per week, in 2019 employees in Asia Pacific commuted 548,722km, representing only 8% of global kilometres travelled. While the region's workforce is 14% of the global total employees, the resulting 73,981 kgCO$_2$e was proportionate to 7% of global emissions.

This is a per capita value of 673 kgCO$_2$e (figure 25). The total emissions require an estimated 89 acres of forest to sequester the pollution, indicating that for each employee 0.81 of an acre is required annually to offset commuter emissions. The per capita pollution proved less than half the value of that reported in the Americas despite the western counterparts working from home on average twice as much per week as noted. The achievement is directly attributed to the shorter average journeys combined with more sustainable modes of transport. As an example, Asia Pacific employees utilise public transport for 18% of journeys whereas the Americas achieved only 1%. As a result, not only did the carbon intensity of fuel reduce per commuting km, the adoption reduced the reliance upon car travel by 37%.

In EMEA, the number of remote working days matched the global value of two per week. Ninety, percent of employees (180 people) indicated that they commute, travelling an average of 72km per day, again reflecting the global value. While 10% (21 people) worked remotely at all times, only 16% worked permanently from a company office. Employee transportation modes included 55% by combustion propelled car, 20% by train, 6% bicycle, 5% walking, 3% hybrid car, 3% electric car, 3% bus and 2% motorbike. Consequently, in 2019 employees in EMEA commuted 1,787,688km, representing only 26% of global kilometres travelled.

This generated 207,277kgCO$_2$e GHG emissions, representing 20% of global emissions and creating a per capita value of 1,031 kgCO$_2$e (figure 25). The total emissions require an estimated 249 acres of forest to sequester the pollution, indicating that for each employee 1.24 acres is required annually to offset commuter emissions. The per capita pollution for EMEA is 30% lower than the Americas and 53% higher than Asia Pacific. With twice the number of remote working days undertaken in EMEA compared to Asia Pacific, the increase is due to the average commuting distances being 2.5 times higher. However, the ability to remain a third lower than the Americas is achieved by the high adoption of public transport (25%) and zero environmental impact modes such as cycling and walking at 11% compared to the Americas at 1% and 1% respectively and more fuel efficient cars (BEIS, 2020b; USEPA, 2019).

7.4.2. GHG commuting abatements enabled by IT

To ensure that all employees are able to work remotely should they wish to, the technology company deployed a Citrix digital workspace solution (Citrix, 2022). Employing zero trust security and threat analytics capabilities, the virtual desktop infrastructure enables desktop and applications to be securely accessed on any device from any location. As such, in 2019, the approach enabled 72% of global employees to work remotely. 217 (27%) opted for one day at home, 161 (18%) for two days, 59 (7%) for three days, 41 (5%) for four days, 110 (13%) for five days, while 227 (28%) of employees chose to work from the office full time. The 110 staff already working from home permanently indicated that had office working been mandatory, then their return commute journeys would have averaged 49km daily.

The transportation choices would have included 74% (81) fossil fuel propelled car, 7% (8) walking, 7% (8) specified only as other, almost 4% (4) bicycle, 3% (3) electric car, 3% (3) train, 2% (2) taxi and just

below 1% (1) hybrid car. Reflecting the global reliance on car travel, the main difference in those working from home to the commuter group is the 10% indication that their commute would involve zero impact modes such as walking and cycling. In this instance, those capable of utilising a bicycle to commute would travel on average 10km whereas those walking lived within one to two kilometres of the office.

Consequently, for those working at home permanently in 2019, the 31% reduced average journey distance and sustainable transport choices mean that the commuting emissions values avoided were 209,336 kgCO$_2$e. This creates an elevated group per capita abatement value of 1,903 kgCO$_2$e, up 131% when compared to the commuter group. The total emissions avoidance frees an estimated 273 acres of forest from sequestering commuting pollution. This indicates that for each employee choosing to work from home permanently, 2.48 acres is not required to sequester emissions. The remaining commuter group consisting of 705 people, as discussed, averaged 2 days per week working remotely. As such, triangulating individual remote working statistics with transportation carbon factors and distance travelled, the commuters avoided 579,995 kgCO$_2$e transport (figure 25) GHG emissions in 2019. This creates a commuter group per capita abatement value of 823 kgCO$_2$e. The total emissions avoidance frees an estimated 757 acres of forest from having to sequestering commuting pollution. This indicates that for each employee choosing to work from home on average two days per week, 1.07 acres is no longer required to offset emissions.

Combined, in 2019, the IT remote working solution deployed by the technology company enabled the 815 employees to avoid the generation of 789,331 kgCO$_2$e (figure 25) scope 3 commuting GHG emissions. This creates a per capita abatement value of 969 kgCO$_2$e. The total emissions avoidance frees an estimated 1,031 acres of forest from having to sequestering the commuting pollution. This indicates that for each employee choosing to include remote working as part of their working behaviour, 1.27 acres of mature forest is no longer required to offset emissions.

While during 2019 IT enabled remote working delivered substantial GHG commuting abatements, 2020 inadvertently surpassed all expected improvements to the sustainability metrics. In early February, travel restrictions were set in place for employees in China, and by mid-March a global remote working policy was announced that lasted to the end of the year and beyond. Consequently, due to the initial regional commuting restrictions and all employees working from home for nine months, commuting emissions in 2020 declined by almost 75% to 256,052 kgCO$_2$e. This created a new per capita value of 314 kgCO$_2$e compared to the previous year value of 1,258 kgCO$_2$e.

The total emissions require an estimated 334 acres of forest to sequester the pollution and represent a reduction of 896 acres compared to 2019. For the travel restricted year, the data indicates that for each employee 0.41 acres is required annually to offset commuter emissions; a value of 1.1 acres less per employee than in 2019. The reduced commuting GHG emissions consequently increased the abatement values by 97% compared to the previous year. As such, the IT remote working solution enabled the 815 employees to avoid the generation of 1,558,351 kgCO$_2$e scope 3 commuting GHG emissions. This 769,020 kgCO$_2$e improvement creates a per capita abatement for 2020 of 1,912 kgCO$_2$e compared to 969 kgCO$_2$e in 2019. The restricted commuting total emissions avoidance frees an estimated 2,035 acres of forest from having to sequestering the commuting pollution and represents an increase in twelve months of 1,004 acres. This indicates that for each commuting employee forced by the pandemic to work remotely and for each of those who already choose to include remote working as part of their working behaviour, 2.5 acres of mature forest is no longer required to offset emissions. This value represents an additional 1.2 acres relieved during 2020. Considering that the total forest land mass no longer required is equal to 8.2 km^2 and more than four times the size of Monaco, this is arguably a positive environmental outcome for the eight hundred and fifteen employees who each played a part in releasing almost 2.5 acres (USEPA, 2022a) each by reduced commuting in 2020.

7.4.3. 'New normal' IT enabled remote working behaviours

With the lifting of travel restriction and office access in 2021, it is reasonable to state that there will initially be a desire to re-enter the office and engage in person with colleagues. As noted previously, research projections agree that there will certainly be an increase in remote working (Gartner, 2020a; b; IDC, 2020; Scientific American, 2020). However, the success of IT enabling GHG commuting emissions abatement via remote working in the longer term will rely on three factors. Firstly, working behavioural changes driven by experiencing remote working. Secondly, people's attitude towards reducing their carbon footprint. Thirdly, by instigating long term behaviour changes related to transportation modes. In the first instance, it is too early to accurately determine whether employees will wish to hold onto the work life balance afforded by remote working or revert to the same working behaviours displayed in 2019. However, prevailing research indicates that three quarters of employees would welcome the ability to remain a remote worker. The sentiment was in fact so strong that the employees would accept a 14% pay decrease to do so (Citrix, 2021b). Arguably, it is unlikely that all 815 employees would remain permanent remote workers for the long term. While the 2020 figures already highlight the abatement for such a scenario, encouraging those who are not already achieving the average remote working days indicated in 2019 would make a significant difference. Theoretically, if the company mandated a working behaviour that required a minimum of two days remote working in all regions for all employees, commuting emissions would reduce by 20% to 827,474 kgCO$_2$e and abatements would increase proportionately by 25% of the new total to 986,930 kgCO$_2$e.

In the second instance, the 815 employees collectively noted a '7.5' score when asked, 'If 10 is the highest importance, how important to you is reducing your carbon footprint?' While no accurate gauge of intention, the fact that the results are in the upper quadrant indicate an axiology of positivism towards actions that may reduce pollution. Asia Pacific's positive attitude towards environmental impact exceeds the Americas by 19% at 8.7. Comparatively, the Americas per capita GHG emissions value is 93% higher than Asia Pacific. As previously discussed, the 74% reliance on car travelled compared to Asia Pacific (54%) combined with extended commuter distances is key to this disparity. Considering that Asia Pacific appears to have already exercised the adoption of more sustainable transport driven by its opinion of carbon footprint reduction then it is fair to state that increasing awareness and therefore improved attitude in the Americas (and EMEA) may prove an important factor. To support this view, the survey conducted in activity 5 suggests that of all the resistance factors preventing the adoption of sustainable practices, a lack of awareness and subsequent impact perception can increase barriers by between 20-30% (table 9) as determined by the output stage survey.

Relating to the third point, if increased levels of sustainable travel could be adopted through awareness programs related to the carbon intensity of differing transport modes, further impact could be achieved by unifying the minimum number of remote working days. Switching fossil fuel cars for more sustainable transport modes such as electric cars and public transport that produce x37 and x4.6 less GHG emissions per km (BEIS, 2020b) will significantly reduce commuter emissions. While the former will come to fruition slowly and organically as legislation ceases the production of petrol and diesel cars from 2030 onwards (HM Gov., 2022a;c), validity of any suggested adoption level ahead of the market within the commuter group would be speculation. In order to create an accurate projection additional data such as affordability and available charging infrastructure not gleaned by this research would be required. Additionally, available data does not geographically confirm if public transport links and schedules are available to all employees as post and zip code location data was not collected.

As such, where an assessment can be made in order to highlight the benefits of sustainable transport is in relation to an adoption of zero impact transportation. The data indicates that the average commuting bicycle return journey is 7km and the average walking journey 3.2km. As such it is feasible, unless physically unable, for employees to conduct any commute of up to 7km daily by a form of zero carbon transport. Globally, there are 98 employees with a round trip journey of less than 7km who are not currently walking or cycling. Statistically, the survey results reveal that 92% (90 people) travel by fossil

fuel propelled cars. Encouraging this group, representing 12% of employees, to switch to cycling or walking in conjunction with the new extended remote working mandates would further reduce commuting emissions by 5,247 $kgCO_2e$ per year. Consequently, with what could be seen as a relatively uncomplicated transport program, the company could reduce total commuting to access IT emissions a further 0.6% to an annual figure of 822,227 $kgCO_2e$. This new normal would create a per capita value 1,008 $kgCO_2e$ and delivering a reduction of 20% when compared to 2019. The total emissions require an estimated 1,074 acres of forest to sequester the pollution, indicating that for each employee 1.32 acres would be required annually to offset commuter emissions

Using the survey technique, the research is able to bring context to the results of commuting to access IT emissions reduction by transitioning from reliance upon secondary national statistics data to primary data reflecting employee commuting habits. Like case study A and C, substantial emissions abatement is achieved when enabled by end user computing remote working technologies. However, in this example working remotely for two days creates a per capita scope 3 emissions value far higher than the previous examples. Specifically, the primary data determines that each employee creates 1,258 $kgCO_2e$ of GHG emissions (figure 25). Using car travel statistics for case study A, this value is 62% lower at 474 $kgCO_2e$. Introducing a further level of granularity by transport mode in study C reduces the per capita value further to 240 $kgCO_2e$ per employee (table 20) and 81% lower than the primary data results. The incongruence is caused by increased mileage documented by the survey when compared to the 18.2 miles per day average determined by the statistics. As an example, the determined global average for case study A is 44 miles per employee and 26 miles in the UK. Comparatively, the statistics data (HoC, 2019) proved to be 30% lower than the primary data in terms of mileage travelled. The point made is that the necessity for contextual data will become emphasised if diffusion of the framework approach includes assessment of organisations operating internationally. This is because all countries will experience differing miles travelled, modes used plus engine types and efficiencies that will all influence the meaningful data produced by the proposed Px3 framework.

7.5. Impact case study E: Examining end user computing supply chain abatement in the UK government sector

As noted in the introduction, the UK public sector is subject to mandatory GHG emissions accounting and reporting (HM Gov., 2013) plus regulations stipulating sustainability as a selection criterion for new computer devices (HM Gov., 2021b). In central government, each of the twenty four ministerial departments (HM Gov., 2022d) is required to complete an end user computing annual electricity consumption and scope 2 emissions estimation for all personal computers. This is achieved using the existing Joint Information Systems Committee (JISC) model (JISC, 2019). The exercise involves government IT managers populating an .xls spread sheet with quantities of computers owned by the department. The computer quantities are classified by major device type categories (e.g. notebook or desktop) as formalised by Kenma et al., (2005). For each device type the JISC model applies an annual electricity consumption value (kWh/y) derived from original field measurement conducted by Cartledge (2008) and Hopkison and James (2009). The total electricity consumption value for all computers by department is then submitted to the Department of Environment, Food and Rural Affairs (DEFRA) who lead the government's Sustainable Technology Advice & Reporting (STAR) team. Analysts then use the relevant UK electricity to GHG emissions conversion factor (BEIS, 2022) to calculate end user computing device scope 2 emissions. The results are published in the Greening government ICT annual report (HM Gov., 2022b).

In their own words, *'STAR ensures that government ICT services are designed, delivered and operated with sustainable principles at their core. This includes our procurement choices, how our ICT is used*

ranging from kit which uses less energy to technology which reduces the need for travel and disposal.' (HM Gov., 2022b). As such, reducing end user computing emissions is imperative to this strategy from both a scope 2 and 3 perspective.

The group became aware of this research via the long term greater London council impact case study A (Sutton-Parker, 2022e) and two media publications called, 'Time IT Changed' (The Guardian, 2020) and 'Sustainable IT' (The Guardian, 2021). The magazines feature articles from early research papers (Sutton-Parker, 2020a; b; 2021). Distributed at events attended by STAR such as the Conference of the Parties (COP) 25 and 26 and including commentary from stakeholders working with STAR (Baroness Brown of Cambridge, chair of the Carbon Trust and General Tom Copinger-Symes, director of military digitisation, Ministry of Defence) the team decided to make contact in 2021.

Key stakeholder Adam Turner, UK government and public sector head for sustainable digital and ICT of DEFRA, expressed that currently UK public sector organisations do not have the ability to meaningfully select low carbon footprint end user computing devices and have to rely upon third-party certifications (Energy Star, 2022; EPEAT, 2022; TCO, 2022) for guidance. The reason given was that using published product carbon footprint reports was too complex, recognised as incomparable due to the scope 2 emissions issue examined in activity four. Consequently the process was considered too costly to achieve due to excess time spent with limited perceived impact. The comments reflect the findings determined in activity 5 (Sutton-Parker, 2020a).

The Department for Work and Pensions (DWP), a STAR member responsible for 22% of computer users (figure 26), also recognised that the JISC process was potentially highly flawed due to the assumed legacy electricity consumption values being potentially obsolete due to age (Cartledge, 2008; Hopkison and James, 2009; JISC, 2019). Additionally, it was indicated that due to the latest scientific targets included in the greening government ICT policy (HM Gov., 2020b) that require proof that ICT products will contribute to abatement targets and an impending ruling in Europe that will require large organisations to begin supply chain emissions reporting (EU, 2022b), STAR wished to understand what tools had been created by the research to assist in selecting devices and quantifying end user computing GHG emissions.

Figure 26. Employee numbers by HM Government department (2021)
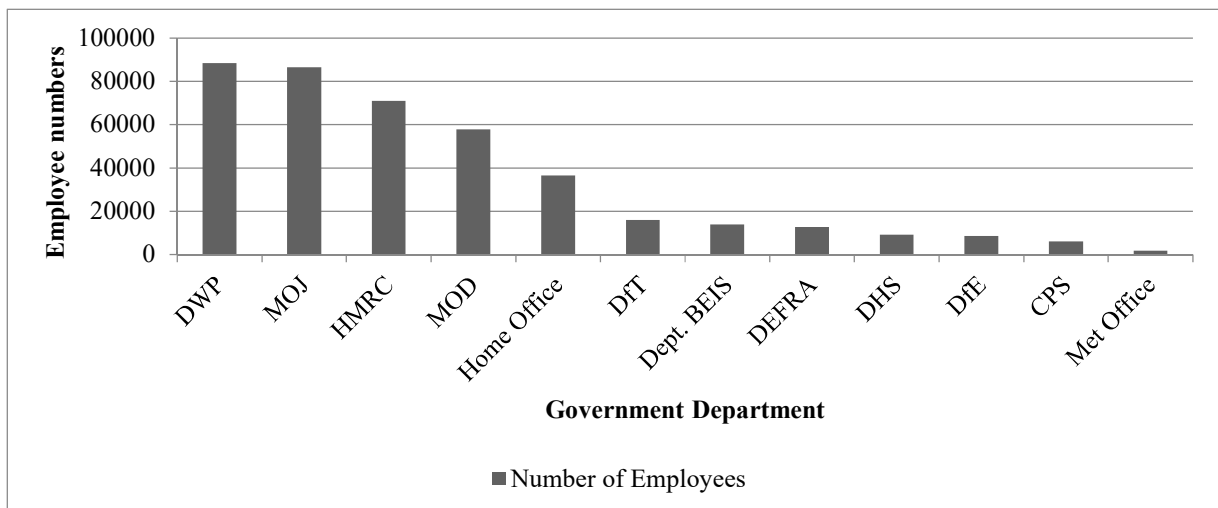
Note figure 26. The employment statistics for each department are derived from Office of National Statistics publication for 2021 (ONS, 2022). The graph is used to visually demonstrate the high numbers of employees working within the DWP and subject to scope 2 end user computing regulations.

To overcome the initial device selection by sustainability criterion barrier, STAR agreed to pilot the Dynamic Carbon Footprint application as discussed in output 2 previously. The pilot was successful, as previously noted and now all participating departments use the application to assess and select suitable end user computing devices ahead of procurement and to comply with the greening ICT policy (HM Gov., 2020b).

Further to this, a number of central government departments requested quantification of scope 3 end user computing emissions for their existing install base. The intention was to determine the current emissions value and highlight the feasible impact of selecting low carbon footprint devices upon the supply chain. If sustainable the new strategy to reduce end user computing supply chain emissions by using the dynamic carbon footprint application would be included in the forthcoming greening government ICT strategy and policy document due for publication in autumn 2022 (HM Gov., 2022b).

This departments included DEFRA, the Department for Business, Energy and Industrial Strategy (BEIS), the Crown Prosecution Service (CPS), the Department for Education (DfE), the Department for Transport (DfT), the Department for Health and Social Care (DHS), the DWP, Her Majesty's Revenue and Customs (HMRC), the Home Office, the Met Office, the MOD and the Ministry of Justice (MOJ) plus the Chief Digital Information Office (CDIO). Collectively, the departments employ 408,200 staff (figure 26) (ONS, 2022) representing 7% of the UK public sector workforce (HoC, 2022).

The scope 3 quantification exercise was conducted by first accessing asset profile data created during the most recent JISC scope 2 GHG emissions reporting process. As such, the data excluded make and model information, instead focusing upon device type and quantities for existing standard desktops computers, thin client computers, notebooks and tablets. In this format, 2,221,938 devices are identified including 1,226,722 computers and 995,216 displays (table 21).

Table 21. Information and communication technology supply chain scope 3 emissions (kgCO$_2$e) and feasible abatement (%)

Hardware Type	Units	Scope 3 Per Device (kgCO$_2$e)	Scope 3 Total (kgCO$_2$e)	Car Miles Equivalent	5-year Annualised Supply Chain (kgCO$_2$e)	8-year Annualised Supply Chain CFP (kgCO$_2$e)	Lowest Available Scope 3 (kgCO$_2$e)	Selection by CFP Reduction (kgCO$_2$e)
Computers								
Desktops	383,466	221	84,745,986	307,095,180	16,949,197	10,593,248	153	31%
Notebooks	724,750	266	192,783,500	698,592,187	38,556,700	24,097,938	124	53%
Tablets	68,795	110	7,567,450	27,422,271	1,513,490	945,931	65	41%
Thin clients	49,711	108	5,368,788	19,454,950	1,073,758	671,099	106	2%
Displays								
Monitors	983,009	324	318,494,916	1,154,134,353	63,698,983	39,811,865	169	48%
Screens	12,207	1,184	14,453,088	52,373,851	2,890,618	1,806,636	970	8%
Computers	1,226,722	237	290,465,724	1,052,564,589	58,093,145	36,308,216		
Displays	995,216	335	332,948,004	1,206,508,204	66,589,601	41,618,501		

Note table 21. Hardware type is defined by the asset profile categorisation used by the UK Government to complete the JISC (2019) process. Units represent the number of devices owned by the UK government departments. Scope 3 per device values are an average by type (e.g. notebook) derived from the dynamic carbon footprint database. The car miles equivalent represent the number of miles driven by a combustion engine vehicle to produce the equal quantity of GHG emissions generated by the scope 3 device emissions. This is calculated using the UK GHG conversion factors (BEIS, 2020). The 5 and 8 year annualised supply chain values represent the scope 3 device total divided by either 5 or 8. The lowest available scope 3 emissions value is derived from the dynamic carbon footprint database and represents the lowest available scope 3 supply chain value listed on the application. The selection by carbon footprint (CFP) percentage represents the difference between the average and lowest scope 3 device GHG emissions.

For the four categories an average scope 3 GHG emissions value was generated using the supply chain product carbon footprint data already available within the dynamic carbon footprint application. Similarly, the lowest available carbon footprint for each device type was determined (table 21) using the application in order to demonstrate feasible scope 3 emissions abatement via informed selection. This is represented by the column in table 21 called 'selection CFP reduction ($kgCO_2e$)'.

As guided by the Px3 framework a car miles equivalent value was also included in the findings (table 21) to ensure the environmental impact was tangible to all stakeholders. To emphasise displacement opportunities to reduce future demand for new devices, annualised scope 3 data was also included to determine the impact of both 5-year and 8-year retention device period (table 21).

The 1,226,722 (table 21) end user computers owned by the UK central government generate an average scope 3 GHG emissions total of 290,465,724 $kgCO_2e$ (table 21). In context, this is equivalent to emissions generated by driving a combustion engine car 1,052,564,589 miles (table 21) (BEIS, 2022). Desktop computers account for 31% of the end user computing estate, being 383,466 units (table 21). The data supports findings in activities 3 and 4 contradicting analyst indications that at only 14% of all devices produced are desktops (Gartner, 2021; Statistica, 2021) and substantiating that the decline in popularity of desktops is isolated currently to consumer markets.

The data indicates that the average supply chain value for computers in general is 237 $kgCO_2e$ (table 21) per device. It was highlighted to DEFRA that a significant reduction could be achieved by leveraging the scope 3 reductions of 31% and 53% (table 21) for desktops and notebooks by using the dynamic carbon footprint application and introducing sustainability criteria during procurement. As an example, replacing the current devices at the appropriate moment in the future with the lowest available scope 3 devices would reduce the overall supply chain impact by 44% to 161,475,536 $kgCO_2e$ (table 21). This could be further improved by moving from a current 5-year device retention period to an 8-year period, proven feasible by activity 2 and case studies B and C (Google, 2021; 2022a; Sutton-Parker, 2022e). Coupled with sustainable device selection the actions could reduce the current annualised supply chain emissions value of 58,093,145 $kgCO_2e$ (table 21) by 65% in total to 20,184,442 $kgCO_2e$ per year. Doing so would be equivalent to avoiding the pollution caused by 137,370,281 car miles each and every year (BEIS, 2022).

Displays are categorised by two types (table 21). The first is a computer monitor used as an interface with a primary function to display visual information supplied by a computer to an individual user. The size range for such devices is set to 14-38" based upon the rationale that an interface larger than this will arguably be inappropriate for desk-based user productivity. The second type is a screen used to display visual information to a group or within a communal area. The size range for such devices is set to 40"-70" to enable an average quantification of scope 3 emissions. Both use case assumptions are validated by the extensive asset data generated by activity 4 (table 8).

Monitors represent almost 99% of all displays, being 983,009 units (table 21). The average supply chain value for the monitor category is calculated as 324 $kgCO_2e$ (table 21). This generates a supply chain total of 318,494,916 $kgCO_2e$ or 63,698,983 $kgCO_2e$ when annualised to 5-years (table 21). The total scope 3 emissions for monitors are equivalent to pollution generated by 1,154,134,352 car miles (BEIS, 2022). Abatement is available based upon assessing and selecting monitors for sustainability criteria such as a low embodied carbon footprint. In this instance, a popular sized 24" model with a scope 3 value of 169 $kgCO_2e$ per unit would deliver a 48% (table 21) reduction in supply chain impact if selected as a replacement when necessary.

Screens represent just 1% of all displays, being 12,207 units (table 21). The average supply chain value for the screen category is 1,184 kgCO$_2$e (table 21) and the total scope 3 emissions generated is 14,453,088 kgCO$_2$e (table 21). As with monitors, the annualised representation is based upon the 8-year retention period as advised by STAR. This creates 1,806,636 kgCO$_2$e (table 21) of scope 3 emissions for each year of the device useful lifespan. The total supply chain environmental impact is equivalent to pollution created by 52,373,851 car miles (BEIS, 2022). In total, the 995,216 displays (table 21) generate scope 3 GHG emissions of 332,948,004 kgCO$_2$e (table 21). This is equivalent to 1,206,508,204 average miles (table 21) being driven in a standard passenger car.

The high number of computers identified suggested that based upon published employee figures (figure 26) the data indicates the thirteen government departments have 3 computers and 2.4 displays for every member of staff (figure 26). The exact values include 383,466 desktops, 724,750 notebooks, 68,795 tablets and 49,711 thin clients (table 21). Assuming that desktop devices and thin clients will be used as kiosk devices for general public interaction, the notebook values appear excessive with 1.8 units available per employee (figure 26 and table 21). Triangulating government statistics suggesting 67% of roles require access to computers to conduct their role (BEIS, 2018b), the total ratio rises to 4.5 computers to every staff member. The finding supports the concept that contextual data, such as actual operational use, must be generated if meaningful scope 2 emissions are to be generated. Currently, this is not addressed by the JISC (2019) process as all devices owned, whether in use or not, have an assumed kWh/y applied. While the apparent excess of devices does not affect the quantification of scope 3 emissions as the devices evidently exist, the lack of contextual data relating to the device use-profile will produce inaccurate assumptions for concomitant scope 2 reporting regulations (HM Gov., 2020b). As an example, should a proportion of the devices be stock items or held for new staff, part-time workers or device replacement purposes then applying energy consumption and concomitant scope 2 emissions values during the JISC reporting process is flawed.

Secondly, the high level example of devices in stock but not used in the work place being counted in JISC reports, led to the DWP undergoing end user computing GHG emissions analysis using the cTEC methodology, dynamic carbon footprint tool and Px3 framework to determine the impact to inaccuracy. As the largest department, with 88,380 staff (figure 26) the organisation owns 227,987 (table 22) or 19% of the total computer stock within the thirteen departments (table 21). The assets consist of 97,565 desktops (43% of total), 13 integrated desktops (<0.01%), 130,409 (57%) notebooks plus 128,757 monitors (0.6 displays to every computer) (table 22). Excluding 5,557 desktop computers and 24" display combinations used for customer kiosks, this means that the department holds sufficient hardware to supply 2.5 end user computer devices to each employee (figure 26 and table 22).

Table 22. JISC electricity consumption (kWh) and scope 2 emissions (kgCO$_2$e) versus measured values

Hardware Type	Units	Status	JISC kWh/y value per unit	JISC Total kWh/y value	Scope 2 emissions total kgCO$_2$e	Measured kWh/y value per unit	Measured Total kWh/y value	Scope 2 emissions total kgCO$_2$e	JISC vs. Measured
Desktops	97,565	Owned	200	19,513,000	4,143,195	31.92	3,114,275	661,254	+850%
Desktops	64,351	In use	200	12,870,200	2,732,730	31.92	2,054,083	436,143	+526%
Notebooks	130,409	Owned	30	3,912,270	830,692	21.02	2,741,197	582,038	+114%
Notebooks	87,088	In use	30	2,612,640	554,742	21.02	1,830,590	388,689	+42%
Displays	128,757	In use	179	23,047,503	4,893,676	21.65	2,787,589	591,889	+726%
Total	356,731	Owned		46,472,773	9,867,563		8,643,061	1,835,181	+697%
Total	280,196	In use		38,530,343	8,181,148		6,672,262	1,416,721	+478%

Note table 22. Devices are determined by type. The number of units is supplied by the DWP. The JISC kWh/y values are derived from the tool (JISC, 2019). The measured kWh/y is determined during activity 1 (table 2). Scope 2 emissions are calculated using the UK GHG conversion factor (BEIS, 2022). The JISC versus (vs.) measured value is the % of over reporting of both electricity consumption and emissions currently experienced by the UK Government.

On further examination and discussion with the department, it was discovered that as anticipated, only 156,452 computers (table 22) were in use meaning that 71,535 (table 22) remained in storage awaiting use. Examining historical employment records indicates that from 2019 DWP staffing numbers have risen by 5,110 from 83,270 (ONS, 2022) and as such the overstocking cannot be assumed as legacy equipment no longer required. Two errors in scope 2 quantification are generated by not including use-profile data within the JISC methodology. Firstly, the total number of devices will have kWh/y and concomitant emissions values applied regardless of whether they are in-use or dormant as previously noted. Secondly, the average kWh/y values used by JISC will be applied to all models of computer type regardless of specification.

As the desktop devices used at the DWP are the same as the Lenovo desktop measured in activity one, the opportunity to accurately quantify the error arose. As table 22 shows, the JISC tool calculates the total for all desktop computers to be 19,513,000 kWh/y (table 22) producing 4,143,195 kgCO$_2$e (table 22). Using the same JISC (2019) process but this time recognising only the in-use devices reduces the values by 34% to 12,870,200 kWh/y and 2,732,730 kgCO$_2$e (table 22). This substantiates the first point that contextual data noting whether the device is operational or simply store must be accounted for in the process.

Applying the field measurements to the devices further compounds the issue related to using the JISC model. In this example it is determined that the JISC tool (JISC, 2019) over estimates desktop energy consumption by +526% (table 22). Specifically, the tool suggests desktop devices consume 200 kWh/y whereas when measure with a watt meter (activity 1), the exact same model actually consumes 31.92 kWh/y (table 2 and 22).

The new calculation produced using the measured values calculate the total in-use electricity consumption to be 2,054,083 kWh/y and 436,143 kgCO$_2$e (table 22). It is therefore feasible that by using the non-contextual asset profile data in conjunction with the JISC tool, the UK government departments are over reporting desktop energy consumption and scope 2 emissions by as much as +850% (table 22).

Similarly, the department has a significant number of Dell Latitude 5000 series notebooks and Microsoft Surface Books within the mobile computing estate. Following the same approach and using the measured average for the two models from activity 1 (table 2 and 22), the over quantification for notebooks is +114% (table 22) due to the more realistic 30 kWh/y (table 22) used by the JISC tool for a standard laptop compared to the 21.02 kWh/y measured value (table 2 and 22). Comparatively, the 128,757 displays (table 22) were all confirmed as in use. Therefore, the over quantification of energy and emissions is +726% (table 22).

In total, the error created by using the JISC model without considering whether a device is in use or in storage increases reported electricity consumption and scope 2 emissions by +20% (table 22). However, this rises substantially when both in-use devices quantities and measured electricity consumption values are included into the quantification process. Specifically, the inclusion causes over reporting to increase to +697% (table 22). The total JISC value of electricity consumed by end user computing devices in the DWP is calculated to be 46,472,773 kWh/y (table 22) with concomitant scope 2 emissions of 9,867,563 kgCO$_2$e (table 22). Comparatively, the measured value is 6,672,262 kWh/y (table 22) and producing scope 2 emissions of 1,416,721 kgCO$_2$e (table 22).

The largest department within the STAR group is therefore potentially over reporting end user electricity consumption by 39,800,511 kWh/y (table 22) and concomitant emissions by 8,450,842 kgCO$_2$e (table 22) by using the non-contextual JISC model.

In terms of utility costs calculated using government published values (BEIS, 2021d) this indicates that, the department is actually spending £14,328,83 less on end user computing electricity than the current scope 2 reporting process suggests. To emphasise the reality of the error created by the tool it was suggested to the department that based upon their current JISC reporting they are spending £16,730,198

per year of end user computing utility costs. The response was that this is entirely incorrect. Suggesting that it could be closer to £2.4m or £200,000 a month equating to £2.26 per user, this was suggested to be approximately correct. As such, setting aside the proven environmental errors generated by the current methodology, the utility costs using the cTEC methodology proved to be closest to real-world values thus substantiating the new approach.

Further to presenting the findings to the STAR group during their quarterly autumn 2022 meeting, two outcomes followed. Firstly, due to the obvious significant impact of scope 3 emissions, the dynamic carbon footprint application was adopted by HM Government to be used as a procurement tool moving forward. While too early to determine, the intention is to deliver a change in behaviour that reduces future scope 3 emissions at scale as devices are replaced.

Adam Turner, head of STAR noted (October 2022), '*STAR pioneers, and is responsible for the reduction of the government's ICT carbon footprint. This is especially important within the supply chain when the majority of environmental impact occurs. Having access to never previously available scope 3 data is essential to evolving our policies, procurement practices, accurate government reporting and ensuring our technology partners focus on low carbon footprint production and supply.*'

Secondly, the DWP confirmed that based upon the scope 2 analysis, the approach developed by this research would be used in 2023 to quantify end user concomitant scope 2 and supply chain emissions.

Tony Sudworth, sustainability lead at the DWP noted (February, 2023), '*the analysis of the scope 2 and 3 GHG emissions from our end user computing estate considerably improved the detail and quality of our annual cross-government STAR (Sustainable Technology Advice and Reporting) submission. I'm really pleased to be informed that following this exercise STAR has decided to adopt the Px3 methodology across all its members for the coming year. This is an important step in improving both the quality and standardisation of the data covering millions of public sector employees*'.

Specifically, the findings and decision are included in the 2022 government ICT strategy and policy report (HM Gov., 2022b) to the UK parliament with a recommendation that scope 3 emissions reporting become part of the greening ICT policy in the coming years.

8. Chapter 8: Conclusions, recommendations and limitations

The overarching objective of this research is to answer the question, 'can meaningful end user computing carbon footprint information drive human behavioural changes to abate GHG emissions?' The research is necessary to support the UN emissions bridging strategy (UN, 2019) to leverage existing technology to abate societal emissions as further key strategies such as renewable energy mature. As noted, doing so will target the 1% contribution of end user computing to global GHG emissions (Andraea and Edler, 2015; Bekaroo et al., 2014; Belkhir and Elmeligi, 2017; GeSI, 2008, 2012, 2015, 2019; Malmodin et al., 2013; Malmodin and Lunden, 2018) as a source of abatement. The literature review identifies that currently a series of quantitative and qualitative barriers and gaps exist that prevent organisations from accessing, interpreting or generating meaningful end user computing related carbon footprint information. These include existing product carbon footprint information being inaccurate due to scope 2 calculation errors that exclude consideration of human-computer interaction influence on power draw (Energy Star, 2020) and differing methods used to present scope 2 emissions data (Apple, 2022; Dell, 2022; HP, 2022; Lenovo, 2022; Microsoft, 2022).

Consequently, as highlighted by activity 5, such complexity and doubt causes businesses to avoid gathering data that would otherwise enable the diffusion of end user computing sustainability strategies (Sutton-Parker, 2022a). Instead, issues of cost, time and a limited perception of environmental impact caused by IT are used to excuse current inertia and a continued reliance upon third-party eco-label certification (Sutton-Parker, 2020a). As such, organisations are unable to respond meaningfully to increasing levels of environmental legislation that require scope 2 and scope 3 computing emissions to be planned for during procurement and reported during use (DEFRA, 2020; EC, 2021a; b; EU, 2022, HM. Gov., 2018b; d; 2020b; 2021; LUPC, 2021; OEERE, 2022; USEPA, 2015; 2020a; b; US Gov., 1993; 2021).

Using the impact value chain model, the research question is answered by following stages of input, activities, output, outcome and impact (Dahlmann, 2021). Ultimately, the impact case studies demonstrate that participant organisations transition from a position of limited end user computing carbon footprint data availability, to one of improved sustainable device identification, computing focused environmental impact reporting and financial justification to act reflecting elements of Elkington's (1997) triple bottom line. In doing so, behavioural changes related to adopting sustainable IT and abating emissions are achieved. Specifically, 9.3 million $kgCO_2e$ (case studies A-D) of emissions is avoided by adopting sustainable device selection and displacement (2.1 million $kgCO_2e$), computer re-purposing (1.4 million kgCO2e) and remote working enabled by information technology (5.8 million kgCO2e). This indicates that if adopted at scale, the newly proposed approach to end user computing emissions quantification and presentation is capable of contributing to the UN bridging strategy (UN, 2019). In doing so the UNSDGs number 12, responsible production and consumption and number 13, climate action, are demonstrated as achievable (UN, 2015).

However, pragmatically, it is reasonable to concede that each research question tested to contribute to the end goal achieved mixed levels of success and partial failure.

As an example, activity one asks, 'Does the current end user computing use-phase electricity consumption quantification method accurately reflect device electricity use when subjected to human-interaction in the workplace?' The results reveal empirical evidence of unexpected operating system

efficiencies (Sutton-Parker, 2020b; 2022c) and prove conclusively that the current benchmark measurement practice (Energy Star, 2020) is no longer adequate in its existing form.

However, in an attempt to find an alternative approach, by asking, 'Can analytics software measure end user computing electricity consumption?' in activity 3 the research faces its own barrier. The experiment determines that analytics cannot achieve the objective by proving inaccurate by 46% (figure 6 and table 7) and is subject to similar failure experienced by previous attempts to achieve field measurement at scale Bekaroo et al, 2014; Kansel, 2010) despite increasing device mobility (Greenblatt et al., 2013; Gartner, 2022; Statistica, 2022).

The positive finding is however, that the OT metric measured by the analytics software proves accurate (figure 6). This enables use-profile contextual data to be generated to highlight how long computers are used in the workplace (figure 6). When combined with the electricity consumption results from activity one and two and the low power mode data from the existing benchmark practice (Energy Star, 2022) a new methodology for device electricity is created. Specifically, the cTEC solution devised in output one accepts that the original Energy Star (1992) concept of measuring use-phase energy consumption before sale is not as counterintuitive as originally perceived. In fact, rather than setting aside three decades of typical energy consumption research, testing, development and calculation discussed in the literature review; building upon it proves to be the most effective solution to quantifying meaningful scope 2 data rather than measuring it on a user-by-user basis.

Adopted by Acer and Google (Acer, a; b; c; d; e; Google, 2022a; b) evidence is formed that the responsible production element of SDG 12 (UN, 2015) has been influenced by this research. The rationale being that the companies are responsible for 7% of annual device production (Gartner, 2022, Statistica, 2022). As a result, the existing electricity benchmark measurement practice used globally (Energy Star, 2020) is arguably challenged when requiring real world use comparison (Sutton-Parker, 2020b) and proven to require enhancement as discussed in output 1.

The break through is however arguably challenged for importance from an environmental impact perspective by supply chain data discovered in the literature review (table 1) and generated by activity 2 (figure 4), activity 4 (table 8) and case studies (table 16, figure 21, table 21). The collective findings proving that scope 3 emissions are dominant at 73% (table 8) of the total device carbon footprint. In context, this arguably supports the focus of lifecycle assessment researchers on supply chain emissions rather than scope 2 emissions (Kim et al., 2001; Tekawa et al., 1997; Williams and Hatanaka, 2005).

This emphasis of scope 3 emissions importance is evident in activity 2 when the research question 'To what extent is GHG abatement delivered by alternative computer operating system displacement strategies?' is asked. The finding identifies that the carbon footprint caused by the manufacturing emissions of a new device will take over 90-years (figure 4) to overcome through innovative energy consumption gains. The results dispel current thinking that new more energy efficient devices will deliver reduced environmental impact than retaining existing devices for longer periods (Bakker et al., 2014; Boyd, 2012; Cooper and Gutowski, 2017; Deng et al., 2011; Prakash et al., 2016; Schiscke et al., 2003; Vadenbo et al., 2017; Wolf et al., 2010). With all of this in mind, perhaps in time, as energy grid supply declines in carbon intensity (figure 23), scope 3 importance will become more so until the issue of end user computing electricity consumption returns to being a planning and financial issue, as it was when this specific field of energy consumption research began (Piette et al., 1985; Schultz, 1984; Roach, 1985; Yu et al., 1986).

However, to examine feasible behavioural change that will drive end user computing emissions reduction during the procurement phase, activity 4 asks, 'Is sufficient carbon footprint information

available to make sustainability focused computer procurement strategies meaningful?' (Sutton-Parker, 2022d). Finding that mixed methodologies are used to generate product carbon footprint reports due to differing electricity to GHG conversion factors and the number of years of use, the exploratory research enables the creation of the dynamic carbon footprint application (output 2). Capable of harmonising scope 3 emissions data by including contextual influences such as location and duration of use, the application brings parity and simplicity to the process of assessing computers for sustainability criteria (Sutton-Parker, 2022d). Consequently, as proven by the pilot phase in output 2, compliance with new ICT sustainability legislation (HM Gov., 2020b; 2022a) is achievable within minutes; potentially removing the barrier of complexity identified by activity 5 (Sutton-Parker, 2020a) that is indicated to slow the adoption and diffusion of sustainable IT (table 9 and 10).

Combining data generated by the cTEC methodology and the dynamic carbon footprint application via the developed Px3 framework (output 3) allows for the data to translate to meaningful information. Equipped with this information, two large public (case study A and E) and two commercial organisations (case study B and C) are able to prove that such information does indeed change human behaviour in relation to end user computing procurement and use and most certainly abates significant associated GHG emissions (Google, 2022a; Sutton-Parker, 2022e; 2023). This proves that the responsible consumption aspect of SDG 12 (UN, 2015) and ultimately SDG 13, climate action is achieved. The impact is such that STAR, the body responsible for creating the greening government ICT policy (HM Gov., 2020b) regulating procurement and use practices for over 5.3m (HoC, 2021; ONS, 2022) public sector workers in the UK, has openly adopted the Px3 framework and contributing tools produced by this research (HM Gov., 2022b) moving forward.

As such, although the research addresses the gaps identified by the literature review, no body of work can be considered as final. Consequently, recommendations for improvements to the solutions designed and tested during the research are made as follows.

In relation to the cTEC methodology the mode weighting applied to the active state will benefit from further use-profile contextual data to adjust the proposed active 1 and 2 mode weighting (table 11 and 12). This is most likely to be enabled by analytics software capable, as is the case of Lakeside software, of highly accurate OT data capture. Consequently, it is recommended that further studies be conducted to compile patterns of use associated with specific business sectors. Doing so will refine the use-phase electricity consumption quantification and therefore concomitant GHG calculations. Currently, Microsoft has been approached to discuss if this is feasible via their Surface devices and specifically Windows 11 operating system. The reason being is that the new software has an analytics feedback user opt in option that allows for use time data to be gathered. While this is designed to facilitate a new update feature that waits for low activity before beginning, the feature may prove useful in this instance. Additionally, the DWP has been approached to offer OT data reflecting its 88,380 employees. Doing so would create a sizable data set against which to improve the mode weightings.

For the cTEC methodology to become effective on a global basis, it is recommended that the newly proposed active states 1 and 2 (see output 1) and measurement practice must be adopted by Energy Star to ensure international diffusion. As noted, Acer and Google (as noted) have both committed to using the methodology, although this is currently restricted to certain models of devices. Comparatively, ASUS, a company responsible for 6% of end user computing device manufacturing (Gartner; 2021; Statistica, 2021) has committed to testing its entire range of computer during 2023. Additionally, Microsoft has begun research testing using the cTEC methodology for both the Surface portfolio and original equipment manufacturers including Dell, HP and Lenovo. It is hoped that with manufacturers representing over 80% of device production and supply (Gartner; 2021; Statistica, 2021) now aware of the issue of excluding the

active state from electricity consumption measurement, Energy Star may begin to engage and progress the new methodology.

In relation to the dynamic carbon footprint tool, the scope 2 representation must evolve from relying upon the Energy Star eTEC values to truly represent valid use-phase emissions. While the tool harmonises retention periods and carbon conversion factors to deliver parity between reports, the influence of the active state remains unaccounted for. The solution lies in the adoption of the cTEC approach by Energy Star as previously described.

From an eco-certification perspective, the research is being appraised currently by TCO Certified (TCO, 2022), an organisation responsible for the European equivalent to EPEAT. The potential being that the cTEC data may be included within their certification criteria. Additionally, the question of differing scope 3 lifecycle assessment methodologies is only partially addressed by selecting the mean value from the PAIA tool. It is therefore recommended that additional research inspecting the percentage differences in supply chain emissions between the existing PAIA, Sphera and SimaPro methodologies for identical products be examined. Should a theme or trend appear then compensation can be applied to the tool to further increase comparative accuracy. This aspect of the recommendations has been accepted by TCO Certified and a project is will occur in 2023.

In relation to the Px3 framework, it is recommended that data centre use-phase emissions quantification be included into the tool. While end user computing is the focus of this research, cloud data centres examined in prior research (Sutton-Parker, 2015) and reviewed in précis together with Professor Procter and Susanna Kass of the United Nations (Sutton-Parker, 2020d) are substantiated as having improved power and carbon usage effectiveness when compared to on premise data centres. As such quantifying scope 2 emissions transitions to scope 3 cloud services emissions and the positive abatement delivered will be a clear incentive for sustainable IT adoption and subsequent behavioural changes. An opportunity to achieve this may lie with case study A as the council is anticipating a move to cloud computing and as part of the renewed focus upon scientific based target setting wishes to examine the option from an academic perspective. Currently, the recommendation has been proposed to Microsoft for their Azure cloud platform and for the new Windows 365 cloud PC application. A research project to achieve this has been accepted by Microsoft and will progress in 2023. Additionally, Amazon Web Services has been engaged and early consumption calculations and measurements are being undertaken.

For the Px3 framework to become truly integrated with cTEC and the dynamic carbon footprint application the current version is recommended to progress from an .xls application to an online service. Currently, this is being developed with the first version of an application capable of being populated by an end user organisation to generate computer scope 2 and 3 emissions plus tangible equivalent data planned to be available in April, 2023.

While expansive in inclusion of a wide variety of devices, the research is limited by scale when compared to the volume of end user computing devices available today and the sheer number of users across the globe. As the introduction notes, over 460 million new desktops and mobile computers are produced annually with an estimated 4.6bn users. Activity 4 reflects this in the fact that asset profiling just six organisations identified over 70,000 devices, documenting 707 unique models. This indicates that for every ten users there is a potential difference device being used. Consequently, the results of energy consumption emissions measurement and GHG calculation is limited by those inspected during the research and the activities of those users participating in the experiments and case studies. As such, as noted in the recommendation section, inclusion of the cTEC methodology in the Energy star benchmark process will relieve such a limitation and begin to generate active state values at scale.

It is recognised that the control user in activity 3 was conducted on one notebook and a wider experiment with increased numbers of devices, brands and operating systems is suggested to further improve the comparative results. Where mechanical hard drives exist in legacy equipment the software may prove more accurate.

The case studies are currently limited to five organisations and while credibly proving the research question it cannot be considered that all organisations will experience similar gains. As such further studies must be undertaken in order to triangulate patterns of abatement in order to project a feasible and meaningful contribution to the UNEP strategy and the goal to reduce the current 1% contribution of end user computing the global GHG emissions. The opportunity to do so may lie with the global technology companies participating in this study and further associated organisations being influenced by their actions.

References

Accace, (2022). 'Labour Law and Employment in Romania – 2023 Guide'.

Acer. (2022a), 'Sustainability'. Available at: New Taipei City, Taiwan: Acer. Available at: <https://www.acer-group.com/sustainability/en>

Acer. (2022b), 'Acer Green Rewards' New Taipei City, Taiwan: Acer

Acer, (2022c), 'Sustainability as a key factor in making IT decisions – where are organisations today?' New Taipei City, Taiwan: Acer

Acer, (2022d), 'Sustainable IT in education – issues, trends & attitudes among decision makers'. New Taipei City, Taiwan: Acer

Acer, (2022e), 'Product Carbon Footprint: Recognizing Our Impact and Taking Action'. New Taipei City, Taiwan: Acer

Acquaviva, Y. and Hartman, G. C. (1993), 'Survey of Energy and Power Usage in Copiers, Duplicators, and Electronic Reprographic Devices Xerox Corporation, Webster, NY

Andrae, A. S. G, and Andersen, O. (2010), 'Life cycle assessments of consumer electronics – are they consistent?' International Journal of Life Cycle Assessment 15 (8), 827-836

Andrae, A. S. G., and Edler, A.T., (2015). 'On global electricity usage of communication technology: trends to 2030.' Challenges 6, 117e157.

Andre, H., Ljunggren Soderman, M., Nordelof, A. (2018), 'Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse'. Gothenburg, Sweden: Chalmers University of Technology.

Apple, (2022). 'Your product's environmental report card.' Cupertino, USA.

Arushanvan, Y., Ekener-Petersen, E., Finnveden, G. (2014), 'Lessons learned – review of LCAs for ICT products and services'. Amsterdam: Computers in Industry Journal.

Asus. (2022), 'Product Environmental Information: Eco Products'. Taipei City, Taiwan

Atlantic Consulting and IPU. (1998), 'LCA study of the product group personal computers in the EU Eco–label Scheme LCA study (Version 1.2). EU Eco–labels for personal computers'. Atlantic Consulting and IPU

Arthur D Little lnc. (1993), 'Characterization of Commercial Building Appliances'. Prepared for the Building Equipment Division, Office of Building Technologies, US Department of Energy, Arthur D Little lnc, Cambridge, MA

Association of Issuing Bodies (AIB). (2022), 'European Residual Mix'. Brussels, Belgium: AIB

Australian Government Department for Industry Science and Resources (AGDISR). (2021), 'National Greenhouse Accounts Factors: 2021'. Canberra, Australia: AGDISR

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

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

Belady and Malone. (2006) "Metrics to Characterize Data Center & IT Equipment Energy Use," Proceedings of 2006 Digital Power Forum, Richardson, TX.

Belkhir, L., and Elmeligi, A. (2017) 'Assessing ICT global emissions footprint: Trends to 2040 & Recommendations'. Oxford: Science Direct

Bibr, S. E. (2018), 'Backcasting in futures studies: a synthesized scholarly and planning approach to strategic smart sustainable city development'. 6.13. European Journal of Futures Research

Blue Angel. (2022), 'The German Eco Label'. Germany

Bolin B, et al. (1986), 'The Greenhouse Effect, Climatic Change, and Ecosystems.' SCOPE Report, Scientific Committee on Problems of the Environment.

Boyd, S.B. (2012), 'Semiconductor LCA: the road ahead'. Springer: Life-cycle assessment of semiconductors.

Brack, S., Walsh, G., and Shaw, D. (2018) 'Sustainable consumption and third-party certification labels: Consumers' perceptions and reactions.' European Management journal

Cabinet Office. (2012), 'Digital Government Strategy'. London, England: Crown Copyright

Cabinet Office, (2013), 'Government's Estate Strategy'. London, England: Crown Copyright

California Appliance Efficiency Regulations (CAER). (2021), 'Title 20 Appliance Efficiency Regulations / Section 1605. Energy Performance, Energy Design, Water Performance, and Water Design Standards: Section 1605.3. State Standards for Non-Federally-Regulated Appliances.'

California Energy Commission. (2016), 'Revised Analysis of Computers, Computer Monitors, and Signage Displays'. 14-AAER-2. California, USA: CEC

California Office of Environmental Health Hazard Assessment (COEHHA). (1987), 'California (USA) Proposition 65 (Device does not contain chemicals that would trigger notification.' California, USA: COEHHA

Carbon Footprint. (2020), '2020 Carbon Footprint Country Specific Grid Greenhouse Gas Emissions Factors.' Hampshire: Carbon Footprint.

Carroll, A., (1979) A Three Dimensional Conceptual Model of Corporate Performance. Academy of Management Review.

Carson, J. R. (1962). Silent Spring. Massachusetts, USA: Houghton Mifflin Harcourt.

Cartledge, C. (2008), 'Energy Impacts of ICT at the University of Sheffield, Bradford: SusteIT, July, 2008.' Bristol: SusteIT

Central Digital and Data Office (CDDO). (2021), 'Technology Code of Practice'. London: HM Government Crown Copyright.

Centre for Energy and Climate Solutions (CECS). (2021), 'Renewable Energy'. Virginia, USA: CECS

China Environmental United Certification Centre. (2022), 'The China Certification of Environmental Labelling (CCEL) Program.'

China RoHS, Measures for the Administration of the Control of Pollution by Electronic Information Products. (2006), 'Management Methods on the Prevention and Control of Pollution caused by Electronic Information Products. China: RoHS

Choi, B., H. Shin, S. Lee, and T. Hur. (2006), 'Life cycle assessment of a personal computer and its effective recycling rate'. International Journal of Life Cycle Assessment 11(2): 122–128.

Cisco. (2020), 'Cisco 2020 Environment Technical Review'

Citrix Inc. (2021a), 'The Sustainability Era'. Fort Lauderdale, Florida: Citrix Inc

Citrix Inc. (2021b). 'Workers prepared to take pay cut for fully remote roles'. Fort Lauderdale: Citrix

Citrix Inc. (2022). 'Citrix Workspace'. Fort Lauderdale: Citrix

Clark, C., Rosenzweig, W., Long, D., and Olsen, S. (2004), 'Double Bottom Line Project Report: Assessing Social Impact In Double Bottom Line Ventures, Rockefeller Foundation.

Climate Change Committee. (2020), 'Reducing UK emissions: 2020 Progress Report to Parliament'. London: CCC

Climate Emergency. (2020a), 'List of councils who have declared a climate emergency.'

Climate Emergency. (2020b), 'List of Universities who have declared a climate emergency.'

Climate Transparency. (2020), 'The Climate Transparency Report 2020'.

Computing. (2020), 'Deskflix Series 5, Public Sector: Culture, Success, Efficiency'. London, England: Incisive Media

Cone. (2019). 'The Cone Communications Millennial Employee Study.'

Cooper, D. R., and Gutowski, T.G. (2017), 'The environmental impacts of reuse: a review'. Journal of Industrial Ecology.

Dahlmann, F. (2021). 'Strategic thinking and planning – skills and tools. IB2C60 – AISP: Global Environment of Business'. Warwick, UK: Warwick Business School.

Dandridge, C. (1994). 'Office Technology and Energy (published Masters thesis)'. Cambridge, Mass.: Massachusetts Institute of Technology.

Datareportal. (2021), 'Digital Around the World'.

Datareportal, (2022), 'Digital 2022: Time spent using connected tech continues to rise'.

Dedrick, J. (2010), 'Green IS: Concepts and Issues for Information Systems Research'. School of Information Studies, Syracuse University

DeLaHunt, M. J. (1990), 'Trends in electricity consumption due to computers in miscellaneous equipment (CME) in office buildings'. BR Associates, Inco

Delforge, P. and J. Whitney. (2014), 'Data Center Efficiency Assessment.' National Resources Defense Council. New York: NRDC

Dell. (2022), 'Select Product Carbon Footprint Assessments'. Roundrock, Texas.

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.

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.

Department for Business Energy and Industrial Strategy (BEIS). (2018a). HM Government, 'Business Population Estimates for the UK and Regions 2018'

Department for Business Energy and Industrial Strategy and Department for Environment Food and Rural Affairs. (2018b), 'UK Government GHG Conversion Factors for Company Reporting'. London: Crown Copyright.

Department for Business Energy and Industrial Strategy (BEIS). (2019a), 'Provisional UK greenhouse gas emissions national statistics 2019'. London: Crown Copyright

Department for Business Energy and Industrial Strategy and Department for Environment Food and Rural Affairs. (2019b), 'UK Government GHG Conversion Factors for Company Reporting'. London: Crown Copyright.

Department for Business Energy and Industrial Strategy (BEIS). (2020a), 'Energy white paper: Powering our net zero future'. London: Crown copyright.

Department for Business Energy and Industrial Strategy (BEIS) and Department for Environment Food and Rural Affairs. (2020b), 'UK Government GHG Conversion Factors for Company Reporting'. London: Crown Copyright

Department for Business Energy and Industrial Strategy (BEIS) and Department for Environment Food and Rural Affairs. (2020c), 'UK Government GHG Conversion Factors for Company Reporting'. London: Crown Copyright

Department for Business Energy and Industrial Strategy. (2021a) 'BEIS and National Statistics 2021 Energy Statistics.' London, England:

Department for Business Energy and Industrial Strategy (BEIS). (2021b), 'Energy consumption in the UK 2021 Update.' Table 5.05

Department for Business Energy and Industrial Strategy (BEIS) and Department for Environment Food and Rural Affairs. (2021c), 'UK Government GHG Conversion Factors for Company Reporting'. London: Crown Copyright

Department for Business Energy and Industrial Strategy (BEIS). (2021d), 'Gas and electricity prices in the non-domestic sector'. London: Crown Copyright

Department for Business Energy and Industrial Strategy (BEIS). (2021e), 'Net Zero Strategy: Build Back Greener'. London: Crown Copyright

Department for Business Energy and Industrial Strategy (BEIS) and Department for Environment Food and Rural Affairs. (2022), 'UK Government GHG Conversion Factors for Company Reporting'. London: Crown Copyright

Department for Education. (2021), 'One million laptops and tablets for disadvantaged children and young people'. London: Crown copyright.

Department for Environment, Food & Rural Affairs, Cabinet Office. (2011 & revised 2017), 'Sustainable procurement: The Government Buying Standards (GBS).' London: The Stationery Office Limited.

Department for Environment, Food & Rural Affairs, Cabinet Office. (2016), 'Greening Government Commitments, Overview of reporting requirements 2016-2020.' London: The Stationery Office Limited.

Department for Environment, Food and Rural Affairs (DEFRA). (2020), 'Greening government: ICT and digital services strategy 2020-2025'. London: Crown copyright.

Department for Transport (DFT). (2019a), 'Transport Statistics Great Britain 2019'. London: Crown copyright.

Department for Transport (DFT). (2019b), 'Vehicle Licensing Statistics'. London: Crown copyright.

Department for Transport (DFT). (2021), 'Transport Statistics Great Britain 2021'. London: Crown copyright.

Department of Toxic Substances Control (DTSC). (2004), 'Health & Safety Code, division 20, chapter 6.5, article 10.4 beginning with §25214.11'. California, USA: DTSC

Dolin, J., R., and Raynolds, N., (1998) 'The ENERGY STAR Purchasing Initiative'.

Dialpad, (2022), 'The state of video conferencing 2022'.

Duan H, Eugster M, Hischier R et al. (2009) Life cycle assessment study of a Chinese desktop personal computer. Sci Total Environ 407:1755– 1764

ECMA International. (1996), 'ECMA-370 The Eco Declaration'

Ecoinvent. (2022), 'Ecoinvent Database, the world's most consistent and transparent life cycle inventory database'. Zurich, Switzerland: Ecoinvent.

EcoLeaf. (2022), 'EcoLeaf Environmental Label'. Japan: SuMPO.

Electronic Design, (2015). 'Functional Testing and Validation for DDR4 and LPDDR4'. Nashville, Tennessee: Electronic Design.

Elkington, J., (1997) 'Cannibals with Forks: The Triple Bottom Line of 21st Century Business'. New York Capstone Trade

EPEAT. (2022), 'Electronic Product Environmental Assessment Tool (EPEAT)'. Oregon, USA: Green Electronics Council.

Energy Star, (2005), 'The External Power Supply International Efficiency Marking Protocol'. Washington, USA: USEPA

Energy Star. (2007). 'ENERGY STAR® 1 Program Requirements 2 for Computers'. Washington, USA: USEPA

Energy Star. (2012), '20 Years of Helping America Save Energy Save Money and Protect the Environment'. A Star Is Born: 2. Washington, USA: USEPA

Energy Star. (2020), 'Energy Star Program Requirements for Computers version 8.0'. Washington, USA: USEPA

Energy Star (2022) 'Product finder, product, certified computers, results.' Washington, USA: USEPA

Enroth, M., (2009). Environmental impact of printed and electronic teaching aids, a screening study focusing on fossil carbon dioxide emission. In Advances in printing science and technology, Proceedings of the 36th International Research Conference of IARIGAL, Vol. 36. Darmstadt: IARIGAI.

ESOMAR. (2020). 'ICC/ESOMAR International Code on Market, Opinion and Social Research and Data.'

Espo CRM, (2023). 'How many work days in a year? (2023) Updated'.

European Commission. (1994), 'Eurostat, European system for the collection of economic information on the environment - 1994 version'. Brussels: European Union

European Commission. (2008), 'Regulation for Standby and Off Mode Power Consumption for Electronic Household and Office Equipment 1275/2008'. Brussels: European Union

European Commission. (2021a), 'EU green public procurement criteria for computers, monitors, tablets and smartphones'. Brussels: European Union

European Commission. (2021b), 'JRC Science for Policy Report Revision of the EU Green Public Procurement (GPP) Criteria for Computers and Monitors (and extension to Smartphones)'. Brussels: European Union

European Commissions, (2022). 'REPowerEU: affordable, secure and sustainable energy for Europe'. Brussels: European Union

European Environment Agency (EEA). (2021), 'Greenhouse gas emission intensity of electricity generation in Europe.' Copenhagen, Denmark: EEA.

European Space Agency (ESA). (2020), 'Coronavirus lockdown leading to drop in pollution across Europe'. Paris, France: ESA

European Parliament. (2020), 'EU e-waste facts and figures'. Brussels, Belgium

European Union. (1994). 'European Union Packaging and Packaging Waste Directive 1994/62/EC'. Brussels: European Union

European Union. (2002a). 'Restriction of Hazardous Substances Directive (RoHS) Directive 2002/95/EC as amended by the RoHS Recast Directive 2011/65/EU'. Brussels: European Union

European Union (2002b). 'EU Waste Electronic and Electrical Equipment (WEEE) Directive 2002/96/EC'. Brussels: European Union

European Union. (2003) 'Directive 2002/96/EC of the European Parliament and of the Council.' Brussels: European Union

European Union. (2005a) 'A framework for the setting of eco design requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council'. Brussels: European Union

European Union. (2005b). 'European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste amended to CEN packaging standards EN 13427:2005'. Brussels: European Union

European Union. (2006a), 'Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) Regulation 2006/1907/EC'. Brussels: European Union

European Union. (2006b), 'Battery Directive 2006/66/EC as amended by Directive 2013/56/EU'. Brussels: European Union

European Union. (2009), Directive 2009/125/EC of the European Parliament and the council establishing a framework for the setting of eco-design requirements for energy-related products'. Brussels: European Union

European Union. (2011), 'Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast) Text with EEA relevance'. Brussels: European Union

European Union (2012). 'EU Waste Electronic and Electrical Equipment (WEEE) Directive Recast 2012/19/EU'. Brussels: European Union

European Union. (2015), 'Closing the loop - An EU action plan for the Circular Economy'. Brussels: European Union

European Union (2016), 'General data protection regulation (GDPR): Regulation (EU) 2016/679 on the protection of natural persons with regard to the processing of personal data and the free movement of such data'. Brussels: European Union

European Union, (2018). 'Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)'. Brussels: European Union

European Union. (2022a), 'The EU Ecolabel Product Catalogue'. Brussels: European Union. Brussels: European Union

European Union (2002b), 'Corporate sustainability reporting directive (CSRD)'. Brussels: European Union. Brussels: European Union

Eurostat, (2022). 'Employment - annual statistics'. Brussels: European Union

Exploding topics, (2023), 'Alarming Average Screen Time Statistics (2023)'.

Finnveden, G., Arushanyan, Y., Brandao, M, (2016). 'Exergy as a measure of resource use in life cycle assessment and other sustainability assessment tools'. Basel, Switzerland: Resources MDPI

Flohn, H. (1970), 'Climatology—descriptive or physical science?' WMO Bulletin, 19, 4, 223-229

Freeman, R.E. (1984), 'Strategic Management: A stakeholder Approach.' Boston, MA: Pitman.

Froning, A J (1994) 'Lab report: 70 color monitors' Byte January, 202

Gard, D. L. and G. A. Keoleian. (2003). 'Digital versus print. Energy performance in the selection and use of scholarly journals'. Journal of Industrial Ecology 6

Gartner, (2006). 'Gartner: PC shipments will top 200 million in 2005'. Arlington, VA: Gartner Inc.

Gartner, (2019). 'Gartner Top 3 Priorities for HR Leaders in 2019.' Arlington, VA: Gartner Inc.

Gartner. (2020a), 'Gartner CFO Survey Reveals 74% Intend to Shift Some Employees to Remote Work Permanently'. Arlington: Gartner Inc.

Gartner (2020b), 'Gartner HR Survey Reveals 41% of Employees Likely to Work Remotely at Least Some of the Time Post Coronavirus Pandemic'. Arlington: Gartner Inc.

Gartner, (2021). 'Gartner Says Worldwide PC Shipments Grew 10.7% in Fourth Quarter of 2020 and 4.8% for the Year.' Arlington, VA: Gartner Inc.

Glassdoor. (2019), 'British Workers Average Lunch Breaks.'

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

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

Global e-Sustainability Initiative. (2015), '#SMARTer2030 ICT Solutions for 21st Century Challenges.' Executive Summary: ICT Solutions for 21st Century Challenges: 8. Brussels: GeSI

Global e-Sustainability Initiative. (2019), 'Digital with Purpose: Delivering a SMARTer2030'. Brussels: GeSI

Google. (2021), 'Sustainability starts locally in Kingston and Sutton with Chrome OS, Acer, Px3, and Citrix'. Mountain View, California: Google

Google. (2022a), 'Modernising and extending device lifecycles to support climate action'. Mountain View, California: Google

Google. (2022b), 'Build a sustainable future with Chrome OS'. Mountain View, California: Google Available at: < https://chromeenterprise.google/os/sustainability/>

Granat, L. (1972). 'Deposition of sulfate and acid with precipitation over northern Europe.' Report AC; 20. Stockholm, Stockholm University.

Greenblatt, J. B., Stacy Pratt, Henry Willem, Erin Claybaugh, Louis-Benoit Desroches, Bereket Beraki, Mythri Nagaraju, Sarah K. Price and Scott J. Young. (2013), Field data collection of miscellaneous electrical loads in Northern California: Initial results.' Ernest Orlando Lawrence Berkeley National Laboratory research paper: 4-5

Guardian, (2020), 'Time I.T. Changed: The Digital Transformation Edition'. London, England: My Green Pod, The Guardian.

Guardian, (2021), 'Sustainable IT, COP 26 Special Edition'. London, England: My Green Pod, The Guardian.

Guinee, I. B. Heijungs, Huppes, G. Zamagni, A. Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T. (2011), 'Life cycle assessment: past, present, and future. Environmental Science and Technology 45.

Haque, N. (2020), 'The Life Cycle Assessment of Various Energy Technologies'. Australia: Science Direct

Harris, J., Roturier, J., Norford, L. K. and Rabl, A. (1988) 'Technology Assessment: Electronic Office Equipment'. Lawrence Berkley National Laboratory, University of California

Hart, J. (2016), 'Carbon Emission Implications of ICT Reuse at the University of Edinburgh'. University of Edinburgh Department for Social Responsibility and Sustainability

Hischier, R., M. Classen, M. Lehmann, andW. Scharnhorst. (2007), Life cycle inventories of electric and electronic equipment: Production, use and disposal. Ecoinvent report 18. Duebendorf, Switzerland: Swiss Centre for Life Cycle Inventories.

HM Government. (2006), 'Climate Change and sustainable energy Act'. London: The Stationery Office Limited.

HM Government. (2011a), 'Greening Government: ICT Strategy'. London, England: Crown Copyright

HM Government, (2011b). 'Green government ICT case studies'. London, England: Crown Copyright

HM Government. (2012a), 'HM Government green ICT roadmap'. London, England: Crown Copyright

HM Government. (2012b), 'Green ICT workbook'. London, England: Crown Copyright

HM Government. (2012c), 'The Greening Government Commitments, Annual Report on Government Departments Progress against 2015 Targets in 2011-12'. London, England: Crown Copyright

HM Government. (2013a) 'The Companies Act 2006 (Strategic Report and Directors' Report) Regulations).' Section 416 (c)

HM Government. (2013b), 'Green ICT maturity model'. London, England: Crown Copyright

HM Government. (2013c), 'The Greening Government Commitments, Annual Report 2012-13'. London, England: Crown Copyright

HM Government. (2013d), 'Greening Government: ICT Annual Report.' London, England: Crown Copyright

HM Government. (2014), 'The Greening Government Commitments, Annual Report 2013-14'. London, England: Crown Copyright

HM Government. (2015a), 'The Greening Government Commitments, Annual Report 2014-15'. London, England: Crown Copyright

HM Government. (2015b), 'Greening government: ICT energy and carbon footprinting tool'. London, England: Crown Copyright

HM Government. (2016), 'The Greening Government Commitments, Annual Report 2015-16'. London, England: Crown Copyright

HM Government. (2017), 'The Greening Government Commitments, Annual Report 2016-17'. London, England: Crown Copyright

HM Government. (2018a). 'Regulations: waste electrical and electronic equipment (WEEE)'. London, UK: Crown Copyright

HM Government. (2018b), 'Greening government: sustainable technology strategy 2020.' London: The Stationery Office Limited

HM Government, (2018c), 'A Green Future: Our 25 Year Plan to Improve the Environment'. London, England: Crown Copyright

HM Government, (2018d), 'Greening government: sustainable technology strategy 2020'. London, England: Crown Copyright

HM Government. (2019a), 'Rests and Breaks at Work.' London: The Stationery Office Limited

HM Government. (2019b), 'Clean Air Strategy.' London: The Stationery Office Limited.

HM Government. (2020a), 'Holiday Entitlement Rights.' London: The Stationery Office Limited

HM Government. (2020b), 'Greening government: ICT and digital services strategy 2020-2025'. London, England: Crown Copyright

HM Government. (2021a), 'Procurement Policy Note 06/21: Taking account of Carbon Reduction Plans in the procurement of major government contracts'. London, England: Crown Copyright

HM Government. (2021b), 'Net Zero Review Final Report'. London: The Stationery Office Limited

HM Government. (2021c), 'Climate Change Levy)'. London: The Stationery Office Limited

HM Government. (2022a), 'Transitioning to zero emission cars and vans: 2035 delivery plan'. London, England: Crown Copyright

HM Government. (2022b), 'Greening government ICT: annual report 2021 to 2022'. London, England: Crown Copyright

HM Government. (2022c), 'Government takes historic step towards net-zero with end of sale of new petrol and diesel cars by 2030'. London, England: Crown Copyright

HM Government. (2022d), 'Departments, agencies and public bodies'. London, England: Crown Copyright

Hopkinson, L and James, P. (2009), 'Energy and Carbon Impacts of ICT User Guide for the SusteIT Footprinting Tool'. Bristol: SUSTEIT

Hosni, M.H., Jones, B.W., and Xu, H. (1999), 'Measurement of Heat Gain and radiant/Convective Split from Equipment in Buildings, Final Report'. ASHRAE Research Project 1055-RP, March.

Houghton, J. T., G.J. Jenkins, and J.J. Ephramus. (1990) 'Climate Change, The IPCC Scientific Assessment.' Intergovernmental Panel on Climate Change, Cambridge: Cambridge University Press.

House of Commons. (2018), 'Business Statistics. London: House of Commons Library'.

House of Commons. (2022), 'Business Statistics. London: House of Commons Library'.

HP Inc. (2022), 'Product Carbon Footprint Reports: Notebooks'. Palo Alto: HP Inc.

HR Magazine, (2022). 'Hours of the workday are being wasted on video calls'.

Illinois Learning Technology Purchase Program. (2020), 'Share These '7 Tips to Extend Your Chromebook's Battery Life' With Your Students'

Intellect. (2016), 'Evaluating the carbon impact of ICT or The answer to life, the universe and everything. Understanding the limitations of LCA-based carbon footprinting methodologies. London, England: Intellect.

Intergovernmental Panel on Climate Change (IPCC). (1990), 'Climate Change The IPCC Scientific Assessment'. Cambridge, UK: Cambridge Press

Intergovernmental Panel on Climate Change (IPCC). (1992a) McG.Tegart, W.J. and Sheldon, G.W. 'Climate Change, The Supplementary Report to The IPCC Impacts Assessment'. Canberra: Australian Government Publishing Service

Intergovernmental Panel on Climate Change (IPCC). (1992b) Houghton, J.T., and Callander, B.A., Varney, S.K. 'Climate Change, The Supplementary Report to The IPCC Scientific Assessment'. Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (1992c) Obasi, G.O.P., and Tolba, M.K. 'Climate Change, The IPCC 1990 and 1992 Assessments'. Canada: Intergovernmental Panel on Climate Change.

Intergovernmental Panel on Climate Change (IPCC). (2018a), 'Global warming of 1.5oC'. Switzerland: IPCC

Intergovernmental Panel on Climate Change (IPCC). (2018b), 'Changes in Atmospheric Constituents and in Radiative Forcing'. Switzerland: IPCC

Intergovernmental Panel on Climate Change (IPCC). (2018c), 'Climate Change and Land'. Switzerland: IPCC

Intergovernmental Panel on Climate Change (IPCC). (2023), 'Synthesis Report of the IPCC sixth assessment report (AR6)'. Switzerland: IPCC

International Association of Microsoft Channel Partners (IAMCP). (2020). 'IAMCP UK Webinar, Justin Sutton-Parker, Why Sustainable IT?' Available at: < https://www.iamcp.uk/events/ >

International Data Corporation. (2006), 'Worldwide Quarterly Personal PC Tracker'. Massachusetts: IDC

International Data Corporation. (2020), 'U.S. Mobile Worker Population Forecast, 2020–2024'. Massachusetts: IDC

International Electrotechnical Commission (IEC). (2011), 'Standard IEC 62301:2011 household electrical appliances measurement of standby power.' Geneva, Switzerland: IEC

International Electrotechnical Commission (IEC). (2012), 'Standard IEC 62301:2012 desktop and notebook computers measurement of energy consumption.' Geneva, Switzerland: IEC

International Energy Agency. (2019), 'Global Energy & CO2 Status Report 2019'. Paris, France.

International Energy Agency. (2021a), 'Data Centres and Data Transmission Networks'. Paris, France.

International Energy Agency. (2021b), 'Aviation'. Paris, France.

International Energy Agency. (2021c), 'Renewables are stronger than ever as they power through the pandemic'. Paris, France: IEA

International Energy Agency. (2022), 'World energy outlook''. Paris, France: IEA

International Standards Organisation. (2015a), 'ISO 14001:2015 Environmental management systems. Requirements with guidance for use'. Geneva: International Organization for Standardization

International Standards Organisation. (2015b), 'ISO 9001:2015 Quality management systems — Requirements'. Geneva: International Organization for Standardization

International Standards Organisation. (2016), 'ISO 14040:2006 Environmental management, Life cycle assessment Principles and framework'. Geneva: International Organization for Standardization

International Standards Organisation. (2018a), 'ISO 14067:2018 Carbon footprint of products'. Geneva: International Organization for Standardization

International Standards Organisation. (2018b), 'ISO 14024:2018 Environmental labels and declarations'. Geneva: International Organization for Standardization

IVF Industrial Research and Development Corporation. (2007), 'European Commission DG TREN Preparatory studies for Eco-design Requirements of EuPs. IVF Report 07004. Laptop used in office.' Table 91, 93 & 97

JISC. (2019), 'SusteIT ICT Energy and Carbon Footprinting Tool'

Johnson, B.J., & Zoi, C.R. (1992). EPA ENERGY STAR Computers: The Next Generation of Office Equipment. Published in the 1992 Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings.

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

Kansel, A. (2010): Joulemeter: Computational Energy Measurement and Optimization. Redmond, WA, USA: Microsoft.

Karpagam, S. and Yung, W. K. C. (2017), 'Life cycle assessment study of an integrated desktop device: comparison of two information and communication technologies: Desktop computers versus all-in-ones'. Journal of Cleaner Production

Kellogg, W.W. (1977). Technical Note 156 Effects of Human Activities on Global Climate.' Geneva, Switzerland. Word Meteorological Organisation

Kemna, R.,M. van Elburg, W. Li, and R. van Holsteijn. (2005). Methodology study of energy-using products. Delft, Netherlands and Brussels, Belgium: VHK and European Commission.

Kim S, Hwang T, Overcash M (2001) Life cycle assessment study of a colour computer monitor. Int J LCA 6:35–43.

Kolodinsky, J., Stewart, C., Bullard, A. (2006), Measuring economic and social impacts of membership in a community development financial institution, Journal of Family and Economic Issues, 27(1): 27-47

Komor, P. (1997), 'Space Cooling Demands from Office Plug Loads', ASHRAE Journal, December, pp. 41-44.

Koomey, J., Oey, T. and Bergman, E. (1992) 'The Economics of Cycling Personal Computers'. Lawrence Berkeley Laboratory, Apple Computer Inc., Sun Microsystems Inc.

Koomey, J., Cramer, Piette, M.A., and Eto, J. (1995) Efficiency Improvements in U.S. Office Equipment: Expected Policy Impacts and Uncertainties. LBNL, 1995. LBNL-37383

Koomey, Jonathan G, Mary Ann Piette, Mike Cramer, and Joseph H Eto (1996). "Efficiency Improvements In U.S. Office Equipment: Pollution Prevention at a Profit." ACEEE Summer Study on Energy Efficiency in Buildings. Pacific Grove, CA: ACEEE, 1996

Koomey, J.G., Laitner, J. A., Worrell, E., and Gumerman, E. (2000) 'Re-estimating the Annual Energy Outlook 2000 Forecast Using Updated Assumptions about the Information Economy'. EPA Office of Atmospheric Programs and Lawrence Berkeley National Laboratory

Koomey, J., Mitchell-Jackson, J., Nordman, B., Blazekc, M. (2001), 'Data Center Power Requirements: Measurements From Silicon Valley'.

Koomey, J., (2007). Estimating Total Power Consumption by Servers in the U.S. and the World.

Koomey, J., (2011), 'Growth in Data Center Electricity Use 2005 to 2010.' Berkeley: Analytics Press

Kumar, B., Manrai, A., and Manrai, L. (2017) 'Purchasing behaviour for environmentally sustainable products: A conceptual framework and empirical study'. Journal of Retail and Consumer Services.

Kunz, M. (1997), 'Energy Consumption of Electronic Network Components', Report of the 'Electricity' Research Programme, Swiss Federal Office of Energy, Berne, Switzerland.

Laitner, J. A. (2000), "The Information and Communication Technology Revolution: Can It Be Good for Both the Economy and the Climate?", a working paper for the EPA Office of Atmospheric Programs, Washington, DC, January 2000.

Lapujade P., and Parker, D. (1994), 'Measured Energy Savings of an Energy Efficient Office Computer System'. Florida Solar Energy Center.

Lavin, G., (2022), 'Email 26th April 2022: Sustainability Research Influence'.

Leaderonomics, (2022). 'How much time do you spend in virtual meetings?'.

Ledbetter, M, and L. Smith. (1993). Guide to Energy-Efficient Office Equipment. Washington, DC: American Council for an Energy-Efficient Economy, prepared for the Office Technology Consortium.

Lenovo. (2022), 'ECO Declarations and Product Carbon Footprint Information Sheets'. Quarry Bang: Hong Kong.

Local Government Association. (2020), 'A-Z of councils online.' Westminster, London

Lovins, A., and Heede, H., (1990). Electricity Saving Office Equipment. Competitek/Rocky Mountain Institute.

Lu L, Wernick IK, Hsiao TY et al. (2006), 'Balancing the life cycle impacts of notebook computers: Taiwan's experience. Resources, Conservation and Recycling.' 48:13–25

LUPC. (2021), 'National Desktop and Notebook Agreement (NDNA)'. London, England: London Universities Purchasing Consortium

Maas, K., (2009), 'Corporate Social Performance from Output Measurement to Impact Measurement'. Netherlands Open University.

MACEBUR. (1998), "Energy Efficient Office Technologies: the 1 Watt / 1 VoltAmpere Challenge", Final Report of the MACEBUR Work Group, April.

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.

Malmodin, J., Bergmark, P., Lunden, D., (2013). The future carbon footprint of the ICT and E&M sectors. In: On Information and Communication Technologies.

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.

Massachusetts Institute of Technology (MIT). (2016), 'Intended Uses and Limitations of the Product Attribute to Impact Algorithm (PAIA) Model. Massachusetts: MSL

McManus, T. (2002), 'Moore's Law and PC Power'. Tulane Engineering Forum

Melville, N. (2010), "Information Systems Innovation for Environmental Sustainability," MIS Quarterly

Michaels, H., DaSilva, J. and Gould, W. (1990), 'Electronic Equipment Load Growth'. XENERGY Inc and Consolidated Edison of New York

Microsoft. (2022), 'Eco Profiles.' Redmond: USA

Mills, (1999) 'The Internet Begins With Coal'.

Moberg, A., M. Johansson, G. Finnveden, and A. Jonsson. 2010. Printed and tablet e-paper newspaper from an environmental perspective: A screening life cycle assessment. Environmental Impact Assessment Review 30

Moorefield, L., Frazer B., and Bendt, P. (2008) 'Office Plug Load Field Monitoring Report'. Durango: ECOS

National Renewable Energy Laboratory. (2021), 'U.S. Life Cycle Inventory Database'. Colorado, USA.

Newsham, G. R., and Tiller, D.K. (1993) 'Desktop Computers and Energy Consumption: A Study of Current Practice and Potential Energy Savings. CEA 9101 U 829, Canadian Electrical Association, Montreal. Quebec Canada.

Nguyen, H.D., Alereza, and Hamzawi, (1988) 'Energy Consumption by Computers and Miscellaneous Equipment in Commercial Buildings,' Proceedings of the 1988 Summer Study on energy Efficiency in buildings, Volume 3, August 1988

Nokia (2022). 'Phones, environmental profiles'. Espoo, Finland: Nokia Corporation.

Nordman, B., Piette, M. A. and Kinney, K. (1996). 'Measured Energy Savings and Performance of Power-Managed Personal Computers and Monitors. LBNL Report Number LBL-38057. Berkeley, California: Lawrence Berkeley National Laboratory.

Nordman, B., Piette, M. A., Kinney, K. and Webber. (1997) 'User Guide to Power Management for PCs and Monitors'. California: Lawrence Berkeley National Laboratory.

Nordman, Bruce, Mary Ann Piette, Brian Pon, and Kristopher L Kinney. (1998) It's Midnight … Is Your Copier On?: Energy Star Copier Performance. Berkeley, CA: Lawrence Berkeley National Laboratory, 1998. LBNL-41332.

Norford, L. K. and Dandridge, C. (1993), 'Near-term technology review of electronic office equipment.' Massachusetts: MIT

Norford. L. K., Rabl, A., Harris, J., and Roturier, J. (1988). 'The sum of megabytes equals Gigawatts: Energy Consumption and Efficiency of Office PCs and Related Equipment.' In Proceedings of the ACEEE 1988 Summer Study on Energy Efficiency in Buildings. Volume 3, pp. 3.181-3.196. American Council for an Energy Efficient Economy, Washington DC.

Norford, L., K., Hatcher, A., Harris, H., Roturier, J., and Yu, O., (1990). "Electricity Use in Information Technologies." In Annual Review of Energy 1990. Palo Alto, CA: Annual Reviews, Inc.

Office for National Statistics (ONS). (2022), 'Public sector employment'. London, England: Crown copyright

Office for National Statistics (ONS). (2023), 'Average actual weekly hours of work for full-time workers (seasonally adjusted)'. London, England: Crown copyright

Office of Energy Efficiency and Renewable Energy (OEERE). (2022), 'Federal energy Management Program'. Washington DC, USA: US Government

Office of Personnel Management (OPM). (2022), 'Policy, Data, Oversight Data, Analysis and Documentation'. Washington DC, USA: US Government

Passmark Software, (2020). 'Intel Core m3-8100Y CPU Benchmark.' California, United States: Passmark Software Pty Ltd.

Passmark Software, (2022). 'CPU benchmarks'. California, United States: Passmark Software Pty Ltd.

PE International. (2008), 'Environmental footprint of ICT equipment in manufacture, use, and end-of-life. Brussels, Belgium: Presentation held at ECOC

Peters, J., Weil, M. (2016), 'A critical assessment of the resource depletion potential of current and future lithium-ion batteries. Switzerland: Resources

Piette, M., A., Wall, L., and Gardiner, B., L., (1985). "Measured Energy Performance of Energy-Efficient New Commercial Buildings: Results from the BECA-CN Data Compilation." ASHRAE Journal (1985). LBL-19413.

Piette, M.A., Harris, J., and Eto, J., (1991) 'Office Equipment Energy Use and Trends', report for the California Institute of Energy Efficiency. September. LBL Report No.31308. Lawrence Berkley Laboratory, Berkeley, California 1991

Piette, M., A., Cramer, M., Eto, M., Koomey, J., (1995). Office Technology Energy Use and Savings Potential in New York. LBNL Report Number LBNL-36752 Berkley. California: Lawrence Berkeley Laboratory.

Porter, M., (1979), 'How Competitive Forces Shape Strategy'. Harvard Business Review.

Porter, S., Moorefield, L., and May-Ostendorp, P. (2006). 'Energy use of plug load devices in California homes: Field research report. Durango,CO, USA: Ecos Consulting.

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.

Preston, L. E. (Ed.). (1988), 'Research in corporate social performance and policy'. (Vol. 10). Greenwich, CT: JAI Press

Quickbooks, (2019). 'Understanding UK Lunch Break Law'.

Rebsdorf, A. 1993. "Results from the Report: 'Electric Savings on Office Equipment, Standards'.

Rees, W., Wackernagel (1996). 'Our Ecological Footprint, Reducing Human Impact on Earth.' Canada: New Society Publishers

REN 21 Renewables Now. (2019), 'Renewables 2021 Global Status Report'. Paris, France: REN21 Secretariat

Reichart I., and R. Hischier. (2003). 'The environmental impact of getting the news. A comparison of online, television, and newspaper information delivery'. Journal of Industrial Ecology 6

Rigamonti, L., Falbo, A., Zampori, L., Sala, S. (2016), 'Supporting a transition towards sustainable circular economy, sensitivity analysis for the interpretation of LCA for the recovery of electric and electronic waste'. International Journal of Life Cycle Assessment.

Roach, C. (1985), 'Estimated Power Requirements for Electronic Office Equipment'. The Electric Power Research Institute.

Robalino, D. A. and Lempert, R., (1999). Carrots and sticks for new technology: Abating greenhouse gas emissions in a heterogeneous and uncertain world. Santa Monica, CA: RAND.

Robinson, J. B. (1990), 'Futures under glass: A recipe for people who hate to predict' p. 820. Science Direct

RoHS Worldwide. (2022), 'RoHS Initiatives Worldwide'. Available at: https://www.rohsguide.com/rohs-future.htm

Romm, J., Rosenfeld, A. & Herrmann, S. (1999) 'The internet economy and global warming: A scenario of the impact of e-commerce on energy and the environment'. Center for Energy and Climate Solutions, Global Environment

Romm, J. (2001). ''The Internet and the New Energy Economy'. Center for Energy and Climate Solutions, Global Environment and Technology Foundation

Rorbech, J. T., Vadenbo, C., Hellweg, S., Astrup, T.F. (2014), 'Impact assessment of abiotic resources in LCA: quantitative comparison of selected characterisation models'. Environmental Science and Technology.

Roth, K., Goldstein, F,and Kleinman, J., (2002) Energy Consumption by Office and Telecommunications Equipment in Commercial Buildings--Volume I: Energy Consumption Baseline. Washington, DC: Prepared by Arthur D. Little for the U.S. Department of Energy. A.D. Little Reference no. 72895-00.

Roth, K., and McKenney, K., (2007). Energy Consumption by Consumer Electronics in U.S. Residences. Lexington, SC: TIAX LLC. TIAX LLC., Lexington, SC.

Routurier, J., Greenwood, R., Bertoldi, P. (1994). 'Energy Efficient Technologies in Europe EC-DGXVII, Number 4.1031/E/92-07. Bordeaux, France: University of Bordeaux.

Routurier, J. and Harris, (1993). "New Loads in Office Buildings: Opportunities for Improving Efficiency of Office Equipment. II In Proceedings of the NATO Advanced Workshop. A. de Almeida (ed.). Espinho, Portugal.

Royal Borough of Kingston and Sutton Councils. (2019), 'Tackling the climate emergency, news and events'. London.

Sahni, S., Boustani, A., Gutowski, T.G., Graves, S.C. (2010), 'Reusing personal computer devices – Good or bad for the environment?' New Jersey: Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology.

Sanchez, M. C., J. G. Koomey, M. M. Moezzi, A. K. Meier, and W. Huber, (1998), "Miscellaneous Electricity Use in the U.S. Residential Sector," Lawrence Berkeley National Laboratory Report, LBNL-40295, April.

Sarkis, J. (1995), 'Supply Chain Management and Environmentally Conscious Design and Manufacturing'. University of Texas.

Samsung, (2022). 'Definitive performance for mobile storage'. South Korea: Samsung Group.

Scharnhorst, W. (2008), 'Life cycle assessment in the telecommunication industry: A review'. International Journal of Life Cycle Assessment 13

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

Schlomann, B., C. Cremer, M. Friedewald, P. Georgieff, R. Corradini, D. Kraus, U. Arndt, W. Mauch, E. Schaefer, M. Schulte, and R. Schroder. 2005. Technical and legal application possibilities of the compulsory labelling of the standby consumption of electrical household and office appliances. Karlsruhe, Germany: Fraunhofer Institute for Systems and Innovation Research ISI.

Schultz, D. K. (1984), 'End Use Consumption Patterns and Energy Conservation Savings In Commercial Buildings'. California Energy Commission (CEC)

Schmuck, D., Matthes, J., Naderer, B., & Beaufort, M. (2017) The Effects of Environmental Brand Attributes and Nature Imagery in Green Advertising

Scientific American. (2020), 'Telecommuting Could Outlive the Pandemic, Lowering Emissions'. New York: Springer Nature

SimaPro. (2022), 'Sustainability, Life Cycle Assessment, Carbon Footprinting'. Utrecht, Netherlands: SimaPro

Smith, L., Harris, J., Blatt., M. (1994), 'Office Equipment Energy Efficiency Taking the Next Few Bytes'. Berkley, CA: ACEEE 1994 Summer Study on Energy Efficiency in Buildings, 3:241-3:249

Sodexo UK Active. (2019), 'Lunch break 20-minutes average time'.

Socolof ML, Overly JG, Geibig JR (2005) Environmental life–cycle impacts of CRT and LCD desktop computer displays. J Clean Prod 13:1281–1294

Socolof, M.L., Overly, J. G., Kincaid, L. E., and Geibig, J. R. (2017), 'Desktop Computer Displays: A LifeCycle Assessment'. Tennessee, USA: University of Tennessee Center for Clean Products and Clean Technologies

Sonderegger, T., Dewulf, J., Fantke, P., de Souza, D.M., Pfister, S., Stoessel, F., Verones, F., Viera, M., Weidema, B., Hellweg, S. (2017), 'Towards harmonising natural resources as an area of protection in life cycle assessment.' International Journal of Life Cycle Assessment

Sphera. (2022), 'Life Cycle Assessment Software'. Chicago, USA: Sphera

Spreckley, F. (1987). Social Audit: A Management Tool for Co-operative Working. Beechwood College.

Statistica Research Department. (2020). 'Global shipment of tablets, laptops and desktop PCs 2010-2023'. Amsterdam: SRD

Statistica Research Department. (2021). 'PC unit shipments worldwide from 2019 to 2025, by type.' Amsterdam: SRD

Statistica Research Department (2022), 'Number of working days in Poland from 2015 to 2023'. Amsterdam: SRD

Steen, B.A. (2006), 'Abiotic resource depletion – different perceptions of the problem with mineral deposits'. International Journal of Life Cycle Assessment

Subramanian, K., Yung, W.K.C. (2016). 'Review of life cycle assessment on consumer electronic products: developments and the way ahead.' Critical Review of Environmental Science and Technology. 46 (18), 1441-1497.

Sutton-Parker, J. (2015), 'Corporate Social Responsibility as a critical decision making factor for adopting cloud computing'. Cumbria, UK: University of Cumbria

Sutton-Parker, J. (2020a), 'Quantifying resistance to the diffusion of information technology sustainability practices in United Kingdom service sector'. 1877-0509. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.

Sutton-Parker, J. (2020b), 'Determining end user computing device Scope 2 GHG emissions with accurate use-phase energy consumption measurement'. 1877-0509. Procedia Computer Science. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.

Sutton-Parker, J. (2020c), 'All About EVE: Decoding personal IT sustainability success'. London, England: My Green Pod, The Guardian.

Sutton-Parker, J., Procter, R., and Kass, S. (2020d), 'Cloud Computing Gives a Dam(n)'. London, England: My Green Pod, The Guardian.

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.

Sutton-Parker, J. (2022a), "2021 JSP UK Service Sector Sustainable Device Selection Survey Data", Mendeley Data, V2, doi: 10.17632/6d7r874jtz.2

Sutton-Parker, J. (2022b), 'Can analytics software measure end user computing electricity consumption?' Clean Technologies and Environmental Policy. 1618-9558. New York, USA: Springer.

Sutton-Parker, J. (2022c), '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.

Sutton-Parker, J. (2022d), '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.

Sutton-Parker, J. (2022e), 'Determining the impact of information technology greenhouse gas abatement at the Royal Borough of Kingston and Sutton Council'. 1877-0509. Procedia Computer Science. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.

Sutton-Parker, J. (2022f), 'The Dynamic Carbon Footprint'. Available at <https://dcf.px3.org.uk/>

Sutton-Parker, J. (2023). 'Determining use phase energy consumption reduction delivered by power management peripherals'. In peer review with Procedia Computer Science. Amsterdam, the Netherlands: Science Direct, Elsevier B.V.

Sutton-Parker, J. and Procter, R. (2022), 'Determining greenhouse gas abatement achieved by repurposing end user computing devices'. Warwick, UK: University of Warwick, Computer and Urban Science Dept.

Szydlowski, R.F. and Clivala, W., (1994). Energy Consumption of Personal Computer Workstations. PNL Report Number-9061. Richland, Washington: Pacific Northwest Laboratory

TCO Certified. (2022), 'TCO Certified, generation 9'. Stockholm, Sweden: TCO

Teehan, P., Kandlikar, M., (2012). 'Sources of variation in life cycle assessments of desktop computers. J. Ind. Ecol. 16 (no. S1), S182eS194.'

Tekawa, M., Miyamoto, S., Inaba, A. (1997), 'Life cycle assessment; an approach to environmentally friendly PCs'. Proc IEEE International Symposium of Electronic Environment, May 5–7, San Francisco, CA, 125–130

Thiebaud, E., Hilty, L.M., Schluep, M., Widmer, R., Faulstich, M. (2017), 'Service lifetime, storage time and disposal pathways of electronic equipment: A Swiss case study.' Journal of Industrial Ecology.

Thomson Reuters, (2022). 'Practical Law'.

Toffel, M. W. and A. Horvath. (2004). Environmental implications of wireless technologies:News delivery and business meetings. Policy Analysis 38(11): 2961–2970.

United Nations (1992). 'United Nations Framework Convention on Climate Change'. New York: United Nations.

United Nations. (1997), 'The Kyoto Protocol to the United Nations Framework Convention on Climate Change'. Annex B pg. 24. New York: United Nations.

United Nations (2015), 'Sustainable Development Goals'. New York: United Nations.

United Nations Environment Programme (UNEP). (1987), 'The Montreal Protocol on Substances that Deplete the Ozone Layer'. Nairobi, Kenya: UNEP

United Nations Environment Programme. (2019), 'Emissions Gap Report'. Table ES1 Page 8. Nairobi, Kenya: UNEP

United States Energy Information Administration (2022). 'EIA projects that renewable generation will supply 44% of U.S. electricity by 2050'. Washington: United States Congress

United States Environmental Protection Agency (USEPA). (2015), 'EPA Design for the Environment (DfE) Program's Cleaner Technologies Substitutes Assessment'. Washington: United States Congress

United States Environmental Protection Agency (USEPA). (2019), 'Emission Factors for Greenhouse Gas Inventories'. Washington: United States Congress.

United States Environmental Protection Agency (USEPA). (2020a), 'Sustainable Marketplace, Greener Products and Services: Computers: Desktops, Notebooks (including 2-in-1 notebooks), Displays, Integrated Desktop Computers, Workstation Desktops, Thin Clients, and Slates/Tablets'. Washington: United States Congress.

United States Environmental Protection Agency (USEPA). (2020b), 'Environmentally Preferable Purchasing Program'. Washington: United States Congress

United States Environmental Protection Agency (USEPA). (2020), 'Global Greenhouse Gas Emissions Data.' Washington United States Congress

United State Environmental Protection Agency (USEPA). (2021), 'EO 14057: Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability'. Washington United States Congress

United States Environmental Protection Agency (USEPA). (2022a) Greenhouse Gas Equivalencies Calculator. Washington: United States Congress.

United States Environmental Protection Agency (USEPA). (2022b), 'Emissions & Generation Resource Integrated Database (eGRID)'. Washington: United States Congress.

United States Federal Government (1993), Executive Order 12845 of April 21, 1993. Washington D.C. Federal Register Presidential Documents Vol. 58, No.77

United States Government. (2021), 'The Federal Acquisition Regulation Part 23.7'. Washington DC, USA: US Government

University of Bath. (2022), 'Audio visual equipment list'. Bath, UK: University of Bath

Uptime Institute, (2018). 'Global Data Centre Survey 2018'. WA, USA

Urban, B., Shmakova, V., Lim, B., Kurt, R., (2014). Energy Consumption of Consumer Electronics in u.S. Homes in 2013. Fraunhofer USA Center for Sustainable Energy Systems, Boston.

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.

Van Heddeghem, W., Lambert, S., Lannoo, B., Colle, D., Pickavet, M., Demeester, P., (2014). Trends in worldwide ICT electricity consumption from 2007 to 2012. Comput. Commun. 50, 64e76.

Wall Street Journal, (2022), 'Inside a Ransomware Hit at Nordic Choice Hotels'. New York, USA: Wall Street Journal

Wheeler-Wyatt, M. (2022), 'Email May 22, 2022'.

Williams, E. (2004), 'Energy intensity of computer manufacturing: Hybrid assessment combining process and economic input–output methods'. Environmental Science and Technology 38:6166–6174

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.

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'.

Workthere. (2019), 'Average British Worker Takes 34 Minutes Lunch Breaks'.

World Business Council for Sustainable Development and World Resources Institute (WBCSD and WRI). (2004), 'The Greenhouse Gas Protocol. A Corporate Accounting and Reporting Standard'. Geneva, Switzerland and New York, USA.

World Business Council for Sustainable Development and World Resources Institute (WBCSD and WRI). (2013), 'Technical Guidance for Calculating Scope 3 Emissions'. Fig. 1.1 Pg. 6. Geneva, Switzerland and New York, USA.

YouTube. (2022a), 'How local UK government focuses on IT sustainability with Chrome OS and Android Enterprise'. Mountain View, California: Google

YouTube. (2022b), 'Earth Day: Sustainable IT with Chrome OS'. Mountain View, California: Google

Zamojska, A and Próchniak, J., (2017), 'Measuring the Social Impact of Infrastructure Projects: the Case of Gdańsk Internatonal Fair Co'. Poland: University of Gdansk

Appendix

Activity 1 field experiment test set-up and conduct

Energy Star Computer TEC Benchmark Test Conditions

Energy Star benchmarking conditions are designed to satisfy the recognised International Electrotechnical Commission (IEC) Standards of IEC 62301 and IEC 62623. Standard IEC 62301, "Household Electrical Appliances – Measurement of Standby Power" Edition 2.0, 2011-01, Section 4, "General Conditions for Measurements" is used as a standard for the test setup phase.

The standard defines five criteria that must be adhered to in order to be compliant.

1. The 'Input Power' using alternating current (AC) mains supply must be connected to a voltage source appropriate for the intended market (country).

2. The 'Ambient Temperature' must remain between 18 C and 28 C for the duration of the test.

3. Relative Humidity' shall remain between 10% and 80%, for the duration of the test.

4. Light measuring devices used to test monitors must meet published criteria, although this outside of this experiment.

5. Power meters used to measure device electricity consumption must have an available current crest factor of 3 or more at its rated range value and a bound on the current range of 10 milliamperes (mA) or less. Additionally, the meter must have a minimum frequency response of 3.0 kilo-hertz (kHz), minimum resolution of 0.01 W for measurement values less than 10 W; 0.1 W for measurement values from 10 W to 100 W; and 1.0 W for measurement values greater than 100 W. The meter measurement accuracy should account for uncertainty of less than or equal to 2% at the 95% confidence level for values greater or equal to 0.5W and less or equal to 0.01W at 95% confidence level for values of less than 0.5W.

Standard IEC 62623, 'Desktop and Notebook Computers - Measurement of Energy Consumption' Edition 1.0 2012-10 is used for the test conduct phase.

The standard defines five criteria that must be adhered to in order to be compliant.

1. Any benchmark requires a test procedure that enables the measurement of power and or energy consumption for equipment under test (EUT) in all available modes before being marketed as final products. Energy Star tests include four modes; Long Idle, Short Idle, Sleep and Off mode. Long idle measurement must start no more than 20 minutes after input ceases with display sleep settings set to default. Short Idle measurement must start no more than 5 minutes after input ceases with display sleep settings switched off. Sleep and off are self-explanatory.

2. Formulas must be included for calculating the total energy consumption (TEC) during a set period (usually per year). Energy Star's TEC equation (eTEC) is 8760/1000 x (Poff x Toff + Psleep x Tsleep + Plong_idle x Tlong_idle + Pshort_idle x Tshort_idle).

3. A profile that enables conversion of average power into energy used with the TEC formulas must be utilised. For the notebook category Energy Star publishes an annual use profile as Toff 25%, Tsleep 35%, Tlong_idle 10% and Tshort_idle 30%.

4. The process must include a system of categorisation and defined presentation format enabling like for like comparison of energy consumption results between EUTs. Energy Star uses categories by type including desktop, integrated desktop, integrated thin client, mobile workstation, notebook, slate / tablet, thin client, two in one notebook, workstation. At the component level comparison is achieved with a categorisation system that accounts for performance rating (P) calculated by (# CPU cores) x (CPU clock speed GHz) and varying graphics capability determined on frame buffer bandwidth.

5. As the standard does not set a pass or fail criteria the organisation generating the results must define such criteria. The results of the Energy Star testing are published via the regularly updated online comparison tool 'Energy Star Certified Products'.

With regards to this research the data supplied by Energy Star is well established and considered accurate due to the adherence to international standards during the test setup and conduct phases. As discussed in the field test methodology section, the Energy

Star test set up phase will be replicated during the field experiment. Additionally, the published Energy Star TEC data presented in kWh (along with other sources) will be used to draw a comparison to the field results.

<u>UL Benchmarking Conditions</u>
UL Benchmarking is one of the world's leading information technology benchmarking companies. UL specialises in PC components, smart tablet and phone performance benchmarking. While the organisation's focus does not incorporate energy consumption data for PCs, laptops and tablets included in this research, it does offer best practice recommendations for benchmark tests. Most are included within the Energy Star recommendation although battery calibration was determined as useful to this experiment to ensure all devices were tested from an equal battery standpoint. The procedure is discussed in the

<u>Computer TEC Measurement Methodology</u>
Identifying the key specifications of the Energy Star benchmark standards and relevant compliance with international regulations enabled the design of the field benchmark setup and test conduct. Using a similar approach ensures that the data produced is generated under equivalent standards of measurement but allows for the measurement of an Active State beyond short idle.

The following section describes the methodology used for the field benchmark test setup and conduct phases together with rational for each condition.

<u>Field Benchmark Test Set-Up</u>
In order to ensure accurate measurement and to comply with the IEC 62301 standards used by Energy Star partners, the devices measured were subject to the following pre-measurement test set-up:

1. Devices were fully powered and left to drain twice before being connected and fully charged before the test began. This conduct was introduced as each device tested was categorised as mobile (e.g. a notebook) and therefore it was deemed important to use the battery calibration process utilised by UL benchmarking to ensure parity across the different makes and models.

2. Connected to an appropriate UK 'Input Power' using alternating current (AC) mains supply connected to a UK voltage source.

3. Operated in an 'Ambient Temperature' maintained between 18 C and 28 C.

4. Connected to a watt meter meeting the IEC 62301 standards plugged in between the input power and the mains supply.

5. Installed with a Lakeside Systrack analytics software node (with the exclusion of the Chromebooks) to measure energy consumption

6. While light measuring devices were not used during the field test, the brightness of all screens were set to 100% with the automatic brightness adjustment disabled in order to ensure parity between devices and comply with Energy Star recommendations.

7. Display Sleep Mode was to initiate after 15 minutes of user inactivity as per Energy Star recommendations.

8. Sleep mode was set to initiate after 20 minutes of user inactivity as per Energy Star recommendations.

<u>Field Benchmark Test Conduct</u>
As the objective of the experiment was to measure device energy consumption in the work environment (field) the devices were measured for a five day Monday to Friday inclusive period using the wattmeter to register energy consumption. The working period is detailed below as between 9am and 5pm; a period commonly recognised as the working day and published by the majority of Service Sector companies as opening hours. To ensure the test reflected common working patterns, a statutory lunch break during the day was introduced to reflect a most likely less active (short idle followed by sleep) period experienced in a business environment. To determine a suitable length of break, related laws and surveys were examined. The UK Government states that workers are entitled by law to one uninterrupted break of twenty minutes during any working day longer than six hours (HM. Gov., 2019a and 2020b). Despite the law existing this does not necessarily determine that this period is adhered to. To determine an acceptable average survey results were assessed. A recent global study (Quickbooks, 2019) of fifteen thousand people produced results that the average lunch break in the UK was thirty-five minutes being a median between the results of 60% of the countries surveyed that ranged from thirty to forty minutes. A comparative study (Sodexo and Ukactive, 2018) suggested that the average lunch break was twenty-two minutes based on the responses of eight hundred workers. A further survey (Glassdoor, 2019) concluded that the average of two thousand workers was 31 minutes. Finally, a Workthere survey

(2017) of 2000 staff confirmed 34 minutes. The average figure was thirty and a half minutes. Therefore, thirty minutes was selected as an appropriate break time away from the computer based on the law and survey studies.

As such and in order to ensure accurate measurement and to comply with the IEC 62623 standards used by Energy Star partners, the equipment under test (the notebook) was subjected to the following conduct conditions:

1. Operated during the measurement phase by the same worker for all devices to ensure similar working patterns were adhered to for each device and working week.

2. In order to create parity with regards to software application impact on energy consumption and to reflect modern working practices, all business applications were accessed via a Google Chrome browser utilising software as a service (SaaS). These included Microsoft Office 365 for business productivity, Citrix Files for file storage, Salesforce for customer relationship management, Workday for financial and human capital management, and Concur for travel and expense management.

3. Measured for energy consumption between 9am and 5pm Monday, Tuesday, Wednesday, Thursday and Friday while permanently connected to a power source.

4. One 30-minute break included per working day away from the computer. The operator was asked to set the notebook to 'lock' at the beginning of the break as would be standard 'away from the device' security protocol in the majority of business environments.

5. Watt meter reset to zero at 9am before notebook use began.

6. Collection of watt meter and Systrack readings at 9am (to ensure zero), 12pm (before the break), 12.30pm (after the break), and at 5pm when the active use and measurement period concluded.

7. Set to 'off' after 5pm until 9am the following morning.

List of Figures and Tables