Determining desktop computer energy consumption and GHG emissions reduction delivered by power management peripherals

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Abstract

The objective of this research is to determine the reduction in desktop computer electricity consumption and concomitant use phase greenhouse gas emissions enabled by a peripheral keyboard device capable of incremental power management. The value of the research is to examine if such a device can support information sustainability strategies designed to address the 1% of global greenhouse gas emissions already generated by end user computing. In doing so, adoption at scale would support the United Nations Environment Programme initiative to combine existing technology, such as computing, with innovation to reduce societal emissions. Identifying that desktop computers require a peripheral keyboard as standard, remain significant within commercial environments and consume between 3-5 times more electricity than notebooks, the keyboard is tested in such a context. Using analytics, asset management software and survey techniques, 417,880 business computers are profiled to determine substantiated parameters used to calculate the impact of the peripheral device. These include install base device types, age categorisation, number of attached displays and existing power management settings. To determine accurate electricity consumption measurements before and after the keyboard is introduced, a field experiment is also conducted. Specifically, adhering to internationally recognised test conditions, legacy (>6 years old), mid-point (4-5 years old) and new (1-3 years old) desktop computers are measured using watt-metres. The results are applied accordingly to the profile parameters and results relating to annual kilo-watt hour values for standard operation and the keyboard's three energy management settings. In order to highlight the positive environmental impact, the energy values are subsequently converted to scope 2 use phase carbon dioxide equivalent greenhouse gas emissions values for three major geographical regions. The findings determine that the reduction of energy consumption and concomitant emissions ranges from between 40-43% on average per year of use. In a global context, universal diffusion of such a device is calculated to avoid greenhouse gas emissions that would otherwise require the sequestration capacity of a mature forest the size of the Netherlands.

Keywords: Computer carbon footprint; computer energy efficiency; human-computer interaction; computer greenhouse gas emissions.

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1. Introduction

International standards [1, 2, 3] determine that end user computers will experience four use-phase modes including off, sleep, idle (long and short) and the active state. The power draw (watts) required by the computer for each modes differs as the device experiences lesser or greater workloads. As an example, a notebook computer may require 0.4W in off, 0.5W in sleep, 1.9-4W in idle and between 6.3W-11.3W in active depending upon activities being undertaken [4, 5]. The percentage of time (hours) per year spent in each state determines the mode weighting used to generate a use profile [6]. Multiplying this outcome by the relevant power draw for each mode determines the annual electricity consumption measured in kilo-watt hours (kWh). The calculation is represented as follows:

$$Electricity\ consumption = \frac{8760}{1000}\ x\ (POFF\ x\ TOFF + PSLEEP\ x\ TSLEEP + PLONG_{IDLE}\ x\ TLONG_{IDLE} + PSHORT_{IDLE} x\ TSHORT_{IDLE} + PACTIVE\ x\ TACTIVE)$$

In this example, 8,760 represents the number of hours in one year. This value is divided by 1,000 to convert watts (represented by P) into kilo-watts. T represents the percentage (%) of time (hours) during one year the computer spends in each mode. It is notable that two idle sub-states exist. Long idle is when the computer has assumed the idle condition due to inactivity and the associated computer display backlight has extinguished and entered a low power state. Comparatively, short idle is when the computer has become idle but the screen remains illuminated. As an example, the long and short idle power draw for the previously noted computer is 1.9W and 4W respectively [4] highlighting the additional energy required to light the screen. Based upon this process it is logical that a computer spending more time in increased power draw modes, such as idle and active, will consume more electricity [5,6]. The impact is significant and research identifies this increase is in the region of 107% [5].

Identified initially in 1984 as a rapidly emerging new commercial power use case [7,8,9], end user computers such as desktops and notebooks, have become commonplace with 460m personal computers manufactured each year [10,11] to meet the demand of 4.2bn active users [12]. Consequently, the carbon footprint of end user computing is responsible for 1% of global greenhouse gas (GHG) emissions [13-15]. Between 14-50% is caused by electricity consumed during the use phase [4, 5, 13,15, 16]. As manufacturing output is predicted to rise between 3-5% to 2030 [10-12], it is logical to ensure that electrical efficiency represents a key design criterion. This is emphasised by computer use habits, such as video conferencing, are increasing both power demand and active mode use times [17,18] to as much as 7.5 hours per day [19]. Consequently, notebook and desktop computer use is now responsible for approximately 3-7% of domestic and commercial electricity consumption [20-22]. The long term solution to reducing computing use phase emissions rests with a transition to low carbon energy options, although progress is slow. Currently, only 29% of global electricity supply is generated by such options and forecast to rise 6% by 2030 [23-25]. The United Nations recognises the gap long term adoption issues cause in relation to achieving significant global abatement by 2030 [26]. Consequently, it suggests combining existing technology, such as computing, with innovation to reduce societal emissions [26] as a short term bridging strategy. The urgency to act is based upon an already evident 1.0°C global warming and 1.5°C expected between 2030-52 if emissions increases continue [27, 28]. However, the same research suggests that taking action now to reach and sustain net zero CO_2 emissions by mid-century, will halt global warming on a multi-decadal scale and temperature gains will begin to peak [27, 28]. Fortunately, to support such action, a body of research exists in relation to the identification and reduction of use phase energy consumption and concomitant emissions abatement [7-9, 29-37]. Historically, this led to the emergence in 1992 of the Energy Star programme [38] that focuses upon three key computer efficiency measures.

The first is a scoring system created to ensure computer design is focused upon electrical efficiency [1]. Components included within new devices must either meet power efficiency parameters or not exceed, as a collective, the maximum typical energy consumption thresholds determined for each device type [39]. Additionally, components such as core processing units are subject to power draw ceilings governed by allowances [1]. The second measure is the advent of a power draw test set up and conduct benchmark that ensures the resulting product is certified as energy efficient [1]. Created to accurately determine the wattage required by a computer when experiencing the no-user modes of off, sleep and idle, the results allow public comparison between device types such as notebooks and desktops [4]. Today, the majority of computers manufactured annually are subject to this procedure and the results are published online [4]. Such is the popularity of the programme that 70% of companies use the data to select energy efficient computers [40]. The third measure is the ability for all new computers to conduct automated power management in an expedient manner without user intervention [1]. As an example, a desktop computer must be capable of automatically transitioning to sleep mode within 15-minutes of inactivity for the screen and 30-minutes of inactivity for the device. A resume time from sleep mode to active capability has also been introduced to ensure that useful work can begin without delay. Set to between 5-10 seconds, this is designed to avoid the legacy perception of lost productivity being attributed to powering down computers [34, 37].

After sale power management is key to ensuring that such energy efficiency by design is realised during the use phase. As an example, if the power management options are disabled, then unless the computer is manually set to sleep or switched off by the user, the device will only experience the two highest energy consumption modes of active and idle during its useful lifespan. Although inconclusive, research suggests that 50% of users do continue to switch off the power management settings, instead relying upon manual intervention [41]. If an ongoing perception of lost productivity [34, 37] is the cause for this action, it is reasonable to question why this is so if computers are now required to have the capacity to resume within 5-10 seconds. The answer may lie in the fact that the transition to low power mode relies upon the operating system being subject to no user interaction. As such, a user may still be examining computer screen content, whilst engaged in a phone call. Whilst the content is relevant to the call, the computer will shut down unless interaction occurs. Such is the inconvenience of this, applications and hardware exist to mimic computer mouse movement to prevent what is described as 'screen shut down' [42]. Employing this tactic causes power management software to be ineffective and the same increase in power consumption is experienced as is the case when disabling the pre-shipment standard settings [1]. To overcome this a keyboard exists that uses radar technology to sense when a user remains present [43]. The simple concept being that a user can remain with the computer without interaction and the keyboard will ensure the computer and screen remain available. When the user moves away, then the keyboard can set the computer to sleep within settings of 30 seconds, 3 or 6 minutes. Beyond the obvious practical benefit of overcoming the lost productivity perception barrier, it is suggested that energy consumption will also be reduced. As an example, a transition to the sleep mode can be enabled regardless of whether the operating system power management controls have been disabled. Additionally, the device can also make the transition far quicker than the standard 15-30 minutes, potentially avoiding extended durations of the active and idle modes. As the radar device is a keyboard, the most likely application will be in association with desktop computers as they, unlike notebooks, cannot operate without a keyboard. Arguably this is positive because when combined with a display, desktop computers exhibit a typical energy consumption value between three and five times higher than a notebook [4, 5, 13, 44-48]. As such, focusing upon a device type that exhibits high use phase emissions may help to support the United Nations' bridging strategy [26]. Consequently, the objective of this research is to quantify the potential electricity consumption reduction and GHG abatement reduction delivered by the device in the workplace.

2. Method

To achieve this, the summary methodology is threefold. The first stage is to substantiate the electricity consumption reduction delivered by the keyboard to three desktop computer devices. To represent devices at different stages in their useful lifespan [49-54], a desktop computer more than 6 years old (legacy), one between 4-5 years old (midpoint) and one less 1-3 years old (new) are selected for electricity consumption measurement. The selection rationale is adopted to reflect the fact that organisations will own desktop computers at different stages of a retention cycle [49-54]. As such, by defining three categories, the research is able to determine the difference in electricity consumption saved between devices that are, through design innovation, lowering in power draw as each iteration occurs [55]. The energy consumption test set up and conduct measurement is based upon Energy Star conduct parameters [1] and adheres to international standards [2, 3]. For each computer, five periods of energy consumption measurement are conducted using watt meters to capture power draw (W) and energy consumption values (kWh). The first captures data for five-days as the computer is operated with standard power management settings by a user in a work environment between 9am to 5pm with rest breaks included [56, 57]. The second measurement period repeats the process for three days using the 'never' power management setting to highlight the impact of users overriding the power management settings [41]. The final three tests are conducted for three days each, using the keyboard to determine a 30-seconds, 3-minutes and 6-minutes sleep setting for each period. Throughout, the same 24" monitor is used to ensure parity between the desktop computer results. It is noted that the radar detection capability of the keyboard is not tested having previously been proven as effective [58].

The second stage is designed to create a valid representation of a typical business end user computing environment. Characteristics include the number of device types and ages, device power management settings overridden by users and the average number of displays attached to each desktop computer. Whilst holistic secondary data exists, the necessity to do this is driven by speculation that desktop computers remain prevalent in commercial settings compared to consumer adoption that is moving towards predominantly mobile computing [10-12]. In order to generate the primary data, analytics and asset management software plus survey techniques are used to profile 417,880 end user computers currently in use in businesses across the globe. This exercise was undertaken during a 12-month period as part of wider research into the effect of end user computers upon the environment [5, 40, 48, 59-61]. Finally, the third stage determines the annual use phase greenhouse gas emissions generation and abatement of each desktop computer category when operated with and without the peripheral device in a large organisation of 250 computer users. This is achieved by extrapolating the measured electricity consumption data to one-year using a combination of the average number of working days experienced in both Europe and the United

States [56, 57, 62] and the data points generated in stage 2. The results are then multiplied by electricity to GHG conversion factors [63] applicable to use locations such as Europe, the United States and 'worldwide' to produce kilogramme carbon dioxide equivalent ($kgCO_2e$) values as required by international GHG accounting protocol [64].

3. Results

As anticipated, the measured desktop computers produced differing results (table 1) depending upon age. This finding supports existing research indicating that energy efficiency will improve with each device replacement due to ongoing computer innovation [55]. The legacy Dell OptiPlex 7010, consumed 81.1 kWh/y in a business environment using standard power management settings. With the radar capable keyboard connected a 15% reduction to 69.2 kWh/y, 12.5% to 70.9 kWh/y and 10.5% to 72.6 kWh/y is achieved subject to the 30-second, 3 and 6-minute settings respectively. This increased significantly when used to manage the 'never' setting. In this example the keyboard reduced the unmanaged consumption value of 279 kWh/y by 75%, 74.5% and 74% accordingly. Consequently, the full range of annual electricity reduction experienced further to introduction of the keyboard for the legacy device category is determined to be between 15-75% (11.9-209 kWh/y) for the 30-second setting, 12.5-74.5% (10.2-208 kWh/y) for the 3-minute setting and 10.5-74% (8.5-206.4 kWh/y) for the 6-minute setting.

Table 1. Computer device electricity consumption (kWh/y) for five power management (PM) settings

Computer	Standard PM (kWh/y)	Never PM (kWh/y)	30s Keyboard PM (kWh/y)	3m Keyboard PM (kWh/y)	6m Keyboard PM (kWh/y)
Dell OptiPlex 7010	81.1	279.1	69.2	70.9	72.6
Lenovo M700	40.9	149.4	34.1	35.1	36.04
Prime Computer Prime Mini 5	23.6	42.6	22.5	22.6	22.8
Acer 24" B246WL Display	24.7	105.4	21.3	21.94	22.7

Comparatively, the midpoint Lenovo M700, proved 51% more energy efficient than the Dell device consuming 40.91 kWh/y (table1) with standard settings. Using the keyboard, a 17% reduction to 34.1 kWh/y, 14% to 35.1 kWh/y and 12% to 36.4 kWh/y is exhibited with each incremental setting and reduces the unmanaged result from 149.4 kWh/y by 77%, 76.5% and 76% accordingly. As such, the full range of reduction is between 17-77% (6.8-115.3 kWh/y), 14-76.5% (5.8-114.3 kWh/y) and 12-76% (4.9-113.3 kWh/y). The new Prime Computer Prime Mini-5, consumed 23.61 kWh/y proving 77% and 53% more energy efficient than the legacy (Dell) and midpoint (Lenovo) computers (table 1). Introducing the keyboard reduced consumption by 4.3% to 22.47 kWh/y, 4.1% to 22.63 kWh/y and 3.5% to 22.79 kWh/y. Comparing the outcome to the never setting, the reduction achieved from 42.59 kWh/y is 47.25%, 47% and 46.5% accordingly. Consequently, the full range of annual electricity reduction is between 4.3-47.25% (1.14-20.13 kWh/y), 4.1-47% (0.98-19.96 kWh/y) and 3.5-46.5% (0.82-19.8 kWh/y). The diminished reduction compared to the legacy and midpoint devices is due to the new device's active mode power draw being extremely low at between 9-10W. This is enabled by sustainable design features such as fan less cooling and a condensed motherboard. Such innovation reflects the increasing efficiency expectation defined by both certification [1] and international efficiency legislation [65, 66]. As an example, in 2021, Energy Star compensatory allowances for notebook and desktop computer components decreased by as much as 78%, meaning that new computers must meet lower typical energy consumption thresholds in general [1]. The requirement is also reflected in the United States where recent specific regulations have reduced electricity consumption benchmark incremental allowances for newly manufactured computers by as much as 44% [65]. In this instance, it is reasonable to indicate that whilst still operational, the majority of legacy desktop computers and some of the midpoint devices would not meet these criteria, emphasising the importance of alternative power management options. Comparatively, the Acer display consumed 24.7 kWh/y with standard power management settings (table 1). With the keyboard in place a 14% reduction to 21.29 kWh/y, 12% to 21.93 kWh/y and 8% to 22.66 kWh/y is achieved. As before, the reductions when applied to the never setting are far greater, reducing consumption from 105.383 kWh by 80%, 79% and 78.5% accordingly. Consequently, the full range of annual electricity reduction experienced is between 14-80% (3.42-84.1 kWh/y), 12-79% (2.76-83.44 kWh/y) and 8-78.5% (2.1-82.73) kWh/y.

Having measured the energy efficiency savings for the three desktop computer categories and the common display, five further values are required to calculate the substantiated energy saving and concomitant greenhouse gas emissions abatement that can be expected to be achieved within large business environments. As described in the methodology, to determine the first four values, asset and use profile data was collected for a total of 417,880 end user computers operated currently in large organisations. This was achieved using a combination of analytics and asset management software, plus survey techniques developed and undertaken as part of an associated wider body of research [5, 40, 48, 59-61]. As noted, it is speculated that desktop computers occupy a higher proportion of computer types in a commercial setting when compared to consumer demand. Currently, manufacturing and annual shipping data that combines both commercial and consumer data, indicates that 53% of end user computers are notebooks, 33% tablets and 14% desktops [10-12]. Analyst install base data indicates a marginally lower value, noting that desktop computers represent 12.6% of personal computers [67]. However, specific commercial and public sector organisation install base statistics suggest this to be higher at 31% [22]. As such, examining the large primary data sample, it is determined that the speculation is founded. Specifically, the latter statistics are closest to the findings that deduce 34.7% of computers operated in a business environment are desktop computers. In context, the relevance of substantiating this value is to enable accurate representation of desktop users during the impact analysis. As an example, using the secondary data that includes consumer quantification, a 250 user computer group would consist of 31 desktop users. Comparatively, using the primary data this is defined as 87 users (table 2). In relation to device retention periods, 64% of computers were identified as being between 1 and 3-years old therefore categorised as 'new'. 21% were between 4 and 5-years old and categorised as 'midpoint', whilst 15% were older than 6 years and categorised as 'legacy' devices. The relevance of this finding is that as indicated by the device measurement results the new desktop computer is between 53-77% more energy efficient than the midpoint and legacy devices. Consequently, as the new device is most prevalent, this will reduce the total electricity consumption valuation of a large company accordingly. It is however noted in the results (table 2) that the legacy energy use is sufficiently high to contribute 37% of all desktop electricity consumption despite only representing 15% of devices.

Display connection data revealed that 40% of desktop computers use dual screens. This is particularly relevant, as an additional display increases the total kWh value for each user proportionately. In this instance, if 87 desktops exist within a 250 user computer group, then the display count is 122 or 1.4 per user. As the measurement data reveals, the 24" display is approximately equivalent to the electricity consumption of the new computer when operating standard power management settings. However, this increases by 326% when the never power setting option is selected due to displays effectively having only active, sleep or off settings with no idle mode [1]. The rationale being that the active/on value for the monitor is 12.03W compared to the new desktop idle of 3.5W [4]. This influence substantiates the need to validate the percentage of computers, and therefore monitors, that remain switched on for 100% of the time. Of the data sample, the analytics extracts reveal that 21% were subject to no power management and therefore remained in either idle or active modes permanently. For the fifth and final value, secondary data in the form of electricity conversion to GHG emissions factors are used [63]. This is undertaken as it is recognised that the carbon intensity of electricity supply grids will differ for each geography where the keyboard may be used. As such, three regional electricity conversion factors are constructed. These include the dominant markets of the United States (factor 0.45322), Europe (factor 0.31607) and a worldwide value constructed from fifty countries reporting emissions values across six continents (factor 0.37002).

The triangulation of data enables the creation of an annual electricity and GHG reduction value for a large company of 250 computer users (table 2, 3). The rationale for quantifying a 250 user group is that this employee threshold is recognised by the majority of countries as signifying a large organisation (68, 69). Where other countries with expansive employment markets, such as the United States, have a variety of thresholds depending upon the industry (70), the number of users can be multiplied to represent 500 or 1,000 thresholds as necessary. The number of desktop computers within the 250 computer user group is 87 based upon the proportionate representation findings. As such, only the electricity consumption of the 87 desktop users is represented in order to highlight the impact of the keyboard on desktop computer and monitor combinations. Of these, 56 devices are aged between 1-3 years, 18 between 4-5 years and 13 more than 6 years old and 21% of the total are assumed to exhibit the 'never' power management setting. To represent the percentage of desktop computers determined to use dual monitors, the total number of displays exceeds the desktop computers at 122 units, reflecting the 1.4:1 ratio.

The total electricity consumption in a business setting before the radar keyboard is introduced is 9,382 kWh/y for the group (table 2). As noted, this is based upon 79% of desktop computers being subject to standard power management settings. This determines that when combining the three age categories of computers, the average desktop and display combination consumes 108 kWh/y. When the keyboard is set to 30 seconds sleep activation, this value is reduced by 43% to 5,373 kWh/y saving 4,009 kWh/y and reducing the per user consumption to 62 kWh/y. Set at 3-minutes, the reduction is 41% to 5,501 kWh/y saving 3,881 kWh/y and reducing the user consumption value to 63 kWh/y. Comparatively, at 6-minutes, the reduction is 40% to 5,638 kWh/y saving 3,744 kWh/y and reducing the user value to 65kWh/y.

Table 2. Desktop computer electricity consumption (kWh) and proportionate representation applied to a 250 computer user group

Status	**Total Devices**	**Total Desktops**	**Total Displays**	**Total kWh/yr**	***New Desktops 1-3 years***					***Mid-point Desktops 4-5 years***				
					No.	*Stan. PM*	*kWh year*	*No PM*	*kWh year*	*No.*	*Stan. PM*	*kWh year*	*No PM*	*kWh year*
No KB	250	87	122	9,382	*56*	*44*	*1,036*	*12*	*497*	*18*	*14*	*589*	*4*	*571*
KB 30s	250	87	122	5,373	*56*	*44*	*985*	*12*	*262*	*18*	*14*	*491*	*4*	*130*
KB 3m	250	87	122	5,501	*56*	*44*	*993*	*12*	*264*	*18*	*14*	*505*	*4*	*134*
KB 6m	250	87	122	5,638	*56*	*44*	*1,000*	*12*	*266*	*18*	*14*	*519*	*4*	*138*
					Legacy Desktops >6 years					***Displays***				
					13	*10*	*834*	*3*	*763*	*122*	*97*	*2,387*	*25*	*2,707*
					13	*10*	*711*	*3*	*189*	*122*	*97*	*2,057*	*25*	*547*
					13	*10*	*729*	*3*	*194*	*122*	*97*	*2,120*	*25*	*564*
					13	*10*	*746*	*3*	*198*	*122*	*97*	*2,189*	*25*	*582*

As such, it is determined that within a standard 250 computer user group, the keyboard is capable of reducing desktop electricity consumption between 40-43% and 43-46 kWh/y per desktop computer user. As anticipated due to the prior energy measurement results, the displays consume 54% of the total electricity before the peripheral device is introduced. Consequently, at the most efficient setting, the display consumption is reduced by 49% compared to the 36% experienced across the desktop computers. As such, the results highlight the effectiveness of the keyboard when interacting with devices such as displays that are by nature of their use, subject to raised active (on) mode power draw and no idle mode capability [1].

The greatest annual use phase greenhouse gas emissions impact is experienced in the United States with a per user carbon footprint being 22.4% higher than the worldwide value and 43.5% higher than Europe. This is because adoption of non-fossil fuel energy infrastructure in the country trails global averages by 9% [23-25] with just 19.8% of electricity generation from renewables [71]. Without the keyboard in place, the annual emissions for the computer user group is 4,253 kgCO_2e/y generating 49 kgCO_2e/y per desktop user (table 3). Introducing the keyboard logically reduces emissions by the same percentages as experienced with the electricity consumption, creating a range of 40-43% annual abatement delivered by each incremental power management setting. Specifically, per 250 user group the range of abatement achieved is between 1,697-1,817 kgCO_2e/y reducing the per user value to 28 kgCO_2e/y. Considering that the United States was the first country to mandate public sector organisations must procure Energy Star certified computers [72] and continues to evolve both computer energy standards [65] and sustainable procurement programmes [73, 74], a reduction in concomitant emissions of 43% per year is arguably compelling. In context, whilst including homes as well as businesses, statistics indicate that 183m active desktop computers exist in the United States [67]. Additionally, manufacturing and shipping data indicates that 15.4m new desktops are purchased in the country each year [75]. As such, based upon the determined device age categories generated by this research, over 4-years will pass before sufficient new computers are purchased to replace the existing inefficient midpoint and legacy devices. Consequently, if an estimated 36% of desktop computers (table 2) are below the new 2021 44% reduced energy thresholds [65], then it is reasonable to suggest the 43% delivered by the keyboard may assist to bridge the excess power consumption and concomitant emissions gap in the mid-term [26]. From a European perspective, the standard use phase greenhouse gas emissions for the desktop computer group is the lowest of the three regional values at 2,965 kgCO_2e/y and 34 kgCO_2e/y per user due to high levels of renewable energy adoption within the region [63, 76]. As before the same percentage reductions are achieved due to the kWh equivalence, reducing the per user annual use phase emissions to as low as 19.6 kgCO_2e/yr. When applied to major European employment markets, the abatement delivered by the keyboard translates from being environmentally practical to something arguably quite significant. As an example, the United Kingdom Service Sector employs 16.1m people with 10.74m working in large companies and 5.37m in the public sector [69]. Representing over 50% of the country's total workforce (32.4m), statistics highlight that 67% of workers use an end user computing device as part of their job role [22]. As such, based upon the findings of this research, 3,743,089 desktop computers are active daily within this sector consuming 404,253,612 kWh of electricity per year. Using the country's greenhouse gas emissions factor [77], the use phase value is 85,835,169 kgCO_2e. Consequently, deploying the power management keyboard at its highest setting an abatement of 36,909,122 kgCO_2e could be achieved annually. This is equivalent to preventing almost 134m car miles from being driven each year [77] and releasing the sequestration capacity of over 44,000 acres of mature forest [78]. Similar to the United States, the abatement is relevant to existing and emerging legislation related to computer carbon footprint. This includes European mandates applicable to twenty-seven nations, requiring the public procurement of sustainable end user computing devices [79, 80] and ongoing efficient design improvements [66]. As an example, the United Kingdom service sector, is subject to greenhouse gas emissions reporting that includes scope 2 electricity purchased for use disclosure [81-83]. Recognising that the sector consumes 32% of all UK electricity with 10.4% attributed to the use of information technology solutions [21, 22], supplementary computer related policies have been introduced to abate the total carbon footprint [84]. The legislation requires end user computing device procurement to be underwritten by valid science based targets capable of supporting the government plan for net zero by 2050 [85]. As before, evidence of such an opportunity to reduce both existing and new desktop computing use phase emissions respond to this requirement. Arguably, as a keyboard must be purchased to operate a desktop computer then existing financial barriers determined to prevent the adoption of sustainable information technology in the service sector [59] are also removed. As an example, in the United Kingdom, the 87 desktop user group would avoid 20,045 kWh during a five-year device retention period, saving an estimated £2,806 in utility costs based on current values.

Table 3. Scope 2 GHG emissions (kgCO_2e) generated annually by 87 desktop computers in a 250 computer user group

Emissions	**Worldwide**				**United States**				**Europe**			
	No KB	KB 30s	KB 3m	KB 6m	No KB	KB 30s	KB 3m	KB 6m	No KB	KB 30s	KB 3m	KB 6m
GHG Total	3,472	1,938	2,036	2,086	4,253	2,436	2,494	2,555	2,965	1,698	1,739	1,782
Total Avoided		1,483	1,436	1,386		1,817	1,759	1,697		1,267	1,227	1,184
GHG Per User	40	22.9	23.5	24	49	28.1	28.7	29.5	34.2	19.6	20	20.5
Avoided Per User		17.1	16.6	16		20.9	20.3	20		14.6	14.1	14

Examining the worldwide average, indicates that logically this value produces a midpoint between the extremes. Without the keyboard in place, the annual use phase emissions for the user group are 3,472 kgCO_2e/y generating a per desktop user value of 40 kgCO_2e/y (table 3). As before the three settings reduce emissions by between 40-43% producing a best case scenario of 1,988 kgCO_2e/y and 22.9 kgCO_2e/y per user. Consequently, the abatement value per desktop and display combination is 17.1 kgCO_2e/y. Determining an exact number of desktop computers currently active in the world is beyond the scope of this research. However, statistics indicate that there are 1.25bn information workers in the world that require an end user computing device to carry out their job role [86]. Based upon the desktop proportionate representation, it is suggested that as many as 433,750,000 business desktop computers are currently in operation. As such, it is reasonable to also suggest that an annual worldwide abatement of concomitant use phase emissions of 7,417,125,000 kgCO_2e/y is theoretically achievable if the power management capable keyboard experienced universal adoption. In analogous context, such a reduction in pollution would free the sequestration capability of 8.9m acres of mature forest [78] covering a landmass greater than the entire Netherlands.

4. Summary

Since 1992, the success of the Energy Star programme is recognised as having reduced cumulative electricity consumption by 5 trillion kWh due to over 7bn billion certified products being sold [88]. Whilst evidently critical to delivering energy efficient products to both the commercial and home markets, this research identifies that post-sale factors will influence use phase computer electricity consumption and concomitant greenhouse gas emissions, thus diminishing the success of design led efficiency and power management capabilities. These influences include human-computer interaction impacts such retaining or improving upon standard power management settings. Plus, innovative impacts related to computers comparatively diminishing in energy efficiency with age. In context, desktop computers are highlighted as particularly exposed to such influences and therefore worthy of remedial intervention. This is because desktops consume between 3-5 times more energy per year than equivalent end user computing devices, such as notebooks [4, 5, 13, 44-48]. Specifically, this research finds that the average desktop and monitor combination proved to consume 108 kWh/y compared to notebooks consuming just 22 kWh/y [5]. As it is determined that desktops also exist in higher proportions within business environments than within the consumer market, and in all cases require a peripheral keyboard, the case for an alternative method of energy management that overcomes issues of speculative user inconvenience is strengthened. As the results highlight, the tested keyboard, capable of utilising radar technology to sense the presence of a user and switching a device to sleep when absent, certainly proposes a viable solution. Examining the desktop computer estate as a whole, the incremental reduction of both electricity consumption and concomitant use phase greenhouse gas emissions proved to be between 40-43% annually. Practically, as highlighted, adoption of the device is arguably self-funding as between 44-46 kWh of electricity consumption and associated cost is avoided per desktop user for every year that the keyboard remains in place. Strategically and environmentally, the peripheral certainly supports sustainable information technology approaches that contribute to corporate and social responsibility and environmental and social governance frameworks and policies. This is made possible by delivering annual incremental use phase greenhouse gas emissions abatement of between 14-20.9 kgCO_2e/y per desktop user (table 3) depending upon location of use. Additionally, the power management peripheral will also actively address the fact that, from 2021 onwards, the majority of legacy and a proportion of midpoint devices will no longer meet new efficiency certification [1] nor efficiency legislation [65]. As such, businesses can potentially compensate for existing desktop computer energy inefficiency shortfalls until necessary replacement or repurposing occurs. In addition, the same organisations will also reduce new desktop computer energy consumption by 35% (table 2) and offer an opportunity to achieve compliance with international computer procurement and use legislation and policies [65, 72-74, 79, 80, 84].

Whilst the research offers an impact example of a typical computer user install base of 250 employees to indicate the abatement achieved by a large company (table 3), the positive environmental impact is far greater when applied to large employment markets and the world's information workers as a whole. As determined, in the latter case, adoption of the keyboard at scale delivers a 43% reduction to worldwide desktop computing electricity consumption and concomitant emissions. Doing so, feasibly avoids annual greenhouse gas emissions pollution that would otherwise require a forest greater than the land mass of Holland. Theoretically, the capability of the keyboard to reduce electricity consumption and greenhouse gas emissions is not limited to desktop computers. As such, it is reasonable to suggest that the device would also benefit organisations with notebook users connecting to docking stations and larger peripheral screens. As an example, using data points from associated research [5], a MacBook Pro or Microsoft Surface Laptop 3 with dual 32" external displays will consume in the region of 155 kWh/y in a working environment whether that be in the office or at home. Applying the daily electricity reduction values generated in the measurement tests of 4.4% for the contemporary device and 12.5% for the displays, the keyboard would deliver an 11% total reduction in annual energy consumption and 6.3 kgCO_2e/y in use phase emissions per user. In this configuration, the values suggest that beyond desktop computers, the keyboard is also a viable proposition for organisations investigating sustainable information technology strategies for mobile workforces using peripheral displays.

Consequently, based upon the results of this research, it is reasonable to state that reducing computer electricity consumption and concomitant greenhouse gas emissions via the introduction of this energy management keyboard, represents a convenient and effective way in which to support the United Nations goal of examining technology and innovation to reduce ongoing societal emissions [26].

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