Preparatory study on the Review of Regulation 617/2013 (Lot 3)

Computers and Computer Servers

Task 3

Users

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Abbreviations

AC	Alternate Current
AVFS	Adaptive Voltage and Frequency Scaling
B2B	Business to Business
B2C	Business to Consumers
BAT	Best Available Techhnology
BOM	Bill of Materials
CCFL	Cold cathode fluorescent lamp
CPU	Central processing unit
DBEF	Dual Brightness Enhancement Film
DC	Direct Current
dGfx	Discrete Graphic Card
DFS	Dynamic frequency scaling
DIY	Do-it-yourself
DVS	Dynamic voltage scaling
EC	European Commission
EEE	Electrical and electronic equipment
EGA	External graphics adapter
EMEA	Europe, Middle East and Africa
EPA	Environmental Protection Agency (USA)
EPS	External power supply
ESOs	European Standardisation Organisations
EU	European Union
GPU	Graphics processing unit
HDD	Hard disk drives
iGfx	Integrated graphics processing unit
IPS	Internal power supply
JRC	Joint Research Centre
LCD	Liquid crystal display
LED	Light emitting diode
Li-ion	Lithium-ion battery
NiCad	Nickel-Cadmium battery
NiMH	Nickel-metal hydride battery
ODD	Optical disk drive
OS	Operating System
PCB	Printed Circuit Board
PRO	Producer Responsibility Organisation
PSR	Panel self-refresh
PSU	Power Supply Unit
RAM	Random access memory
RPM	Revolutions Per Minute
SME	Small and medium enterprise
SoC	State of charge of a battery

SRAM	Static RAM
SSD	Solid state drives
SSHD	Solid state hybrid drive
VR	Virtual Reality
WEEE	Waste Electrical and Electronic Equipment

3 Introduction to Task 3

Task 3 follows the MEErP methodology and aims to identify barriers and restrictions to possible ecodesign measures, due to social or infrastructural factors. It also aims to quantify relevant user-parameters that influence the environmental impact during product-life and that are different from the standard test conditions as described in Task 1. It includes the following sections:

1. Use patterns: Overview on the use patterns including frequency and characteristics of use.
2. Energy consumption data: Overview of the energy consumption patterns.
3. Standardised test methods: Discussion of potential standardised test procedures that could be used to support energy efficiency requirements on computers.
4. End-of-life behaviour: Discussion of the current state of play in terms of end of life options and practices.

3.1 Use patterns

Given the large divergence in the types of personal computers available on the EU market, use profiles vary significantly. This depends on the type of computer and their users, and their functionalities .

3.1.1 Frequency and characteristics of use

Personal computers often have a number of different states of operation called "power modes" or "power states". Table 1 shows a basic outline found in most personal computers. "On" is either when a computer is in active state where work is being performed, or in idle mode where no useful work is being performed. Power saving modes called "low power modes" are where the computer appears to be "off" but some basic functionality remains, such as the ability to quickly "wake" (i.e. power up) to an on mode on user command. Off states can range from the computer being able to wake, via user or network prompts (e.g. 'keyboards', 'mouse'), - to no functionality where the product is disconnected from a power source or completely switched off via a mechanical switch.

Table 1. Personal Computer Power States/Modes.

Computer Power States/Modes								
On modes					**Low Power modes**			
Active states			**Idle modes**				**Off states**	
Computational Intensity			Short Idle	Long Idle	Sleep	Hibernate	Off Mode	Mechanical Off
Maximum	<->	Low						

There are many factors that affect how computers are used, including the durations

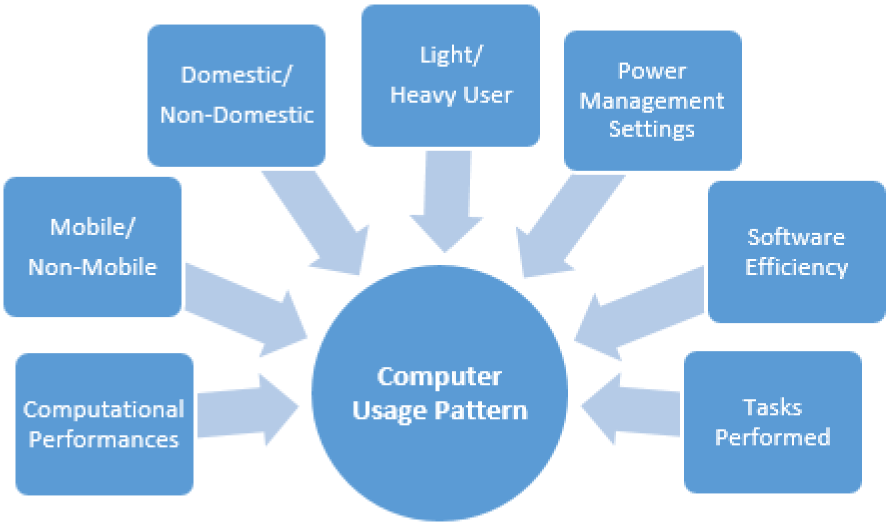

Figure 1 illustrates some of the factors that determine computer use patterns. The multi-faceted nature of computer usage means there are considerable differences in how computers are used, what they are used for and how long they are used for over a given period of time.

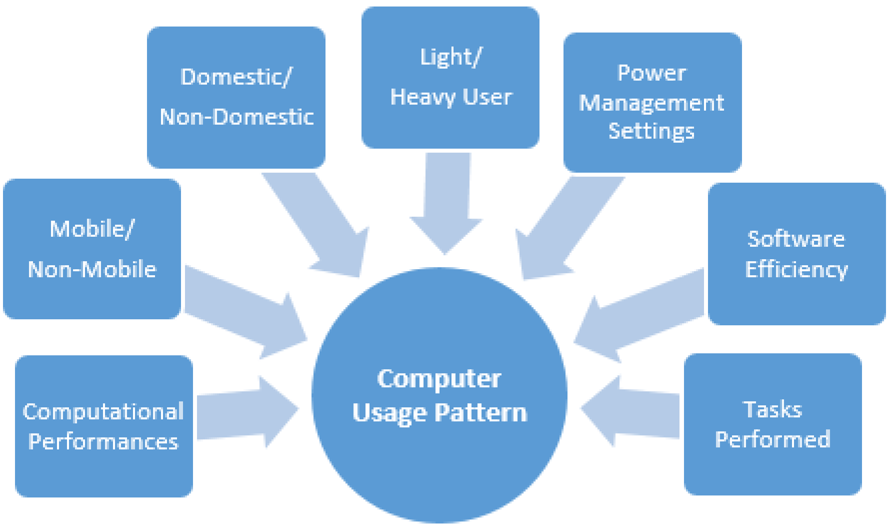

Figure 1. Some of the factors influencing Computer Usage Patterns.

The type of user is likely to be one of the most important factors dictating computer usage patterns. For example, a computer used by a domestic user will have very different usage profiles to a computer used by an office worker, which will affect the overall number of hours a computer is used. There is more variation in domestic than non-domestic use since office hours vary less than domestic leisure time, depending on the type of user (e.g. heavy or light user).

Whether a computer is designed for mobile or non-mobile use will also have a large impact on usage.

Mobile computers have integrated batteries to provide functionality for extended periods of time away from a mains power supply. The mobile nature of these products means that they are often used on battery power and then connected to a mains socket to recharge the battery.Mobile computers may have usage profiles similar to desktop computers when used permanently plugged, e.g. in a docking station, with or without an external display connected.

Some types of computers (e.g. tablets or low specification notebook computers) are used for relatively simple tasks such as web-browsing, checking email and use of office software. Other computers are more likely to be used for computational intensive tasks. The latter are more likely to spend additional time in an active state, because components have less opportunity to enter low power modes.

Power management functionality controls the ability to power down into low power modes after a period of user inactivity[1]). This functionality has been available for many years in most personal computers.

The power management settings on each personal computer have a large impact on the overall usage pattern. Where power management is not enabled computers will spend more time in "on" states. As such, power management enabling rates are an important factor in computer use profiles.

There have been many studies into the usage of the power management functionality. Some of these results suggest that power management is often not enabled (see Table 2),. Some of the studies are outdated but the most recent study shows that power management enabling rates are still low. The low enabling rates might be a result of user dissatisfaction with the functionality (e.g. wake up times are too long). Good quality power management that does not impact usability will result in higher enabling rates, and hence save more energy.

Table 2. Computer Power Management Enabling Rates.

Study	Number Computers Sample	Year	Power Management Enabling Rate
LBNL	1,453	2004	6%
California Energy Commission	119	2014	20%
Nordman et al	-	2000	25%
Georgia Institute of Technology	51	2009	53%

Newer power management technologies provide for significantly more control over power demand in personal computers. For example, some allow for CPUs to power down in millisecond intervals when not being used and more importantly, can also power up again in milliseconds. These power-down intervals are fast enough to allow CPUs to power down in-between keystrokes without impacting user behaviour. These more sophisticated types of power management can be found in smartphones and tablets.

Other fast reacting power management techniques are CPU frequency scaling, network interface power management, display dimming, adaptive brightness, hybrid sleep

[1] e.g. maximum 20 minutes as dictated in Commission Regulation No 617/2013

(combination of sleep and hibernation) and graphics CPU scaling (both discrete and on-board).

3.1.1.1 Desktop computers

Computers covered under the "desktop computer" definition encompass a wide range of functionalities, ranging from high specification gaming and graphics work to basic functionalities such as internet browsing and general office work. This divergent functionality causes divergences in the usage patterns. Desktop computers are also used in a wide variety of settings, such as homes and offices, which results in very different usage profiles.

Power management software settings and enablement rates also have considerable impacts on the usage profiles of computers. Where power management settings are not enabled more time will be spent in idle modes rather than in sleep or off modes.

It is not possible to identify a single set of usage profiles that accurately reflect the usage patterns of all desktop computers. Most studies into desktop computer use patterns arrive at different answers, being skewed by the type of desktop computers in their datasets and types of user surveyed (see Table 3).

Table 3. Desktop Computer – Published Usage Times [2].

Study	Average Usage (hours/day)	Average Usage (hours/year)	Average Standby Usage (hours/year)
Pixley et al (2014)	7.4	2716	6044
Desroches et al. (2014)	7.3 +2.3 / -1.9	2670 +840 / −690	-
Urban et al. (2014)	7.7	2789	2088
Zimmerman et al. (2012)	4.5	1649	3407
Urban et al. (2011)	9.4	3420	2150
Bensch et al. (2010)	11.2	4088	-
Ecma 383 (2010)	12.0	4380	2190
Microsoft (2008)	9.8	3574	-
Roth & McKenney (2007)	8.2	2990	330
Porter et al. (2006)	8.4	3066	5694
Chase et al. (2005)	9.2	3372	319

The results of a more recent use profile analysis within a German government department can be seen in Table 4. The results are separated into different user types and based on 203 work days per year. Using less working days would result in a lower total number of hours computers spend in on conditions compared to other studies.

Table 4. Desktop Computer – Usage Times German Study [3]

	Working Days	**Non-Working Days**

[2] Desroches et al, 2014, "Computer usage and national energy consumption: Results from a field-metering study" available from https://eetd.lbl.gov/sites/all/files/computers_lbnl_report_v4.pdf
[3] Prakash et al, 2016, "Ökologische und ökonomische Aspekte beim Vergleich von Arbeitsplatzcomputern für den Einsatz in Behörden unter Einbeziehung des Nutzerverhaltens (Öko-APC)" available from https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/endbericht_oko-apc_2016_09_27.pdf

Desktop	Active (Hours)	Idle (Hours)	Sleep (Hours)	Off (Hours)	Off (Hours)
High Use	5.0	2.5	2.5	14.0	24.0
Medium Use	3.5	2.5	4.0	14.0	24.0
Limited Use	2.0	2.5	5.5	14.0	24.0

ENERGY STAR, have developed average use profiles used across all types of desktop computer under all usage scenarios.[4] These are based on findings from a 2010 industry initiative into usage profiles across computers found in enterprise settings.(see Table 5),[5]. Given the large dataset used (i.e. over 500 computers), most initiatives focussing on the energy use of computers have adopted the ENERGY STAR use profiles.

Table 5. ENERGY STAR V6.1 Specification (Power Mode Use Times) - Desktop Computer.

Power Mode	% Time Spent in Each Power Mode	Use Hours Per Year	Eqv. Hours Per Day
Off	45%	3942	10.8
Sleep	5%	438	1.2
Long idle	15%	1314	3.6
Short idle	35%	3066	8.4
Total	100%	8760	24

ENERGY STAR use profiles assume that power management settings are enabled as required under the initiative, and so reflect a product that is "power managed". Products not power managed would spend considerably more time in the short or long idle. Furthermore, these use profiles do not address active states. The active states of computers have not been covered by any major energy efficiency initiative (apart from an intent to do so during the development of ENERGY STAR version 5). They have rather concentrated on increasing energy efficiency in idle, sleep and off modes, with most energy savings being expected from idle mode efficiency improvements. The lack of coverage of active state is likely due to several factors:

- There is often a strong correlation between computation performance and power demand. Setting stringent power demand limits on other modes only impacts functionality until a certain extent, as in these modes the main functionalities are not supported. Setting limits on active state does have the potential to do so.
- There is no one single "active state" in desktop computers. Active state describes any situation where a computer is providing additional functionality beyond that in an idle mode, so it ranges from simple tasks, such as displaying a single webpage, to complex tasks, such as a high definition game or providing ultra-high definition video playback.
- Power demands vary significantly depending on the task being delivered. Figure 2 shows the power demands of an EU ENERGY STAR registered desktop computer whilst performing a range of different tasks[6], which was tested as part of this project. The ENERGY STAR short and long idle power modes are shown on the graph for comparison. Power demand is highest when a simulated game play programme is run and lowest during simulated web-browsing (and between

[4] http://www.eu-energystar.org/downloads/specifications/Computers%20v6.1%20-%20CELEX_32015D1402_EN_TXT.pdf

[5] Standard Ecma 370, 2010, "Measuring the Energy Consumption of Personal Computing Products" http://www.ecma-international.org/publications/files/ECMA-ST/ECMA-383.pdf

[6] Desktop computer was purchased by the European Commission for ENERGY STAR compliance testing and then subjected to further performance power demand testing at Intertek PLC.

simulated exercises).Greater variability exists in active state power demands between different desktop computers which provide the same functionalities. Much, of this variability can be explained by the varying upper level of computational performance provided by a computer. While most desktop computers can provide the same relatively simple functionalities, some functionalities can only be delivered through higher performance computers.

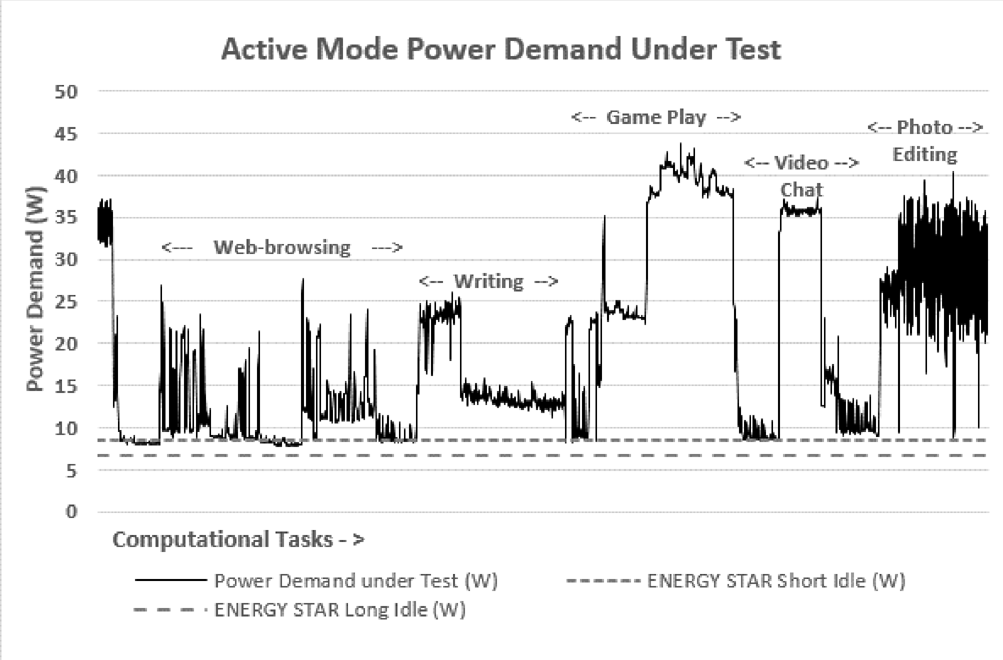

Figure 2. Active State Power Demands in an EU ENERGY STAR Registered Desktop Computer.

Table 6. Microsoft gathered desktop computer usage.

ACPI: Global states				
Power Transitions	**S0 Working**	**S3 Sleep**	**S4 Hibernation**	**S5 Off**
1 - 38 (25%)	62.9%	1.6%	0.3%	35.3%
38-116 (25%-75%)	34.7%	4.6%	0.7%	60.0%
116-246 (75+%)	30.8%	9.4%	1.1%	58.7%
Aggregate	***40.8%***	***5.0%***	***0.7%***	***53.5%***

Table 7. Desktop Computers Active State Share of "On Time".

Study	Year of Study	On Per day (Hours)	Active (Hours)	Idle (Hours)	Active (%)
ECOS	2008	10.3	7.2	3.12	70%
California Plug Load Research Center [9]	2014	7.4	3.8	3.6	52%
Kawamoto et al [7]	2004	6.9	3	3.9	43%
Ecma 383	2010	9.6	3.5	6.1	36%
Georgia Institute of Technology [8]	2009	18.1	1.7	16.4	9%

[7] Kawamoto et al, 2004, "Energy saving potential of office equipment power management", available from http://www.sciencedirect.com/science/article/pii/S037877880400101X

[8] Georgia Institute of Technology, 2009, "It's Not Easy Being Green: Understanding Home Computer Power Management", available from https://www.microsoft.com/en-us/research/wp-content/uploads/2009/04/chiHomePowerManagementchetty.pdf

This shows that desktop computers spend large amounts of time in active states and this has a large impact on the overall energy use. Therefore, active state is important to address in future ecodesign measures.

3.1.1.2 Integrated desktop computers

The usage patterns of integrated computers will closely mirror those of comparable desktop computers. Major initiatives such as ENERGY STAR consider the usage patterns of integrated desktop computers to be the same as those for desktop computers.

3.1.1.3 Notebook computers

The usage patterns of notebook computers will be heavily impacted by many of the same factors listed for desktop computers. Other factors include the length of time a product can be powered by internal battery and user practices around connecting the notebook to mains power. As with desktop computers, it is difficult to outline a single usage profile which accurately predicts the number of hours that notebook computers spend in each power mode. Table 8 shows the results from some studies done into notebook computer usage.

Table 8. Notebook Computer – Published Usage Times [9].

<table>
<tr><th>Study</th><th colspan="2">Average Usage (hours/day)</th><th colspan="2">Average Usage (hours/year)</th><th>Average Standby Usage (hours/year)</th></tr>
<tr><td rowspan="2">Desroches et al. (2014)</td><td rowspan="2">4.8</td><td>+3.5</td><td rowspan="2">1750</td><td>+1280</td><td rowspan="2">-</td></tr>
<tr><td>−2.5</td><td>−910</td></tr>
<tr><td>Urban et al. (2014)</td><td colspan="2">6.3</td><td colspan="2">2058</td><td>2202</td></tr>
<tr><td>Zimmerman et al. (2012)</td><td colspan="2">2.3</td><td colspan="2">832</td><td>554</td></tr>
<tr><td>Urban et al. (2011)</td><td colspan="2">9.4</td><td colspan="2">2915</td><td>2210</td></tr>
<tr><td>Bensch et al. (2010)</td><td colspan="2">10.4</td><td colspan="2">3796</td><td>-</td></tr>
<tr><td>Ecma 383 (2010)</td><td colspan="2">9.6</td><td colspan="2">3504.0</td><td>2190</td></tr>
<tr><td>Microsoft (2008)</td><td colspan="2">-</td><td colspan="2">2330</td><td>-</td></tr>
<tr><td>Roth & McKenney (2007)</td><td colspan="2">6.5</td><td colspan="2">2368</td><td>935</td></tr>
<tr><td>Porter et al. (2006)</td><td colspan="2">8.2</td><td colspan="2">2978</td><td>5081</td></tr>
<tr><td>Chase et al. (2005)</td><td colspan="2">8.1</td><td colspan="2">2968</td><td>437</td></tr>
</table>

The results of a more recent use profile analysis with a German government department can be seen in Table 9. The results are separated into different types of observed user types within the German government department and based on 203 work days per year. Based on the fact that notebooks are assumed to be used for 203 days a year, overall annual on time will be lower than in other studies.

Table 9. Notebook Computer – Usage Times German Study[10]

	Working Days				Non-Working Days
Notebook	**Active (Hours)**	**Idle (Hours)**	**Sleep (Hours)**	**Off (Hours)**	**Off (Hours)**

[9] Desroches et al, 2014, "Computer usage and national energy consumption: Results from a field-metering study" available from https://eetd.lbl.gov/sites/all/files/computers_lbnl_report_v4.pdf
[10] Prakash et al, 2016, "Ökologische und ökonomische Aspekte beim Vergleich von Arbeitsplatzcomputern für den Einsatz in Behörden unter Einbeziehung des Nutzerverhaltens (Öko-APC)" available from https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/endbericht_oko-apc_2016_09_27.pdf

	Working Days				Non-Working Days
High Use	3.5	2.0	2.5	14.0	24.0
Medium Use	2.5	2.0	4.0	14.0	24.0
Limited Use	1.5	2.0	5.5	14.0	24.0

Table 8 and Table 9 show that the reported use patterns of notebook computers vary considerably. The ENERGY STAR v6.1 specification contains average use profiles based on findings from the Ecma 383 standard development work (see Table 10), and therefore reflect usage patterns more likely to be seen in enterprise settings rather than domestic settings

Table 10. ENERGY STAR V6.1 Specification (Power Mode Use Times) - Notebook Computer.

Power Mode	% Time Spent in Each Power Mode	Use Hours Per Year	Eqv. Hours Per Day
Off	25%	2190	6
Sleep	35%	3066	8.4
Long idle	10%	876	2.4
Short idle	30%	2628	7.2
Total	100%	8760	24

No major energy efficiency initiatives currently address the time that notebook computers spend in active states. The lack of coverage of active states is likely due to the same complexities as described for desktop computers (i.e. difficulties in measurement, potential impact on functionality and perceived lack of time spent in active states). Table 11 shows the results of some studies, showing that there is no clear agreement on how much time a notebook spends in active states.

Table 11 – Notebook Computers Active State Share of "On Time".

Study	Year of Study	On Per day (Hours)	Active (Hours)	Idle (Hours)	Active (%)
ECOS	2008	3.8	2.4	1.4	63%
Ecma 383	2010	7.2	3.1	4.1	43%
Georgia Institute of Technology	2009	8.7	1.7	7	20%

3.1.1.4 Desktop thin clients

Desktop thin clients are almost entirely used by office workers in desk based office settings. The level of computational functionality is less diverse since servers provide the main computing functionality. Power management functionality and settings are likely to be the key impacts on usage patterns, given the relatively standard setting and functionality that is found in desktop thin clients.

Usage statistics for desktop thin clients are not readily available. Usage profiles will be similar to desktop computers in office environment given that they are desk based computers primarily used in offices. Indeed, the ENERGY STAR v6.1 specification assigns the same usage profiles to desktop thin clients as desktop computers.

3.1.1.5 Workstations

Workstation computers share a similar form factor to desktop computers in office environments and are mostly used in office settings. They are predominately used for specialist applications and primarily designed to support high levels of computational power. Because of this, there will be less variation in the types of workstation computer users and so less impact on usage profiles. However, the tasks assigned to workstation computers may still have a large impact on usage. There is a higher likelihood that these products will be left on continuously to process data without simultaneous human interaction since they are primarily used to assist with computational intensive tasks. As such, time spent in on states, especially in active states, could be higher for workstation computers than for desktop computers. Usage profiles will be impacted by power management settings, as with most personal computers.

Dedicated workstation computer use profiles are not readily available. The ENERGY STAR v6.1 specification assigns the use profiles shown in Table 12 to workstations. It is clear that there is an expectation that workstation computers will be in use more (i.e. be turned "on" more often) than desktop computers.

Table 12. ENERGY STAR V6.1 Specification (Power Mode Use Times) - Workstation Computer.

Power Mode	% Time Spent in Each Power Mode	Use Hours Per Year	Eqv. Hours Per Day
Off	35%	3066	8.4
Sleep	10%	876	2.4
Long idle	15%	1314	3.6
Short idle	40%	3504	9.6
Total	**100%**	**8760**	**24**

The active states of workstation computers are covered within many environmental initiatives, most notably ENERGY STAR through measurement of maximum power demand. However, the time spent in active state is not considered, as the ENERGY STAR specification simply encourages a reduction in power demand between maximum and idle modes.

3.1.1.6 Mobile workstation

Mobile workstations have the same form factor as notebook computers but have higher computational performances. Mobile workstations are designed to support activities which require a high degree of computing performance, as with desk based workstations. Given their mobile form factor, mobile workstations are more likely to have use profiles that are more similar to notebook computers rather than desk based workstations.

Mobile workstations are not defined as a separate product group under the ENERGY STAR v6.1 specification and as such are considered notebook computers.

3.1.1.7 Small-scale servers

Small-scale servers are desktop computer form factor products designed primarily to provide storage host functionality for other computers and to perform functions such as providing network infrastructure services (e.g. archiving, printer sharing) and hosting data/media. These products are designed to provide continual operation and so they remain "on". Although for small offices they may be turned off during off-hours.

3.1.1.8 External power supplies

External power supplies (EPS) are external devices used to convert mains electric current into DC current or lower-voltage AC current. EPS are mostly used to provide power and battery charging for mobile products but are also used with an increasing number of non-mobile computers such as desktop and integrated desktop computers. The usage profile of EPS will depend on the use of the computer in which they are used to power. For example, an EPS that is primarily attached to an integrated desktop computer will be operational for similar periods of time as the computer. There will be some variance in EPS operation due to the different power demands placed on them during operation. That is, when a computer is actively conducting work it will draw more power through the attached EPS, but when in a low power mode, such as sleep, then power demanded through the EPS will be low.

Typical EPS use for notebook computers comprise:

- battery charging during normal use of notebook
- normal use of notebook with only trickle charging (after battery has been re-charged)
- battery charging only with notebook switched off

3.1.1.9 Internal power supplies

Internal power supplies (IPS) are included within the housing of some non-mobile computers and are used to convert mains electric current into dc current or lower-voltage ac current at one or more voltage levels. As an integral part of many computers, IPS will mirror their usage profiles. The amount of power drawn through an IPS will impact the load placed on the IPS and hence change efficiencies. Where IPS are oversized (i.e. rated output is higher than needed), the load placed on IPS will frequently be lower and further negatively impact efficiency.

3.1.1.10 Discrete Graphics Cards

Discrete graphics cards (dGfx) are included in some computers where greater graphics performance than what available via an integrated graphics solution (iGfx) is required. The usage of dGfx will be highly dependent on how the graphics solution is implemented within the system. For example, in some notebook computers and integrated desktop computers, dGfxs are used alongside iGfxs with switching between the two. The main purpose of this "graphics switching" or "hybrid graphics" technology is to allow for usage of lower powered iGfx's when only low graphics performance is required, switching to dGfx's when greater functionality is required… Some notebook computers with switchable/hybrid graphics will always run the dGfx when connected to mains power and then the iGfx when the notebook is running on battery power. The amount of time a computer with hybrid/switchable graphics will spend using the dGfx will be highly dependent on user preferences, user activities and switchable/hybrid graphic automatic settings.

3.1.1.11 Internal storage

Most personal computers include internal storage devices to permanently save data (non-volatile memory). Whilst most computers only have one storage device it is increasingly common to have more. This often takes the form of the OS on a small, fast storage device with a larger storage device used for saving additional data. The main types of storage devices are detailed below.

Hard Disk Drives (HDD)

HDDs are the oldest and still least expensive (per unit of storage space) type of non-volatile storage device. The size of magnetic platters currently in the market varies with

3.5 inch HDDs primarily used in desktop computers (and other similar non-mobile personal computers) and 2.5 inch HDDs used in notebook computers. HDDs come in a range of rotational speeds normally ranging from 5,500 revolutions per minute (RPM) to 10,000 RPM. The spin rate influences access times and transfer rates. Generally, the higher the spin rate, the higher the energy use. The size of the platter also impacts energy performance, with smaller diameter (i.e. 2.5 inch) HDDs usually demanding less power. Power demand also increase with each platter included in a HDD due to the need for extra componentry.

Power demand is generally reduced through increasingly powering down parts of the HDD, starting with part of control circuitry, then reducing platter spin rate and then finally stopping spinning completely.

Rewakening a HDD takes time. For this reason, primary HDDs do not tend to power down into their lowest power states unless the associated computer is in a low power state. This would increase waiting times for the user before the HDD can be accessed. The IEC 62623 computer energy measurement standard used as the basis for the ENERGY STAR v6.1 computer specification, requires that an HDD, if present, is not allowed to enter low power states (i.e. the disk must remain spinning) during short idle measurements HDDs and it may spin down only in long idle and lower power modes. As such, primary HDDs are likely to remain in an active, or a high degree of ready state when computers are in a short idle state but may be in a reduced state of ready in long idle. Further powering down of HDDs should occur when computers are in sleep and off modes.

Some high end personal computers and workstations contain more than one HDD. Most major operating systems allow for these additional HDDs to be powered down when the computer is on but the HDD is not used for a while. This therefore allows for reduced power demand without major impact on user experience. IEC 62623 standard does not explicitly cover additional HDDs so it is unclear whether secondary HDDs in ENERGY STAR qualified products are power managed in idle modes or not. For non-ENERGY STAR products, it is also unclear to which extent power management functionality is used for additional HDDs beyond the first.

Solid State Drives (SSD)

SDDs are now common in laptops[11] or higher end desktops and workstations. Rather than using mechanically spun platters to store data, SSDs use flash memory and as such have no moving parts. SSDs offer faster read and write data speeds as well as reduced power demands.

SSDs provide enhanced power management capabilities compared to HDDs, as they support low latency times (i.e. the time it takes a product to wake from a low power mode to full functionality). Low latency allows SSDs to enter low power modes and then return to full functionality without impacting user experience. As such, the usage profile of an SSD, with power management functions enabled, will be different to that of a primary HDD, as they will spend more time in lower power modes.

Solid-State Hybrid Drive (SSHD)

SSHD typically contain a relatively small SSD, alongside a larger HDD. They combine the cheap, vast storage of a HDD with the speed and efficiency of flash storage, with the

[11] Some vendors, such as Apple, include already exclusively SDDs in laptops.

operating system automatically and smartly moving files from the hard drive to the flash storage as needed to make those files instantly accessible.

Usage patterns of SSHDs will again depend on how often the drive is used and for what purposes. SSHDs are becoming common in desktop computers and workstations. The IEC 62623 standard does not specifically address how SSHDs should be configured under test. However, SSHDs contain HDDs and the standard states that HDDs should not be spun down under short idle testing conditions. As such, it is likely that under ENERGY STAR testing conditions SSHDs will show similar usage profiles to HDDs.

3.1.1.12 Power management enabling rate and other user settings that influence energy consumption and efficiency

Amongst the most important settings that users can impact are power management settings. As previously shown, power management settings may not always be optimised, even though most energy efficiency initiatives include requirements on power management settings and the benefits are widely communicated.

Despite power management requirements being included in many initiatives, it is likely that some users change settings because of poor experience. Detailed studies have been conducted into user acceptance of power management settings in personal computers, showing that non-optimised power management settings often annoy users, leading to settings being changed or disabled.[12,13] The published research also claims that presence detection technology (i.e. identifying when the user is no longer in front of the computer) can help to improve acceptance of power management and increase overall energy savings.

While it is easy for most users to alter system level power management settings, advanced power management functionalities that control power states of individual components is more complex. For example, many CPUs support advanced automatic power management functionality that allows CPUs to draw very little power (e.g. when in a C7 State) when no processing is being undertaken. When this functionality is enabled, access to the BIOS (basic input/output system) is needed to make changes. Only settings that can be safely adjusted via a graphical interface at operating system level are used by most people.

Users can also alter the usage characteristics and energy use of products through other settings and activities. For example, integrated displays in notebook and integrated desktop computers are often shipped at a luminance level (minimum 90 and 150 cd/m^2 under ENERGY STAR v6.1 test conditions for notebook and integrated desktop displays respectively) below their brightest possible setting. If users increase the luminance levels of integrated displays, then overall energy used by the product can increase significantly.

Similarly, users may install programs and plug-ins that stop computers from powering down into low power modes (e.g. screen savers).

Power management settings can also be impacted by software that is installed to support distributed computing and grid computing projects. That is, there are a wide range of

[12] Schuchhardt et al, 2012, "Understanding the Impact of Laptop Power Saving Options on User Satisfaction Using Physiological Sensors", available from http://empathicsystems.org/Papers/islped12.pdf
[13] Tarzia et al, 2009, "Display Power Management Policies in Practice", available from https://stevetarzia.com/papers/DPM_icac10.pdf

projects that seek to use spare processing power of individual personal computers in a distributed system in order to process large amounts of data.

Many computers have fans to draw air through vents to facilitate internal component cooling. When vents are obstructed the fans do not provide useful work and even increase energy use because of increased speed and usage. One of the main causes of cooling inefficiency is dust built up on fans, fan vents and different internal components that need to be cooled. Dust build up is consequently a cause of increased energy use, fan noise and potential shortening of product life through overheating of internal components.

3.1.2 Impact of load on power supply efficiency

Converting AC to DC results in efficiency losses varying according to the energy efficiency of the PSU rating and the level of loading. The loading level is the ratio between demanded power and the total maximum amount of power that can be supplied by a PSU (i.e. rated output power). Typically, PSU efficiency reduces as loading reduces.

The efficiencies of most EPS used with personal computers that are placed on the EU market are already covered by an ecodesign regulation[14]. However, EPSs with a rated output power exceeding 250W, or those that are able to convert to more than one DC or AC output voltage at a time, are not covered.

3.1.2.1 Internal power supplies

IPS efficiency is covered under the EU ecodesign regulation on computers and computer servers[15], which were adopted from the 80PLUS programme[16]. This programme includes a tiered set of six efficiency requirements - from 80PLUS to Titanium - reflecting increasing energy efficiency (see Table 13).

The different loading rate points (10%, 20%, 50%, 100%) reflect the load curve and the corresponding efficiencies, recognising that IPS efficiencies are lower when loading rates are low. This is because conversion efficiencies decrease as loading rates decrease. This is problematic for desktop computers which exhibit low loading levels during idle modes.

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[14] Commission Regulation (EC) No 278/2009 of 6 April 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for no-load condition electric power consumption and average active efficiency of external power supplies, available from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009R0278

[15] Commission Regulation (EU) No 617/2013 of 26 June 2013 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for computers and computer servers, available from http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32013R0617

[16] Ecova Plug Load Solutions, 80PLUS programme, available at http://www.plugloadsolutions.com/80PlusPowerSupplies.aspx

Table 13. 80 PLUS Certification IPS Efficiency Requirements.

80 PLUS Certification	230V EU Internal Non-Redundant			
% of Rated Load	**10%**	**20%**	**50%**	**100%**
80 PLUS	---	82%	85%	82%
80 PLUS Bronze	---	85%	88%	85%
80 PLUS Silver	---	87%	90%	87%
80 PLUS Gold	---	90%	92%	89%
80 PLUS Platinum	---	92%	94%	90%
80 PLUS Titanium	90%	94%	96%	94%

Figure 3 shows the average short and long idle IPS loading rates found in desktop computers within the EU ENERGY STAR database[17] - as measured according to the ENERGY STAR test method, showing that IPS loading rates are often far below 10% of the rated output power of the IPS. It is also clear that as IPS rated output increases there is a general trend towards lower loading rates during idle modes.

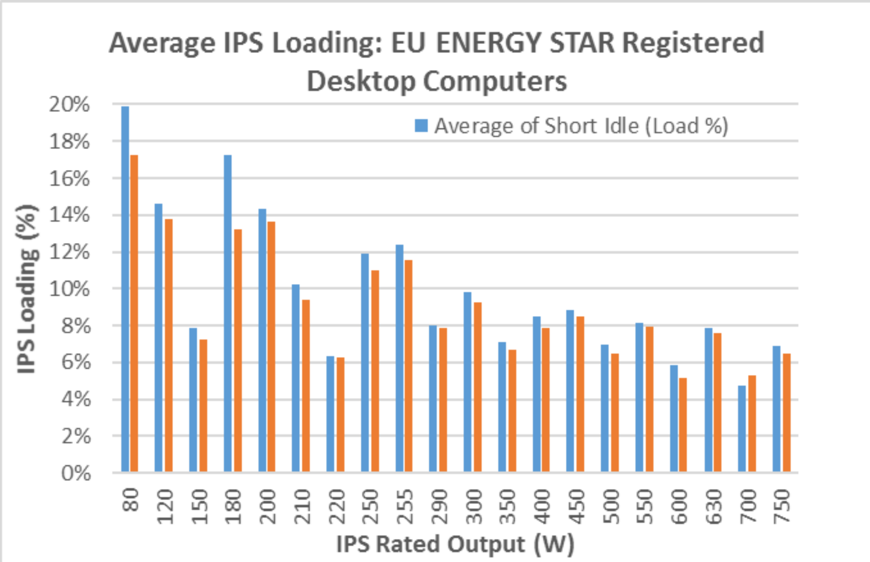

Figure 3. Average IPS Loading Rates seen in EU ENERGY STAR Desktop Computers.

Figure 4 illustrates the spread of efficiencies seen at different load levels for the most popular types of IPS registered with the 80PLUS scheme (i.e. restricted to products tested at the EU electricity voltage and frequency combinations of 230v/50Hz)[18]. The results show that there is a wide range of efficiencies across all loading factors and rated output powers. It is also clear that efficiency at 10% loading is significantly lower than efficiencies at other higher loading points. IPS efficiencies fall even lower when loading is below 10%.

[17] EU ENERGY STAR Database (July 2016) available at http://www.eu-energystar.org/db-currentlists.htm
[18] Ecova Plug Load Solutions, 80PLUS Certified Power Supplies and Manufacturers (230v EU Internal), downloaded 23rd July 2016 from http://www.plugloadsolutions.com/80PlusPowerSuppliesDetail.aspx?id=0&type=4

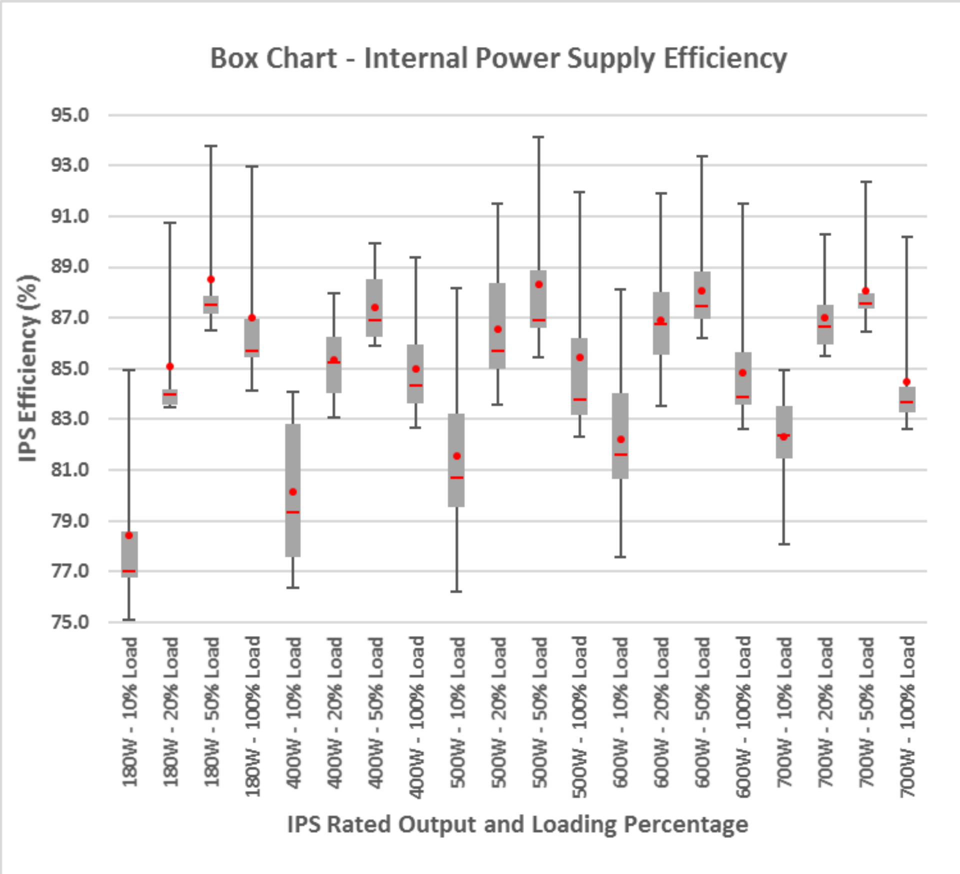

Figure 4. Average IPS Loading Rates seen in EU ENERGY STAR Desktop Computers.

Table 14 illustrates IPS efficiencies at a range of loading factors, including loading factors below 10%.[19] IPS efficiency is shown to be very low across almost all tested products when loading falls below 10%. The ENERGY STAR and 80PLUS datasets show that significant amounts of energy are being wasted whilst computers are in idle modes. IPS loading rates are often far below 10% of the rated output power of the IPS. Significant amounts of energy are being wasted whilst IPS loading rates are low.

[19] Douglas McIlvoy Results from laboratory testing for the performance of desktop-computer power supplies operating at minimal loading, available from http://docketpublic.energy.ca.gov/PublicDocuments/14-AAER-02/TN210102_20160130T110353_Douglas_McIlvoy_Comments_Results_from_laboratory_testing_for_th.pdf

Table 14. 80 PLUS Certification IPS Efficiency Requirements.

Sample #	Rated Power	80 PLUS Badge Level	Loading							
			6W Load	1%	3%	5%	10%	20%	50%	100%
1	200	Bronze	58.0%	37.5%	58.2%	67.5%	77.0%	83.3%	86.6%	83.8%
2	300	Standard	53.4%	41.9%	59.1%	65.6%	74.4%	81.6%	85.3%	83.5%
3	350	Bronze	52.8%	43.7%	61.8%	67.0%	77.1%	83.5%	86.6%	85.3%
4	350	Platinum	56.9%	45.2%	69.7%	77.8%	86.1%	91.0%	92.5%	90.2%
5	400	Bronze	59.9%	53.5%	68.3%	74.2%	81.4%	86.1%	87.6%	84.7%
6	400	Bronze	47.7%	37.9%	60.5%	69.9%	79.2%	84.5%	86.8%	85.1%
7	450	Gold	42.0%	35.7%	61.2%	71.5%	83.6%	88.6%	90.8%	88.1%
8	450	Standard	32.5%	27.9%	50.5%	61.7%	73.7%	81.4%	84.9%	82.5%
9	500	Titanium	35.0%	38.9%	83.1%	87.7%	92.0%	94.1%	94.2%	91.9%
10	500	Bronze	44.8%	40.3%	65.0%	73.8%	82.7%	87.2%	88.2%	83.7%
11	500	Bronze	43.2%	40.3%	61.8%	69.7%	79.3%	84.4%	86.3%	83.2%
12	500	Gold	43.8%	43.6%	50.5%	71.0%	83.4%	89.3%	90.8%	88.4%

3.1.2.2 External power supplies

EPS are covered by a separate ecodesign regulation[20]. However, it is important to consider these products within this project due to potential material savings from encouraging the use of common connection types. An example of a common connection type is the USB Type-C socket which facilitates USB based EPS for use with computers will likely become popular over the next few years.

Figure 5 and Figure 6 below show the EPS loading rates at short and long idle for products registered in the US ENERGY STAR database. The results show that EPS loading rates during short and long idle are relatively low, except for products with small EPS. Figure 7 and Figure 8 show that the spread of EPS efficiencies is smaller than as seen in IPS.

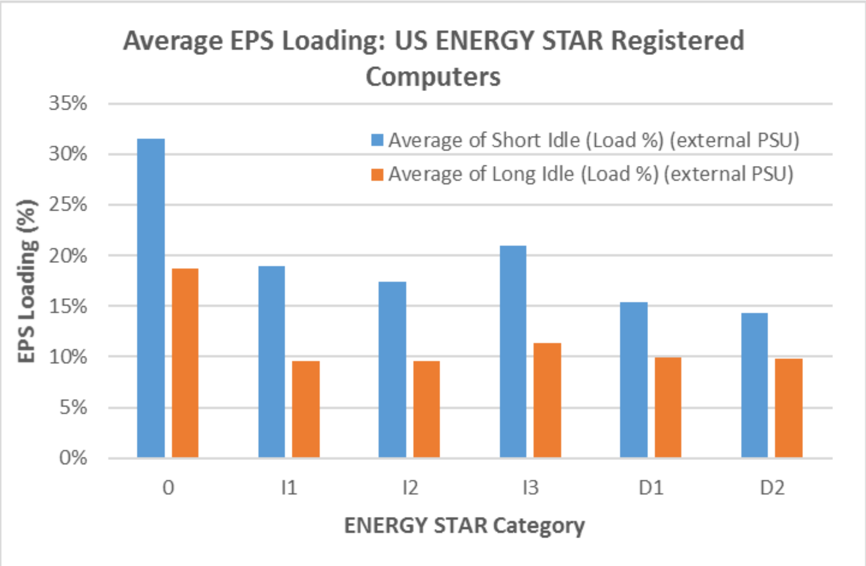

Figure 5. Average EPS Loading Rates seen in US ENERGY STAR Computers (per category).

[20] COMMISSION REGULATION (EC) No 278/2009. ecodesign requirements for no-load condition electric power consumption and average active efficiency of external power supplies. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:093:0003:0010:EN:PDF

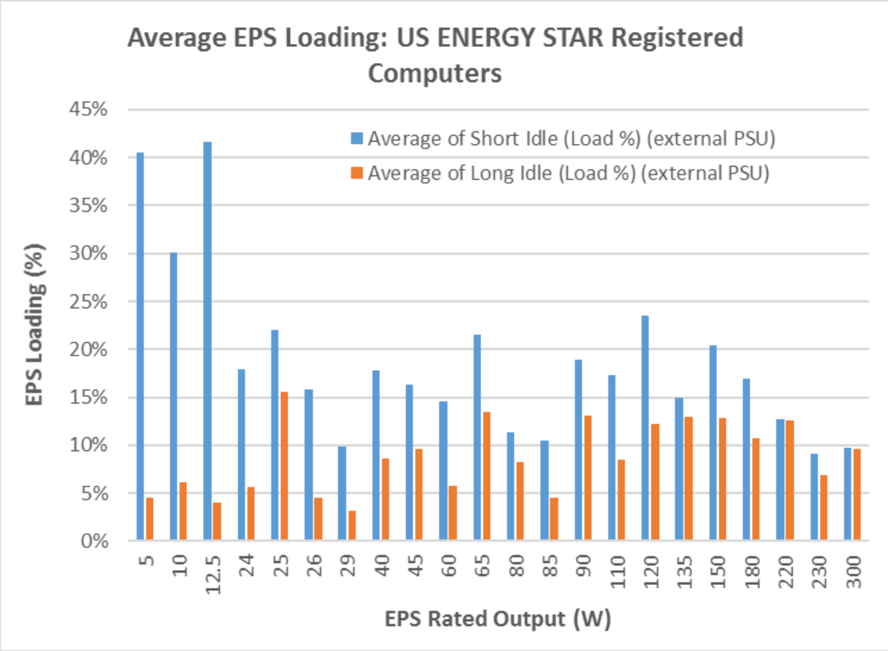

Figure 6. Average EPS Loading Rates seen in US ENERGY STAR Computers (per EPS rated output).

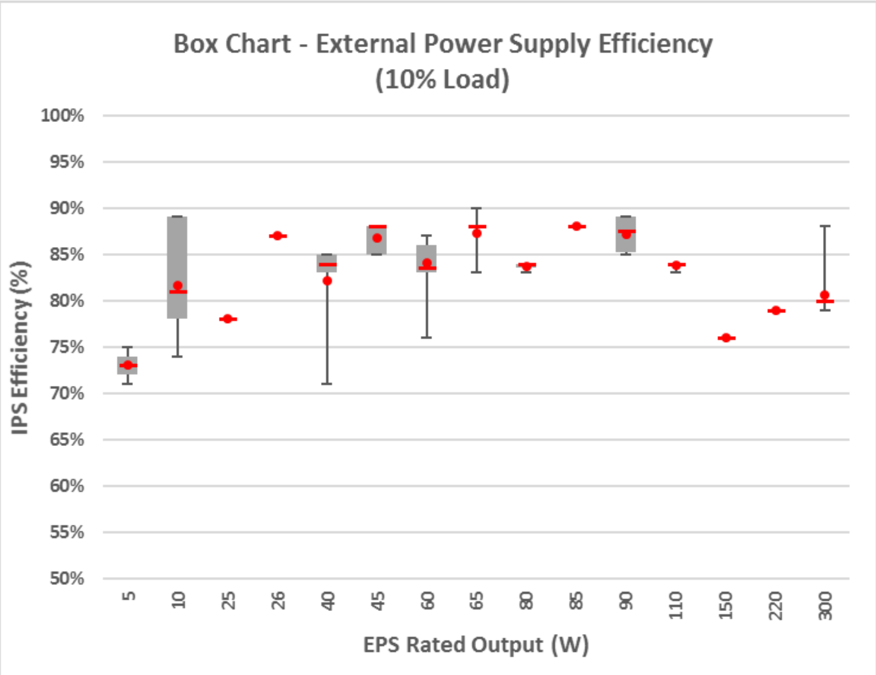

Figure 7. Distribution of EPS Efficiency at 10% Load in US ENERGY STAR Computers (per EPS rated output).

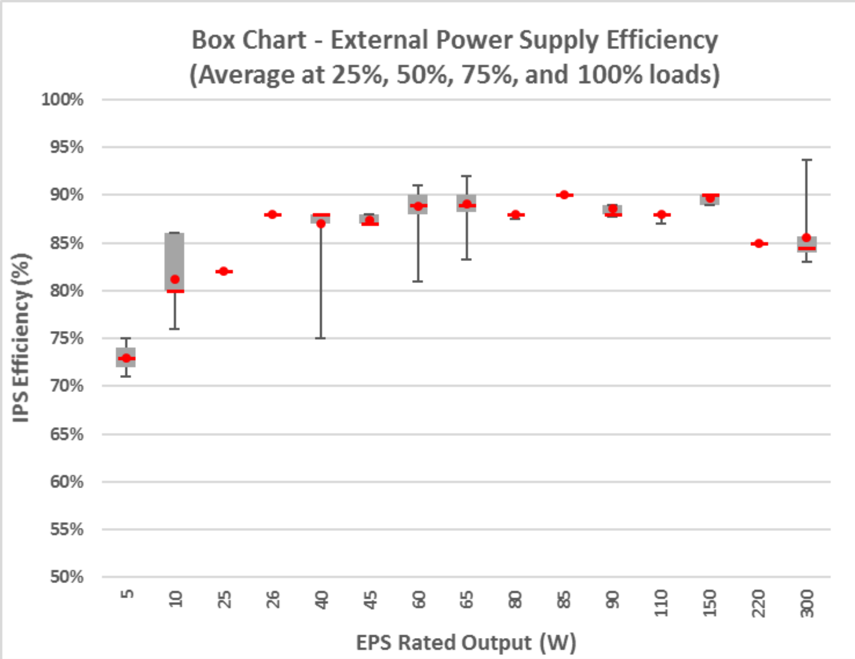

Figure 8. Distribution of Average EPS Efficiency in EU ENERGY STAR Computers (per EPS rated output).

3.1.3 Auxiliary products used during usage

Auxiliary products are important since they affect the energy consumption of personal computers.

There are a large number of auxiliary products that may be attached to personal computers during use. These range from low power devices, such as keyboards and mice, to higher power demanding devices such as external displays and external graphics card adapters. The extent to which these auxiliary products impact computer energy use is dependent on many variables such as user type, auxiliary product type and connected product type. The amount of energy used by auxiliary products is also highly variable depending on product type and usage patterns. Table 15 illustrates example power demands of some common auxiliary products, with the data suggesting that power demand of many auxiliary products is low.

Table 15. Measured Power Demand of Example Auxiliary Devices. [21,22]

Auxiliary Device	Estimated Power Demand During Use (mW)
Mouse (Bluetooth)	67
Memory Stick (16MB)	150
Headset (average)	546
Card Reader	950
Webcam	1080
DVB-T TV Box	1365
Portable SSD (2TB)	2345
Portable SSD (1TB)	2037
USB flash drive (120GB)	2542
USB flash drive (128GB)	792

Many of the highest power demanding auxiliary products, such as some external graphics adapters, have their own PSU, because their power demand is too high to be delivered via a connection from an attached computer. Table 16 shows the PSU sizes for some of the most common external graphics adapters.

Table 16. External Graphics Adapters' PSU size.

External Graphics Adapters	PSU Size (W)
EGA 1	680
EGA 2	500
EGA 3	450
EGA 4	400

As mentioned above, the power demands of auxiliary products that are connected to a personal computer are constrained by the amount of power that can be delivered via a connection. Table 17 provides examples of common personal computer connections, maximum supported output power, maximum data bandwidth and the year in which the connections were first used in computers placed on the market.

The amount of power demand supported through connection types has grown in recent years. The relatively new Thunderbolt 3 connection type, which can be delivered via a USB Type C socket, can provide up to 100W of power for product charging (e.g. charging of a notebook via a wall socket) and up to 15W to auxiliary products. The increasing amount of power demand that is supported could diminish the incentive to decrease power demand from auxiliary products.

[21] Harald Thon, 2015, Squeezing More Life Out of Your Notebook's Battery Part II, available from http://www.tomsguide.com/us/squeezing-more-life-out-of-your-notebook,review-583-26.html
[22] Ganesh, 2016, USB Flash Drives - Power Consumption Measurement using Plugable's USBC-TKEY, available from http://www.anandtech.com/show/10163/usb-flash-drives-power-consumption-measurement-using-plugables-usbctkey/3

Table 17. Common Personal Computer Connection Types, Supported Power Output, Data Bandwidth and Year Released.

Connection Type	Connection Socket Type	Max Supported Output Power (W)	Max Bandwidth (Gbit/s)	Year Released
HDMI 2.0	HDMI connectors	0.275	18	2013
DVI	DVI connector VGA connector	0.25	7.9	1999
DisplayPort (1.3)	DisplayPort Connector USB Type-C	8/**100	32.4	2014
Thunderbolt 2	Mini DisplayPort	10	20	2013
Thunderbolt 3	USB Type-C	15/100*	40	2015
USB 3.0	USB Type-A USB Type-B USB Type-C	4.5/25/**100	4	2008
USB 3.1		4.5/25/**100	10	2013
* when USB Power Delivery (2.0) implemented; up to 100W system charging and 15W to bus-powered devices				
** when USB Power Delivery (2.0) implemented				

The amount of bandwidth supported by computer connections may have a large impact on the type of auxiliary products used with computers and consequently increase energy use. Relatively new connections, such as Thunderbolt 3 and USB 3.1 support a large amount of data bandwidth which in turns facilitates the use of auxiliary products, such as external graphics adapters, which require large amounts of data throughput. The usage of external graphics adapters has been somewhat restricted by the amount of available bandwidth, but with this restriction lifted there is a possibility of a growth in these types of auxiliary products. This growth may be encouraged by the ability of external graphics adapters to support very high graphics capabilities without impacting the battery life of an attached notebook. That is, users can choose to have a large amount of graphics functionality, only when required, simply by connecting an external graphics adapter (with included discrete graphics card) into their notebook computer (or desktop computer). This allows users to purchase notebook computers with less powerful graphics solutions (e.g. integrated graphics) and to rely on external graphics adapters for added graphics support. This has the potential to increase overall energy use, as external graphics adapters will use desktop external graphics cards which are less efficient.

As can be seen in Table 17, there is some standardisation of common connection types occurring in personal computers with the uptake of the USB-Type C connection socket being used to support different connection standards. It has been shown that the USB Type-C sockets can be used, alongside a suitable connection standard, to provide up to 100W for the purposes of charging a personal computer. This suggests that if standard charger is encouraged manufacturers could avoid placing on the market new EPS with new computers under the assumption that purchasers already had a suitable EPS. This could be relevant in terms of material savings and reduced electronic waste.

In 2009, the European Commission facilitated an agreement among major mobile phone manufacturers to adopt a common charger for products sold in the EU[23]. Many of the major phone manufacturers agreed to adopt a universal charger, based on the micro-

[23] European Commission, Campaign for the introduction of the voluntary agreement (MoU) for a common charger for mobile phones, available at https://ec.europa.eu/growth/sectors/electrical-engineering/rtte-directive/common-charger_en

USB connector. A study conducted in 2014 suggested that the anticipated savings in raw material consumption did not appear to have materialised as manufacturers still shipped new chargers with new phones[24]. Indeed, it was shown that only 0.02% of EU mobile phone shipments from 2011 to 2013 were supplied without a mains charger but there had been a reduction in sales of EPS, saving an estimated 400 to 1,300 tonnes of raw materials.

The study briefly investigated the opportunity to promote standard connections in notebook computers to reduce the number of EPSs placed on the EU market. The micro-USB and USB Type-C connections, with USB Power Delivery implemented, were investigated as potential targets for promotion as standardised connections. The study concluded that due to the diverse nature of notebook computers on the EU market, standardisation of connections and power supply units would be complex. It was suggested that the micro-USB connector would not be suitable for use in notebook computers due to lack of physical robustness and its inability to support large power demands. It was further noted that the USB Type-C connector, with implemented USB Power Delivery, could provide potential for standardisation in connectors and chargers. However, it was further noted that USB Power delivery supports power demands of up to 100W but that some notebook computers have EPS's with output power ratings above 100W. A review of the US ENERGY STAR database (which holds rated output power data for EPS used with notebook computers) suggests just over 12% of notebooks have EPSs with rated output power demands above 100W. As such, approximately 88% of US ENERGY STAR registered products could, theoretically, use standardised EPS based on the USB Type-C connector with USB Power Delivery implemented in the notebook.

The savings potentials that could be achieved through standardisation of USB Type-C EPS need to take into account the potential efficiency losses through the use of non-bespoke EPS. Notebook computers are normally placed on the market with EPS that are tailored to that particular product. For example, the rated output power of EPS will reflect the expected maximum power demand of the notebook. Using an EPS with a higher power output rating than required by a notebook could result in efficiency losses due to lower loading levels at idle. In addition, the efficiency levels of USB EPSs available on the market can vary considerably. Table 18 illustrates the results of some informal average active efficiency testing on low voltage USB EPSs[25]. The results show that the efficiency of most manufacturer EPSs can be higher than non-branded USB EPSs available on the market. Whilst it is not certain that larger USB Type-C based EPS efficiencies would follow a similar pattern.

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[24] Study on the Impact of the MoU on Harmonisation of Chargers for Mobile Telephones and to Assess Possible Future Options Final Report (Main Report) prepared for DG Enterprise and Industry 22nd August 2014 , available from https://ec.europa.eu/growth/sectors/electrical-engineering/rtte-directive/common-charger_en

[25] Shirriff, 2012, "*A dozen USB chargers in the lab*", available at http://www.righto.com/2012/10/a-dozen-usb-chargers-in-lab-apple-is.html#ref11

Table 18. Example USB EPS Average Efficiency under Load.

USB Charger Source	Average Efficiency under Load (%)
OEM (branded)	80
	78
	77
	76
	75
	74
	72
	69
	66
After Market (non-branded)	66
	63
	63

3.1.4 Noise levels

The amount of noise emitted by computers varies significantly and it is caused by components such as fans, hard disks and optical disk drives. In general, computer noise levels are normally not a major concern unless a large number of computers are used within a relatively small office space or users have particular requirements for low noise level.

The ecodesign regulation 617/2013 requires that manufacturers report the noise levels (the declared A-weighted sound power level) of computers in scope. Table 19 illustrates some examples manufacturers reported. A conversational whisper would equate to a sound power level of approximately 5(B), showing that the noise levels for each type of computer are not very high.

Table 19. Example Reported Noise Levels under ecodesign regulation 617/2013 Declarations.

Declared A-weighted sound power level LWAd (B)		
Power mode	**Idle**	**Operation**
Workstation	4.1	4.1
	3.0	3.2
	3.8	4.5
Desktop	2.9	2.9
	3.6	3.6
	3.8	3.9
Notebook	2.7	4.6
	3.4	4.0
	3.1	3.4
Tablet	2.2	2.3
	2.5	2.5
	2.7	2.7

3.1.5 Replacement parts during maintenance and repair practices

Although computers do not use consumable parts, there are a number of components that are routinely replaced or repaired during the useful computer lifetime.

3.1.5.1 Batteries

Most types of mobile computers contain at least one type of battery, and can range from small button cell batteries (i.e. complementary metal-oxide-semiconductor -CMOS- batteries) used to maintain settings on BIOS memory, to larger batteries that support operation of mobile computers. CMOS batteries typically last up to ten years and therefore replacement is infrequent. Main power providing batteries, typically based on lithium-ion technologies, degrade in performance over time/use and so it is not unusual to change them at least once during the life of a computer.

Degradation of lithium-ion batteries occurs due to chemical changes on the electrodes and is characterised by a reduced ability to hold a charge (i.e. stored electricity). This degradation varies across different battery technologies, but is always due to either age of the battery (i.e. "calendar loss") or due to the number of charge/discharge cycles (i.e. "cycle loss") and the associated heating. The current EU ecodesign regulation on computers includes an information provision requirement for manufacturers to report the minimum number of loading cycles that the batteries can withstand.

The environmental impacts associated with batteries used in computers are addressed by the EU Batteries Directive[26]. The Directive includes restriction of some hazardous substances and establishment of schemes for collection and recycling and targets for collection and recycling activities. It also states that manufacturers should design appliances in such a way that waste batteries can be readily removed by either the end user or, failing that, by qualified professionals that are independent of the manufacturer. The EU Batteries Directive also states that if "*for safety, performance, medical or data integrity reasons, continuity of power supply is necessary and a permanent connection between the appliance and the battery or accumulator is required*", then manufacturers may still include batteries that cannot be replaced by end users or non-manufacturer related professionals.

The current EU ecodesign regulation on computers includes a requirement for when a battery in a notebook computer cannot be accessed and replaced by a non-professional user. Manufacturers must publish the following statement in the product technical documentation and on free-access websites; '*The battery[ies] in this product cannot be easily replaced by users themselves*'.

3.1.5.2 External Power Supplies

External power supplies (EPS) used with mobile computers may sometimes be changed during the life of a computer due to failure of the cable or connections. This is especially common when mobile computers are frequently moved.

3.1.5.3 RAM Modules

The amount of Random Access Memory (RAM) within a personal computer can have a strong impact on performance. This is because when insufficient RAM is available, a CPU sets up virtual memory files on a hard disk (or SSD) to simulate additional RAM. This results in the CPU being able to access data much more slowly than when data is stored in RAM. Replacing and adding RAM modules is often, but not always, a relatively simple

[26] DIRECTIVE 2006/66/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC, available from http://ec.europa.eu/environment/waste/batteries/

task in personal computers and therefore it is a quick way to improve the performance of a computer.

3.2 Energy consumption data

This section investigates the energy consumption of computers in scope of the EU ecodesign regulation and placed on the EU market. The energy consumption of different computer types is analysed to show where the current energy consumption levels are in relation to the ecodesign regulatory requirements.

3.2.1 Data availability and data quality

3.2.1.1 Data collected from manufacturers' ecodesign data sheets

In order to establish this comparison, information from manufacturers was collected, since the computer ecodesign regulation on computers and computer servers includes mandatory information reporting requirements. These information reporting requirements are detailed in section 7 of the Regulation and state that *"From 1 July 2014 Manufacturers shall provide in the technical documentation and make publicly available on free-access websites the following information […]"*.

The European digital technology industry association, Digital Europe, was approached to provide the mandatory ecodesign information. Digital Europe provided URLs for four manufacturers' (Dell, HP, Lenovo and Panasonic) websites with this information. Three of these manufacturers were found in the top five of personal computers sales in the EMEA region in the first half of 2016 (see Table 20), accounting for 56.4% of the market. In addition, other computer manufacturers' websites were reviewed and declarations were obtained for Fujitsu, Asus, Apple and Acer. The ErP/Eco declarations were compiled into an Excel workbook and used for the analyses.

Table 20. Statista EMEA PC Shipments by Vendor Q1 to Q2 2016[27].

Manufacturer	PC EMEA Market Share
Q1-Q2 2016	
HP	25.2%
Lenovo	19.9%
Dell	11.3%
Asus*	10.9%
Acer*	8.2%
Others	24.6%
TOTAL	**100%**

*: The study team has gathered their ecodesign information from their websites after a thorough evaluation of their data quality.

Table 20 shows that data provided by Digital Europe accounts for about half of the market. Considering Apple and Fujitsu are in the top 6 and top 7[28], and that data was also gathered from Asus and Acer, it is estimated that the manufacturers for which data was collected, account for around 75% of the personal computer market in the EU.

Besides the seven manufacturers mentioned above, there are a significant number of additional producers. 58 more are registered in the ENERGY STAR program. An unknown additional number of manufacturers not listed in the ENERGY STAR database, especially

[27] http://www.statista.com/statistics/262370/number-of-pc-shipments-in-emea-by-vendor/
[28] https://www.idc.com/getdoc.jsp?containerId=prEMEA40979216

SMEs, are also expected to be placing computers on the EU market. This data has not been included here because collecting the disparate information would be prohibitively time consuming.

On transcribing the declaration data it was clear that many of the product information requirements in Annex II (7) of the Computer Regulation were not met.

Of primary concern is the lack of data in the requirements regarding ETEC values:

- (e) ETEC value (kWh) and capability adjustments applied when all discrete graphics cards (dGfx) are disabled and if the system is tested with switchable graphics mode with UMA driving the display;
- (f) ETEC value (kWh) and capability adjustments applied when all discrete graphics cards (dGfx) are enabled.

The ETEC value is the electricity consumption of the product weighted by the various consumption modes. Whereas the capability adjustments refer to the installed hardware giving rise to adder allowances in maximum energy consumption according to the regulation, i.e. CPUs, GPUs, tuners and storage.

When the manufacturers' websites were searched, a number of the listed products did not have data declarations, and of those that had declarations, none of them fulfilled the entire list of information requirements in the computer regulation. Hence, **0% of the brands constituting 75 % of the market comply with all of the ecodesign reporting requirements**. Furthermore, Lenovo and HP did not provide information on the capability adjustments, making it impossible to identify the extra allowances that are relevant for their products, and hence whether they are compliant with the EU Ecodesign Regulation on computers. In other words, **45% of the brands constituting 75% of the market comply only partly with the ecodesign requirements and specifically do not fulfil (e) and (f) of Annex II**. The remaining five manufacturer brands fulfilled the requirements in (e) and (f) in differing degrees, hence **approximately 30% of the brands constituting 75% of the market comply partly with the ecodesign requirements, including requirements (e) and (f) of Annex II**. An example is the declarations from Asus and Apple, where there is a lack of specification on whether discrete GPUs (Graphic Processing Units) are enabled or disabled when declaring ETEC, which makes it difficult to identify how much energy is being used by these components.

Table 21 shows the number of datasheets that were found within each product category ("collected data") and which brands the products were form. However, in order to analyse the energy consumption of the products, the product sub-category (i.e. the A-D or A-C categories for desktops and notebooks) as well as the two ETEC values with graphics disabled (or integrated graphics used) and enabled should at minimum be present. The "usable data" in Table 21 is the number of products within each category that fulfils this minimum amount of information to be useful for simple energy consumption analysis. For workstations it is not a requirement to have any of this information, and therefore no data is given for workstations.

Table 21. Count of the ErP/Eco datasheets collected from manufacturers' websites.

Product category	Collected data sheets	Usable data	Brands with available data
Desktops, integrated desktops & all-in-ones	640	172	Acer, Apple, Asus, Dell, Fujitsu, HP, Lenovo
Notebooks & ultrabooks	363	258	Acer, Apple, Asus, Dell, Fujitsu, HP, Lenovo, Toshiba
Tablets & convertible tablets	19	7	Lenovo
Workstations	28	N/A	Asus, Fujitsu, HP, Lenovo

Based on the findings presented in Table 21, it is clear that the data availability and data quality available on the manufacturers' websites is not sufficient to be representative of products on the whole EU market. The data that was usable is nevertheless analysed in the following sections. But due to the low number of brands represented, the low market share of the usable data, and the absence of data for some categories entirely (such as small scale servers), the ENERGY STAR databases for computer products were consulted.

3.2.1.2 ENERGY STAR data

The data in the ENERGY STAR databases (both the US and the EU database) is submitted to the ES program on a voluntary basis by computer manufacturers and made publicly available for download. Many of the data points are the same as in the ecodesign regulation, which makes the ENERGY STAR data a good proxy for the average performance of products on the whole EU market.

The ENERGY STAR program has databases set up in both EU and the US. Products registered in the US database might be sold in both the US and EU as well as other parts of the world. The EU database is for products that are not sold, and hence not registered, in the US. The EU database was obtained directly from the US EPA on the 12th May 2016. The US database was obtained directly from the US EPA, since this version contained more products and more information than the version available online. Within the US database only products put on the EU market were considered.

Some of the issues encountered when comparing both databases, are:

- Even though the criteria for registering a product in the ENERGY STAR program are the same in EU and the US, the data fields in the columns do not appear to be in the same order or amount (105 columns in the EU database and 630 columns in the US database).
- The names of the parameters are not the same in both databases. This makes it difficult to compare both databases.
- Some of the data is not given in the same unit. In the US database all products appear with a "PD_ID" as well as an ENERGY STAR model identifier. However, no such number or identifier is present in the EU database, and there is therefore no way to compare the models in the two databases.

Table 22 shows the number of products in the various categories obtained from the ENERGY STAR databases. As well as the usable data from each where it was possible to determine which ecodesign sub-category the products belonged to (based on number of CPU physical cores, system memory, and graphic card(s)), as well as power demand in idle, sleep and off mode. As seen in the table, most of the products in the US database had the required data listed, whereas many products in the EU database, especially in the desktop and integrated desktop categories, did not.

Table 22. ENERGY STAR data obtained from US EPA and the EU ENERGY STAR websites.

Product category	Products in US database	Products in EU database	Usable data in US	Usable data in US (%)	Usable data in EU	Usable data in EU (%)
Desktops	1081	2473	1048	97%	1105	45%
Integrated desktops	795	1121	794	100%	260	23%
Notebooks	2360	2075	1937	82%	1939	93%
Thin Clients (incl. integrated)	57	88	57	100%	73	83%
Tablets	103	119	103	100%	102	86%
Workstations	35	43	35	100%	40	93%
All-in-ones	7	8	7	100%	8	100%

For the analysis of the energy consumption in the various power modes, the data from the two ENERGY STAR databases were compiled and analysed together. In total approximately 7500 products were included across all product types.

3.2.2 Energy consumption in the various power modes

The ENERGY STAR databases were used to improve the available data since the mandatory ErP data declarations proved to be insufficient in both data quantity and quality. To ensure that the ENERGY STAR data was representative of the market, the reported energy consumption in the two datasets was compared.

In the sections below, the ETEC values and the power demand in various power modes are compared for each product type separately. The ETEC values were taken directly from the ErP datasheets where available, and were calculated from the power demand data in the ENERGY STAR database using the use profiles included within the Regulation 617/2013. To ensure good representation of products currently on the market, the ETEC values and the power demand were compared separately for products listed as being placed on the market in 2015 and 2016.

3.2.2.1 Desktop computers

Ecodesign declarations were collected for a total of 567 desktop computers, of which some were integrated desktop computers. It was not possible to identify which were desktops and which were integrated desktops from the ecodesign declarations. However, since integrated desktops are tested with the display off, the energy consumption of the display itself are not included in the measurements, and the difference is therefore considered to be relatively comparable given the similar functionalities and ecodesign requirements. It should be noted though, that it would be more correct if it was always clearly stated in the ErP declarations which type of computer was covered.

In the ENERGY STAR databases, a total of 2140 products in the desktop category had power demand data, which made it possible to calculate the ETEC value according to the eco design regulation. The ETEC values based on collected data and ENERGY STAR data are shown in Figure 9 for each subcategory and year with error bars indicating the maximum and minimum observed value within each category. The ENERGY STAR database contained no data on desktops newer than 2012.

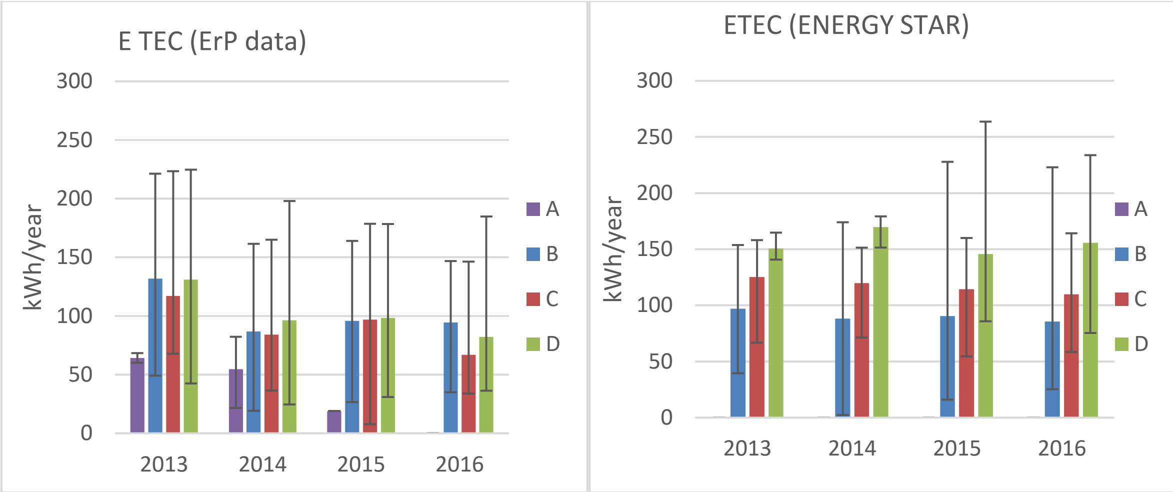

Figure 9. TEC values for desktop computers from the collected ErP data and from the ENERGY STAR databases.

In the ENERGY STAR databases, the desktop and integrated desktop computers are reported as separate product types.Therefore, in Figure 9 the ErP data is compared only to the desktop data in ENERGY STAR. Even though this is the case, the ETEC value averages are still higher in the ENERGY STAR database than in the collected data for subcategory C and D desktops, but slightly lower for subcategory B. It should be noted though, that both datasets contain maximum and minimum values that vary significantly from the averages. Both databases should thus be used with caution.

Since the collected data contained some integrated desktop computers, which were not possible to separate out, another comparison was made with the ENERGY STAR, where desktop and integrated desktop computer data was merged in the ENERGY STAR database as well. This comparison of ETEC values is seen in Figure 10.

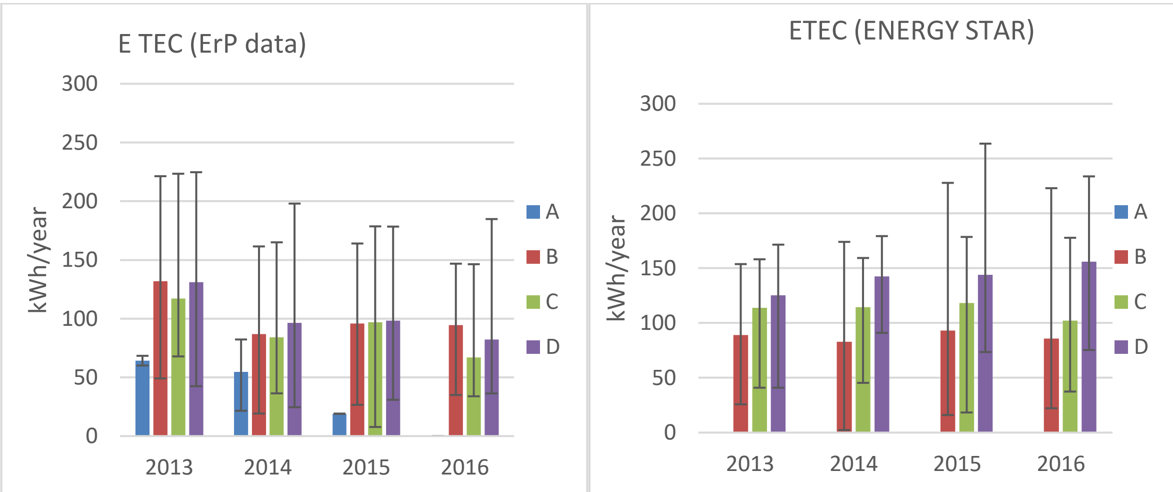

Figure 10. ETEC values for desktop & integrated desktop computers from the collected ErP data and ENERGY STAR databases.

Table 23 shows the overall ETEC values for the collected manufacturers' data (i.e. ErP) and the ENERGY STAR datasets average over all subcategories. The comparison showed that the overall average of ETEC values was slightly higher in the dataset collected from ErP data declarations, than the ETEC values calculated from ENERGY STAR data when considering all data. However, when removing the old data points and considering only products registered in 2015 and 2016, the ETEC values calculated from ENERGY STAR data were higher than those found in ErP datasheets. Even though the ENERGY STAR data should reflect the lowest energy consuming products on the market, this is not reflected in the actual data. Since the ErP dataset is much smaller, the more conservative approach of using the 2015-2016 ENERGY STAR data for further analyses was chosen.

Table 23. Comparison of overall ETEC averages in the two datasets.

Category	Collected ErP data	ENERGY STAR – desktops	Difference	ENERGY STAR desktops+ integrated	Difference
Desktops – all years	102 kWh	97.5 kWh	8%	92.8 kWh	9%
Desktops – 2015/2016	94.1 kWh	96.9 kWh	3%	97.9 kWh	4%

The power demand of desktops in various power modes, are shown in Table 24 for both the collected ErP dataset and the ENERGY STAR dataset. The values are averaged within each subcategory (A to D) for the years 2015/2016. The short idle state power demand from the ENERGY STAR dataset is listed since this is equivalent to idle mode under the EU ecodesign regulation.

Table 24. Power demand data for Desktops in the various power modes, all values in Watts.

(Short) Idle mode			
Subcategory	Collected ErP data	ENERGY STAR data	ENERGY STAR with integrated desktops
A	(5.56)	No data	No data
B	22.4	24.2	27.5
C	22.1	31.1	37.4
D	24.8	42.0	42.2
Total Average	**23.1**	**32.4**	**35.7**
Sleep mode			
Subcategory	Collected ErP data	ENERGY STAR data	ENERGY STAR with integrated desktops
A	(0.64)	No data	No data
B	1.67	1.56	1.86
C	1.34	1.37	1.79
D	1.91	2.31	2.28
Total Average	**1.49**	**1.75**	**1.98**
Off mode			
Subcategory	Collected ErP data	ENERGY STAR data	ENERGY STAR with integrated desktops
A	(0.44)	No data	No data
B	0.42	0.49	0.67
C	0.41	0.53	0.94
D	0.40	0.58	0.58
Total Average	**0.41**	**0.53**	**0.73**

As seen from the values in Table 24, the power demand is higher for all product types in the ENERGY STAR dataset than in the collected ErP data, but all values lie relatively close. The ENERGY STAR data is thus representative of the market, and encompasses a greater range of products than the collected data set, since it contains around 4 times as many products (around 2000).

3.2.2.2 Notebook computers

For the notebooks, 258 of the 363 collected data declarations had recorded a ETEC value, 6 of which had TEC for both enabled and disabled dGfx. These graphs are not shown here, because this number is too small to add any value to the analysis. None of these 6 products had any data recorded regarding the graphic card type. On the other hand, another 50 products out of the remaining 252 had recorded the discrete graphic card type (G1, G2, G3 etc.), but not recorded the ETEC value with graphic cards enabled, even though the ecodesign regulation requires that both values are reported.

Figure 11 shows the ETEC values with dGfx disabled, based on the 258 products. The data shows no unambiguous development, but fluctuates for all three notebook categories over the four analysed years. There was not enough data recorded in the data sheets to explain the fluctuations based on for example, added functionality.

For some of the subcategories of notebook computers, the total average of ETEC values with dGfx disabled are *higher* than the ETEC values with dGfx enabled. This is because all but 6 of the collected ErP datasheets had only ETEC value; either with or without discrete graphic cards enabled. Hence, the two averages are not directly comparable, since they are based on different products.

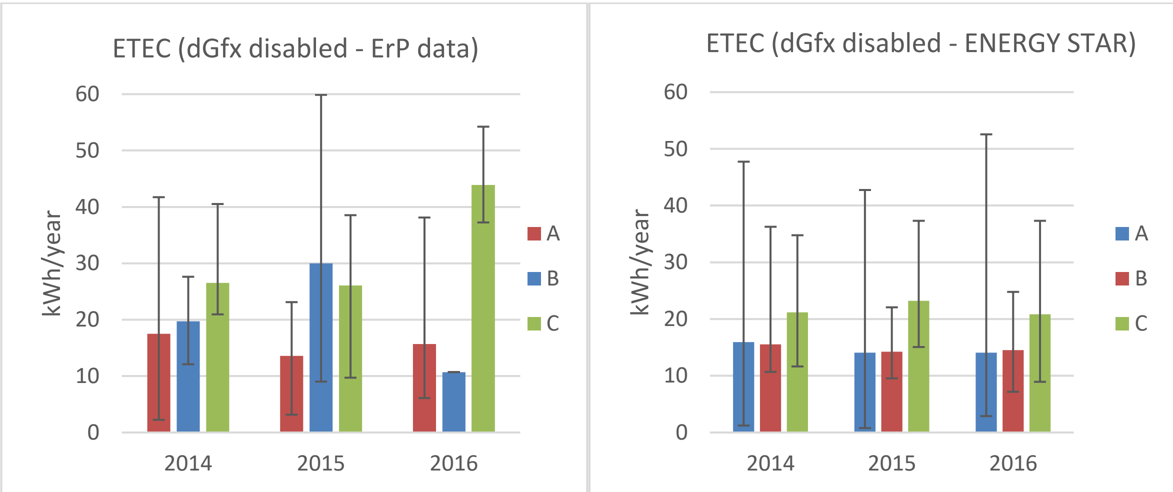

Figure 11. ETEC values with graphic cards disabled from collected ErP data and ENERGY STAR databases.

In the ENERGY STAR dataset, it was possible to calculate the ETEC value for approximately 2900 notebook computers. It was not stated in the ENERGY STAR database whether the power demand was measured with dGfx enabled or disabled. This was therefore determined by looking at the information on discrete graphic cards and switchable graphics in the database. Whenever a notebook was equipped with a discrete graphic card, but did not have switchable graphics, the ETEC value was noted as "enabled dGfx". In all other cases the ETEC value was noted as "disabled dGfx". In total, 2780 of the notebooks had disabled graphics and 183 had enabled dGfx according to these criteria. The ETEC values from the ENERGY STAR dataset are shown in Figure 12.

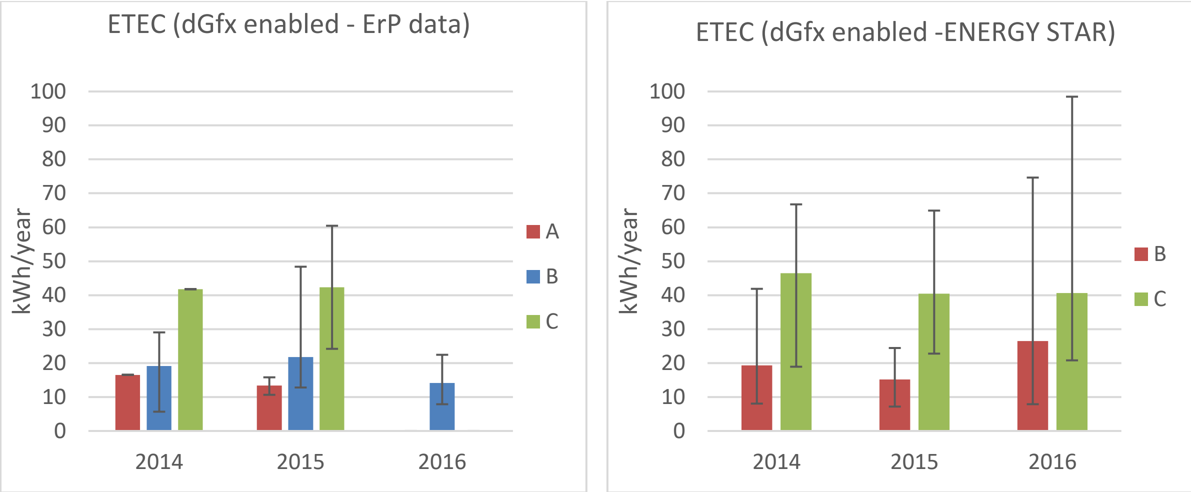

Figure 12. ETEC values with graphic cards enabled from collected ErP data and from ENERGY STAR data for notebooks.

For the calculation of ETEC in the ENERGY STAR dataset, long idle power demand was used, as this is almost the same as the idle state used in the ecodesign regulation. However, an important difference is that during the long idle mode measured for ENERGY STAR, any hard disk drives (HDD) are spun down, which is not the case during the idle mode measured for ecodesign. Therefore, the ETEC values will be slightly lower when calculated using the ENERGY STAR data than they would be if the ecodesign idle mode values were used.

In Table 25 the overall ETEC averages from the two datasets are compared with all data points included and then only for the 2015/2016 products.

Table 25. comparison of overall ETEC averages in the two datasets.

Category	ErP average	ES average	Difference
Notebooks	21.0 kWh	16.9 kWh	19.5%
Notebooks - only 2015/2016	19.2 kWh	15.1 kWh	21.4%

Table 26 shows the power demand data for notebook computers from both the ErP datasheets and the ENERGY STAR databases in various power modes. For notebooks, the long idle demand was used from the ENERGY STAR data to represent the idle mode consumption, and for when calculating the ETEC values. The power demand data is averaged for each subcategory (A-C) for the years 2015/2016.

Table 26. Power demand for Notebooks in the various power modes for Notebooks, all values in Watts.

(Long) Idle mode		
Subcategory	**Collected ErP data**	**ENERGY STAR data**
A	4.59	4.6
B	6.17	5.02
C	10.9	11.69
Total Average	**6.18**	**7.09**
Sleep mode		
Subcategory	**Collected ErP data**	**ENERGY STAR data**
A	0.61	0.68
B	0.76	0.79
C	1.02	1.26
Total Average	**0.73**	**0.88**
Off mode		
Subcategory	**Collected ErP data**	**ENERGY STAR data**
A	0.27	0.30
B	0.31	0.28
C	0.28	0.33
Total Average	**0.29**	**0.30**

For the subcategories A and B, the ENERGY STAR dataset shows slightly larger power demand in all three power modes, but slightly lower for subcategory B in Idle and Off mode. The collected ErP data might be skewed slightly towards the higher consuming products, since products with power demand below 6 watts in Idle mode are not covered by the ecodesign regulation. Since the ENERGY STAR database thus encompass a greater range of products, and is also more comprehensive in numbers than the ErP dataset, it is considered to be more representative of the market.

3.2.2.3 Tablet/slate computers

ErP data declarations were found for only 19 tablets, most likely because most tablet computers fall outside the ecodesign regulation, which states that products with a viewable diagonal screen size below 9 inches, and idle state power demand of less than 6 watts, are not considered to be covered by the regulation. Only 7 of the tablet data sheets had a subcategory recorded as well as an ETEC value, and hence the comparison values are based on very few data points.

As can be seen on the graphs in Figure 13, the average values are higher for the ErP dataset, but the dataset consists of only 7 products. The ENERGY STAR data for tablets shows lower averages, but on the other hand the data set contains products with far higher ETEC values, up to 40 kWh/year, compared to 20 kWh/year in the collected ErP data.

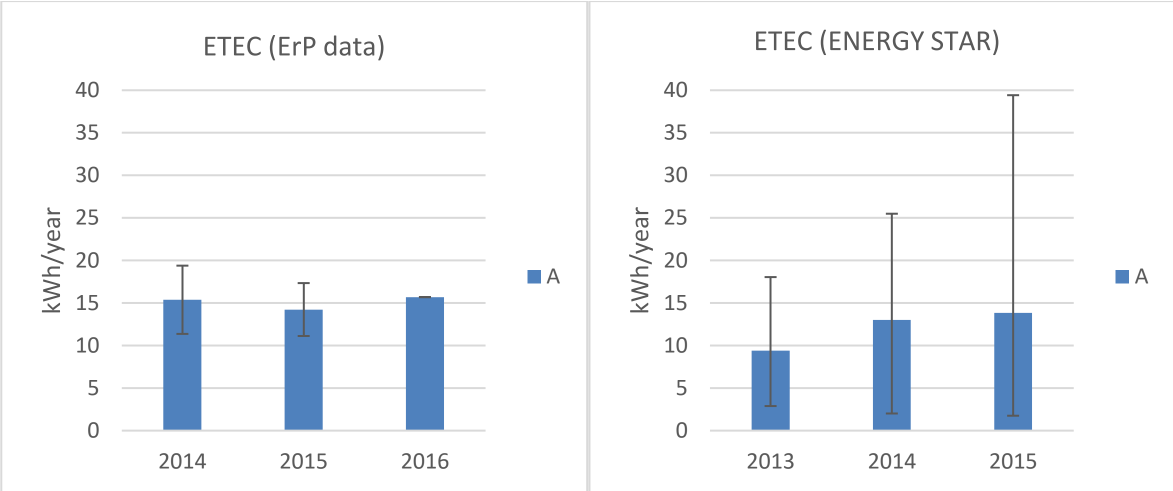

Figure 13. ETEC values for Tablets based on the collected ErP data sheets and the ENERGY STAR data, respectively.

Since the ENERGY STAR data set contains 212 data points, this alone is enough to make this data more reliable. When removing the products released before 2014, as showed in Table 27, the difference between the average ETEC values is below 10%, which shows that the two data sets are quite similar, and thus the ENERGY STAR is a good representation of the market.

Table 27. Comparison of overall TEC averages in the two datasets.

Category	ErP average	ES average	Difference
Tablets	13.7 kWh	11.7 kWh	-14.5%
Tablets – only 2014/2016	13.7 kWh	12.5 kWh	-8.8%

The power demand in various power modes for tablets are shown in Table 28. Two of the 7 ErP data declarations were for subcategory B tablets, while 5 were for subcategory A. However, due to the very low quantity of products, the power demand data form the ErP sheets are not considered representative.

Table 28. Power demand data for Tablets in the various power modes, all values in Watts.

(Short) Idle mode		
Subcategory	Collected ErP data	ENERGY STAR data
A	4.59	3.82
B	7.72	No data
Total Average	**6.15**	**3.82**
Sleep mode		
Subcategory	Collected ErP data	ENERGY STAR data
A	1.21	0.65
B	0.63	No data
Total Average	**0.92**	**0.65**
Off mode		
Subcategory	Collected ErP data	ENERGY STAR data
A	0.36	0.31
B	0.37	No data
Total Average	**0.36**	**0.31**

The exclusion of tablets with under 6 watts' power demand in idle mode, does not only mean that fewer data is available, but might also cause the average power demand data to be higher in the ErP datasheets than the ENERGY STAR data, since ErP datasheets are not published for the lowest power demanding products. Since tablets in general have low power demands compared to other computer types, this product category does not provide an opportunity for large energy savings.

3.2.2.4 Workstations

ErP data declarations were collected for 28 workstations, 7 of which were from 2015/2016. The PTEC value was calculated using the formula from ENERGY STAR. The ENERGY STAR dataset contained 75 workstation computers, all with PTEC values recorded. The comparison between PTEC values in the two datasets is seen in Figure 14.

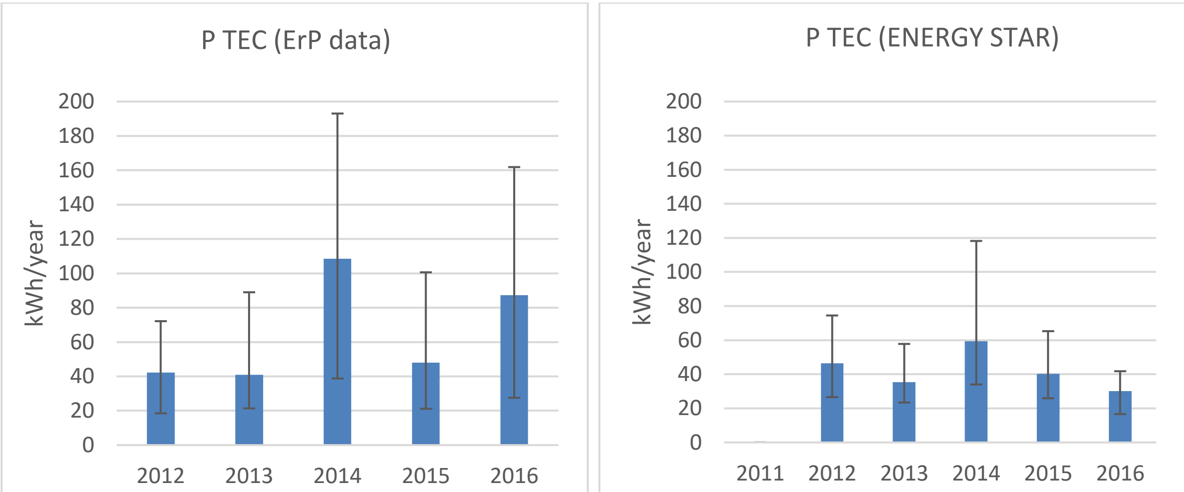

Figure 14. Calculated P TEC for Workstations, data form collected data sheets.

As seen from the graphs in Figure 14, the PTEC values are higher in the collected data than in the ENERGY STAR data. This is most likely because there is no PTEC requirement in the ecodesign regulation, but the workstations only have information provision requirements. The ENERGY STAR data might not cover all workstation computers on the market as it is an open-ended product category in terms of performance. The highest performing workstation computers on the market may therefore struggle to meet the ENERGY STAR specifications and would not be found in the database.

Also when only looking at the 2015/2016 data, shown in Table 29, the PTEC values are significantly higher in the ErP dataset. For this product category it is therefore necessary to look at other data sources than just the ENERGY STAR databases alone, which will be taken into account in the further work.

Table 29. P TEC values comparison for Workstations in the two datasets.

Category	ErP average	ES average	Difference
Workstations	68.8 kWh	48.4 kWh	29.7%
Workstations – only 2014/2016	70.4 kWh	33.4 kWh	52.6%

For workstation computers the maximum power demand along with the other power modes, as shown in Table 30, need to be reported under the EU ecodesign regulation. As it was also shown above with the PTEC values for workstations, the power demand is significantly higher in the ErP dataset than in the ENERGY STAR dataset. ENERGY STAR therefore most likely does not cover all product types on the market within this product group, and in this instance it is therefore worthwhile looking at other data sources than ENERGY STAR.

Table 30. Power demand data in the various power modes for Workstations, all values in Watts.

Maximum power		
	Collected ErP data	ENERGY STAR data
Total Average	380	311
Max value in dataset	791	854
(Short) Idle mode		
	Collected ErP data	ENERGY STAR data
Total Average	121	85.4
Max value in dataset	291	117
Sleep mode		
	Collected ErP data	ENERGY STAR data
Total Average	8.42	5.41
Max value in dataset	33.1	14.8
Off mode		
	Collected ErP data	ENERGY STAR data
Total Average	1.65	1.85
Max value in dataset	6.11	2.40

3.2.2.5 Thin Clients

No thin client data declarations were found when searching the computer manufacturers' websites, so only the data for the 126 products in the ENERGY STAR databases are presented in this section. The ETEC value was not calculated because there are no energy consumption requirements for thin clients in the ecodesign regulation.. Alternatively, the power demand in different power modes were analysed, and this is shown in Table 31.

Table 31: Power demand data in the various power modes for Thin Clients, all values in Watts.

Long Idle mode	
	ENERGY STAR data
Total Average	8.68
Max value in dataset	25.3
Short Idle mode	
	ENERGY STAR data
Total Average	10.8
Max value in dataset	28.5
Sleep mode	
	ENERGY STAR data
Total Average	4.19
Max value in dataset	25.3
Off mode	
	ENERGY STAR data
Total Average	0.75
Max value in dataset	2.20

As seen in Table 31, the maximum values in the power demand data differs greatly to the average values, as it is also seen for the other product types. The average values should therefore be used with caution.

3.3 Standardised test methods

The dominant test methodology for measuring the energy use of personal computers is IEC 62623:2013 which is used to support a number of initiatives, such as ENERGY STAR. The IEC 62623:2013 comprehensively details how to measure computer power demand in a number of power modes including long and short idle, sleep modes and off modes. The IEC standard does not dictate how to measure energy use whilst a computer is performing work[29].

3.3.1 Methods for measuring active state power demands

As discussed in section 3.1, there are a number of difficulties associated with measuring power demand on active state. The most difficult issue to address is the fact that there is no single active state in computers. In order to measure active state power demand, it is therefore necessary to firstly identify what is meant by "active state" and then to identify a manner of measuring power demand during the pre-defined active state that is accurate, repeatable and flexible enough to be used across different types of computers and software packages.

"Active state" is defined under the ENERGY STAR v6.1 specification for computers as:

"*Active State: The power state in which the computer is carrying out useful work in response to a) prior or concurrent user input or b) prior or concurrent instruction over the network. Active State includes active processing, seeking data from storage, memory, or cache, including Idle State time while awaiting further user input and before entering low* power modes".

The above definition does not provide detail about the exact activities that a computer would be performing in active state. As "active state" is not well defined in any of the established energy efficiency initiatives it is necessary to look elsewhere to identify how "active state" for computers could be defined and measured.

There are a significant number of software packages available called "Benchmarks" whose aim is to measure the computational performance of computers. Benchmarks mostly consist of measuring performance through running pre-defined workload(s) on a computer. Benchmarks may be designed to identify performance of whole computer systems or individual components such as the CPU or dGfx. Given that Benchmarks provide a means of testing the performance of a computer they could be used alongside power demand measurements to provide an indication of computer efficiency whilst performing work.

Attempting to use a benchmark to support development of computer active state energy efficiency measurements, and potential requirements based on those measurements, is not a simplistic task as there are many complexities involved. Indeed, attempts to use Benchmarks coupled with power demand measurements to describe computer energy efficiency have been made in the past within major initiatives. During development of the ENERGY STAR v5.0 specification attempts were made to use a benchmarking tool called EEcoMark developed by Business Applications Performance Corporation (BAPCo) (a non-profit computer manufacturer organisation which aims to develop and distribute

[29] The exception being workstation computers where maximum power demand during an active workload is measured.

computer performance benchmarks) [30,31,32]. The EEcoMark benchmark was due to include two workloads comprised of representative tasks performed by typical users including:

- *Office Productivity: Focuses on office worker oriented tasks (web browsing of sites with increasing complexity; Microsoft Word documents creation revision)*
- *Media Rich: Focuses on consumer media consumption/creation tasks (MP3 encoding from CD, MP3 playback multitasked with other program operations)*[33]

Due to concerns regarding the quality of EEcoMark and the timing of its availability the benchmark was not used in the ENERGY STAR v5.0 specification for computers[34].

While using benchmarks to measure energy efficiency in personal computers has not yet been adopted within a major energy efficiency initiative, benchmarks have been used to measure the energy efficiency of server computers within major initiatives. The ENERGY STAR specification for Computer Servers v 2.0 (v2.1 in the USA) includes requirements to test active state efficiency using the Server Efficiency Rating Tool (SERT tool) benchmark[35]. This includes measuring power demand of the server whilst running the SERT tool.

The SERT tool includes a number of "worklets" which are software simulations of work that would be conducted by a server. The worklets are designed to stress different components of the server that they are installed upon in order to gain a holistic measure on server performance. Using a range of different worklets helps to ensure that results are not biased towards one particular type of server architecture. The outcomes of the SERT tool include performance scores and measured power demands which are combined to give an overall efficiency score. The ENERGY STAR v2.0 specification for servers does not include requirements based on the SERT scores, but rather requires that the results are communicated when a server is registered as meeting the ENERGY STAR requirements. This information can be used for the customer to select the right server according to the needs and it also provides the US EPA and the European Commission with the ability to assess the SERT scores and their ability to support future active state efficiency requirements.

As part of a larger European Commission funded project a small beta testing project on the SERT tool was conducted, into standards that could support potential ecodesign measures on servers.[36] While important to note that the testing was only conducted over one server, the test results suggested a high level of repeatability with a maximum deviation of less than 1.5% in the key summary efficiency scores when testing was conducted multiple times. This suggests that a benchmark similar to the SERT tool could be developed for personal computers and provide a certain degree of repeatability.

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[30] US EPA, ENERGY STAR v5.0 Development Archive, available from https://www.energystar.gov/index.cfm?c=archives.computer_spec_version_5_0
[31] EEcoMark available from https://bapco.com/products/eecomark-v2/
[32] BAPCo https://bapco.com/about/
[33] US EPA, ENERGY STAR® Computer Stakeholder Online Meeting Version 5.0: Draft 1 April 8, 2008, available from https://www.energystar.gov/ia/partners/prod_development/revisions/downloads/computer/Apr8_Webmeeting.pdf?b2f2-dc4c
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[35] COMMISSION DECISION of 20 March 2014 on adding specifications for computer servers to Annex C to the Agreement, available from http://www.eu-energystar.org/specifications.htm
[36] Intertek report for the European Commission, 2016, Final Report ecodesign Technical Assistance Study on Standards for Lot 9 Enterprise Servers and Enterprise Data Storage, available from http://www.server-standards.eu/

3.3.2 Current computer benchmarks

Table 32 lists some of the more common benchmarks available on the market that are used to measure personal computer performance. Some of these attempt to measure performance of individual components such as the CPU or GPU. While this is useful in understanding the performance of some of the more important components, computer performance is determined by the overall combination of components in a product. Some of the available benchmarks test the individual performance of different components and then provide an overall performance score. This approach gives a truer indication of the overall performance of a computer. Other benchmarks go further and include software packages that are designed to mimic actual activities carried out on a computer (e.g. opening web pages, viewing video files etc.).

Table 32. Common personal computer benchmarks and attributes.

Benchmark	Operating System Support	Power Demand Meas-urement Support	Overall System Score	Reflects Actual Usage	Components Tested			
					CPU	GPU	Memory	Storage
PCMark8	Windows & Android	No	Yes	Yes	Yes	Yes	Yes	Yes
Novabench	Windows & OS X	No	Yes	No	Yes	Yes	Yes	Yes
EEcoMark v2	Windows	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SYSmark 2014	Windows	No	Yes	Yes	Yes	Yes	Yes	Yes
PassMark PerformanceTest	Windows	No	Yes	No	Yes	Yes	Yes	Yes
SiSoftware Sandra 2016	Windows	No	Yes	No	Yes	Yes	Yes	Yes
Cinebench R15	Windows & OS X	No	No	No	Yes	Yes	No	No
Geekbench 3	Windows, Linux Mac OS X, iOS, Android & BlackBerry	No	No	No	Yes	No	No	No

There are a number of other conditions that a benchmark would have to meet in order to be suitable for supporting active mode efficiency specifications. Firstly, given that there are a wide range of personal computers on the market and using a number of different operating systems, a benchmark would need to be adaptable. Table 32 shows that operating system coverage amongst the common benchmarks varies considerably with 50% only supporting a single operating system. Any benchmark used to support active state efficiency requirements would also have to show high levels of repeatability (i.e. the results should be the same or nearly the same each time the test is run). Even small variances in benchmark results could mean the difference between a computer meeting a requirement or not. Variances would therefore not only be problematic for manufacturers but they could also be problematic for initiatives and market surveillance authorities. It should be noted that some variability in test results is often allowed within energy efficiency initiatives. For example, the EU ecodesign regulation on computers provides for up to 10% tolerance in power demand measurements (i.e. if the resulting power demand value obtained from testing is up to 7% higher than the required level then the product is deemed to comply).

Any benchmark used as a basis for energy efficiency metrics would be installed and tested on computers ahead of shipment to end users. Under this approach the upgradability potential of a computer would not be assessed. This could therefore have the consequence of favouring computers that were not upgradable and potentially leading to shorter product lifetimes. These limitations could be overcome with other requirements that address mandatory upgradability potentials where suitable.

The high level of configurability in computers could also prove problematic for benchmark based efficiency requirements. That is, many models of personal computer are highly configurable in terms of components that can be changed or added. An individual computer model may have hundreds of different configurations due to small changes that can be made to the components. Given this high level of configurability it would not be possible to require benchmark testing on each configuration. This is a common issue in energy efficiency initiatives that focus on computers though and can be somewhat overcome by requiring testing on representative configurations of products. Both the current EU ecodesign regulation on computers and the ENERGY STAR computer specification take this approach.

Another major concern with benchmarks is the continual need for updates to account for changes in other computer software. These updates can be major or minor depending on the extent to which software has changed on the computers being tested. For example, the launch of a new widely adopted operating system is likely to require a major update to a benchmark. Minor iterative changes to benchmarks are often required to deal with bugs or changes to other programmes used on computers. The changeable nature of benchmarks would therefore likely require that energy efficiency initiative were also able to continually update to reflect changes in the test procedure.

Computer benchmarks are often commercial products and as such a licence is often required to use them. Whilst licences fees are not always excessively high it could result in added costs for computer manufacturers, which may be a higher burden for SMEs. Some of these costs could be offset by negotiation with the benchmark developers or through the development of a bespoke benchmark developed as part of an energy efficiency initiative.

Another potential issue with using benchmarks arises where specific test procedures are not allowed to be mandated within an energy efficiency initiative. For example, the EU Ecodesign Directive 2009/125/EC extols the importance of developing harmonized standards (i.e. technical specification adopted by a recognised standards body under a mandate from the Commission) to guide manufacturers when measuring the environmental performance of their products in relation to ecodesign requirements, but also states that the use of harmonized standards is not compulsory.

That means that manufacturers would be free to use an alternative means of measuring active state efficiency rather than the procedure laid out in a harmonized standard. However, when verifying compliance to an EU ecodesign regulation, EU member state market surveillance authorities are required to use published harmonized standards. Whilst the onus is on the manufacturers to prove that their products are compliant with any ecodesign regulations there is enhanced scope for uncertainty where complex benchmarks are involved.

There are clearly many issues to consider before using a benchmark to support active state efficiency measures on computers. However, given the potential opportunities, further investigation is warranted. The next section of the report details some benchmark testing that has been conducted as part of this EU preparatory study.

3.3.3 Benchmark testing

To further understand the potential that benchmarks may have in supporting requirements on active state efficiency, a number of ENERGY STAR qualified computers were subjected to benchmark and power demand testing.

The computers tested were those purchased by the European Commission as part of their EU ENERGY STAR compliance testing programme.[37] All testing was conducted between March and May 2016 at the Intertek laboratories in Milton Keynes, UK. Intertek personnel did not conduct the actual testing but Intertek provided the necessary testing equipment. The authors would like to thank Intertek for their kind collaboration on this testing activity, without which the testing would not have been possible.

The power meter used was a Yokogawa WT210 with voltage at 230V a.c. ±5%. Given the experimental nature of the benchmark testing and relatively low power demand's, most of the power meter settings (e.g. cresting) were set to automatic.

Given time limitations, testing was limited to two benchmarks:

- PCMark8 [38]
- Novabench [39]

These benchmarks were chosen because the first is one of the most popular benchmark used for testing personal computer overall performance, is developed in co-operation with a large number of computer manufacturers and a free trial version was available. The first benchmark stimulates real world usage of a product through embedded applications in the following areas:

- Web browsing
- Writing
- Casual gaming
- Video chat
- Photo editing

The second benchmark is a freely available piece of software that includes the following tests:

- CPU Tests
  - Floating Point - Tests CPU's floating point arithmetic speed
  - Integer - Tests CPU's integer arithmetic speed
  - MD5 Hashing - General CPU test
- GPU Test
  - 3D Graphics - Tests GPU with a heavily shader dependent 3D scene
- Hardware Tests
- RAM Speed - Tests RAM read and write speed

[37] European Commission, Evaluation of effectiveness of the EU Energy Star programme, available from http://ec.europa.eu/smart-regulation/roadmaps/docs/2016_ener_009_energy_star_evaluation_en.pdf
[38] https://www.futuremark.com/benchmarks/pcmark8
[39]

- Disk Write Speed - Test write speed of primary or selected storage device

The benchmarks were tested on a total of 13 personal computers as shown in Table 33. Significantly more Novabench tests were able to be conducted due because of the following benefits:

- Small programme able to install/uninstall quickly
- Quick run time
- Ability to support Windows and OS X operating systems

Table 33. Number of Benchmark and Power Demand Tests.

Computer Type	Project Product Code	PCMark8 Tests Run	Novabench Tests Run
Desktop	EC01	1	9
Integrated Desktop	EC03	4	5
Integrated Desktop	EC04	5	7
Integrated Desktop	EC05	0	8
Notebook	EC06	3	8
Notebook	EC07	5	10
Notebook	EC09	4	10
Desktop	EC10	3	8
Desktop	EC11	3	8
Integrated Desktop	EC13	3	6
Integrated Desktop	EC14	3	5
Desktop	EC15	4	5
Notebook	EC19	7	10

Table 34 shows the average time taken to run each of the benchmark tests. It is clear from the results that the more sophisticated real-world based PCMARK8 benchmark takes a considerably longer time to run than the more simplistic Novabench benchmark.

Table 34. Benchmark Testing Duration.

Benchmark	Average Test Duration (mins)	Max Test Duration (mins)	Min Test Duration (mins)
PCMark8	45.3	67.7	37.0
Novabench	0.8	1.1	0.7

3.3.3.1 Benchmark test results

Ten of the thirteen product performances are reviewed further below. Three products were removed due either to the benchmark not being able to support non-Windows operating systems, or suspected data errors.

The overall average results illustrated in Figure 15 show that there is a general trend of increasing power demand with increasing performance score. It is also clear that the correlation is not perfect suggesting that there is either differentiation in products' energy efficiency or that the benchmarks do not adequately test the products. It is suggested that it is more likely that there is differentiation in products' energy efficiency as the benchmarks simply stress the systems and then record performance.

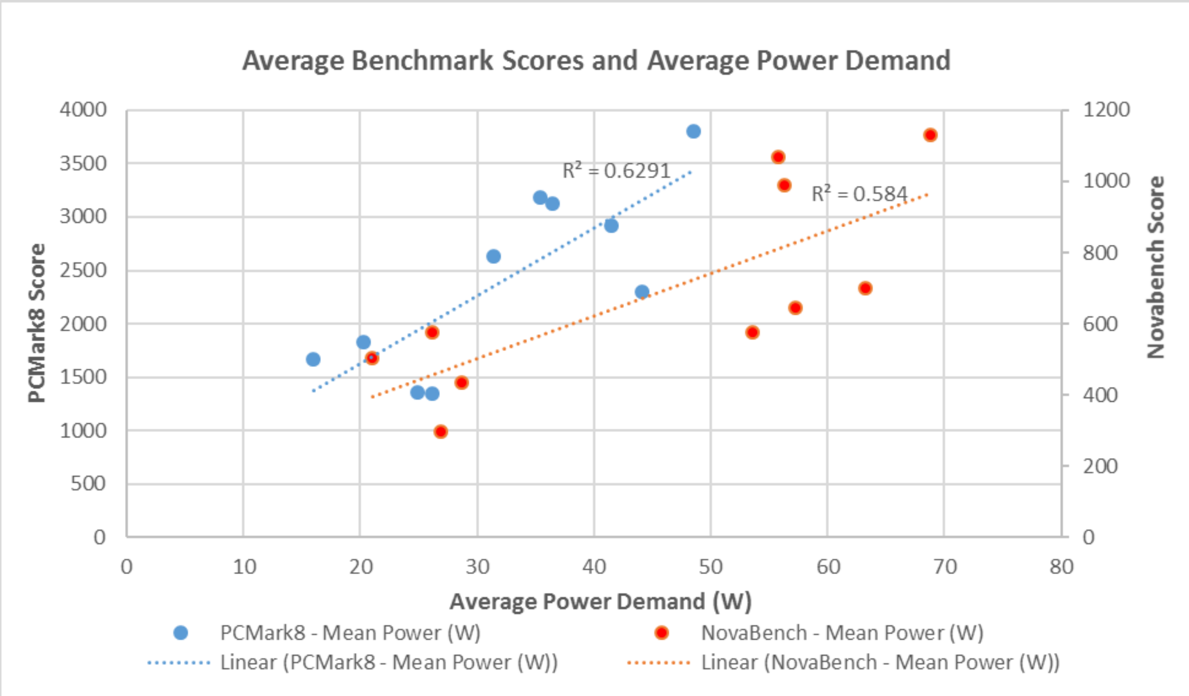

Figure 15. Overall Average Benchmark Score and Power Demand.

The results shown in Table 35 provide a clearer representation of the average results. It is clear that there is a considerable difference amongst the products in terms of efficiency when calculated as "Benchmark Score"/"Mean Power (W)". It is also clear that the ranking of products from highest efficiency to lowest efficiency is different for each of the benchmarks. This suggests that some products perform better under one benchmark than the other.

Table 35.Overall Average Benchmark Score, Power Demand and Efficiency.

Product Type	Project Product Code	PCMark8 - Mean Score	PCMark8 - Mean Power (W)	PCMark8 - Efficiency (Score/W)	Novabench - Mean Score	Novabench - Mean Power (W)	Novabench - Efficiency (Score/W)
Notebook	EC07	1663	16.0	103.9	502	21.0	23.9
Notebook	EC19	3188	35.4	90.1	990	56.3	17.6
Desktop	EC10	1823	20.3	89.8	575	26.1	22.0
Notebook	EC06	3128	36.5	85.7	1067	55.8	19.1
Desktop	EC11	2634	31.4	83.9	578	53.6	10.8
Notebook	EC09	3807	48.5	78.5	1130	68.8	16.4
Integrated Desktop	EC13	2920	41.5	70.4	702	63.2	11.1
Integrated Desktop	EC03	1364	24.9	54.8	298	26.9	11.1
Integrated Desktop	EC14	2295	44.1	52.0	644	57.2	11.3
Integrated Desktop	EC04	1345	26.2	51.3	434	28.6	15.2

Table 35 shows the mean power demand results as measured but it represents an unfair comparison between the products due to the fact that both integrated desktops and notebooks have integrated displays whilst desktop computers are used with an external display. This means that under test the power demand of the display used to output the computer is measured for integrated desktops and notebook computers but not for desktop computers. As such, notebook and integrated desktop computers are whilst under test providing an additional functionality compared to desktop computers,, and so the comparison is unfair. This discriminating factor can be corrected in two ways.

The first way would be to measure all products connected to the same external display with any integrated display turned off. This first approach would need to assume that all products with an integrated display could also be connected to the same external display, or at least an external display with the same technical features, and the integrated display could be turned off.

The second method to account for display energy is to calculate the delta between short idle (integrated display is on) and long idle (integrated display is off) and subtract this from the average measured power value obtained during the benchmark test. There are some other minor differences between long and short idle and so this second approach is not 100% accurate but it is a good proxy for identifying display power.

Table 36 illustrates the results of the benchmark testing with the integrated power demand removed through the subtraction of the short-long idle delta. The results are sorted by highest efficiency levels. The colouring serves to illustrate how the products perform against each benchmark in terms of efficiency (green highest efficiency to dark red lowest efficiency).

The products were coloured according to their PCMark8 efficiency scores. The same colour was then used for products under the Novabench scoring in an attempt to easily show the differences. The short and long idle values were measured as part of the EU ENERGY STAR compliance testing programme. The results show that work notebook computers when performing are on average the most efficient types of products but some notebooks can be inefficient during work. The results also show that there is significant rank reversal when comparing performance against the PCMARK8 and Novabench test results. This suggests that different benchmarks stress computers in different ways which leads to different answers in terms of efficiency. This is witnessed by the fact that average power demand levels are higher under the Novabench test than the PCMARK8 test for all products. Given these differences it is therefore suggested that a benchmark should mirror actual real world usage as closely as possible in order to give a better indication of computer active efficiency.

Table 36. Overall Average Benchmark Score, Power Demand and Efficiency (Minus Integrated Display power demand): Sorted by highest efficiency.

Product Type	Project Product Code	PCMark8 - Mean Score	PCMark8 - Mean Power (minus display power) (W)	PCMark8 - Efficiency (Score/W)	Product Type	Project Product Code	Novabench - Mean Score	Novabench - Mean Power (minus display power) (W)	Novabench - Efficiency (Score/W)
Notebook	**EC07**	**1663**	**11.7**	**141.8**	**Notebook**	**EC07**	**502**	**16.7**	**30.0**
Notebook	**EC19**	**3188**	**30.2**	**105.5**	**Integrated Desktop**	**EC04**	**434**	**16.2**	**26.7**
Integrated Desktop	**EC14**	**2295**	**21.9**	**105.0**	**Desktop**	**EC10**	**575**	**26.1**	**22.0**
Notebook	**EC06**	**3128**	**32.2**	**97.3**	**Notebook**	**EC06**	**1067**	**51.5**	**20.7**
Integrated Desktop	**EC04**	**1345**	**13.8**	**97.1**	**Notebook**	**EC19**	**990**	**51.1**	**19.4**
Integrated Desktop	**EC03**	**1364**	**14.2**	**95.7**	**Integrated Desktop**	**EC14**	**644**	**35.0**	**18.4**
Desktop	**EC10**	**1823**	**20.3**	**89.8**	**Integrated Desktop**	**EC03**	**298**	**16.2**	**18.3**
Integrated Desktop	**EC13**	**2920**	**33.1**	**88.3**	**Notebook**	**EC09**	**1130**	**63.9**	**17.7**
Notebook	**EC09**	**3807**	**43.6**	**87.3**	**Integrated Desktop**	**EC13**	**702**	**54.8**	**12.8**
Desktop	**EC11**	**2634**	**31.4**	**83.9**	**Desktop**	**EC11**	**578**	**53.6**	**10.8**

Table 37 shows the same benchmark results but sorted by highest PCMark8 performance score first. This table illustrates the fact that some high performance products are efficient and others are inefficient. This suggests that an efficiency approach based on performance per watt type calculation could function well. Table 37 also shows that there is less rank reversal between the PCMark8 and Novabench when sorted on performance score. This suggests that it is possible to accurately rank computers on performance through the use of benchmarks.

Table 37. Overall Average Benchmark Score, Power Demand and Efficiency (Minus Integrated Display power demand): Sorted for PCMark8 score.

Product Type	Product	PCMark8 - Mean Score	PCMark8 - Mean Power (minus display power) (W)	PCMark8 - Efficiency (Score/W)	Product Type	Project Product Code	Novabench - Mean Score	Novabench - Mean Power (minus display power) (W)	Novabench - Efficiency (Score/W)
Notebook	**EC09**	**3807**	**43.6**	**87.3**	**Notebook**	**EC09**	**1130**	**63.9**	**17.7**
Notebook	**EC19**	**3188**	**30.2**	**105.5**	**Notebook**	**EC06**	**1067**	**51.5**	**20.7**
Notebook	**EC06**	**3128**	**32.2**	**97.3**	**Notebook**	**EC19**	**990**	**51.1**	**19.4**
Integrated Desktop	**EC13**	**2920**	**33.1**	**88.3**	**Integrated Desktop**	**EC13**	**702**	**54.8**	**12.8**
Desktop	**EC11**	**2634**	**31.4**	**83.9**	**Integrated Desktop**	**EC14**	**644**	**35.0**	**18.4**
Integrated Desktop	**EC14**	**2295**	**21.9**	**105.0**	**Desktop**	**EC11**	**578**	**53.6**	**10.8**
Desktop	**EC10**	**1823**	**20.3**	**89.8**	**Desktop**	**EC10**	**575**	**26.1**	**22.0**
Notebook	**EC07**	**1663**	**11.7**	**141.8**	Notebook	EC07	502	16.7	30.0
Integrated Desktop	**EC03**	**1364**	**14.2**	**95.7**	**Integrated Desktop**	**EC04**	**434**	**16.2**	**26.7**
Integrated Desktop	**EC04**	**1345**	**13.8**	**97.1**	**Integrated Desktop**	**EC03**	**298**	**16.2**	**18.3**

Figure 16 and Figure 17 illustrate comparisons between the benchmark performance scores and the performance score based on CPU performance used in the ENERGY STAR computer specification v6.1. The results show that there is at least some correlation between ENERGY STAR and the benchmark performance scores. It is also shown that the benchmarks provide additional information about computer performance witnessed by the spread in benchmark performance scores for products that are scored equally, or nearly equally, under the ENERGY STAR CPU performance score approach.

Looking at the average power and benchmark score results provides a good picture about how the products' performances interrelate. It is also important to look at the spread of results that were obtained per product tested as this can provide more detail about potential issues within the benchmarks themselves. Figure 18 and Figure 19 show box charts of the benchmark scores and power demand tests obtained for each computer tested. The charts clearly show that there is little divergence in terms of benchmark scores within the series of tests but the same cannot be said for power demand which can vary significantly. The power demand for the products labelled EC19 shows especially large divergence across both the PCMark8 and Novabench tests. This suggests that the computer is drawing different amounts of power during each test despite the fact that exactly the same workload is being run each time.

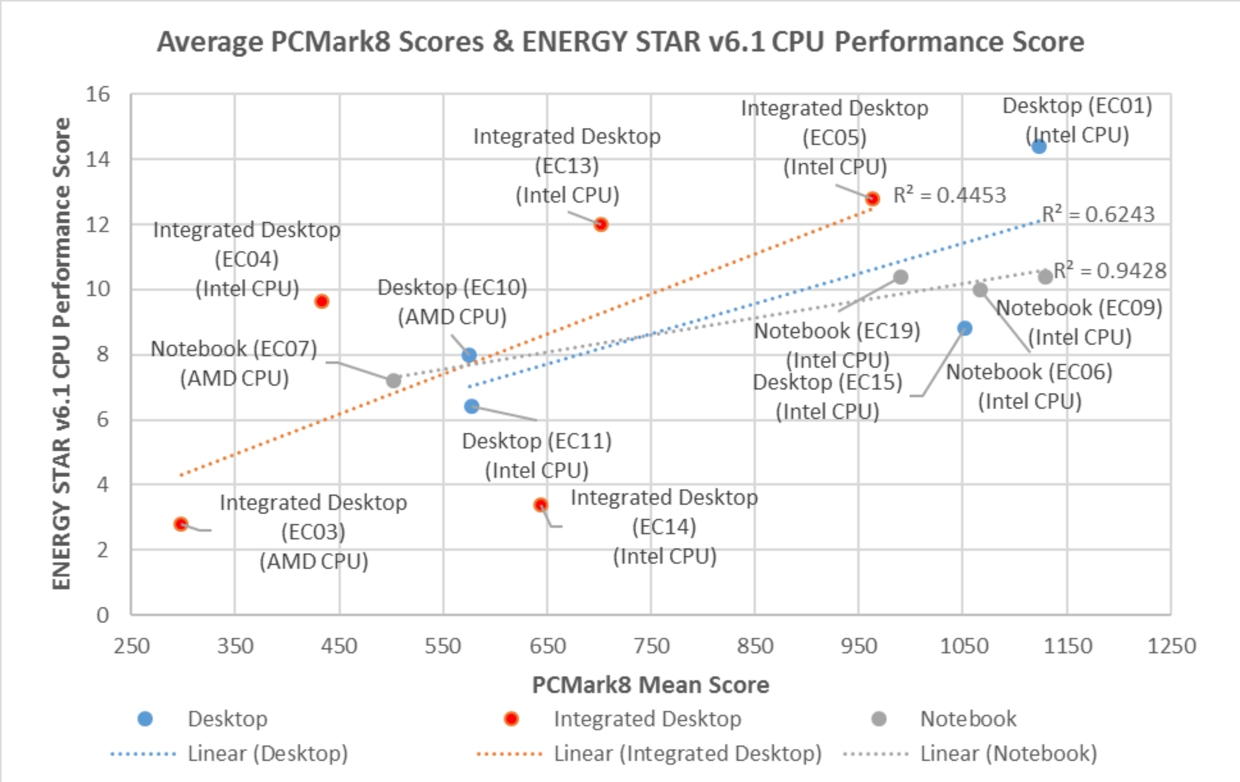

Figure 16. Overall Average PCMark8 Score and ENERGY STAR CPU Performance Score.

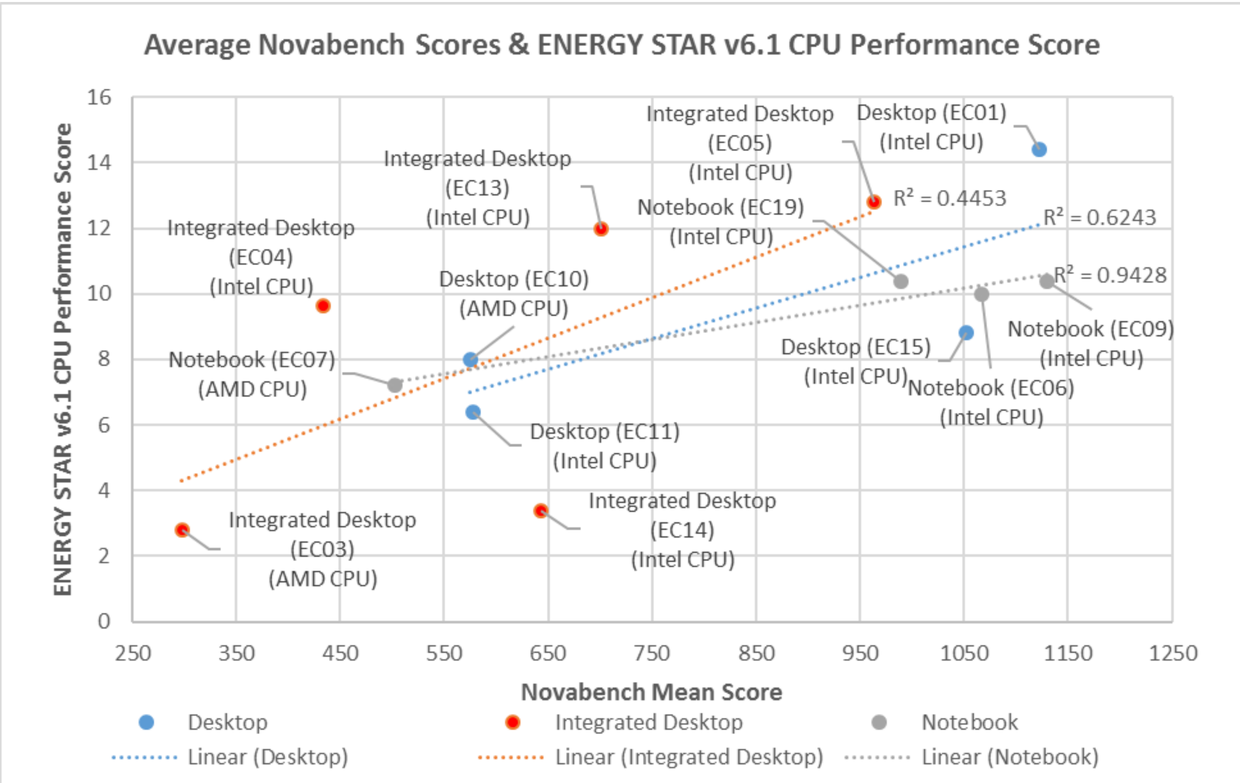

Figure 17. Overall Average Novabench Score and ENERGY STAR CPU Performance Score.

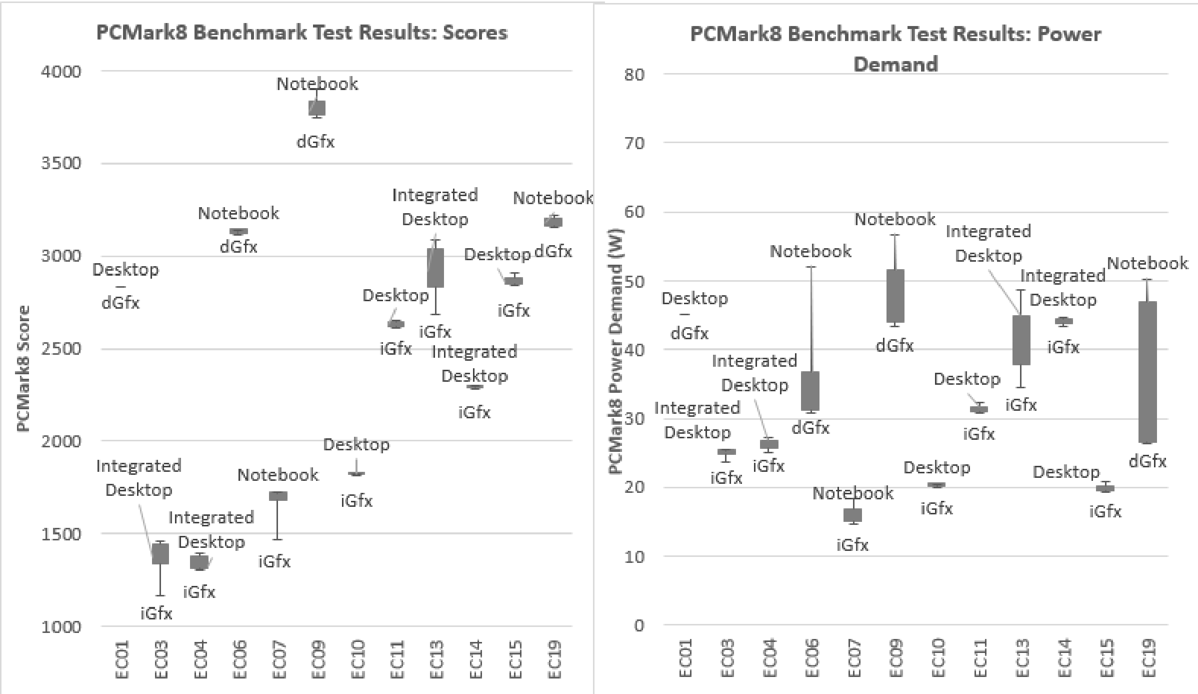

Figure 18. Box Charts PCMark8 Scores and Power Demand.

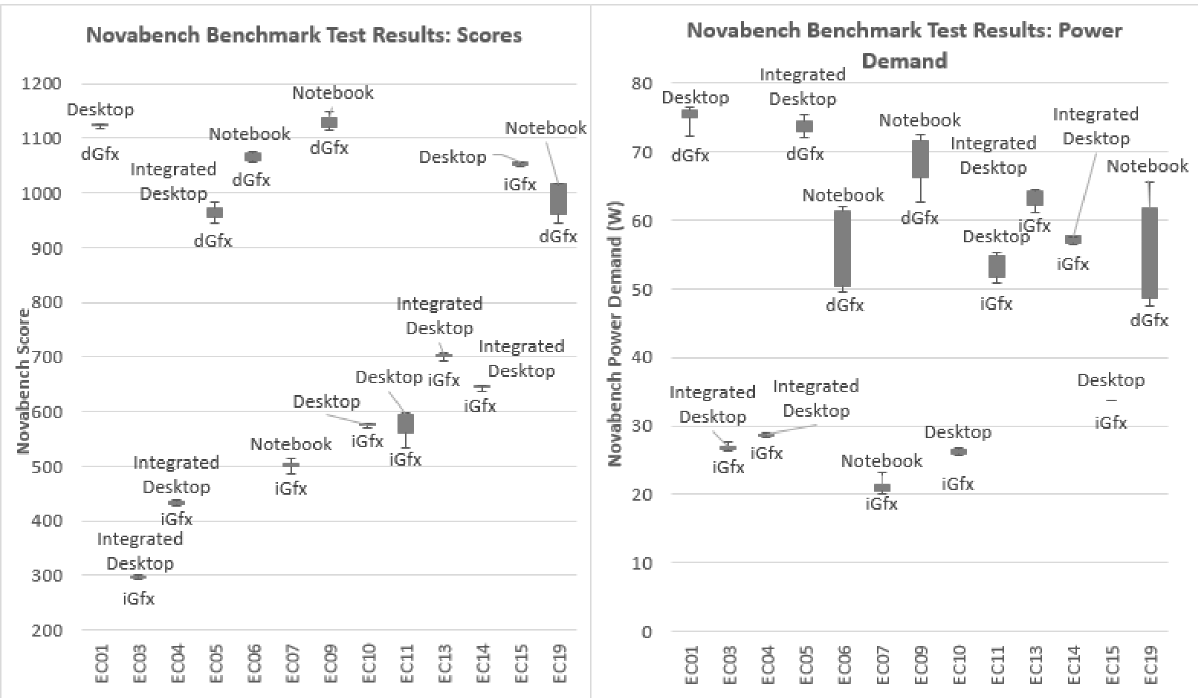

Figure 19. Box Charts Novabench Scores and Power Demand.

To understand what was causing the large spread in power demand in the notebook computer EC19, a further set of tests was run. Figure 20 shows the results of this further testing and the impact that benchmark installing practices has on power demand. The chart shows that power demand drops dramatically on subsequent test runs after a first run. It is also clear that power demand also only returns back towards the first level when the benchmark is stopped, uninstalled and a windows restore point is chosen at a point before the benchmark was first installed. Figure 21 shows the same process happening within a single run[40] of the PCMark8 benchmark, where the average power demand drops with each pass of the tasks. Figure 22 shows a run of the PCMark8 benchmark on a similar product (same CPU and similar discrete GPU), where it is clear that average power demand does not drop with each run.

The results in Figure 20 and Figure 21 undoubtedly show that the notebook (EC19) is remembering the previously conducted tasks and is then able to reduce power demand when running the tasks on subsequent occasions. It is unclear what process is being used to save this energy. It is also curious that the EC09 notebook with the same CPU, higher specification discrete GPU from the same manufacturer and more RAM does not share the ability to reduce power demand through the benchmark test. An answer may lie in the fact that EC19 includes a newer model of discrete GPU that may have additional power saving technology included. Whilst this functionality could prove to save significant amounts of energy when tasks in computers are repeated, there is no guarantee that tasks would be repeated in real-world usage. As such, any benchmark used to support energy efficiency measures should insist on a clean install of a benchmark or only include a single pass of tasks.

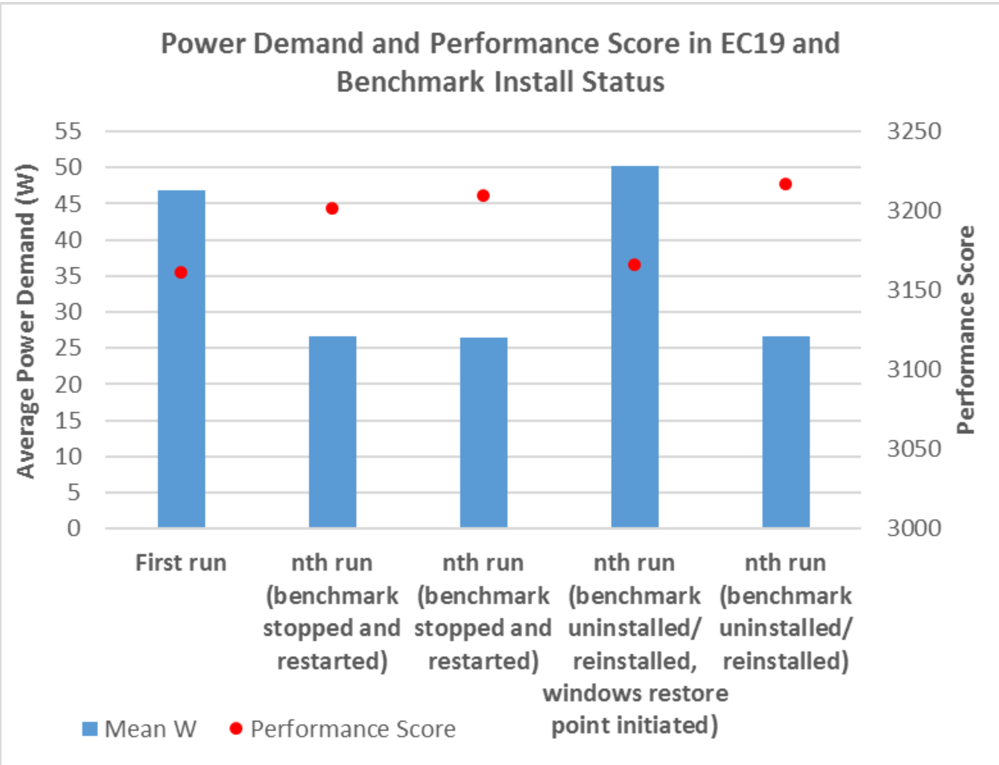

Figure 20. Effect of Install Status on Benchmark Score and Power Demand.

[40] Each PCMark8 test is made up of an Open CL test followed by 3 passes of the same tasks

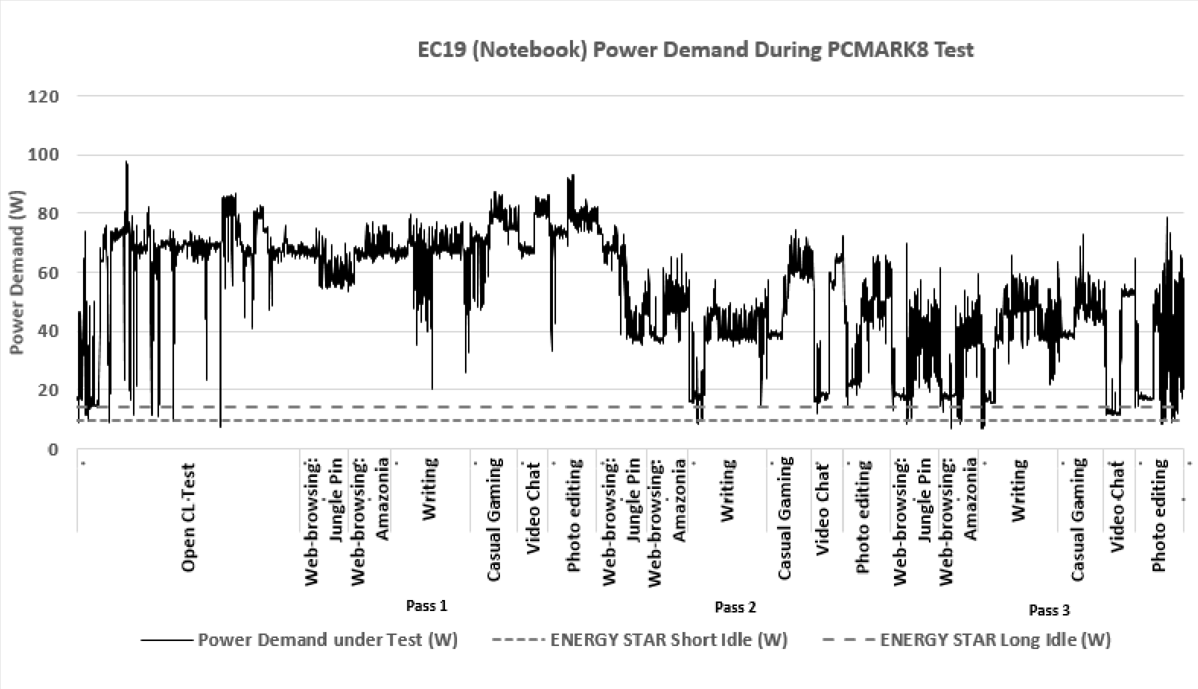

Figure 21. Detailed Power Demand Profile of EC19 during PCMark8 testing.

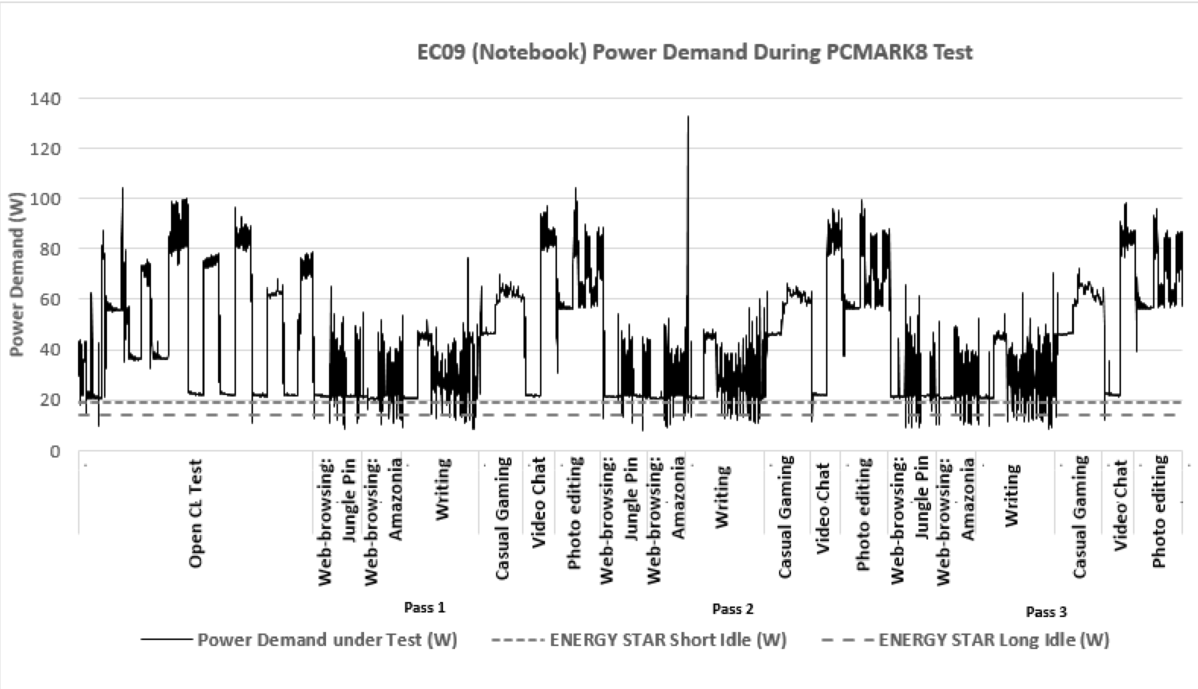

Figure 22. Detailed Power Demand Profile of EC09 during PCMark8 testing.

Another issue noted during the benchmark testing was the problem of manually starting the benchmark test and power demand collection process. Figure 23 shows how relying on a manual start for the testing process leads to different power demand profiles. This would cause issues if an average power demand value was used across a number of benchmark tests. More sophisticated attempts at measuring computer energy efficiency in active states should integrate automatic power demand measurement functionality into the benchmark.

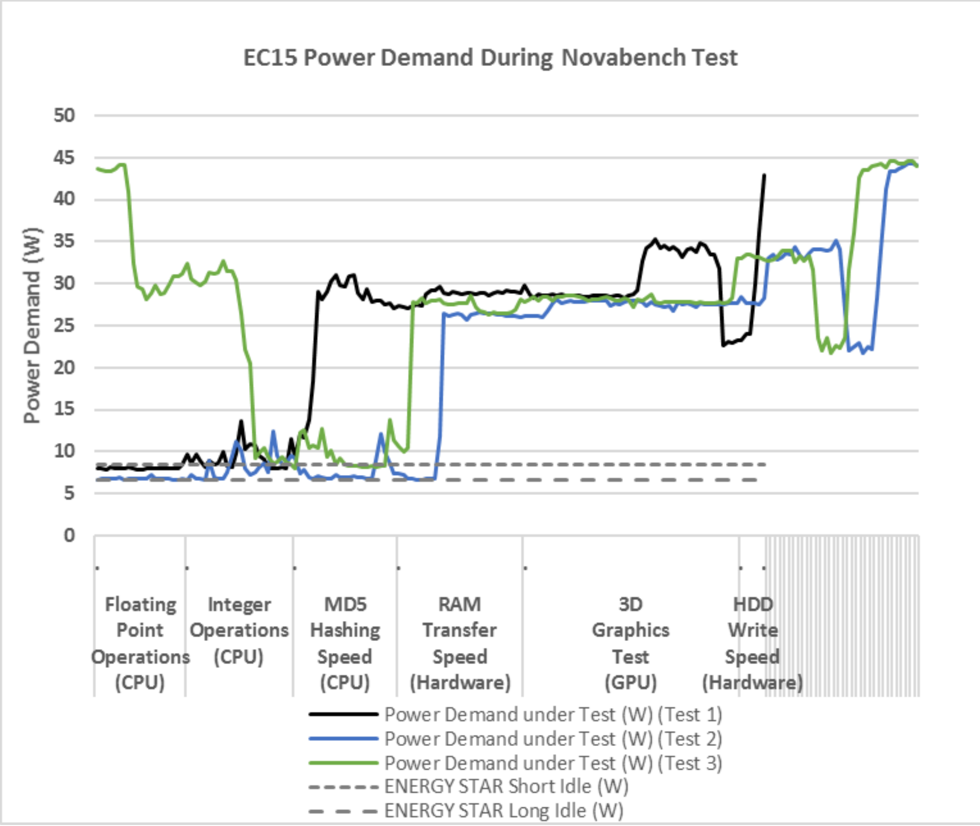

Figure 23. Impact of Manual Start in EC15 Testing.

3.3.4 Basic Active State Measurement Approach

The previous sections of this report have investigated the use of sophisticated benchmarking programmes to measure the active state energy efficiency of computers. It is clear that such an approach is feasible but much work would need to be completed before such a complex benchmarking approach could be used within an ecodesign regulation. This section of the report investigates a possible alternative approach that would allow for the development of a simple test for measuring active state power demand in computers.

Table 38 introduces a basic approach to measuring active state power demand in personal computers. The tests reflect some common functionalities that are regularly provided by personal computers. Testing the average power demand of a computer when providing these tasks would then give an indication of expected power demand under typical work conditions. Testing in this manner would not provide a full picture of the power demands of a computer whilst performing work, since the workload is not intensive. The low level of computational performance needed to run such a workload means that it could be run on many different types of personal computers irrespective of levels of functionality. The consequence of such an approach is that it does not take the performance of a computer into account. If no further categorization between computers was used, high specification computers would therefore be compared on a comparable basis to low specification computers. Given that computing performance and active state energy use are correlated, this would mean that to appear efficient a high specification computer would need to employ more energy efficient features than a low specification computer. The use of categorization via the development of bins of performances could ameliorate the situation and allow for fair comparisons between products whilst at the same time also encouraging improvements in energy efficiency.

Table 38. Basic Active State Test.

	Test Parameters					
Active State Elements	Loaded common web page	Duration 5 mins	Defined file size	Defined content	Sized to full display	Integrated or external display on
	Loaded Word processing dcument	Duration 5 mins	Defined file size	Defined content	Sized to full display	Integrated or external display on
	Loaded common spreadsheet	Duration 5 mins	Defined file size	Defined content	Sized to full display	Integrated or external display on
	Playing HD Video	Duration 5 mins	Defined video (size and content)		Sized to full display	Integrated or external display on
	Combined: Loaded Common web page (x5), loaded word processing document (x5), loaded common spreadsheet (x5), Playing HD Video (x1)	Duration 5 mins	All files of defined size and content with defined video			Integrated or external display on

There are currently a number of initiatives underway to develop a simple active state test procedure for computers, similar to the approach above.. The most established of these initiatives is a Canadian led endeavour that is seeking to develop a test methodology to determine the power demand of computing appliances in various modes in such a way that products with common modes or functions can be easily compared.[41] The Canadian led initiative aims to cover all types of electronic products that provide similar functionalities. That is, the project recognises that electronic devices include a growing number of functions, often with functions being combined into single devices where they were once delivered via multiple products. The scheme also recognises that electronic products are increasingly being built from the same common computing components. The Canadian initiative claims that products are no longer easily separated by their traditional definitions as a result of this continuing divergence of functions and components. At the time of writing, no test procedure has been published for further review.

3.3.4.1 Inclusion of active state efficiency into established metrics

Computer active state energy efficiency could be included into ecodesign measures in a number of ways. This section of the report investigates some of the possible mechanisms for including computer active state efficiencies.

Computer active state efficiencies could be considered separately or could be integrated into established procedures. For example, it would be possible to just list active state power or active state efficiency as a separate value to be met within ecodesign, such as is currently done with sleep and off mode power demand. Alternatively, active state power demand could be included within a typical energy consumption (TEC) procedure. Table 39 provides an example of how active state power demand could be incorporated within a TEC approach.

[41] Canadian Standards Association (CSA), Energy Performance of Computing Appliances, available from https://www.scc.ca/en/standards/work-programs/csa/energy-performance-computing-appliances

Table 39. Example calculation of active state ETEC.

		Maximum power demand (W)	Percentage of time in each active state	Hours Per Year in each active state	Total Active Energy Consumption (kWh)
Active State Elements	Loaded common web page	15.0	12.5%	219	
	Loaded Word processing document	16.0	12.5%	219	
	Loaded xommon spreadsheet	17.0	12.5%	219	
	Playing HD Video	25.0	12.5%	219	
	Combined: Loaded Common WebPage (x5), loaded word processing document (x5), loaded common spreadsheet (x5), Playing HD Video (x1)	28.0	50.0%	876	2
			Total	**1752**	**4**

The above result could then be incorporated into an ENERGY STAR v6.1 style ETEC formula such as that shown below:

$$ETEC = \frac{8760}{1000} \times (P_{OFF} \times T_{OFF} + P_{SLEEP} \times T_{SLEEP} + P_{LONG\_IDLE} \times T_{LONG\_IDLE} + P_{SHORT\_IDLE} \times T_{SHORT\_IDLE} + P_{ACTIVE} \times T_{ACTIVE})$$

Where:

- P_{OFF} = Measured power demand in Off Mode (W);
- P_{SLEEP} = Measured power demand in Sleep Mode (W);
- P_{LONG_IDLE} = Measured power demand in Long Idle Mode (W);
- P_{SHORT_IDLE} = Measured power demand in Short Idle Mode (W);
- P_{ACTIVE} = Measured power demand in Active State (W); and,
- T_{OFF}, T_{SLEEP}, T_{LONG_IDLE}, and T_{SHORT_IDLE}, T_{ACTIVE} are mode time weightings

The ecodesign requirements which dictate the maximum allowable ETEC could then be formulated as:

$$TEC\_MAX = (1+ALLOWANCE_{PSU}) \times (TEC_{ACTIVE} + TEC_{BASE} + TEC_{MEMORY} + TEC_{GRAPHICS} + TEC_{STORAGE} + TEC_{INT\_DISPLAY} + TEC_{SWITCHABLE} + TEC_{EEE})$$

Where:

- $ALLOWANCE_{PSU}$ is an allowance provided to power supplies that meet optional more stringent efficiency levels
- TEC_{ACTIVE} is the Active state allowance specified;
- TEC_{BASE} is the Base allowance specified;
- $TECG_{RAPHICS}$ is the discrete graphics allowance;
- $TEC_{SWITCHABLE}$; and
- TEC_{MEMORY}, $TEC_{STORAGE}$, $TEC_{INT\_DISPLAY}$, $TEC_{SWITCHABLE}$, and TEC_{EEE} are additional allowances given for individual components

Any ecodesign “TEC_{ACTIVE}” requirements would have to be developed using measured data from computers on the EU market. Manufacturers could be asked to provide this data during the development phase of any future ecodesign measures.

3.3.4.2 Conclusion on active state efficiency measures

Computer manufacturers have taken major steps to reduce the power demand of computers during idle, sleep and off modes. While these efforts will have led to some efficiency improvements while computers are conducting work (i.e. providing functionality in active states) it is clear that more efficiency opportunities exist.

Commercially available benchmarks provide an opportunity to accurately rank the performance of computers whilst at the same time offering the opportunity to measure energy consumption during the test. This provides an opportunity to develop active state efficiency metrics that can be largely agnostic in terms of computer form factor and levels of specification. This in turn could facilitate the development of significantly more simplistic ecodesign requirements that would have a broad level of coverage. Requirements based on performance score over energy use could be flexible enough to cover new types of computers coming to market during the life of an ecodesign measure that were not well defined within a regulation.

Despite the opportunities, there are a number of complexities that would need to be resolved before a performance based active state efficiency approach could be developed. Firstly, a suitable benchmark would need to be identified. This could mean the adoption of an existing benchmark in its current form or more likely the adoption of an existing benchmark with amendments made. It is unlikely that any existing benchmark could be used verbatim since at least small changes would likely be required to account for issues such as automatic power demand measurements. Even if an existing benchmark could be developed verbatim there would be a need for a complete review to identify how factors such as performance scores were developed. Another alternative approach would be the development of a bespoke performance based benchmark that was designed to support ecodesign measures. This could be a time consuming process but timing would largely depend on the level of sophistication required.

Addressing active state power demand through the development of a basic test approach also provides advantages and disadvantages. Firstly, there are a number of initiatives around the world that are currently seeking to develop such an approach. As such, a test procedure could be developed more rapidly with shared resources. A major disadvantage of a simple approach to testing active state efficiency is the fact that product performance would not be considered unless categories of products according to performance were developed.

Computers which provide many functionalities typically have higher power demands in all on conditions. This is largely either due to the higher specification products having more components, such as discrete graphics cards, which draw extra power. Or because common components, such as CPUs or PSUs, draw more power when active, due to increased complexity in their designs. With no categorisation of products, higher specification computers would potentially be required to draw the same amount of power in active states as with lower specification products. As such, this would require that higher specification computers include more energy efficiency technologies than lower specification computers without impacting overall performance.

A full review of how higher specification computers could draw the same amount of power in active states as lower specification computers would therefore need to be conducted. Given that computer performance is multi-faceted, in that no single component determines overall performance, development of categories based on component performance may not be suitable unless they are very detailed. Previous attempts to categorise computers based on component based performance attributes, such as within ENERGY STAR and the current ecodesign regulation on computers, have resulted in product categories becoming quickly outdated as a result of changes in product design.

Whichever approach was used to develop an active state efficiency metric, there would be a need to collect and assess measured results from products on the market. This would be required in order to set appropriate ecodesign requirements.

3.4 End-of-Life of personal computers

In this section, the end-of-life of the personal computers within scope of this study is described. The products are traced from their repair and maintenance through to their collection and disposal. The products lifetime is also discussed, in terms of the aspects that define the lifetime which influences not only the total energy consumption of the products but also the repair, upgrade, collection and disposal of the products at their end of life.

The end-of-life aspects are also discussed for batteries and power supply units. Batteries are components that must be removed from the computers at their end-of-life, or collected and disposed separately when being replaced throughout the lifetime of a mobile personal computer. External power supplies are often disposed separately from the computers, but since they are considered finished components from personal computers[42] they are also considered to be WEEE and thus collected and disposed separately.

Trends are presented below for the whole European Union.

3.4.1 Typical product lifetime

3.4.1.1 Personal computers

Personal computers, including peripheral devices, are not only replaced due to being broken or obsolete, but often they are replaced because of increased demands for functionality (often triggered by new software versions), higher performance, and larger internal storage. Mobile personal computers are replaced before they reach typical lifetime due also to durability issues, such as battery degradation. All of the above aspects may shorten the product lifetime, although in some cases this may be compensated by the fact that computers are often stored away for some years (hoarding) after being replaced before they are sent to the end-of-life treatment (according to preparatory study Lot 3[43]).

[42] Some examples are found in WEEE legislative documents in England (https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/393740/LIT_7876.pdf) and in Denmark (Afgrænsning af elektriske produkter og komponenter (WEEE), Dansk Producent Ansvar, November 2014).

[43] Preparatory study for LOT 3 Personal Computers (desktops and laptops) and Computer Monitors, 2007

Table 40 shows the typical lifetime for the first life of the equipment, which was based on findings from the preparatory study, the impact assessment[44], expert assumptions and industry inputs to studies of external power supplies[45] that included data on computer products. According to data from these studies, and expert judgment, the typical lifetime of these products varies between 3 and 7 years depending on the type of the personal computer and peripheral product. Tablets and slate computers have the lowest average lifetime of 3 years while workstations have the highest average lifetime of 7 years. One of the reasons for this difference in lifetime is that tablets and slates are designed in a way that upgrading by accessing and replacing components is more difficult due to product design. Moreover, their product casing is more prone to overheating issues and this can damage the electronics.

A study[46] from Germany presented the minimum useful lifetimes of IT devices and software, which used recommendations from the IT German Council, of 3 years for notebooks and 5 years for desktops and mini PCs (which fall within the product category 'desktop personal computers' in the ecodesign definitions presented in the task 1 report). However, another study[47] in Switzerland presents a median service lifespan of 4 years for notebooks used by business users and about 6 years used by private users. Whilst for the desktops the lifetime is 5 years used by business users and about the same when used by private users. Furthermore, a study[48] conducted by the Joint Research Centre mentioned that notebooks in the Netherlands present a mean residence time of 7 years. The fact that the lifetime of computers is named differently (i.e. 'typical product lifetime', 'service life' and 'mean residence time') may be why they are different. The typical product lifetime is estimated from the product design point of view, whilst service life and residence time may be what is recommended by the user or what is observed in a certain place under certain conditions. The lifetimes of personal computers may vary significantly depending on where and how they are used - as observed in this comparison. This is also shown in the same study from Switzerland[49], which presents a greater variance of lifetimes for notebooks and desktops used by private users - from less than 1 year up to 12 years in notebooks and up to 18 years in desktops – than when used by businesses – from about 1 to 6 years for notebooks and from 3 to 6 years for desktops. This shows clearly that private users tend to hold onto notebooks and desktops longer. However, this study is only representative of Switzerland and no current data was found for the EU.

It was decided in this study that the typical lifetime shown in Table 40 will be used for this review study, since this study is based strictly on the design features of the products. This decision reduces the sources of data variation which cannot be included in this assessment due to lack of data for the whole EU.

[44] Impact Assessment for Lot 3 computers, servers and displays: http://ec.europa.eu/smart-regulation/impact/ia_carried_out/docs/ia_2013/swd_2013_0219_en.pdf
[45] Impact assessment for external power supplies, 2015
[46] Prakash et al., 2016. Paradigm Shift in Green IT – Extending the Life-Times of Computers. Electronic Goes Green Conference Proceedings.
in the Public Authorities in Germany. Conference proceedings Electronics Goes Green 2016+.
[47] Thiebaud et al., 2016. Service lifetime and disposal pathways of business devices. Electronic Goes Green Conference Proceedings.
[48] Technical support for Environmental Footprinting, material efficiency in product policy and the European Platform on LCA. Analysis of material efficiency of personal computers product group. JRC, 2016 (draft version).
[49] Thiebaud et al., 2016. Service lifetime and disposal pathways of business devices. Electronic Goes Green Conference Proceedings.

Table 40. Typical product lifetime of personal computers and peripheral products for their first life.

Category	Typical life time (this study)
Desktop	6
Integrated desktop	6
Workstation	7
Thin client	5
Integrated thin client	5
Notebook	5
Tablet/Slate	3
Portable all-in-one	5
Small scale servers	6
External graphics adapters	5
Docking Stations	5
Peripheral products	6
Power supply units, internal & external	6

3.4.1.2 Batteries

Computer batteries can be replaced several times during the lifetime of a computer. The lifespan of a battery depends on the battery technology (NiCad, NiMH or Li-ion, the latter being the most common type nowadays) and battery durability, which is determined by a battery's *specific cycle life* and *calendar life*.

Cycle life is described usually by the number of charge/discharge cycles a battery can withstand before losing a certain portion of its initial capacity. According to the JRC[48], a battery's cycle life is determined by many factors, such as the quality of the manufacturing processes, the temperature while charging and discharging, and the cycle depth, among others. Today's Li-ion batteries inevitably lose a minor amount of their capacity with each charging cycle due to numerous physical and chemical processes.

Calendar life is described specifically for Li-ion batteries as the portion of capacity they inevitably lose over time, even when they are not in use, for example while in storage. According to the JRC[48], the rate at which a Li-ion battery loses capacity over time is determined by a number of factors, such as the surrounding temperature, the discharge rate, and its state of charge (SoC).

The JRC reports[48] that the battery life is specified usually by manufacturers as the number of charge/discharge cycles that the batteries offer before of the capacity reaches 80% of its original capacity. With some consumer products being between 300 and 500 cycles and others up to 1000 cycles. For heavy users who charge their notebooks or tablets every day, this would amount to a total battery lifetime of up to 1.4 years or 2.8 years (1000 cycles). Of course, batteries can continue to be used even below 80% capacity, although the runtime of the device it is powering will be decreased. A study[50] has shown that at least 55% of Li-ion batteries have the potential to last up to 1000 charging cycles without failure. Failure is when the rated capacity is below 80%. The study was conducted on smartphones and tablets, however it shows that long lasting Li-ion batteries are available.

HP claims that the Li-ion batteries in their notebooks have a battery durability of between 300 and 500 cycles (see Figure 24). The HP batteries are expected to deliver approximately 80% of their rated capacity after 300 cycles or about one year of use with moderate use such as editing spreadsheets, data management applications and other common office work that are not power intensive.. This means that approximately after 1

[50] Durability and Cycle Frequency of Smartphone and Tablet Lithium-ion Batteries in the Field.

year of use, the full charge capacity (FCC) of the battery would have been reduced by approximately 20%. So even when it is fully charged (i.e. when the charge reported by Power Meter of the computer shows that it has reached 100% charge), it will not offer the same amount of power as it did as new, but rather only 80% of its original rated capacity. The Apple MacBook claims to have a maximum life span of 300 (from 2006 - 2009 generations) to 1000 (2009 -2016 generations) charging cycles.

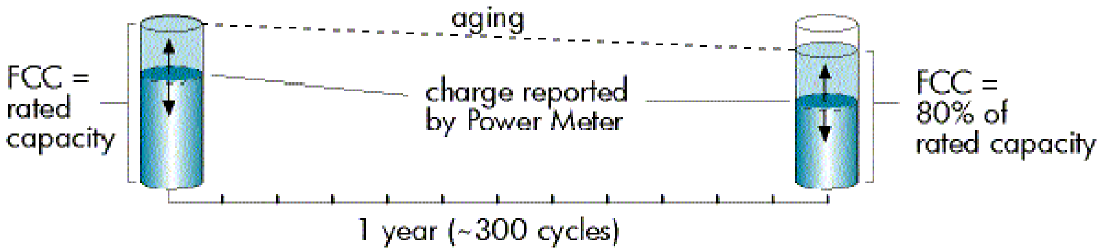

Figure 24. Durability of HP batteries for notebook computers[51].

Some companies such as HP offer a warranty period of one year for batteries, which is based on the assumption that the battery will deliver 80% of its initial capacity after 300 cycles (happening in one year) at low to moderate power loads. High power loads may reach 80% capacity before 300 cycles, and it can reduce the battery cycle time by as much as 25%. See HP's capacity projections of two user types after one year of use in Table 41. According to HP, stationary users, as opposed to mobile users, are more likely have lower capacity after one year of moderate or high usage.

Table 41. Full charge capacity projections after one year of use according to HP.

Power load (applications)	Mobile user Battery cycled daily (25ºC, 77ºF)	Stationary user (with docking station) Battery cycled weekly (>35ºC, 95ºF)
Low (word processing, Internet, e-mail) >	80%	80%
Moderate (wireless, spreadsheets, database management)	80%	70%
High* (CAD, 3D games, DVDs, high LCD brightness)	60%	50%

There has been a proliferation of portable Li-ion rechargeable batteries in the EU, due to the growing market of portable computers, tablets and smartphones. A study[52] from 2014 showed that the average use period of Li-ion batteries in portable computers, including their hoarding period, is 10.6 years. The EU set a target for collecting Li-ion rechargeable batteries of 45% in each Member State by 2016, and it is anticipated that only 10 Member States can meet the target[53], with one of the reasons being the long hoarding period.

State of Charge (SoC)

The SoC of a Li-ion battery is the total energy capacity that is still available to discharge, presented as a percentage. Factors such as age of the battery, charge voltage, temperature, discharge rate and product use patterns affect the measurement[54]. JRC

[51] http://h20564.www2.hp.com/hpsc/doc/public/display?docId=c00596784#c00596784_bcl
[52] How the battery life cycle influences the collection rate of battery collection schemes, bebat, 2014.
[53] An Action Plan on Circular Economy: Outlook for the Portable Power Industry, EPBA, 2016.
[54] http://www.prba.org/wp-content/uploads/State-of-Charge-Li-ion-Batteries-and-DG-Regulations-PRBA-White-Paper-March-2016.pdf

states that the state of charge (SoC) is a major factor determining both the cycle-life and the calendar-life of Li-ion batteries. They show that when a battery is not charged to 100% SoC but it is only charged to 90% or 80%, the number of charging cycles it can withstand increases. Similarly, calendar-life increases considerably with lower levels of SoC. Figure 25 shows that, after 300 days of storage, a battery with 90% SoC has lost more than 20% of its capacity, while a battery with 10% SoC only lost slightly more than 5%. Ideal conditions for a battery over a longer time period is to have a SoC of around 50%. This avoids very high SoCs as well as any damaging deep discharges that may occur via self-discharge of cells over time (e.g. Apple 2016).

Most of the notebook computers nowadays have a battery management system which presents the percentage of charge that is left in the battery, as well as reduce workload when operating on battery only, and limit the threshold for when charging is needed. In many cases when the meter shows capacity below 70% the computer will allow charging of the battery to extend battery life.

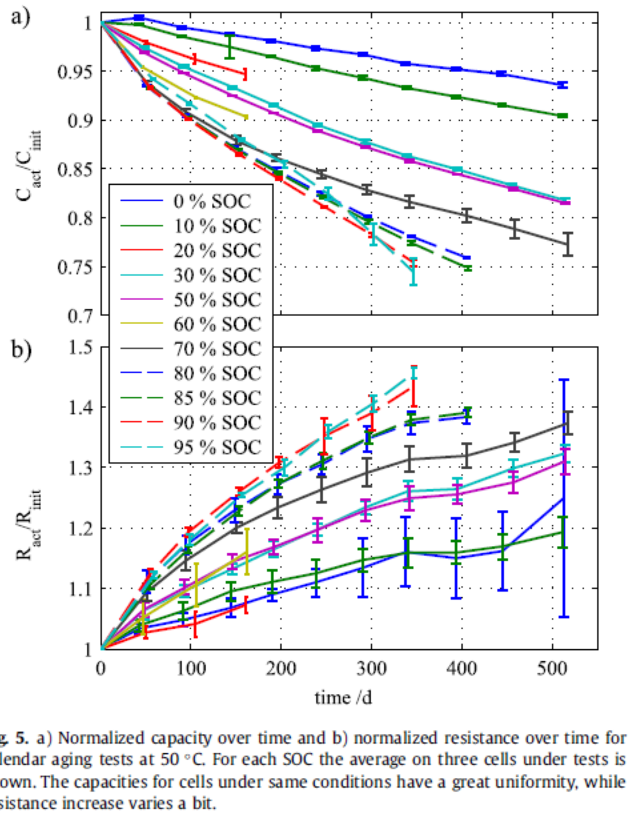

Figure 25. Calendar aging of NMC cells over time depending SOC. Calendar aging under varying SoC is shown in the upper diagram and increase in resistance below[48].

3.4.1.3 External power supplies

The preparatory study for External Power Supplies (EPS)[55] stated that laptop computers' EPS have an average active life time of 5 years. The active lifetime is defined by the lifetime of the end product it serves, which is typically 5 years for a notebook computer. However, this also means that EPS is often disposed before it is defected, mainly due to incompatibility and because every new end product comes with a new power supply unit. According to JRC[48], the EPS design is optimized for the design of the device to be

[55] Preparatory Studies for Eco-design Requirements of EuPs Lot 7: Battery chargers & external power supplies.

powered. In that case, the active lifetime of most EPSs is limited by the lifetime of the end product that it serves.

Concerning sales of new devices, the JRC reports that it has been observed that more than a billion new devices are sold in the worldwide market every year and most of them represent a replacement of the same model, being about 20% of these sold in the EU market. This implies that most of the replaced old EPS are discarded even if still operational, being not compatible with the new devices. EPS used for mobile phones are presented as a case by the JRC. The potential savings in raw material consumption related to universal power supply do not appear to have materialized due to very limited decoupling of mobile phones from their chargers. Only 0.02% of EU handset shipments from 2011 to 2013 were supplied without an EPS. Because of their small size, the likelihood of these products to be discarded in the solid municipal waste fraction is high, while the correct practice would be to send them to a WEEE collection point for recycling. Once an EPS has entered the recycling plant, the recycling process consists of mechanical shredding and material recovery (in particular ferrous metals and copper)[56].

In the JRC study they discuss the European Commission initiative to address the problem of the incompatibility of chargers within the mobile-phone product group. The initiative was where industry agreed to harmonize chargers in the EU with a voluntary commitment, and to ensure chargers compatibility on the basis of the Micro-USB connector. Because of this, CENELEC created a task force to develop the interoperability specifications of a common (universal) EPS, published as EN 62684:2010, and the International Electrotechnical Commission (IEC) released its version of the common EPS standard as IEC 62684:2011. Common EPSs connect to the load with a micro USB type-B connector and a cable, which may be detachable from the EPS enabled by a USB type-A connector (see Figure 26). A standard for universal power supply (UPS)[57] for mobile devices intended for portable computing and entertainment devices (Notebooks and tablets), was issued by the Institute of Electrical and Electronics Engineers (IEEE) in 2015. The objective was to define the features of a generic power supply that was designed for reuse across brands, models, and years: *'A compliant EPS will supply a nominal 21 V at up to 130 W and may negotiate voltages up to 60 V at power levels up to, but less than, 240 W. Each EPS will have one or more power ports to service load devices with control of each port via a serial communications link, an electrical variant of the CAN[58] bus standard'.* The power range delivered to the device for the UPS would be in the range of 10-240 W.

[56] Based on JRC interviews with WEEE recyclers.
[57] The product group is called Universal Power Adapter by the IEEE Computer Society.
[58] Controller Area Network

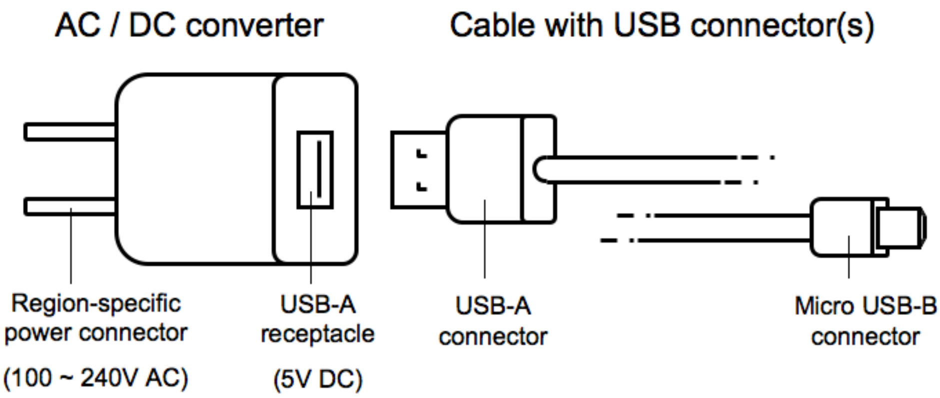

Figure 26. Graphical representation of an EPS with micro USB type-B connector, detachable cable with USB type-A connector and USB type-A receiver (image credits: ©Pugetbill 2011)[48].

Another alternative that JRC discusses is the micro-USB charging solutions (see Figure 26), where the market share of tablets with these solutions has increased over the period 2009-2013. For notebooks, however, very few Micro-USB charging solutions appear to have been adopted and proprietary charging solutions are dominant (e.g. a manufacturer of tablet computers suggests that between 2008 and 2013, 69% of models were supplied with a proprietary EPS). However, JRC also states that the micro-USB charger has become more common place, rising from 17% of sales in 2011 to 47% in 2013. A barrier for the spread of micro-USB is the variation of power requirements of notebooks, which depends on the size and internal components, with most charging in the range 40W to 90W, although this can be as low as 15W and as high as 240W. Therefore, micro-USB is not suitable yet for charging many notebooks.

According to JRC, the IEEE standard 1823 (2015) may contribute to overcoming the latter issue, as it concerns UPS with a power range of 10-240 W delivered to the device. As mentioned before, 2013 was a turning point in terms of EPS, as the use of micro-USB EPS noticeably increased while proprietary EPS decreased. From the tablets sampled by the authors, the use of micro-USB charging is most common in the models.

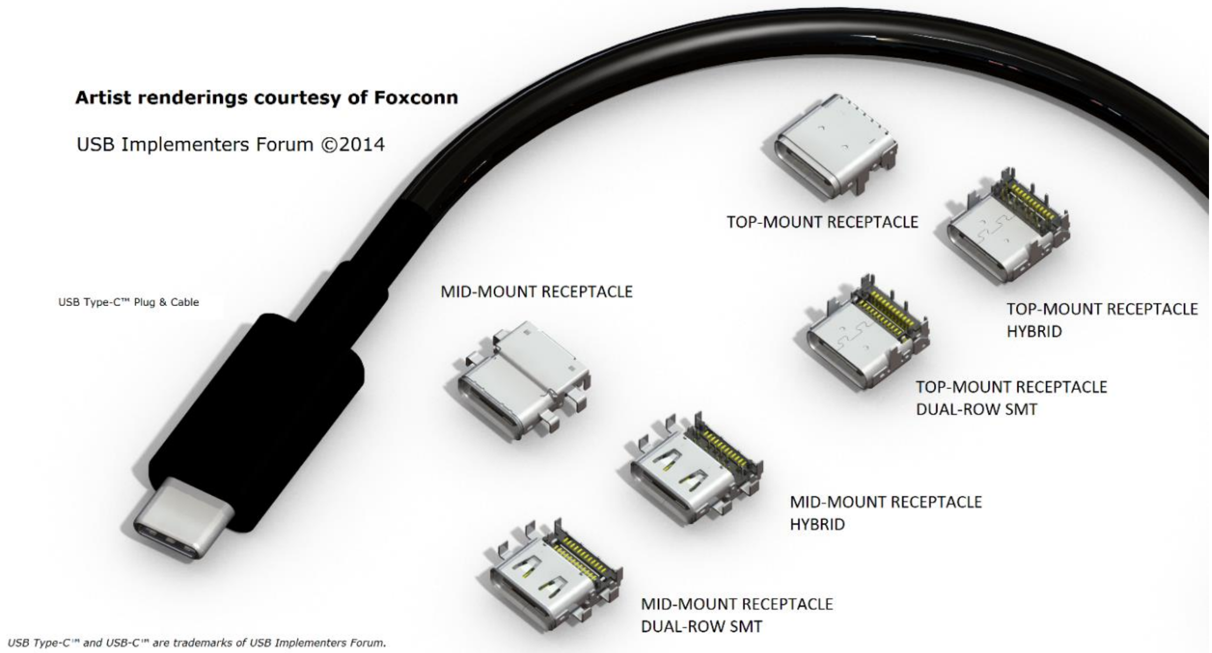

Figure 27. An example of a USB type-C connector[48].

While the common EPS described in the standard IEC 62684:2011 (for mobile phones) adopted a micro-USB connector, another new USB specification for a small 24-pin reversible-plug connector was developed and named USB type-C (see Figure 27). USB type-C cables and connectors were developed to supply mobile devices, including notebooks and tablets, building on the new USB 3.1 Gen 2 standard for power and speed performance, which supports up to 100 W of bidirectional power. Among the main features it is possible to identify the reversible plug orientation, the reversible cable direction and the scalable power.

Another approach to encourage resource efficiency is to limit the materials needed for manufacturing an EPS. EPS has traditionally been bulky and heavy, weighing at least 300 g such as EPS for Lenovo ThinkPad. Newly developed EPSs such as FINsix's Dart[59] (65W), use a Very High Frequency (VHF) power technology, i.e. a much higher frequency of the switching electronics, and at the same time it is physically much smaller than traditional EPS, weighing only 85 g, meaning the demand for materials is largely reduced.

3.4.2 Refurbishment and reuse

Refurbishment for all electronic products is similar. The "broken" computers with defected hardware are collected, and repaired and replaced with functional ones in order to sell computers again, and this implies often the chance of ownership. For computers that can no longer be worthwhile to refurbish, their hardware is most likely harvested. The process of refurbishment of computers is often twofold. Firstly, it is necessary to verify hardware functionality through initial testing, removal of old data and software and installations of new hardware (parts), if this is needed. During this preparatory process, digital data destruction software might also remove all software including the operating system. The second step is to install the required the operating system and applications that control the hardware and provide the desired user functionality[9].

Reuse can be considered as a mild refurbishment, but only limited new or no hardware is needed to be installed for the subsequent life of the computer. Reuse generally occurs when the computer is functional and in adequate condition to be used again, usually only software needs to be updated and small cosmetic refurbishing would take place. Reuse is described as the extension of the product life, or life of its components, to be used for the same purpose for which it was initially sold for. This may or may not involve change of the equipment ownership. It also involves data destruction and functionality test to ensure successful reuse. A lot of reuse of computers occurs in a C2C (consumer-to-consumer) environment, where a consumer sells directly a reusable computer (due to e.g. replacement by a newer generation with more functionality or performance) to another consumer at a lower price than a new computer of the same performance. According to preparatory study Lot 3 for computers and displays, it was estimated that 20% of the equipment had a second life in 2007, indicating that a Swedish study estimated that it would increase to 30% after a few years. Preparatory study used the assumption that 20% of the products would have a second life of years in their calculation. Calculation based on Eurostat statistics, reuse rate out of total WEEE collected is approx. 4% as EU average. This figure covers also other electrical and electronic products that may not commonly reused. Computers should be one of the electronic products that has a high reuse rate.

[59] http://finsix.com/dart/

3.4.3 Repair and maintenance

3.4.3.1 Desktop computers

No recent publicly available data on failure of desktop computers is found at product level, that can provide an indication of the specific trends on repairing and/or maintaining these products. However, the study[49] in Switzerland indicates that the rates of potential reuse of desktop computers by meaning of repair or maintenance are higher in the business sector than in the private sector, as companies often have IT outsourcing contracts as discussed in the task 2 report. Although this outsourcing reduces the lifetime of the desktops down to 3% as presented previously, it increases the possibilities of repair by increased rates of returns to dealers (up to about 40%), resales (up to about 10%), donations (up to about 5%), and reuse by private users (up to about 5%). The same study indicates that the overall rate for all these scenarios when desktops are used by private users in Switzerland is about 7%, however, more than 40% of the users store their obsolete desktop computers before disposing them.

The insurance company SquareTrade showed that in 2006[60], the repair rate of 3-4 years old desktop computers worldwide was 31%. This rate is expected to have decreased in the recent years as it is expected that the consumers of desktop computers may have switched more towards the private use from the business, decreasing the possibilities of repair since most private users do not have IT outsourcing contracts. However, it is also assumed that the private users of desktops are more knowledgeable of their products (due to the increase of DIY computers in the market as discussed in task 2). So they consider replacing or repairing themselves the parts that are more prone to failure. According to a 2006 study by Gartner[61], motherboards and hard drives were the two largest source of failures, which nowadays may have been expanded to other components as source of failure such as video cards, RAM (memory), CPU and power supply according to two more recent studies from 2015[62] and 2011[63]. One of these studies indicates that from products most sold in the US motherboards have about a 7% overall post-shipping failure rate, CPUs about 0.33% (only Intel’s and considering many of Intel CPUs integrate the memory controller, voltage regulator, etc., instead of having these separate in the motherboard), RAM up to 1% (Crucial’s), hard drive (and SSD) less than 1% (Samsung’s, Intel’s and Western Digital Red’s), video cards from 1.6% to 10% (NVIDIA GeForce’s[64] and AMD Radeon’s) and power supplies about a 2.6% overall. Most of these being high-end products (i.e. high performance products). When looking at another study[65] from 2013 and 2014, hard drive failure rates vary greatly between brands starting from about 1% all the way up to 43% in 2014.

The rates presented above for separate components are important, since it is assumed likely that their failure will decrease the lifetime of the desktop computers. However, many of nowadays consumers are also assumed to be willing to replace these parts if prices are not too high, so the overall failure rate is assumed to be close but lower than 31%, and considering the option for replacing components it is assumed that the repair

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[60] https://www.squaretrade.com/htm/pop/lm_failureRates.html
[61] http://www.gartner.com/newsroom/id/493841
[62] https://www.pugetsystems.com/labs/articles/Most-Reliable-PC-Hardware-of-2015-749/
[63] http://www.pcworld.com/article/244481/desktop_pc_reliability_and_satisfaction_dell_and_hp_home_pcs_get_poor_grades.html
[64] https://en.wikipedia.org/wiki/Nvidia
[65] http://www.extremetech.com/computing/198154-2014-hard-drive-failure-rates-point-to-clear-winners-and-losers-but-is-the-data-good

of desktops is high. Finally, it seems that motherboards, video cards (GPUs) and power supplies are the highest source of failure in these products, at least when looking at the few available data from studies done in the US. However, this may not be applicable to integrated desktops, since their design is not modular and thus these components are not easily replaceable.

3.4.3.2 Notebook computers

JRC[48] presents some statistics from a study published by SquareTrade, where 31% of notebook owners reported a failure to SquareTrade (20.4% were related to hardware and 10.6% to accidental damage), compared to 43% reported back in 2006[60]. The parts more prone to damage are keyboards, displays screens and covers (incl. framing joints), batteries and hard disk drives, which seems to be higher when notebooks are used by private users. JRC also discusses that since the main reason for buying a new notebook is that there was a defect (2016 figures from a Germany survey), it is crucial to make these parts repairable and replaceable.

3.4.3.3 Tablets/slate computers

JRC[48] presents also an overview of the most common repair queries for tablets which are:

- Touch screen does not response
- Black screen
- Display has pixel errors/Broken pixels (dots or lines in the display)
- Display glass or touchscreen is broken
- Dust or other dirt behind the screens
- Dust inside the camera
- Overheating batteries (e.g. Samsung recalls 2.5 Mio devices after reports of exploding batteries while charging)
- Other failures depending on the specific device (e.g. home button repair for some Apple tablets or repair of SIM card reader for some Samsung tablets)

The study presents an example of a study where amongst 21 tablet models, huge differences in the design have been found, which leads to a significant variety of process steps required for the device opening, types of connections used, removal of main components and subassemblies. However, based on this study, JRC concludes with some general design recommendations, which are:

- Easy to open and reversible closing mechanism, optimal via several screws. Clips might be used under the condition that they are robust and easy to disengage;
- A modular design, allowing an easy and damage-free removal, as well as substitution of subassemblies, especially the one that are prone to accidental damage. In general, all broken parts could be repaired under the condition that they are easily disassembled from each other;
- Color-coded screws and labelled cables inside the device;
- Non-fusion of front glass with the LCD unit;
- Absence of proprietary screws or fasteners;
- Application of zero insertion force (ZIF) connectors for the connection of battery and display with the mainboard; ribbon cables are also a possible alternative;
- Mainboard fixing to the housing via 3 to maximum 7 screws.

Furthermore, JRC emphasizes the recommendations from other study where information concerning tablets opening and repair should be made available, specially of products just launched in the market. In addition, repair makes no sense, if spare parts are not made available from the manufacturers.

3.4.4 End of life management

Waste treatment practices have improved considerably in the EU since 2000. In 2013, about 43% of the EU's generated municipal waste was recycled or composted[66]. These improvements have been to a large extent driven by EU and national strategies prioritizing efficient waste management through various instruments such as WEEE Directive. However, huge variation in waste treatment remains across the EU. For example, Romania landfills more than 95% of its municipal waste, Malta, Croatia, Latvia and Greece more than 80%, whereas Germany, Sweden and Belgium dispose of less than 1% of their waste by landfill[66]. See Figure 28 for the development of municipal waste disposal routes per capita in the EU over the years.

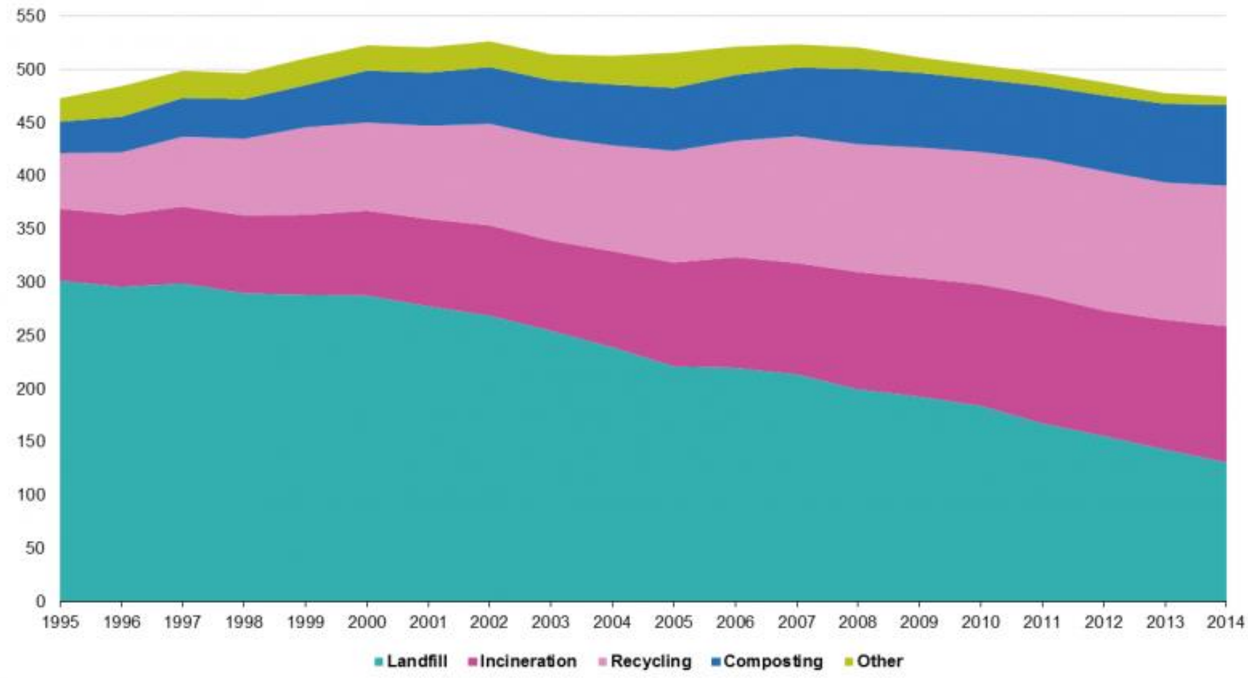

Figure 28. Municipal waste treatment, EU-27, (kg per capita)[67].

WEEE is one of the fastest growing waste streams in the EU. Approx. 9 million tonnes of WEEE were generated in the EU in 2012 and it is expected to exceed 12 million tonnes by 2020[68]. The end-of-life management of electronic products such as computers is therefore crucial.

There are several channels where computers are collected at their end of their lifetime:

- via asset recovery or service agreements for businesses,
- extended producer responsibility (ERP) schemes for private end-users,
- formal collection by municipal authorities, or,
- informal collection from electronic waste stockpiles and from private households.

[66] http://ec.europa.eu/eurostat/documents/3217494/6975281/KS-GT-15-001-EN-N.pdf/5a20c781-e6e4-4695-b33d-9f502a30383f
[67] http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Municipal_waste_treatment,_EU-27,_(kg_per_capita)_new.png
[68] European Innovation Partnership on Raw Materials (2016), Raw Materials Scoreboard.

According to preparatory study Lot 3 for computers and monitors, at the time of the study (2007) 75% of the computers in the EU were recovered. About 87% of these recovered computers were recycled (i.e. 65% of the total computers in the EU). The recovery rate (for recycling, reuse and energy recovery) of computers in the preparatory study was assumed to be 95% because that is what it was used as default figures in the Ecoreport tool (2005 version) and it fitted the practice in Sweden. This is close to some preliminary figures from the WEEE collection system in Denmark, where according to recent interviews the recovery rate for high-grade electronic products such as computers is as high as 95%.

In Figure 29, the figures for the total EEE placed on the market and the WEEE collected and recovered in the EU-28 are shown according to Eurostat. It can be seen that, since 2005 where the data collection starts regarding WEEE, a high amount has been recovered. The figures for EEE placed on the market cannot be equally compared to the WEEE collected, since this does not take into account the lifetime of the products. However, it provides one of the data sources on why the collection of WEEE has increased from 2006 onwards and decreased from 2013. Furthermore, it is assumed that due to the decrease on prices and thus wider accessibility of EEE in the EU, the residence lifetime of these products is shorter in comparison to years before 2010. This means that the amount of EEE placed on the market has a bigger influence on the amount of WEEE generated and afterwards collected. This can be seen particularly in the latest four years and specially in 2014.

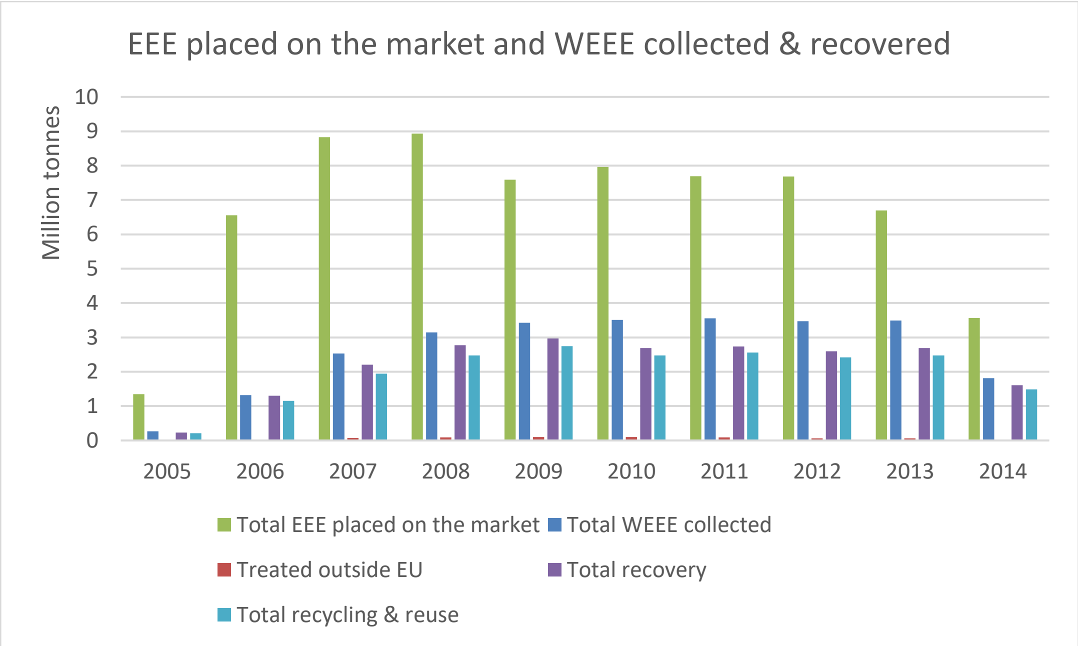

Figure 29. Total WEEE collected and recovered in EU-28[69].

The effect of the WEEE Directive (2012/19/EU) can be observed since the collection rates have increased from the year it entered into force (13 August 2012). However, the amount of WEEE recovered in proportion to the WEEE collected has remained high in the EU since the first years of data registered (~75-99%), and so the amount of WEEE recycled and reused (~70-87%).

[69] http://ec.europa.eu/eurostat/web/products-datasets/-/env_waselee

Figure 30 shows the collection of WEEE under the category 'IT and telecommunications', where computers are a part of. The figure shows that the highest amount of WEEE under this category is collected from households (~82-97% through the time period shown), being the highest in 2010 (~97%) and ~89% in the latest year 2014. The rest is assumed to be collected from offices and businesses, as it has been discussed previously.

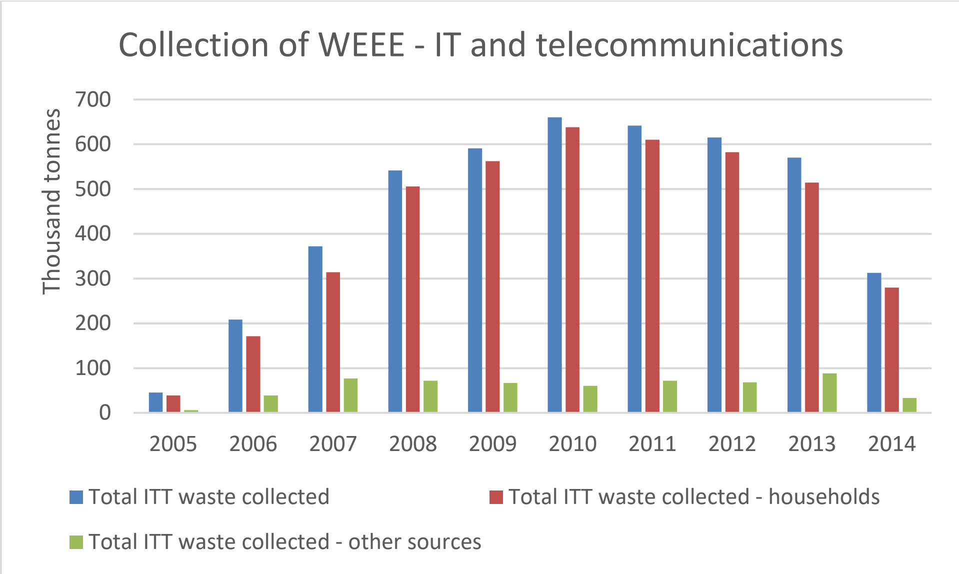

Figure 30. IT and telecommunications waste collected in the EU-28[70].

Figure 31 shows the treatment of WEEE under the category 'IT and telecommunications' in the whole EU-28, and when compared to the amount of WEEE collected (see Figure 30), the share sent for recycling is in the range of ~50-77% during this time period. 77% is of the year 2014. Sweden's share is 84% (2013 in the absence of 2014 data), and Denmark's is 92%. The share of recovered WEEE sent for recycling is obviously higher (, 88% in the EU-28, 90% in Sweden -2013- and 93% in Denmark), since the recycled WEEE is compared to that which is recovered and not collected. These differences show that some of the WEEE collected under the category IT and telecommunications equipment is not recovered, which may be an indication of the WEEE going to landfill. It is also important to notice that the share of collected WEEE under this category sent for recycling is 7% higher than the EU-28 in Sweden and 15% higher in Denmark.

[70] http://ec.europa.eu/eurostat/web/products-datasets/-/env_waselee

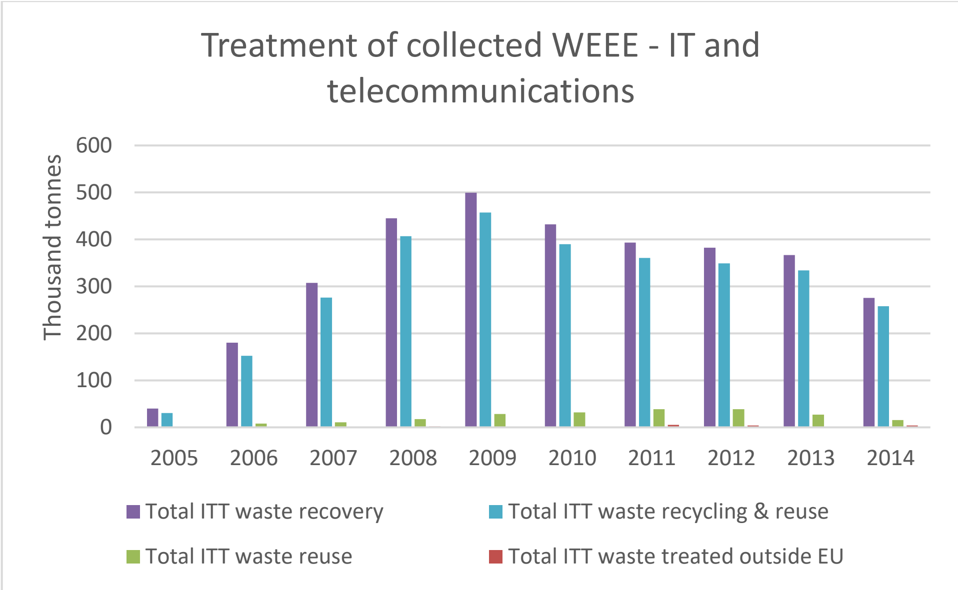

Figure 31. Treatment of IT and telecommunications collected waste in the EU-28[70].

Figure 32 shows that the performance of WEEE management varies significantly across Member States, although the best performing states collect far more than the EU collection target of 4 kg per capita (from households) per year. These Member States also reuse or recycle more than 90% of the collected waste, confirming previously stated countries with well-established recycling facilities and WEEE management, such as Denmark, Sweden, Germany and Finland, are leading in this field. The figure also confirms what presented previously that out of the WEEE collected in each country, the reuse and recycling rate is generally high. This means that high collection rate of WEEE leads to high reuse and recycling rates.

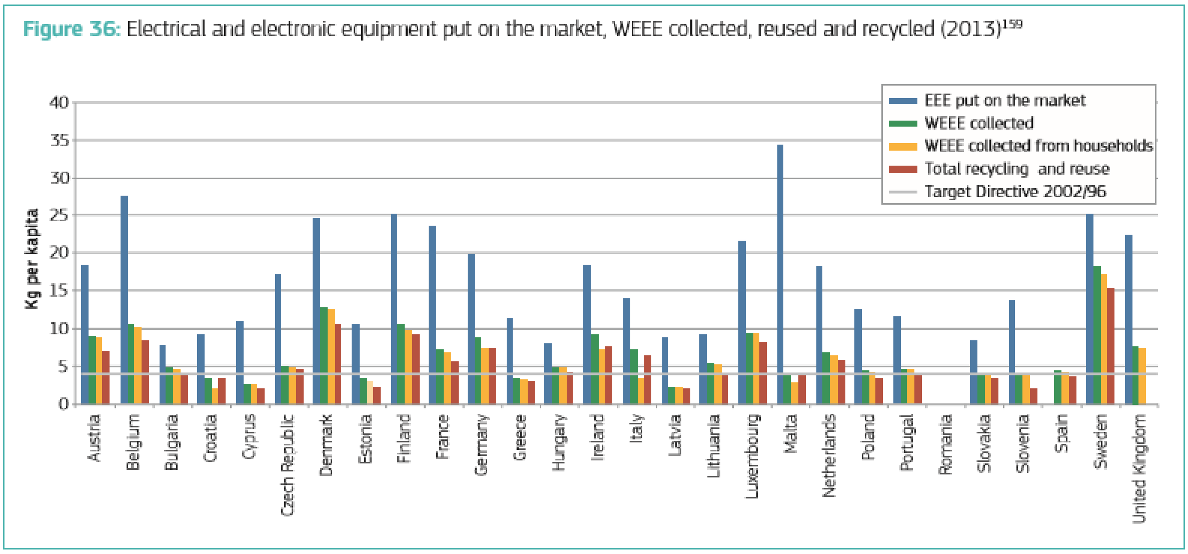

Figure 32. Electrical and electronic equipment put on the market, WEEE collected, reused and recycled (2013). Data from WEEE Forum[71].

Furthermore, the end of life pathways for private and business devices are quite different according to a recent study in Switzerland previously discussed[72]. Business laptops and

[71] http://www.weee-forum.org/

[72] Thiebaud et al. (2016). Service Lifetime and Disposal Pathways of Business Devices.

desktop computers are mainly sent to e-waste collection, returned to dealer and opted for resales, whereas for private consumers, a large proportion of laptops and desktop computers are left in storage or sent to e-waste collection and disposed as presented previously in figures derived from Eurostat. See Figure 33 for detailed pathway distribution. This figure also shows that the storage is quite important for private users of desktops and notebooks in Switzerland, meaning that they reach the e-waste collection after a while, and this creating a difference between the EEE placed on the market and the WEEE collected, as discussed previously. Finally, the possibilities for reuse are higher in businesses than in households due to sending more computers for reuse, resale, donation and return to dealer.

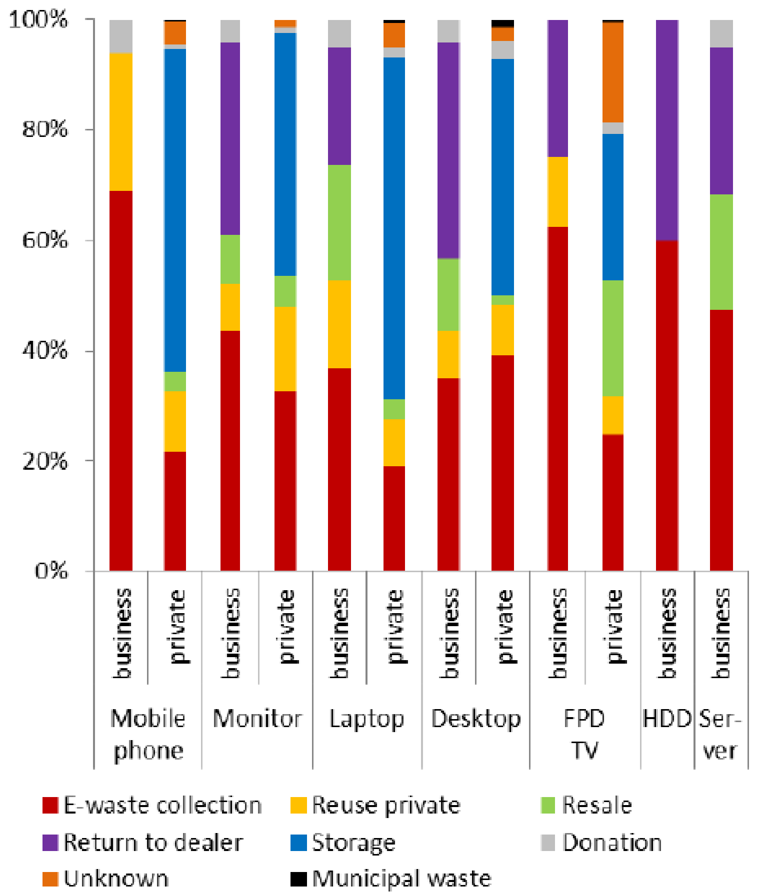

Figure 33. Comparison of disposal pathways of business and private consumers.

All in all, in spite of these differences, Figure 30 showed us that most of the ITT waste collected is from households, and thus these differences are only relevant to provide more possibilities for reuse to households as it is given to businesses. However, these may likely be a part of a service agreement and thus not affordable for private users.

Concerning details of what happen to computers after its collection and according to a study published in 2012 on the end of life management of ICT equipment at a world's level[73], once the computers were collected, they followed the flow depicted in Figure 34. At this stage, it was determined whether the equipment was adequate for reuse, and in which case specific software needed to be run to wipe or purge the hard drive to meet acceptable standards before processing further for the reused and refurbished markets.

[73] https://www.itu.int/dms_pub/itu-t/opb/tut/T-TUT-ICT-2012-13-PDF-E.pdf

This, according to Eurostat data previously presented for IT and telecommunications WEEE, would be a minor share of the EU-28 market (see Figure 31).

Equipment not suitable for reuse was sent to dismantling and separation. First a careful manual separation was needed for removing components which would release hazardous substances into the environment if not separated (such as batteries and cathode ray tube (CRT)). CRT technology was widely used for computer monitors before being superseded by newer display technologies such a LCD, plasma display and LED. CRT can emit a small amount of X-ray radiation, and some older CRTs may contain toxic substances such as cadmium. However, CRT treatment may not be as relevant nowadays since technology has since evolved beyond CRT. After the removal of the problematic components, the equipment was further disassembled and sorted into various material streams e.g. steel, aluminium, circuit boards, and plastics. These streams were then sent to specialised material recovery processes.

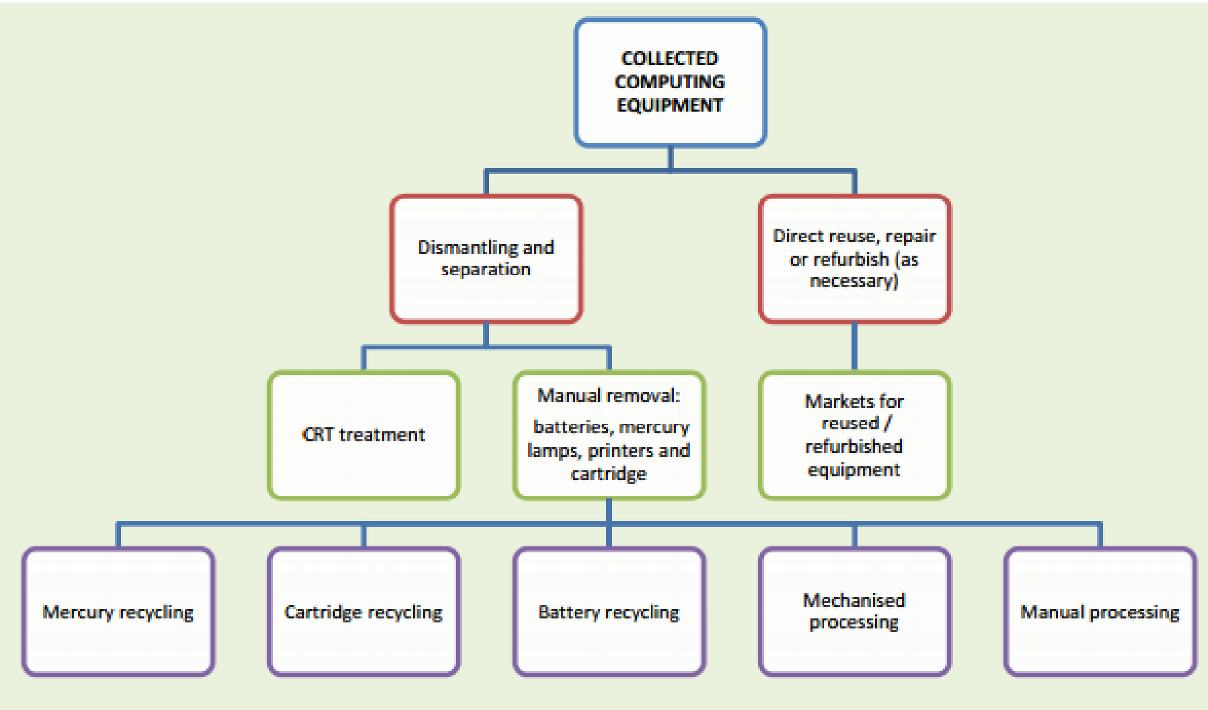

Figure 34. End of life scenarios of computing equipment.

3.4.4.1 End of life of desktop computers

JRC[74] reports similar end of life scenarios for desktop computers as those presented in Figure 34. In one of them there is manual dismantling followed by shredding and mechanical sorting, whilst in the other there is no manual dismantling so the computers go straight to shredding. See Figure 35 for more details. The main difference with what presented in Figure 34 at a world's level is that reuse is not included, but once focusing on the rest of the end of life practices, what suggested by JRC is more relevant to this product group. Figure 35 shows that by introducing manual dismantling at the start, a higher recovery of precious materials is possible since more of the components containing these materials are dismantled. However, according to JRC, the content of steel and aluminium do not represent a discriminating factor between including manual disassembly or not, since these metals are generally recovered at high rates with

[74] Technical support for Environmental Footprinting, material efficiency in product policy and the European Platform on LCA. Analysis of material efficiency of personal computers product group. JRC, 2016 (draft version).

mechanical treatments. On the other side, the separation of plastics does not create an economic gain, since they have a low recyclability (due to the content of several additives as flame retardants and fillers) and low value. Shredded plastics from computers are generally contaminated by various other fractions and suitable for the manufacture of lower quality products (downcycling) or incinerated. Since the balance between introducing manual disassembly or not lies on the potential economic gain from the additional recovery of certain valuable materials (e.g. palladium, gold, silver, copper), the content of these in the products will define whether it pays off to increase the labour costs and time.

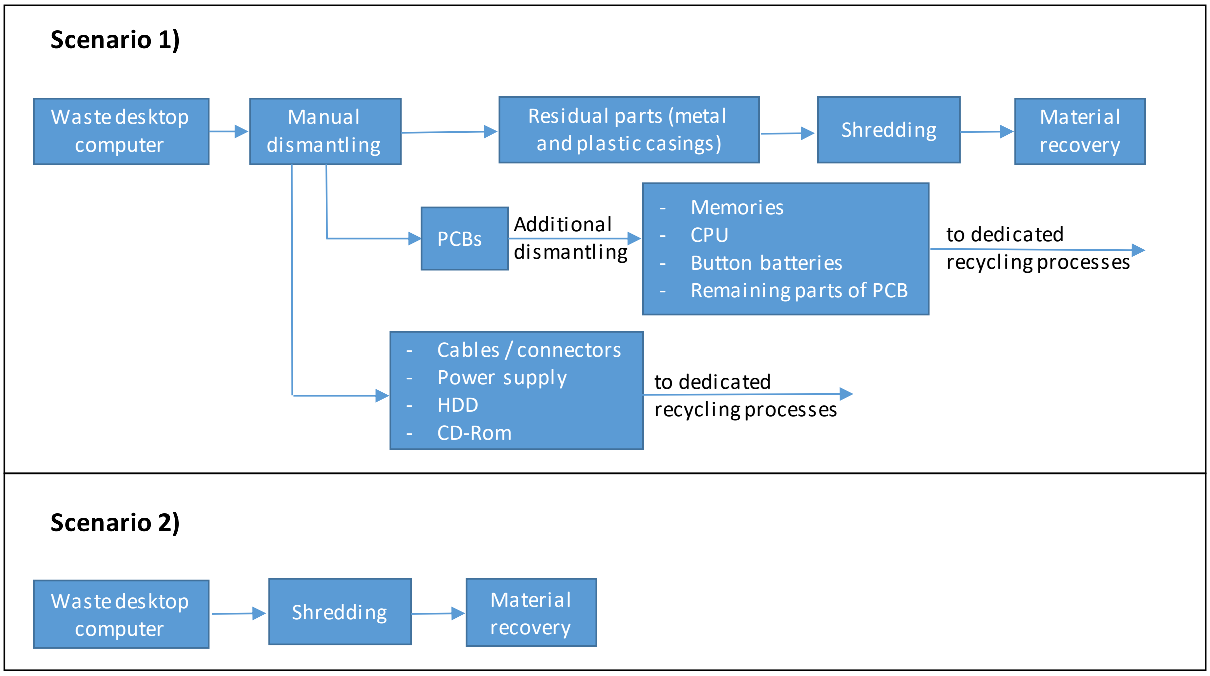

Figure 35. Two end of life scenarios for desktop computers according to JRC[74].

According to JRC, manual disassembly is generally largely implemented for waste electronic products including desktop computers since all components are generally fastened with standard screws and full disassembly takes only 2-4 minutes per piece. However, this analysis was carried out on waste desktop computers at the recycling plants, concerning mainly devices produced some years before. This implies that future products could pose some dismantling problems especially for new devices of very small dimensions, sometimes referred as 'mini' desktop or 'mini-PC'[75]. Since more of these products are being offered on sale in the EU market, it is thus necessary to contemplate the possibility that no manual disassembly will pay-off in some of the recycling plants in Europe.

Finally, it is assumed that apart from steel, aluminium, palladium, gold, silver, copper and other precious or critical raw materials, the other materials are mainly incinerated with energy recovery and in a minor degree and in some cases, landfilled.

Integrated desktop computers

Integrated desktop computers are a particular case of desktop computers which use an integrated display. According to JRC and based on an exemplary manufacturer's

[75] Some examples can be found at: http://www.intel.co.uk/content/www/uk/en/nuc/overview.html, https://minipc.eu/, http://www.ebay.com/sch/i.html?_nkw=mini+pc

instructions for recyclers[76], components requiring selective treatment in the integrated desktop are:

- Four Printed circuit boards
- Coin (or button) style battery
- Liquid Crystal Displays (LCD)
- External cables

However, according to stock data presented in the task 2 report, integrated desktops represent only 4% of the EU market for desktop computers. Due to this and their relatively short time since their market introduction, it is assumed that the amount of these products reaching their end of life is still limited. JRC confirms this in their report[74], where as a result from interviews at recycling plants it was found out that very few samples have been treated so far. Furthermore, operators at these plants mentioned they cannot easily distinguish integrated desktop computers from computer monitors, and thus integrated desktops may be treated as electronic displays. These operators also stated that the disassembly steps for both of these products is very similar. JRC therefore suggests that any policy measure in material efficiency for these products could be built analogously to those for electronic displays which have already been drafted.

3.4.4.2 End of life of notebook computers

The end of life of mobile personal computers is different to that of desktop computers mainly because of the presence of the battery. However, it differs more to desktop computers than to integrated desktop computers because of the presence of the monitor. Since notebooks can be clearly identified, they do not follow the same disposal patterns described for integrated desktops.

JRC reports[74] that dismantling to recover some key components of notebooks is usually done manually. Figure 36 shows the generic end of life scenarios for notebook computers according to JRC research. The key components to recover by manual disassembly, battery and display unit, are first dismantled together with the capacitors[77] (not shown in the figure). Thereafter, other components containing important materials to recover (e.g. removal of circuit boards, hard disc drives, optical drives) are either manually dismantled and/or shredded. Finally, further separation and sorting generates fractions which are then forwarded to final treatment. As it can be seen in this figure, the display unit is also either manually dismantled and/or shredded into fractions and components[78] (e.g. iron and plastic fractions, and LCD panel[79] and circuit board fraction). At present, LCD panels are either stored for future treatment or treated with technologies that are still in an early development stage or under development[80]. Other fractions are forwarded to be further processed using interim and final treatment technologies.

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[76] http://www.hp.com/hpinfo/globalcitizenship/environment/productdata/Countries/_MultiCountry/disassembly_desckto_2016524202927.pdf

[77] Electrolyte capacitors containing substances of concern (height > 25 mm, diameter > 25 mm or proportionately similar volume) have to be separately removed according to annex VII of 2012/19/EU directive. However, newer notebooks do probably contain capacitors with smaller sizes (volume).

[78] E.g. http://www.mrtsystem.com/products/flat-panel-processor/

[79] Liquid crystal displays of a surface greater than 100 square centimetres are those removed as well as the mercury containing CCFL backlighting. However, it is assumed that more recent devices feature LED backlighting, thus the mercury containing fractions are not considered in the present generic illustration of end of life scenarios as shown in Figure 36.

[80] According to JRC research, usually, the polarisation foils are removed from the LCD panel, the LCD panel is mechanically broken down (e.g. crushed) and Indium is mobilized through hydrometallurgical treatment.

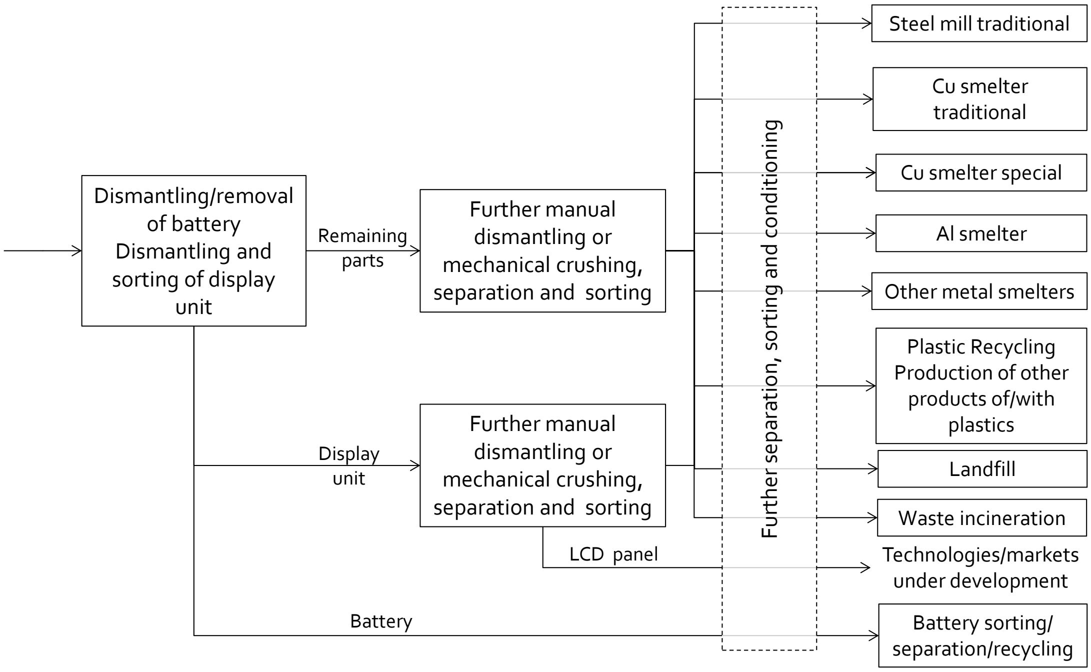

Figure 36. Generic end of life scenarios of notebook computers[74].

According to JRC, treatment operators combine different mechanical and manual dismantling and separation methods, depending on which components they target and whether they can sell special parts which are difficult to process such as hard disk drives. In the following sub-sections, two scenarios of treatment after manual dismantling of the battery, display unit and capacitors are presented based on JRC research: mechanical crushing and sorting (scenario 1), or medium-depth manual dismantling (scenario 2).

Mechanical crushing and sorting

After removal of the battery, display unit and capacitors, the entire device is treated in a medium shredder for further separation of the different fractions, just as it is shown in Figure 36, but with mechanical crushing instead of manual dismantling.

Manual medium-depth dismantling

After removal of the battery and display unit, certain high value components are manually recovered from the notebook (see Figure 37), such as:

- The printed circuit board, containing, amongst others, the CPU, the RAM and the graphic chip directly forwarded to the copper smelter.
- Hard disc drives and optical disc drives, to be forwarded to a medium shredder for further separation of iron, aluminium, magnets and circuit board fractions.

According to JRC research, the rest of the notebook's body goes to a medium shredder for further separation of fractions.

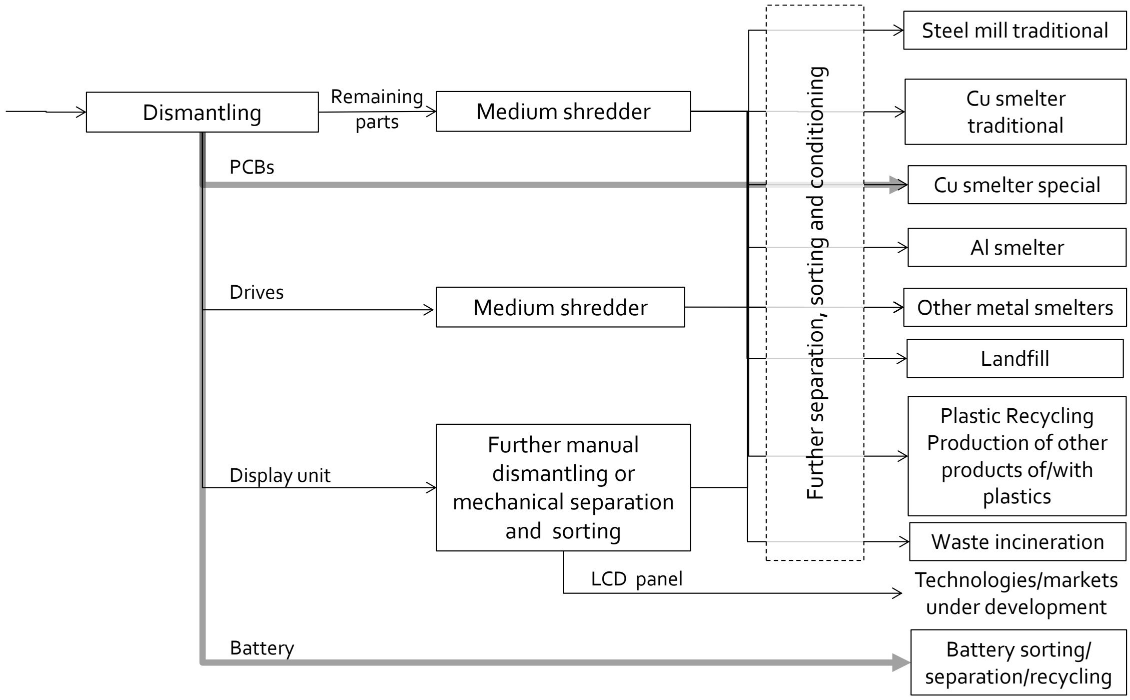

Figure 37. Manual medium-depth end of life scenarios for notebook computers[74].

3.4.4.3 End of life of tablet/slate computers

Because of the limited information on the end of life of tablet computers, it is not possible to present a detailed review of the different disposal scenarios. However, since this is an EEE it is collected according to the WEEE Directive[81]. The recovery and subsequent reuse and/or recycling of the product parts is different to notebook and desktop computers, since these products are more difficult to dismantle.

JRC[74] reports that, due to the still limited number of discarded tablet computers reaching the recycling facilities, end of life scenarios have been only established based on three studies made in 2013 by three recyclers of WEEE in Germany (ELPRO, Braunschweig; Adamec Recycling GmbH, Fürth and EGR Elektro-Geräte Recycling, Herten). Further contact with some recyclers was established by JRC in 2016, but no additional conclusions from the earlier abovementioned studies can be drawn. Based on these studies, two end of life scenarios can be established as tentative descriptions:

1. Battery removal by manual dismantling.
2. Pre-processing, which can be:
    a. shredding of the whole device via cross-flow shredder, or,
    b. manual dismantling of the subassemblies (such as aluminium or plastic housing, PCB, LCD, magnesium frame if present), using predominantly screw drivers (battery powered and hydraulic).
3. Further separation and sorting and conditioning of other metal and/or plastic fractions as shown for notebooks in Figure 36.
4. Final treatment of remaining materials as for notebooks.

For step number 2, it is assumed unlikely that manual dismantling takes place due to the high labour costs which are unlikely to be covered by the material value.

[81] 2012/19/EU

The end of life scenarios for other personal computer product groups presented in task 1 report and assessed afterwards (i.e. thin clients, workstations, portable all-in-one and small scale servers) have not been assessed due to lack of specific information. However, it is assumed that the scenarios for desktops can well represent those for non-mobile personal computers with the exception of integrated desktops as explained previously. It is also assumed the same for notebooks representing mobile personal computers, with the exception of tablets. End of life scenarios for small scale servers have not been investigated.

3.4.4.4 End of life of batteries

According to JRC[74], after collection, batteries are usually sorted manually according to their chemistries (lead acid, alkaline, NiCd, NiMH, Li-ion, etc.) before being conducted to recycling treatments. Sorting workers attempt to identify the battery chemistry primarily via the labels on packaging/casing of the batteries. However, in practice labels are sometimes missing, making identification and sorting difficult. According to the interviews carried out by JRC, dismantling centres remove disposed batteries from the WEEE stream, if batteries are damaged or if the cells are removed from the battery pack. Because of missing label on cell level, cell batteries are classified as not identifiable fraction and are sent to dedicated landfills, thus are lost for appropriate recycling. Currently in Europe no labeling is mandatory to comprehensively identify the battery chemistry. Incorrect sorting of Pb or NiCd batteries with Li-ion batteries complicates the recycling processes and potentially poses risks for the workers and to the environment. For example, in case of mis-sorting of NiCd batteries into Li-ion batteries, the toxic Cadmium metal can be released to the off-gas because the treatment of Li-ion batteries does not intend to treat Cd. Consequently, to avoid environmental pollution a more expensive off-gas cleaning system must be applied. In practice, manufacturers usually do label the batteries according to their chemistries, however not in a coherent manner (see Figure 38 for some examples).

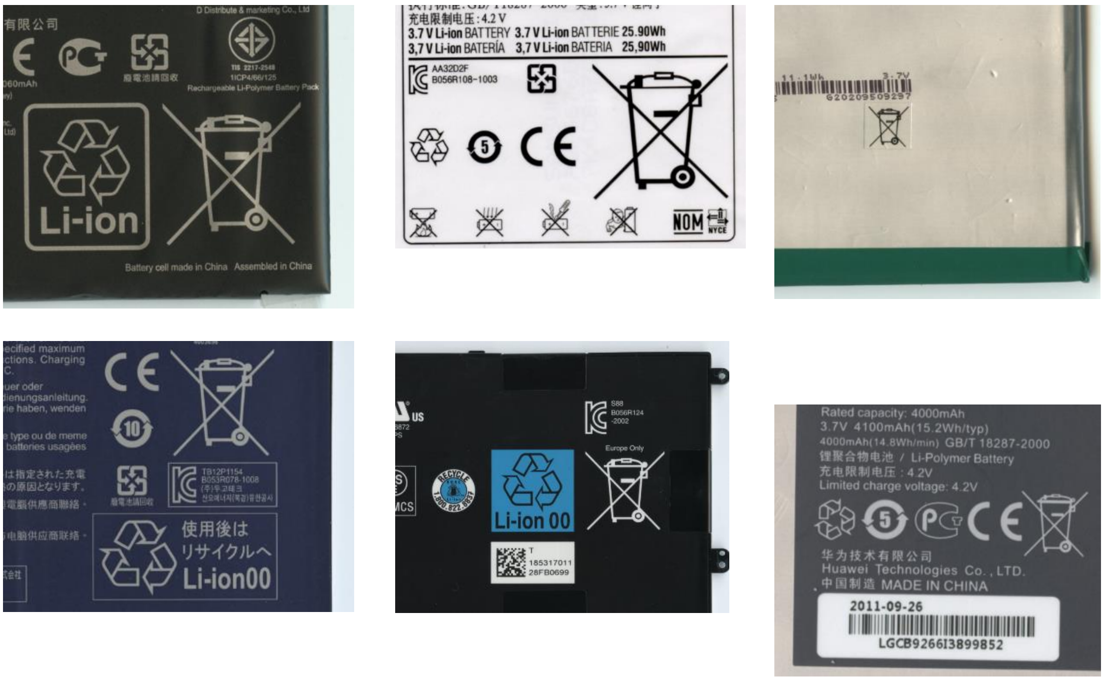

Figure 38. Examples of battery labelling in practice (unreleased data from Slates D4R)[74].

JRC adds that the different chemistries of Li-ion batteries (LCO, NCM, LFP, etc.) are currently not indicated on battery packs or cells, leading to economic and material losses. Depending on the Li-ion chemistry, the content of cobalt varies from 0 % to 15 % by weight. However, usually all Li-ion battery subtypes are co-processed, making the subsequent separation and extraction of metals more difficult and expensive. For example, in the extraction process of cobalt from high cobalt concentrates (LCO-type Li-ion batteries), the iron and phosphorous from mixed processing of LFP batteries become disturbing elements and need to be removed. Such removal would increase the cost of the process. Therefore, a batch-wise treatment allows for better concentration of the target metals than a diluted mixture and is more feasible from both a technical and economical point of view. In order to realize more precise sorting and dedicated treatment of batteries according to their sub-chemistry, a more detailed indication on battery packs as well as on the cell level would be needed. Thus, JRC suggests that the 'Battery Recycle Mark' required in Japan[82], which identifies the four different types of battery chemistries by color and abbreviation (see Figure 39), could be used in mobile personal computers in the EU market. Through standardized use, the label will lead to higher recognition by more users in countries around the world which can be expected to contribute to the global spread of recycling portable secondary batteries.

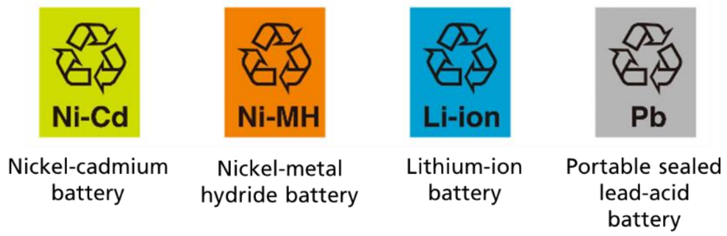

Figure 39. Battery Recycle Mark, mandatory in Japan, which indicates the four different battery types by colour and in text.

According to JRC, the Battery Association of Japan (BAJ) recommends the industry to add a two-digit code to the label for Li-ion batteries to specify whether Co, Mn, Ni, or Fe is the metal predominantly found in the cathode by mass with the first digit and whether tin or phosphorous are contained in the battery exceeding a defined threshold (see Figure 40).

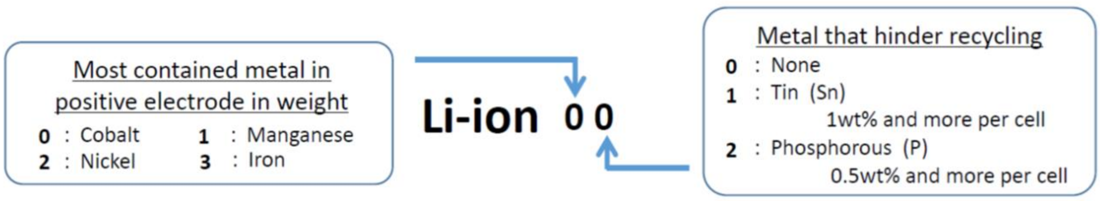

Figure 40. The two-digit code, developed and recommended for use by BAJ.

Considering the end of life scenarios for batteries in the world's market, the current main treatment processes include thermal pretreatment, mechanical treatment, pyrometallurgy and hydrometallurgy, according to JRC. Table 42 summarizes the technologies used at Li-ion battery recycling plants worldwide.

[82] Global Environment Centre Foundation: Law for promotion on effective utilization of resources, 2016: http://nett21.gec.jp/Ecotowns/ .

Table 42. Overview of end of life treatment plants and processes worldwide.

Company	Recovered Elements	Process	Country
Glencore	Ni, Co, Cu	Thermal pretreatment + pyrometallurgy + hydrometallurgy	Canada
Umicore	Ni, Co, Cu, Fe	Pyrometallurgy + hydrometallurgy	Belgium
Accurec	Ni, Co, Cu	Thermal pretreatment + pyrometallurgy + hydrometallurgy	Germany
Kyoei Seiko	Ni, Co, Fe	Pyrometallurgy	Japan
JX Nippon	Ni, Co, Cu, Fe, Mn, Li	Thermal pretreatment + mechanical treatment + hydrometallurgy	Japan
Dowa	Ni, Co, Cu	Thermal pretreatment + pyrometallurgy + hydrometallurgy	Japan
GEM	Ni, Co, Cu, Fe, Mn, Li	Mechanical treatment + hydrometallurgy	China
Brunp	Ni, Co, Cu, Fe, Mn	Mechanical treatment + hydrometallurgy	China
Telerecycle	Ni, Co, Cu, Fe, Li	Mechanical treatment + hydrometallurgy	China
Kobar	Ni, Co, Cu, Fe	Mechanical treatment + hydrometallurgy	Korea
Recupyl	Ni, Co, Cu, Fe, Li	mechanical treatment + hydrometallurgy	France
Retriev	Ni, Co, Cu, Fe	Aqueous + mechanical treatment + hydrometallurgy	US
SNAM	Ni, Co, Cu	Thermal pretreatment	France
AkkuSer	Ni, Co, Cu, Fe	Mechanical treatment	Finland
EDI	Ni, Co, Cu	Mechanical treatment	France
Batrec	Ni, Co, Cu	Mechanical treatment	Switzerland