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

Computers and Computer Servers

Task 4 report

Technologies

Final version for consultation

2nd February 2017

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Specific contract no.: ENER/C3/2012-418 LOT1/11/FV 2015-543
Implements Framework Contract: ENER/C3/2012-418 LOT N° 1

This study was ordered and paid for by the European Commission, Directorate-General for Energy.

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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
DRAM	Dynamic RAM
DVS	Dynamic voltage scaling
EC	European Commission
eDRAM	Embedded Dynamic RAM
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
PCI	Peripheral Component Interconnect
PRO	Producer Responsibility Organisation
PSR	Panel self-refresh
PSU	Power Supply Unit
RAM	Random access memory

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

Introduction to the task reports

This is the introduction to the interim report of the preparatory study on the Review of Regulation 617/2013 (Lot 3) for Computers and Computer Servers. The interim report has been split into five tasks, following the structure of the MEErP methodology. Each task report has been uploaded individually in the project's website. These task reports present the technical basis to define future ecodesign and/or energy labelling requirements based on the existing Regulation (EU) No 617/2013.

The task reports start with the definition of the scope for this review study (i.e. task 1), which assesses the current scope of the existing regulation in light of recent developments with relevant legislation, standardisation and voluntary agreements in the EU and abroad. The assessment results in a refined scope for this review study.

Following it is task 2, which updates the annual sales and stock of the products in scope according to recent and future market trends and estimates future stocks. Furthermore, it provides an update on these trends as well as on consumer expenditure data which will be used on the assessment of additional life cycle consumer costs if/when setting new requirements.

Then it is task 3, which presents a detailed overview of use patterns of products in scope according to consumer use and technological developments. It also provides an analysis of other aspects that affect the energy consumption during the use of these products, such as component technologies, power supply load efficiency and user interface in particular power management practices. Furthermore, it also touches on aspects that are important for material and resource efficiency such as repair, maintenance and replacement practices, and it gives an overview of what happens to these products at their end of life. Finally, this task also touches on standardised methods to quantify energy consumption in the different power modes, touching on the active mode, and it presents an overview of the energy consumption of products in scope based on manufacturers and ENERGY STAR database information.

Task 4 presents an analysis of current average technologies at product and component level, and it identifies the Best Available Technologies both at product and component level. An overview of the technical specifications as well as their overall energy consumption is provided when data is available. Finally, the chapter concludes with an overview of the product configurations in terms of components and key materials of current average and Best Available Technologies placed on the European market.

Simplified tasks 5 & 6 report presents the base cases, which will be later used to define the current and future impact of the current computer regulation if no action is taken. The report shows the base cases energy consumption at product category level and their life cycle costs. It also provides a high-level overview of the life cycle global warming potential of desktops and notebooks giving an idea of the contribution of each life cycle stage to the overall environmental impact. Finally, it presents some identified design options which will be used to define reviewed ecodesign requirements.

Task 7.1 report presents the policy options for an amended ecodesign regulation on computers and computer servers. The options have been developed based on the work throughout this review study, dialogue with stakeholders and with the European Commission. The report presents an overview of the barriers and opportunities for the reviewed energy efficiency policy options, and the rationale for the new material efficiency policy options. This report will be the basis to calculate the estimated energy and material savings potentials by implementing these policy options, in comparison to no action (i.e. Business as Usual – BAU).

The task reports follow the MEErP methodology, with some adaptations which suit the study goals.

4 Introduction to Task 4

Task 4 follows the MEErP methodology and includes the following:

1. A description of the identified average technology at product level on the current European market including technical specifications and energy consumption levels.
2. A description of the identified average technology at component level.
3. A description of the Best Available Technology at product level, including technical specifications and energy consumption information.
4. A description of the Best Available Technology at a component level.
5. A short overview of the potential aspects that will define the Best Not yet Available Technology on the European market.

An overview of the implications in terms of use of materials for average technologies and BAT. A description on the use patterns and end of life has been presented already in task 3. Therefore, this task focuses on the technologies and the demand of components and materials.

4.1 Technical product description

4.1.1 Average technology of personal computers

The average technology of personal computers is described on product type level in the following sections. The average technology was found for each product group by looking at the most frequently occurring performance measures , for various components including CPU, GPU, storage drives, and PSU, i.e. by finding the most frequent statistical values for each product configuration. The analysis to find the most frequently occurring value was made for one parameter at a time. The specific performance parameters are all mentioned for each base case in the sections below. The most frequently occurring values for each parameter were then used as definition for the average technical product design. For each base case the database was searched for the products fitting all of the values for the parameters.

Since even the best available data (from the ENERGY STAR database) did not include full datasets for all products, the number of data points that were used to determine each power demand data point is shown along with the most frequently occurring value (mode). This can be seen in Table 1, where it is not shown how many of the products were equipped with a HDD vs. a SSD, but just shows that out of 1248 that have any data about HD type, *most* have HDD for desktops.

In the ENERGY STAR data, some products are over-specified on some parameters, especially the RAM. An online search at retailer websites[1] was therefore performed, which clearly showed a tendency towards over-specifying RAM for desktops, integrated desktops and notebooks, which has therefore been corrected accordingly in the average technology descriptions. Retailer website search was also used to determine the most common storage capacity, since this parameter was often not reported in the ENERGY STAR database.

[1] https://www.cyberport.de/pc-und-zubehoer/pc-systeme/liste.html and https://www.shop.bt.com/category/computing,desktops-and-monitors,desktop-pcs/11101

The CPU performance score was in most cases not reported in the ENERGY STAR databases, but was calculated by multiplying the most common number of physical cores in the CPU and the base speed per core for each product group.

The ETEC values in all the following tables are based on the ENERGY STAR 6.1 calculation method, and thus the ENERGY STAR use patterns, since these are more up-to-date than the ecodesign use patterns.

4.1.1.1 Desktop computers

The average technology of desktop computers can be seen in Table 1. The table shows that the typical desktop computer has a processor with 2 physical cores, a base speed of 3.4 GHz per core and system memory of 4 GB RAM. The system memory has been found by looking at retailer websites[2], as the ENERGY STAR data was specified too high on this parameter, stating that 32 GB RAM were the most common system memory in desktop computers. The retailer websites, however, showed that 56% of the desktops had a system memory of 4 GB RAM, 32% 8 GB RAM and only 2% had 32 GB RAM. The last column in Table 1 ('no. of products with data available') shows the number of products in the ENERGY STAR database for which the specified product characteristic was found. This shows that while CPU data (both number of cores and speed) were often available, RAM and IPS efficiency data were not found as often.

Table 1. Desktop computer average technology configuration.

Performance parameter	Most frequent value	No. of products with data available
CPU cores	2	2087
Base CPU Speed Per Core, GHz	3.4 GHz	2087
CPU performance score	6.8	
RAM	4 GB	536
HD type	HDD	1248
Storage drives count	1	2077
Total storage capacity	500 GB	816
GPU type	None	641
GPU GB/sec	-	-
PSU rated output	300 watt	1010
IPS efficiency, 10%	79%	401
IPS efficiency, 20%	84%	770
IPS efficiency, 50%	87%	769
IPS efficiency, 100%	83%	771

To determine the power demand for the average technology for desktop computers defined in Table 1, the ENERGY STAR databases were searched. Three computers were found that met the criteria in Table 1. All three computers were from the EU ENERGY STAR database and all were ENERGY STAR category I2 and ecodesign Category B. One of the computers is from 2015, and two are from 2016. The IPS efficiencies were not given for these products in the ENERGY STAR database, but power load factor at 100% load was 90% for 2 of the products and 99% for one product. Table 2 shows the average power demand of the three computers in various power modes, which will be used as the representative of the average technology for further calculations of desktop computers.

[2] https://www.cyberport.de/pc-und-zubehoer/pc-systeme/liste.html and https://www.shop.bt.com/category/computing,desktops-and-monitors,desktop-pcs/11101

Table 2. Power demand in various modes for average technology of desktop computers.

Power mode	Power demand		
	Lowest	Average	Highest
Short idle	22.4 W	22.9 W	23.6 W
Long idle	21.33 W	21.8 W	22.4 W
Sleep	0.9 W	1.3 W	1.82 W
Off	0.30 W	0.45 W	0.57 W
TEC, ENERGY STAR	98.5 kWh/year	101.0 kWh/year	103.4 kWh/year

4.1.1.2 Integrated desktop

For integrated desktops the definition of the average technology includes the size and resolution of the integrated display in the computer. The installed storage capacity was assumed to be the same as for desktop computers, whereas online search showed that most integrated desktops had 8 GB RAM of system memory compared to the 4 GB which is most common in not-integrated desktop computers. One of the reasons might be that it is harder to upgrade RAM in integrated desktops, and therefore they are sold with more RAM from the beginning. Another is that the consumers expect that their integrated desktop take longer to become obsolete since their initial investment was higher.

Table 3. Integrated desktop computer average technology configuration.

Performance parameter	Most frequent value	No. of products with data available
CPU cores	2	1018
Base CPU Speed Per Core, GHz	3.00 GHz	1009
CPU performance score	6	
RAM	8 GB	65
HD type	HDD	762
Storage drives count	1	1018
Total storage capacity	500 GB	816
GPU type	None	
PSU rated output	180	570
IPS efficiency, 10%	87%	344
IPS efficiency, 20%	89%	414
IPS efficiency, 50%	90%	392
IPS efficiency, 100%	89%	414
Integrated Display size (sq in)	161.5	737
Integrated display MP	2.07	901

Three integrated desktops were found that matched the average technology specifications in Table 3, all in the US ENERGY STAR database from 2014, and all category B in ecodesign. Two of the computers are category I2 in ENERGY STAR and from 2014, one is category I1 from 2015. The screen sizes varied a lot in the ENERGY STAR data set, from 1.4 to 26.5 dm^2 (6 inch to 34 inch diagonal) for integrated desktops. None of the three computers that matched the other criteria matched the screen size exactly. Screens sizes of the three computers where between12.8 to 15.0 dm^2 (21.5 inch to 23 inch diagonal). None of the computers had any PSU data available. The average of the three computers' power demand in various power modes are shown in Table 4, and will be used to represent the integrated desktop average technology in further calculations.

Table 4. Power demand in various modes for integrated desktop average technology.

Power mode	Power demand		
	Lowest	Average	Highest
Short Idle	30.7 W	32.93 W	34.8 W
Long idle	16.0 W	22.8 W	33.3 W
Sleep	0.80 W	1.30 W	1.80 W
Off	0.30 W	0.53 W	1.00 W
E TEC	119.7 kWh/year	133.27 kWh/year	151.6 kWh/year

When comparing Table 4 with Table 2 it can be concluded that the short idle mode power demand is significantly higher for the integrated desktop than for the desktop. The reason for this difference is that the short idle mode power demand for integrated desktops has been measured before the display has turned off, which has a large impact on power consumption.

4.1.1.3 Notebook

For notebook computers, the RAM and storage capacity information was found by searching on retailer websites to find the most common values. The search showed that most notebooks (52%) had 8 GB RAM system memory and 33% had 4 GB RAM, whereas only 11% had 16 GB, as the ENERGY STAR database showed the most frequently occurring value. The notebook average technology was therefore defined with notebooks having 8 GB RAM as seen in Table 5. This is the same amount as for integrated desktops, and higher than for desktops, because notebooks are also harder to upgrade with extra RAM for the user, and are therefore provided with more by the manufactures.

Table 5. Notebook computer average technology configuration.

Performance parameter	Most frequent value	No. of products with data available
CPU cores	2	2911
Base CPU Speed Per Core, GHz	2.6 GHz	2891
CPU performance score	5.2	
RAM	8 GB	1039
HD type	HDD	1432
Storage drives count	1	1529
Total storage capacity	500 GB	1257
GPU type	None	
PSU rated output	65	506
EPS average efficiency	88%	182
Integrated display size (sq in)	103	1994
Integrated display MP	1.00- 1.05	1994

As can be seen in Table 5, there was relatively little data available for EPS's shipped with notebook computers in the ENERGY STAR database. Given that EPS efficiency is covered by a separate ecodesign regulation, this data shortage will only have a minimal impact on results of this project.

Three computers fit the average technology configuration shown in Table 5, all three are listed in the US database from 2016. The three products are category I1 in the ENERGY STAR database and category A in ecodesign. None of the computers fit the base CPU speed of 2.6 GHz, but instead has a base speed of 2.4 GHz. Two have a rated PSU output of 65 watts, one has 40 watts, but none of them have PSU efficiency data in the ENERGY STAR database. All of the products have screens that fit with the average technology configuration. The power demand in various power modes, shown in Table 6, is the average of the three products.

Table 6. Power demand in various modes for notebook average technology.

Power mode	Power demand		
	Lowest	Average	Highest
Short idle	6.3 W	7.1 W	8.0 W
Long idle	2.8 W	4.30 W	5.4 W
Sleep	0.40 W	0.43 W	0.50 W
Off	0.20 W	0.40 W	0.50 W
E TEC	17.78 kWh/year	24.75 kWh/year	29.83 kWh/year

4.1.1.4 Tablets/slates

For tablet computers, the storage capacity, which was found by searching online retailer websites, was quite evenly split between 16 GB, 32 GB, and 128 GB with shares of 25%, 22% and 21%, respectively. All sizes are therefore written in the average technology specification in Table 7. For the system memory, the internet search and the ENERGY STAR data showed that 2 GB RAM is the most common for tablets.

Table 7. Tablet computer average technology configuration.

Performance parameter	Most frequent value	No. of products with data available
CPU cores	2	96
Base CPU Speed Per Core, GHz	1.3 GHz	93
CPU performance score	2.6	
RAM	2 GB	204
HD type	SSD	84
Storage drives count	1	90
Total storage capacity	16/32/128 GB	446
GPU type	None	212
PSU rated output	10	64
EPS average efficiency	88%	31
Integrated Display size (sq in)	28-73	83
Integrated display MP	2.07	83

Due to the small dataset of tablets in the ENERGY STAR databases (212 products), no products fit the average technology configuration in Table 7 exactly, but three do with some discrepancies. All three products are form the US database, one from 2013 and two form 2014. The three products are category I1 in ENERGY STAR and category A in ecodesign. All three products have 2 physical CPU cores, but one has 2 GB RAM and base speed of 1.6 GHz, whereas the other two have 1 GB RAM and base speed of 1.3 GHz. Two of the products have screens of 29.96 square inch and 3.15 megapixels, whereas the last product has a screen that is 127.15 square inch and 2.07 megapixel.

The average of three products are despite their differences estimated to be a good representation of an average tablet. The power demand averages and energy consumption, which will be used to represent the tablet average technology in further calculations, are shown in Table 8.

Table 8. Power demand in various modes for tablet average technology.

Power mode	Power demand
Short Idle	4.13 W
Long idle	0.30 W
Sleep	0.54 W
Off	0.20 W
E TEC	13.23 kWh/year

4.1.1.5 Workstation

Workstations are generally higher performing computers, with no upper limit for performance and no energy requirements so far in the ecodesign regulation in force. The performance parameters of workstations might therefore be much higher for some products on the market, than what is shown in Table 9, which is defining the average technology for workstations. As seen in the table the workstations have higher CPU performance than the other product groups with 4 physical cores and 3.5 GHz base speed per core. Also the most common dGfx type is G7, which is the highest category in the ecodesign regulation.

Most of the workstations in the ENERGY STAR database had no data on internal storage capacity, but for the three that had it was 9TB, 3 TB and 1.5 TB. 1.5 TB was therefore used as a conservative estimate.

Table 9. Workstation computer average technology configuration.

Performance parameter	Most frequent value	No. of products with data available
CPU cores	4	42
Base CPU Speed Per Core, GHz	3.5 GHz	75
CPU performance score	14.0	
RAM	16 GB	75
HD type	HDD	35
Storage drives count	2	75
Total storage capacity	1500 GB	
GPU type	G7	32
GPU GB/sec	64	31
PSU rated output	700	7
IPS efficiency, 10%	84%	24
IPS efficiency, 20%	91%	28
IPS efficiency, 50%	92%	28
IPS efficiency, 100%	90%	28

One product fits the workstation average technology description in Table 9. It is from the US database from 2016, and has performance score 14 (4 CPU cores with base speed 3.5 GHz). The product has dGfx G7, but has 2 SSDs instead of HDDs. The total storage capacity is not recorded in the database. The rated PSU output was not reported, but the efficiencies matched for 20%, 50% and 100% load, while the 10% load efficiency was a little higher (87%) than the average technology definition. The power demand in various power modes for the workstation average technology is shown in Table 10.

Table 10. Power demand in various modes for Workstation average technology.

Power mode	Power demand		
	Lowest	**Average**	**Highest**
Short idle	69.5 W	69.5 W	69.5 W
Long idle	72.3 W	72.3 W	72.3 W
Sleep	4.50 W	4.50 W	4.50 W

Power mode	Power demand		
	Lowest	**Average**	**Highest**
Off	2.00 W	2.00 W	2.00 W
Max	243.3 W	243.3 W	243.3 W
P TEC	39.8 kWh/year	39.8 kWh/year	39.8 kWh/year

4.1.1.6 Thin client and integrated thin client

Thin clients and integrated thin clients are analysed as one product group. The ENERGY STAR data set contained no data on total storage capacity, and it was not possible to find it on retailer websites, probably since thin client products are sold under different names. Therefore, no storage capacity has been defined in the average technology description in Table 11. The CPU performance score for thin clients is lower than for other products, since most of the computing work is done on a server.

Table 11. Thin client and integrated thin client computer average technology configuration.

Performance parameter	Most frequent value	No. of products with data available
CPU cores	2	75
Base CPU Speed Per Core, GHz	1.0 GHz	126
CPU performance score	2.0	
RAM	2 MB	126
HD type	SSD	55
Storage drives count	1	65
Total storage capacity	No data	
GPU type	None	126
PSU rated output	N/A	0
EPS average efficiency	88%	21
Integrated Display size (sq in)	226	18
Integrated display MP	2.07	18

Two thin client computers fit the parameters in Table 11, one thin client and one integrated thin client, both from the US ENERGY STAR database and both from 2014. The thin client that is not integrated has only one CPU core, and therefore a CPU performance score of 1 rather than 2. The display in the integrated thin client is 337 square inches and 3.15 megapixels. Neither of the products has any PSU data recorded in the ENERGY STAR database. Table 12 shows the average power demand in various power modes for the two thin clients, which will be used to represent the thin client average technology in further calculations.

Table 12. Power demand in various modes for thin client and integrated thin client average technology.

Power mode	Power demand		
	Lowest	Average	Highest
Short idle	6.0 W	14.4 W	22.8 W
Long idle	5.5 W	8.35 W	11.2 W
Sleep	0.4 W	0.80 W	1.2 W
Off	0.4 W	0.60 W	0.8 W
TEC (ES)	29.3 kWh/year	57.84 kWh/year	86.4 kWh/year

4.1.2 Average technology of components

4.1.2.1 Power supply units (PSU)

Computer power supply units (PSUs) convert AC (alternating current) mains electricity sources into DC (direct current) at specific voltages (e.g. 12 V, 5 V, 3.3 V for IPS) which are then used by different components within the computer. Two main types of PSUs are used with personal computers; External PSUs (EPS) and Internal PSUs (IPS). EPS are typically used with mobile computers, such as notebook computers, and IPS are typically used with non-mobile computers such as desktop computers.

The efficiency of EPS placed on the EU market is addressed in an existing ecodesign regulation[3] and so these products will not be addressed in detail within this report.

The IPS traditionally used in personal computers are normally switched-mode power supplies (SMPS) with power factor correction (PFC)[4] rather than older linear power supplies. Many personal computer power supplies conform to the ATX specification which dictates physical design and voltage tolerances but a range of other IPS types are used especially in smaller footprint products. This means that they do not all confirm the ATX specification. Furthermore, the load rating (i.e. the amount of power that an IPS can supply) of IPS used in personal computers can vary considerably due to the wide range of performances and associated power demands found in this product group.

The efficiency of IPS are determined by system power losses as well as the thermal performance of integrated circuits (ICs), printed circuit boards (PCBs) and other components. The efficiency of IPS has increased considerably in recent years largely as a result of initiatives, such as the 80PLUS programme, ENERGY STAR and the EU ecodesign regulation on computers, placing requirements on these product types. Improvements in IPS efficiencies have been achieved through enhancements in power converter circuitries as well as improvements in semiconductors and magnetic materials. Whilst technical changes to IPS have resulted in vastly increased power conversion efficiencies under load, conversion efficiencies at low loading levels remain low. PSU efficiency is reduced under low load conditions largely due to transistor switching losses with losses being proportional to the switching frequency. Many IPS available on the market include a smaller integrated circuit to provide standby voltage at 5V (named “5VSB”) used for power on via keyboard and mouse. This functionality allows computers with large IPS to meet low power mode requirements included in initiatives such as ENERGY STAR and the EU ecodesign regulation on computers without the need to include a hard-off switch on a computer.

Previous reports written as part of this project have shown how the efficiencies of IPS vary considerably across individual products and loading levels. Figure 1 illustrates the average efficiencies for IPS registered with the 80PLUS programme during the period 2014 to 2016 and tested at 230V/50Hz. The results clearly indicate that average efficiencies seen in products on the market are well above the EU ecodesign regulation on computers IPS efficiency requirements (shown by the horizontal lines and detailed in Table 13). This suggests that the EU ecodesign regulation requirements (shown in Table

[3] 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

[4] The power factor of an AC electrical power supply is defined as the ratio of the real power flowing to the load to the apparent power in the circuit.

14) for efficiencies at 20%, 50% and 100% loading can be updated. In addition, as manufacturers are now reporting efficiencies at 10% loading it would be possible to develop EU ecodesign requirements on this loading level.

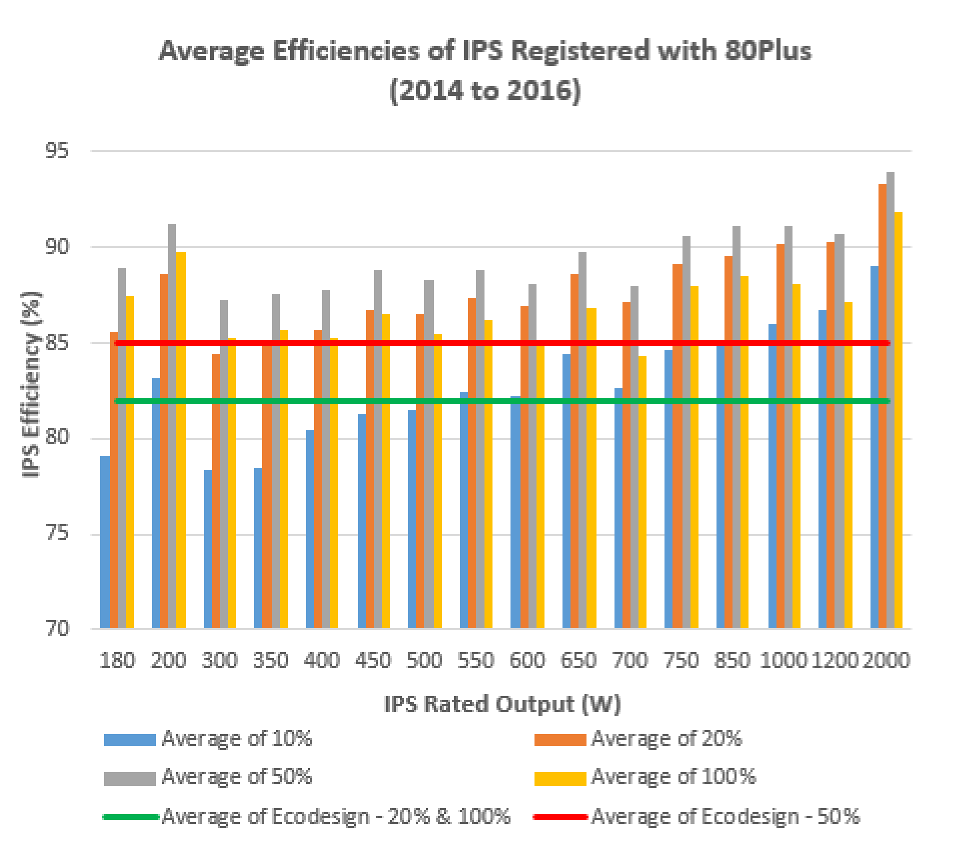

Figure 1. Average Efficiencies of IPS Registered with the 80Plus Programme 2014 to 2016 [5].

Table 13. Maximum levels of efficiency reported in 80PLUS registered IPS.

Maximum Efficiency at loading profile			
10% load	20% load	50% load	100% load
89.9%	94.3%	94.3%	93.5%

Table 14. IPS efficiency requirements in the current computer regulation.

5. INTERNAL POWER SUPPLY EFFICIENCY (R. 617/2013)	
Desktop computer, integrated desktop computer, desktop thin client, workstation, and small-scale server	Requirements on IPS 5.1. From 1 July 2014 All computer internal power supplies shall not perform at less than: (a) 85 % efficiency at 50 % of rated output power; (b) 82 % efficiency at 20 % and 100 % of rated output power; (c) power factor = 0.9 at 100 % of rated output power. Internal power supplies with a maximum rated output power of less than 75W are exempt from the power factor requirement.

[5] Plugload Solutions, 80 PLUS® Certified Power Supplies and Manufacturers, available from https://www.plugloadsolutions.com/80PlusPowerSuppliesDetail.aspx?id=0&type=4

4.1.2.2 Central processing units (CPU)

All personal computers, with the exemption of some thin clients, have a central processing unit (CPU) which is typically located on a motherboard. The CPU can be thought of as the "brains of a computer" in that it performs the basic arithmetic, logical, control and input/output (I/O) operations specified by a programme's instructions.

The computational performances of CPUs have increased considerably over the last decade but the rate of increase in performance appears to be reducing in recent years. The level of computational performance and wider functionality provided by a CPU is determined by many factors including:

- CPU frequency (base and maximum)
- Number of cores
- Number of threads per core
- Process node (i.e. size and number of transistors)
- Cache memory configuration and capacity
- Amount and type of RAM memory supported
- Number, type and control of I/Os (e.g. number of PCIe lanes supported)
- Presence of integrated graphics processing units
- Operating voltage, dynamic voltage scaling functionality
- CPU socket and chipset

Modern personal computer CPUs typically include multiple physical cores (mostly between 2 and 4 but high specification CPUs may have 10 or more) with a number of threads (often between 2 and 4 but high specification CPUs may have 12 or more) which support parallel computing per core.

CPUs can generally perform faster than main system RAM can provide data. CPU caches, which are relatively small amounts of memory either on the CPU package or close to it, bridge the gap between the ability of CPUs to process data and the ability of main system RAM to provide data. The amount and type of cache memory installed in CPUs is also an important consideration in CPU performance. Cache memory is most typically Static RAM (SRAM) but embedded DRAM (eDRAM) is also used.

CPU energy efficiency technologies can be largely split into those that help to reduce energy use associated with dynamic power (i.e. power demand increases due to increased clock speed, transistor count and voltage) and leakage (i.e. the energy associated with transistors conducting small amounts of current even when turned off). CPU manufacturers have been able to significantly reduce the power demand, especially during inactive states, of many of their products in recent years. Some of these savings have been achieved through enhanced voltage and frequency scaling technologies, which reduce the dynamic power demand of CPUs when full performance is not required. Other fixes have involved including new types of materials into the CPU package in order to reduce current leakage. Further improvements have been made through the introduction of deeper sleep states within the "C-state" hierarchy which can allow CPUs to draw very little power in idle states. C-states are CPU idle states where parts of a processor are shutdown when CPU cores are unused. There are two types of C-states, with "core C-states" reflecting the position where individual cores of a CPU are power managed and "package C-states" where the CPU circuitry that supports the CPU cores is also power managed. The "C0 state" represents the situation where a CPU is active and higher C-states (C1 to C7) represent conditions where parts of the CPU are power managed. The higher the “C-state” number the more aggressive the power reduction. Many current CPUs support high C-states (e.g. C6 and C7) but these are not always implemented on products due to incompatibilities with some less advanced IPS.

CPU manufacturers have also made significant advances in reducing power demand when CPUs are in active states. Power management of the CPU during active states is described by “P-states” (performance states). P-states follow a similar nomenclature to the C-states in that higher numbers (e.g. P6) represent reduced levels of activity with P0 representing the highest performing P-State. Dynamic frequency scaling (DFS) and dynamic voltage scaling (DVS) are used, in combination, to implement the various P-states supported the CPU and therefore reduce power demand requirements. Reduction of the CPU core voltages helps to reduce leakage current across the CPU transistors. This leakage can be further reduced in high P-states through inclusion of new materials such as those found in hafnium-based high-k dielectrics or through transistor architecture changes such as in FinFETs (Fin Field Effect Transistor). Whilst higher P-states result in reduced power demand they are also accompanied by a reduced in the maximum transistor speed (i.e. frequency). The P-states of a CPU are decided by the operating system (OS) based on computational demands and so balancing the need between power demand and performance. The time required to change from one P-state to another is relatively short and so there is little to no impact ion usability.

Table 15 illustrates some of the energy efficiency improvements that were made in three CPUs launched to market in 2015 compared to CPUs launched in 2014. The CPUs launched in 2015 have significantly lower idle mode power demands but performance, compared to similar 2014 CPUs, increased. Much of this improvement in energy efficiency was likely brought about by a decrease in the reduction of the node size from 22nm to 12nm. Future reductions in node size are expected in the next few years and so efficiencies are expected improve further.

Table 15. Performances of Range Intel CPUs[6,7]

CPU Manufacturer	Intel							
CPU Name	Core i3	Core i5		Core i7				
	4360	4690K	**5675C**	4790K	**5775C**	5920K	5930K	5960X
Market Release Date	May-14	Jun-14	**Jun-15**	Jun-14	**Jun-15**	Aug-14	Aug-14	Aug-14
Core Count	2	4	**4**	4	**4**	6	6	8
Thread Count	4	4	**4**	8	**8**	12	12	16
Base Frequency (GHz)	3.7	3.5	**3.1**	4	**3.3**	3.3	3.5	3
Turbo Frequency (all cores) (GHz)		3.7	**3.5**	4.2	**3.6**	3.4	3.6	3.3
Manufacturing Process (nm)	22	22	**14**	22	**14**	22	22	22
Integrated graphics (Yes/No)	Yes	Yes	**Yes**	Yes	**Yes**	No	No	No
Thermal Design Power (W)	54	88	**65**	88	**65**	140	140	140
Idle Power Demand (W)	7.6	7.8	**4.6**	7.9	**4.7**	10.6	11.8	12.9
Gaming Power Demand (W)	62.3	64.5	**42.1**	67.5	**51.8**	69.8	72.5	85.8

[6] CPU technical data sourced from http://www.cpu-world.com/
[7] CPU performances data sourced from http://www.tomshardware.com/reviews/intel-core-i7-5775c-i5-5675c-broadwell,4169.html

CPU Manufacturer	Intel							
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Market Release Date	May-14	Jun-14	**Jun-15**	Jun-14	**Jun-15**	Aug-14	Aug-14	Aug-14
Microsoft Word Task (Seconds to completion)	0.80	0.71	**0.77**	0.71	**0.80**	0.78	0.75	0.82
Adobe CC Photoshop Heavy Workload (Seconds to completion)	2.41	2.15	**2.20**	2.02	**2.52**	2.68	2.49	2.94
Arithmetic - Multi-Threaded Performance (GOPS)	57.3	92.5	**96.5**	131.3	**121.6**	154.4	172.6	218.1
Arithmetic - Single-Threaded Performance (GOPS)	14.3	23.1	**24.1**	16.4	**15.2**	12.8	14.4	13.6
Bioshock Infinite (Score)	31.5	39.2	**86.2**	41	**89.1**			

4.1.2.3 Motherboard (i.e. Printed Circuit Board)

All personal computers have a motherboard which is a type of printed circuit board (PCB) that provides connections (i.e. sockets) for most of the main computer components such as the CPU, RAM, storage and discrete graphics cards (dGfx). The motherboard also contains all the circuitry and interface controllers (e.g. network interface controllers, PCIe controllers, USB controllers, voltage regulation, and serial advanced technology attachment (SATA) controllers), which allow for communication amongst the different computer components. Many motherboards, especially those in non-mobile computers, allow for future expandability through multiple sockets that can be populated by additional components (e.g. extra dual in-line memory module (DIMM) sockets for additional sticks of RAM).

Motherboard power demand is highly dependent on both the amount of computational performance supported and the amount of functionality provided. That is, motherboards are designed to accommodate different specification CPUs with the highest performance CPUs only being able to be used in high specification motherboards. Motherboards can also support a wide range of functionalities through the types and numbers of connection sockets that they provide. Whilst motherboard power demand is largely determined by performance attributes it can also be controlled to a certain extent through effective power management technologies. For example, some motherboards include software and hardware solutions that allow specific parts of the motherboard, such as fans and LEDs, to be turned off. In addition, individual unpopulated connections, such as PCIe sockets, can be power managed into sleep states further reducing power demand.

The power demand of a motherboard can also be reduced through the inclusion of higher specification voltage regulators which control the voltage provided by the power supply and convert it into the appropriate voltage required by the CPU, RAM, chipset and other motherboard based components.

4.1.2.4 Random Access Memory

Random Access Memory (RAM), also known as main memory, primary memory, or system memory, is a component that temporarily stores information to be used by the

CPU and graphics processing units (GPUs). RAM is a volatile memory, meaning that it requires constant power in order to keep the data from being lost. The major amount of RAM in personal computers is used in dual in-line memory modules (DIMMS) which are made up of a series of dynamic random-access memory (DRAM) integrated circuits. These memory modules are connected to motherboards via DIMM sockets.

Data from programmes that are running are loaded into RAM for quick access by the CPU. Therefore, the amount and type of RAM installed in a computer can strongly determine overall performance. That is, the faster the CPU can access data in RAM the faster the whole system can run.

Most system memory RAM used in personal computers is double data rate synchronous dynamic random-access memory (DDR SDRAM) with DDR4, the latest DRAM variant, having been released in 2014. DDR4 runs at a lower voltage (1.2V (1.05V for the low voltage version)) than preceding DDR3 RAM. This lower voltage, coupled with improved power management capabilities, means that DDR4 is significantly more energy efficient per GB of installed RAM than preceding DDR technologies. Increasing amounts of RAM in a personal computer can result in higher power demands. This increase in power demand is more closely related to the number of RAM DIMMS installed in a product than the amount of GB provided per DIMM. For example, 8GB of RAM provided over two RAM modules would likely have a higher power demand than a single 8GB RAM module.

Whilst DDR4 is the latest type of RAM used in personal computers, newer memory technologies are likely to be launched to market in the near to medium term. The DDR5 specification is due to be completed by the end of 2016 with market availability expected sometime around 2020. Other memory technologies such as high bandwidth memory (HBM) are already being used in some personal computers albeit not as main system memory. HBM technologies may offer double the amount of memory bandwidth per watt compared to current DRAM technologies.

4.1.2.5 Storage

Most personal computers include at least one component which provides a means of permanently storing data. The most common data storage device used in personal computers is the hard disk drive (HDD). The HDD has been used in personal computers since the 1960s so is a very mature technology. HDDs utilise rapidly rotating disks, called “platters” which are coated with magnetic material. Magnetic heads, flying close to the platter surface on a moving actuator arm, read and write data to the platter surfaces as they are spinning. The most common types of HDD found in current personal computers are based on 3.5 inch or 2.5 inch platters. The 3.5 inch platters, being larger are normally capable of storing more data and are typically found in non-mobile personal computers such as desktop computers. The smaller 2.5 inch HDDs are normally found in mobile products such as notebook computers. As well as size differentiators, HDDs also come in a range of speeds typically ranging from 5,400 revolutions per minute (rpm) to 7,200 rpm. The faster the HDD the quicker data can be accessed and stored onto the platters.

The power demand of HDDs is highly correlated with the spin rate of the platters. That is, HDDs which provide faster speeds also have higher power demands as more powerful motors are needed to achieve the spin rate. Larger sized platters also require more power to spin so 3.5 inch HDDs tend to have higher power demands than 2.5 inch HDDs. HDDs also normally provide at least two lower power modes in additional to their full operational state. During idle states platters are continually spun at a reduced rate in order to minimise the amount of time it takes for the HDD to regain full operability. Given this continued spinning, power demand in idle states can still be significant. HDDs also often support a range of sleep or standby states within which the platters no longer spin and additional components are powered down. Wake up times during sleep or standby states can be relatively high, especially in deep sleep states where most HDD components are powered off, meaning that these low power states can be impractical where quick access to main HDD functionality is required.

Solid state disks (SSDs) are another commonly used type of non-volatile (i.e. permanent) storage device found in personal computers. All SSDs use integrated circuit assemblies as memory, with most being NAND-based flash memory, rather than magnetic disks as with HDDs. Being flash based components SSDs have no mechanically moving parts. SSDs have several advantages over HDDs including faster access times, resulting in programmes can be loaded and saved more quickly, and reduced noise. As a result of the faster access times, SSDs have the ability to wake from idle states much more quickly. This quick transition time from idle to active states, coupled with low idle power demand, can allow SSDs to use significantly less energy than comparable HDDs as it can power down without impacting usability. It is important to note that as the internal DRAM size of SSDs increases more controllers are needed, which can result in higher specification SSDs using more energy than traditional HDDs under some workload situations. Nevertheless, in many circumstances SSDs provide opportunity for energy savings when replacing HDDs. Whilst flash based SSDs first came to market in the late 1980's and have some clear benefits over HDDs, they have not been able to replace HDDs in the market place due to their extra costs. Whilst, SSDs remain more expensive per GB of storage than HDDs, their costs are reducing and are already common in higher-end mobile computers.

The third major type of storage product used in personal computers is the "hybrid drive"[8], combining a small SSD and a larger HDD in a single storage volume. This provides the advantages of the quick response times of the SSD, and is primarily used for storage of the operating system and commonly used files, and the larger storage capacity and cost advantages of an HDD. As well as providing the functionality and costs advantages of both the SSD and HDD, hybrid drives can also share the lower power demand characteristics of the SSD due to the fact that the HDD can be spun down more frequently without impacting usability.

4.1.2.6 Graphic processing units (GPU)

Personal computers include at least one graphics processing unit (GPU) which are specialised processors that render images, animations and video for output to a display. The GPUs used in personal computers are either integrated GPUs (iGfx) or discrete GPUs (dGfx). Integrated GPUs (iGfx) are found either directly on the motherboard, sharing system memory, or on the CPU die. Discrete GPUs (dGfx) are discrete internal components, typically plugged into a PCIe slot, containing one or more GPUs with a local memory controller interface and local graphics-specific memory. The graphics capabilities of dGfxs are typically much higher than those provided by iGfxs. The performances of both dGfxs and iGFxs has increased considerably in the last few years and will likely

[8] Other branded names are commonly used, such as "Fusion Drive" (Apple) or ExpressCache (Condusiv).

increase at an even greater rate with the inclusion of new memory technologies, such as HBM, into new products.

The power demands and energy use characteristics of dGfxs and iGfxs share few similarities due to the way in which the components work and the levels of performance provided by each type. Power demands of dGfx can be very high in active states with this power demand being strongly correlated to performance levels. The idle power demand of some dGfx can also be considerable but dGfx manufacturers have taken a number of steps over the last few years to greatly reduce idle mode power demands. The dGfx manufacturers have included advanced voltage and frequency scaling technologies into their dGfxs but they have also included the ability to power down virtually the entire functional unit of a dGfx and reduce wake times considerably. The energy efficiency improvements are most noticeable in long idle where attached displays are turned off and so the dGfx is providing no functionality. Power demands of dGfx have also been reduced in short idle but to a lesser extent due to the fact that displays remain on in this mode and so any connected dGfx still provide some functionality beyond maintaining system context.

The energy efficiency of iGfxs has also increased significantly over the last few years as improvements in CPU efficiency technologies follow through into iGfxs.

Hybrid graphics approaches have also been developed whereby both an integrated and discrete GPU are included in a computer. These hybrid approaches facilitate the use of the more powerful dGfx when required but then revert to the iGfx when high performance graphics abilities are not required. Hybrid graphics approaches are more commonly implemented in notebook computers and integrated desktop computers due to the integrated nature of the display connections allowing for better management of GPU outputs. Conversely, in a desktop computer with a dGFx installed the display normally connects to the external dGfx display connections therefore bypassing any iGfx. As such it is more difficult to implement hybrid graphics solutions in desktop computers. Whilst attempts have been made to introduce hybrid graphics to desktop computers that have not been widely accepted in the marketplace.

4.1.2.7 Integrated displays

Some personal computers, most notably integrated desktops and notebook computers, have integrated displays rather than relying on connection to an external monitor as with desktop computers.

Virtually all integrated displays are based on liquid crystal display (LCD) panels. LCD panels are made from two sheets of polarizing material, orientated at 90 degrees to each other, with liquid crystal solutions organised into sub-pixels between them. As an electric current is passed through the liquid it causes the molecules to align so that light is either blocked or let through to a colour filter. Colour filters normally consist of three different colours Red, Green and Blue (RGB) with each placed in front of a sub-pixel. The three sub-pixels together form a pixel. The viewable colour of each pixel in an LCD panel is then determined by varying the amount of light that is let through each sub-pixel and onto the colour filters.

LCD panels do not generate their own light and so the light produced within LCD panels comes from backlighting (i.e. lighting behind the first polarising sheet). In the early generations of LCD displays, the backlight was generated by cold cathode fluorescent lamps (CCFLs), a technology now disappeared. Displays now on the market are more commonly backlighted by by light emitting diodes (LEDs). LEDs are either placed around the edge of a display (i.e. edge lit backlighting) or across the span of the display (i.e. full-array backlighting or direct-type structure). In edge lit LCDs an additional light guide plate that reflects the light from the edges across the entire area of the display. Full-array backlighting is typically more expensive to produce, due to a larger number of LEDs required, but can produce more evenly spread light across a display. To aid the spread of light across the back of an LCD panel back reflectors, diffusers and brightness enhancement film (BEF) or dual brightness enhancement film (DBEF) are also used. The luminance of LED backlights is typically controlled using either "global dimming", where all LED backlights are set to the same luminance levels, or "local dimming" (also known as high dynamic range technology) where LED backlights can be controlled individually or in zones.

There are three major types of LCD integrated display panels on the market, Twisted Nematic (TN), Vertical Alignment (VA) and In-Plane switching (IPS), each with their own characteristics and associated advantages and disadvantages. TN panels, which are the cheapest type of LCD panel to produce for integrated displays, typically enjoy fast refresh rates but have narrow viewing angles, reduced colour contrasts and limited luminance. TN panels also benefit from the fact that when no voltage is passed across and LCD cell then white light is let through (rather than being blocked), meaning that less power is needed to produce the white backgrounds of common office applications. VA panels enjoy better viewing angles, colour reproduction and higher luminance levels but tend to have slower refresh times. IPS panels have wide viewing angles, provide accurate colours but have slow response times.

As well as panel type, there are a number of technical features which determine the overall technical performance of an integrated display. The most important feature of displays which dictate performance is display size. Larger displays require more backlighting and LCD cells which in turn increases power demands. The size of displays in mobile computers, such as notebook computers, is largely limited by impacts on portability. The integrated displays in non-mobile personal computers, such as integrated desktop computers, are not limited by portability concerns and so could follow the general trend of display size growth seen in other products such as computer monitors.

The resolution of an integrated display (i.e. the number of pixels it contains) is also an important determinate of performance with higher resolution counts supporting improved image quality. Resolution count, measured in megapixels (MP), has been increasing over the last few years with high definition (HD) (i.e. 2.07MP) displays now common. The resolution of integrated displays is likely to increase further in the next few years as demand grows for ultra HD (UHD) (i.e. 8.3MP) and even higher definition displays. Resolution count can impact power demand in displays as more electronics are needed to drive the extra pixels. The extra pixels often result in increased pixel density (i.e. pixels per area unit) which can in turn reduce the amount of light that reaches the front of the display necessitating the need for more backlighting.

Higher performance displays, known as Enhanced Performance Displays (EPD), are becoming more popular in standalone computer monitors but have yet to find their way into integrated personal computer displays in large numbers. EPD displays, most commonly based on IPS panels, have higher colour gamut, wider viewing angles, greater colour contrast ratios and high resolutions. These types of displays can have higher power demands due to lower transmissivity of light through additional filters and potentially due to increased data processing requirements. Traditionally EPDs have been used in fields such as computer aided design and computer game development, but are increasingly being sold into mainstream uses.

Due to the fact that integrated displays in products such as integrated desktop and notebook computers share a power supply with the rest of the computer, direct measurement of display power demand is difficult without resorting to destructive test procedures (i.e. direct measurement would necessitate opening up the casing to measure power demand). It is possible to estimate the power demands of integrated displays through calculating the delta between short idle, when the display is on, and long idle power modes, when the display is off. Whilst this delta also includes reduced power demand in long idle resulting from the powering down of other components, such as GPUs, it remains the best proxy for integrated display power demand. Figure 2 and Figure 3 identify the short-long idle deltas for integrated desktop computers and notebook computers respectively, with no dGfx installed, registered in the US ENERGY STAR database, during 2015 and 2016, against integrated display sizes. It was necessary to use the US version of the ENERGY STAR database for this analysis due to a lack of data around display size in the EU ENERGY STAR database. The mean results for each size of display are shown by a red dot with the median values represented by a red line. Figure 2 shows that integrated display power demand in integrated desktop computers varies considerably but that average values generally increase with display size increases. Figure 3 shows that power demand of notebook displays also varies considerably but that there is less correlation between increasing display size and average power demand.

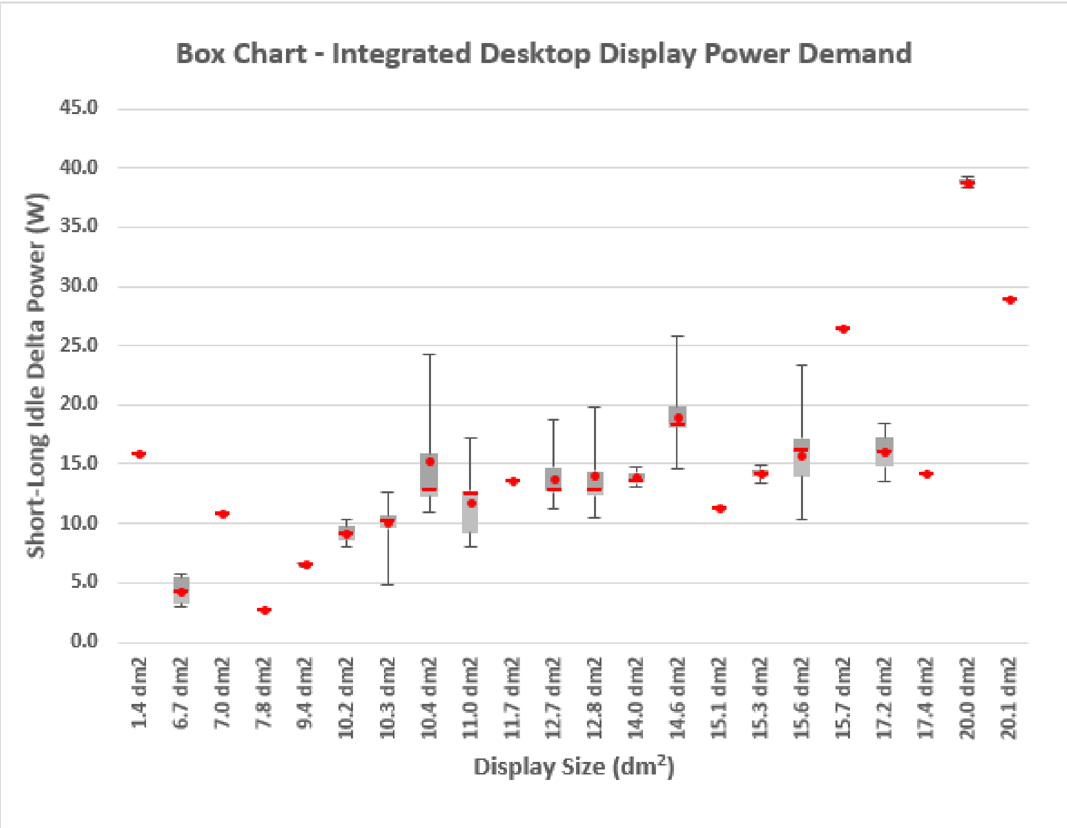

Figure 2. Average Short-Long Idle Delta (W) for Displays in ENERGY STAR registered Integrated Desktop Computers.

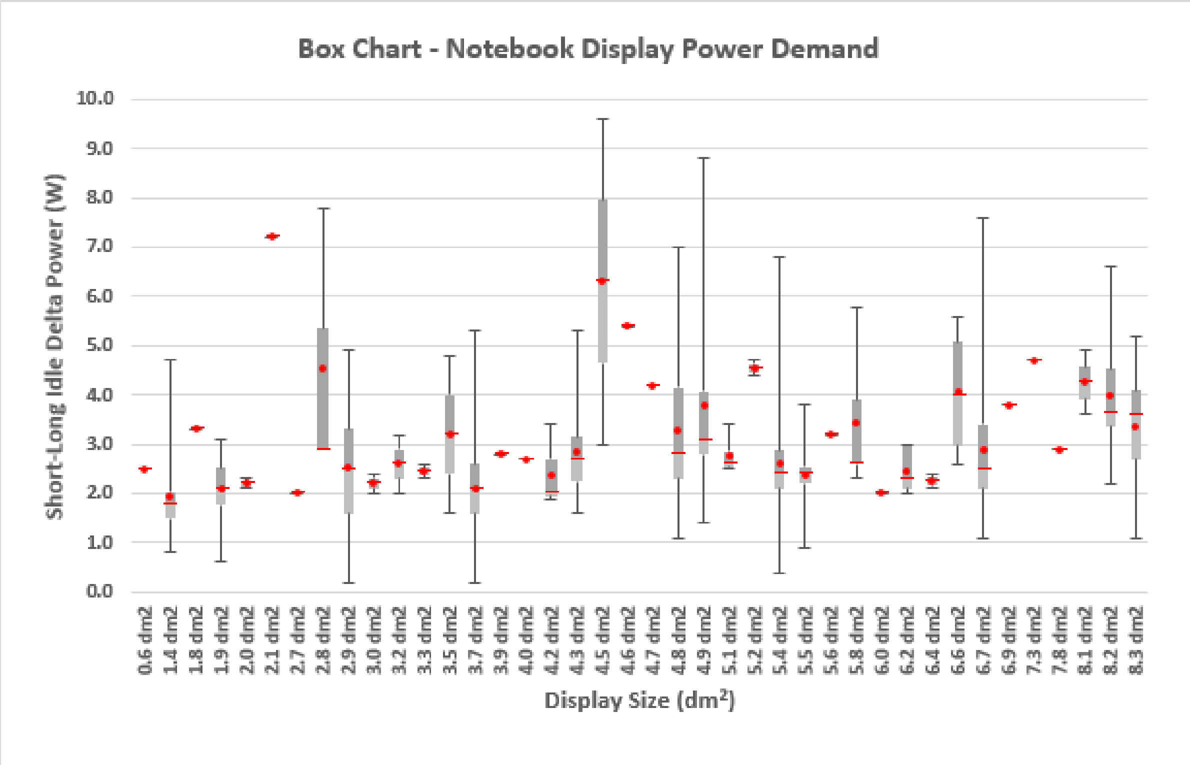

Figure 3. Average Short-Long Idle Delta (W) for Displays in ENERGY STAR registered Notebook Computers.

4.1.2.8 Software

The software installed on computers can have large impacts on functionality. The most important piece of software included on a computer is the operating system. It is the operating system that controls the power management of both the entire computer as well as individual components. This functionality is supported through power management standards such as the Advanced Configuration and Power Interface (ACPI) specification which in turn is supported by most, but not all, commonly used operating systems. To be effective, operating systems need to support power management under a broad range of user conditions without impacting usability of a computer. That is, operating systems should be able to support powering down a computer to a variety of power modes and then also reliably support waking the computer back to an operating condition. When operating systems fail to reliably support power management functionality it can lead to power management settings being disabled and therefore result in more energy use.

As at least some power management functionality is standard on all major operating systems, costs to the user are nil. There may be some costs for the operating system developers, especially where power management functionality has been shown not to be fully functional thereby necessitating changes.

Further detailed information about the potential energy savings of power management functionalities is given in the BAT section. Individual programmes installed on computers can also have a large impact on power demands. Table 16 shows the results of battery life testing on a single notebook using different internet browsers. The results show that internet browsers can have a significant impact on system power demand, resulting in reduced battery life for the most resource intensive programmes. All other software and hardware configurations on the tested notebook remained the same apart from the internet browser.

Table 16. Internet Browser Usage and Notebook Battery Lifetime. [9]

Internet Browser	Battery Life (Minutes)
Edge 13.1	385
Chrome 50	355
Opera 37 (w/Flash 21.0)	352
Firefox 46.0 (w/Flash 21.0)	338
Internet Explorer 11 (w/Flash 21.0)	335

Major pieces of software such as the operating system can also impact energy use of computers. Table 17 shows the results of battery life testing on a notebook computers where different activities were undertaken. Even though Windows 10 is a newer operating system, battery life was reduced during video playback after Windows 8.1 was replaced with Windows 10. Again, the tests were performed on the same notebook computers under the same conditions (i.e. same video, Wi-Fi connected, power saving features turned on and display brightness set to 120 cd/m^2)

Table 17. Operating System and Notebook Battery Life under different usage conditions.

Activity	Battery Life (Minutes)	
	Windows 8.1	Windows 10
Wi-Fi browsing	194	200
Video playback	260	213
Gaming	61	61

In both examples above, the level of functionality provided by the different software packages was broadly comparable but energy use was not. This suggests that some software packages are more energy efficient than others just as some hardware components are more efficient than others. These differences in notebook battery life illustrate the importance of considering software when assessing the energy efficiency of computers.

4.1.3 BAT – Best Available Technology at product level

4.1.3.1 Desktop computers

There are many different types of desktop and integrated desktop computers available on the EU market which provide different levels of functionality and performances. Given these differences in functionality and performance no one single product could be described as offering BAT that covers all usage scenarios. The product selected and shown in Table 18 is an example of a desktop computer that will provide many of the

[9] PCWORLD, 2016, "*Which browser is best for battery life: We test Edge vs. Chrome vs. Opera vs. Firefox*", available from http://www.pcworld.com/article/3087338/browsers/which-browser-is-best-on-battery-we-test-edge-vs-chrome-vs-opera-vs-firefox.html

basic home and office productivity functions that users require, whilst doing so in a small form factor and using little energy in the process.

Table 18. Technical specifications and energy characteristics of BAT for desktop computers.

Performance parameter	Product Details
Manufacturer	Apple
Commercial name	Mac mini[10]
TEC at 230V (kWh)	20.94
Short idle state power (W)	5.00
Long idle state power (W)	3.10
Sleep mode power (W)	0.80
Off mode power (W)	0.30
CPU cores (no.)	2.00
Base CPU Speed Per Core (GHz)	3.00
CPU performance score	6.00
RAM (GB)	16.00
GPU type	iGfx
GPU GB/sec	-
IPS efficiency, 10%	88%
IPS efficiency, 20%	89%
IPS efficiency, 50%	90%
IPS efficiency, 100%	89%
Sound pressure level (operator position)	12dBA at idle

4.1.3.2 Integrated desktop computers

As with desktop computers, the range of functionalities and performances provided by integrated desktop computers varies significantly amongst products on the EU market. As such, in reality there may be many products at different levels of functionality and performance that could be described as BAT. The product shown in Table 19 is an example of BAT for one type of integrated desktop computer. The product has low short idle power demands, is able to significantly reduce power demand in long idle and has reasonable sleep and off mode power demands. In addition, the product includes an IPS that is efficient across all of the reported loading levels.

Table 19. Technical specifications and energy characteristics of BAT for integrated desktop computers.

Performance parameter	Product Details
Manufacturer	Apple
Commercial name	21.5 inch iMac[11]
TEC at 230V (kWh)	59.52
Short idle state power (W)	15.10
Long idle state power (W)	7.00
Sleep mode power (W)	2.00
Off mode power (W)	0.80
CPU cores (no.)	2.00
Base CPU Speed Per Core (GHz)	3.80

[10] Based on Mac mini energy and materials data representing models MGEM2, MGEN2, MGEQ2. See http://images.apple.com/environment/pdf/products/desktops/Macmini_PER_oct2014.pdf

[11] Based on iMac energy and materials data representing models MK142, MK442, MK452. See http://images.apple.com/environment/pdf/products/desktops/21_5inch_iMac_PER_Oct2015.pdf

Performance parameter	Product Details
CPU performance score	7.6
RAM (GB)	2.00
Display Size (dm2)	11.03
Display Resolution (MP)	1.44
Storage Type	HDD
Storage drives count	1.00
Total Storage capacity (GB)	500
GPU type	iGfx
GPU GB/sec	-
PSU rated output (W)	120.00
IPS efficiency, 10%	84%
IPS efficiency, 20%	89%
IPS efficiency, 50%	92%
IPS efficiency, 100%	90%

4.1.3.3 Notebook computers

As with most personal computers, functionality and performances found in notebook computers on the EU market vary considerably. Therefore, identifying a single product as being BAT does not consider the fact that there are likely many BAT products at different levels of functionality and performances. The example BAT product shown in Table 20 reflects a notebook computer that provides a relatively high level of performance in terms of RAM provision but slightly lower performances in terms of CPU, storage and graphics processing abilities. The example BAT notebook has a very low short idle power demand, employs a good degree of power management to reduce long idle power demand to less than 1W and has very low sleep and off mode power demand requirements.

Table 20. Technical specifications and energy characteristics of BAT for notebook computers.

Performance parameter	Product Details
Manufacturer	Apple
Commercial name	12-inch MacBook[12]
TEC at 230V (kWh)	8.94
Short idle state power (W)	2.70
Long idle state power (W)	0.80
Sleep mode power (W)	0.30
Off mode power (W)	0.10
CPU cores (no.)	2.00
Base CPU Speed Per Core (GHz)	1.10
CPU performance score	2.2
RAM (GB)	8.00
Display Size (dm2)	4.18
Display Resoluition (MP)	3.32
Storage Type	Flash
Storage drives count	1
GPU type	iGfx
GPU GB/sec	-

[12] Based on Mac mini energy and materials data representing models MLH72, MLHA2, MLHE2, MMGL2, MLH82, MLHC2, MLHF2, MMGM2. See http://images.apple.com/environment/pdf/products/notebooks/MacBook_PER_April2016.pdf

Performance parameter	Product Details
EPS rated output (W)	29.00
EPS average efficiency	88%

4.1.3.4 Tablet/slate computers

There is less variability in the functional and performances attributes of tablet/slate computers than with other types of personal computer. This reduced variability is primarily due to the fact that these products do not typically offer high levels of computing performance. The main functional variability in tablets is the size and quality of the integrated display. The product shown in Table 21 has very low overall energy use, very low short idle power demand and low off mode power demand. The sleep mode power demand is higher than expected which may be a result of a reporting error.

Table 21. Technical specifications and energy characteristics of BAT for table/slate computers.

Performance parameter	Product Details
Manufacturer	Apple
Commercial name	9.7-inch iPad Pro[13]
TEC at 230V (kWh)	6.92
Short idle state power (W)	1.00
Long idle state power (W)	0.30
Sleep mode power (W)	1.10
Off mode power (W)	0.30
CPU cores (no.)	2.00
Base CPU Speed Per Core (GHz)	2.30
CPU performance score	4.6
RAM (GB)	2.00
Display Size (dm2)	2.91
Display Resoluition (MP)	3.15
Storage Type	Flash memory
Storage drives count	1
GPU type	iGfx
GPU GB/sec	-
EPS rated output (W)	10.70
EPS average efficiency	79%

4.1.3.5 Workstations

Workstation computers are designed to provide a high level of computational performance. Given that there remains a strong correlation between computing performance and overall computer energy use, a BAT workstation computer doesn't necessarily use a small amount of energy. The product shown in Table 22 is a very high performance workstation computer but provides this high level of performance efficiently. Indeed the product's "weighted power consumption" (PTEC) is almost 70% less than the requirement given to this product under the ENERGY STAR v6.1 specification.

Table 22. Technical specifications and energy characteristics of BAT for workstations.

Performance parameter	Product Details
Manufacturer	Lenovo

[13] See http://images.apple.com/environment/pdf/products/ipad/9.7-inch_iPadPro_PER_mar2016.pdf

Performance parameter	Product Details
Commercial name	ThinkStation P910
Power Demand (PTEC)	41.80
Short idle state power (W)	74.00
Long idle state power (W)	71.50
Sleep mode power (W)	6.40
Off mode power (W)	2.40
CPU cores (no.)	14.00
Base CPU Speed Per Core (GHz)	2.00
CPU performance score	28
RAM (GB)	32.00
Storage Type	SSD
Storage drives count	2.00
GPU type	G7
GPU GB/sec	192
IPS efficiency, 10%	84%
IPS efficiency, 20%	91%
IPS efficiency, 50%	92%
IPS efficiency, 100%	89%

4.1.3.6 All in one computers

There are relatively few all-in-one computers on the EU market and so the choices around selecting a BAT product are limited. The product shown in Table 23 shows an example BAT all-in-one that has relatively low short idle power demands in comparison to other products on the market and has employed some power management functionality as witnessed by the relatively low sleep mode power demand.

Table 23. Technical specifications and energy characteristics of BAT for all in one computers.

Performance parameter	Product Details
Manufacturer	DELL
Commercial name	XPS 18
TEC at 230V (kWh)	64.30
Short idle state power (W)	17.00
Long idle state power (W)	7.90
Sleep mode power (W)	1.70
Off mode power (W)	0.30
CPU cores (no.)	2.00
Base CPU Speed Per Core (GHz)	2.00
CPU performance score	4.00
RAM (GB)	8.00
Display Size (dm2)	9.41
Display Resoluition (MP)	2.07
GPU type	iGfx

4.1.3.7 Thin Client

The level of functionality and performance in thin clients on the EU market is less diverse than for other types of personal computers. This is mainly due to the fact that most of the computational performance provided when using a thin client is conducted on servers rather than on the thin client product. The example BAT product shown in Table 24 has relatively low short and long idle power demands in comparison to competing products and employs a sleep mode which is not found on all thin clients. The example BAT products is also equipped with a relatively efficient EPS.

Table 24. Technical specifications and energy characteristics of BAT for thin clients.

Performance parameter	Product Details
Manufacturer	IGEL
Commercial name	IGEL-UD2 Series
TEC at 230V (kWh)	22.29
Short idle state power (W)	4.70
Long idle state power (W)	4.30
Sleep mode power (W)	0.60
Off mode power (W)	0.50
CPU cores (no.)	4.00
Base CPU Speed Per Core (GHz)	1.90
CPU performance score	7.60
RAM (GB)	2.00
GPU type	iGfx
GPU GB/sec	-
EPS average efficiency	85%

4.1.4 BAT – Best Available Technology at a component level

4.1.4.1 CPU efficiency

The performance levels of CPUs vary considerably and as such it is difficult to identify a single CPU that can be identified as "best available technology" (BAT). That is, whilst some CPUs have very low power demands across all power modes they may not offer high levels of performance (e.g. have lower frequencies and core numbers) or may have limited functionality (e.g. no iGfx included). As such, comparisons against CPUs that offer higher levels of performance and greater functionalities but with corresponding higher power demands are not completely justifiable when attempting to identify BAT. If CPU performances and power demand can be accurately measured, then there is a possibility of using a "performance per watt" approach to identify the most efficient CPUs under given conditions. That is, whilst a high-powered CPU may provide more performance per watt of power demand, the level of performance and associated power demand may still be too high for that product to be considered "efficient". However, measuring the power demands of CPUs is complex due to the fact that it is an internal component and as such CPU power demand can be difficult to isolate from the power demands of other components such as the motherboard. CPU power demands can be estimated through measurement of current, or voltage across a shunt resistor placed in the CPU power supply circuit, using a clamp meter but results may not be accurate. Some software packages are also available that estimate the power demand of a CPU during use.

CPU energy efficiencies can vary considerably depending on the amount of work that is being done by the CPU at any given moment. That is, whilst some CPUs may be very efficient in an idle state (i.e. when they are conducting no or very little work) they may not be very efficient during active states (i.e. when the CPU is conducting work).

Rather than identifying a single CPU that represents BAT it is more appropriate to identify the energy efficiency technologies used within CPUs that represent BAT.

CPU support for high core and package C-states (i.e. C6, C7 or above) is an important consideration as these can help reduce idle mode power demand considerably. Many CPUs now support C6 and C7 states which provide the opportunity for much greater granular power management. This has allowed some CPU manufacturers to support “micro-sleeps” where most parts of a CPU can be powered down and brought back to an active state following nano-second periods of inactivity such as the time gasp between keystrokes during typing. Whilst CPU C-state support can be described as BAT it is also important to consider that the rest of the computer components also need to support this CPU energy efficiency functionality. As such, high C-state support will only be BAT in computer systems (so including firmware and software) that fully support this functionality.

Despite significant improvements already having been made across most products, current leakage across CPU transistors remains an important consideration in CPU energy efficiency. As transistor sizes reduce (die shrinking) high leakage current due to short-channel effects and varying dopant levels becomes problematic. New CPU architectures based on non-planar or "3D" transistors (i.e. multiple gate field-effect transistors (MuGFETs)), such as Fin Field Effect Transistor (FinFET) or Tri-gate transistors, can significantly reduce current leakage across transistors compared to traditional planar MOSFETs. As such, CPUs based on 3D transistor structures could be described as BAT, especially for higher performance CPUs where the leakage problems that are solved by the switch in CPU architecture design are more important.

The majority of CPUs on the market support at least some voltage and frequency scaling in response to the amount of work being conducted. In most implementations, the computer OS requests a particular level of performance (i.e. P-state) from the CPU. Based on commands originating from the OS, the CPU frequencies and voltage levels are adjusted. The granularity of this DVFS (dynamic voltage and frequency scaling) is limited to the way in which the P-states are defined by the computer manufacturer. Whilst these technologies are important, due to their ubiquity, they cannot readily be described as BAT. Nevertheless, these technologies have been enhanced in newer CPUs with the OS handing control of frequency and voltage scaling back to the CPU itself. This enhanced control over frequency and voltage scaling requires dedicated microcontrollers included on the CPU package, which can identify the most efficient clock rate at any given time and also support micro-sleeps where no work is being conducted. The increased granularity of DVFS will likely results in further energy savings and so could be described as BAT. These types of technologies are more likely to be found in mobile computers, where there is a strong need to reduce energy use to extend battery life, than in mains powered products for where there are fewer drivers to reduce the amount of energy used. Users of non-mobile products may still have concerns over the amount of energy consumed by their products due to impacts on electricity bills, and so these newer technologies should be encouraged in non-mobile as well as mobile products.

4.1.4.2 Software efficiency

A computer’s OS has a large degree of responsibility for the energy used by a computer across all power states (i.e. active, idle and low power modes).

Many operating systems include power management functionality with settings that can be defined by users, such as the ability to enter low power modes (e.g. sleep mode) after a certain period of inactivity. Whilst this functionality is common practice, and so could not normally be defined as BAT, the functionality is not always reliable. That is, whilst an

OS may support powering down of a computer into a low power mode it may not fully support powering the computer back to an active mode with all settings, such as network connections, intact. This unreliability can cause power management functionalities to be disabled, by either users or central IT staff, due to negative impacts on usability. As such, an OS that reliably supports powering down of computers into low power modes with a smooth transition back to an active, or idle state, with full functionality can be described as BAT.

As discussed in the previous section, a computer's OS currently plays a large part in controlling the efficiency of CPUs but this responsibility is likely to be handed back to the CPU itself as technology improves. A computer's OS may also control power management of other components such as wireless controllers and, to a certain extent, dGfxs. OS can also manage the computing resources that are dedicated to individual programmes opened on the computer. For example, OS can identify when a programme is not being used and then throttle performance, suspend or even terminate the programme. Again, whilst these OS functionalities are common place it could still be described as BAT where the activities are performed without impacting the usability of products.

Some OS on the market do not support ACPI S3 type sleep modes but rather rely on using long idle as a way to reduce power demand during periods of inactivity. The reliance on long idle over sleep modes is normally found in low powered products such as tablet computers but can also be found in some notebook and desktop computers. If long idle power demand is only marginally less than short idle power demand this could be viewed as unacceptable. However, where long idle power demand is significantly less than short idle power demand, and the product is frequently placed in long idle without impacting the usability of the product, then this could potentially be described as approaching BAT.

Newer CPUs support an innovative set of sleep states called S0i"x" states. These include new power states which will allow personal computers to work more like a smartphone in that information, such as emails and software updates, will be able to be sent to a computer even when it is sleeping. From a hardware perspective, it means that during activation of the S0ix states whole parts of a system on chip (SoC design) can be powered down. This means that the system will be very efficient.

Microsoft are actively trying to encourage and support use of S0i"x" states through a functionality called "Modern Standby".[14] "Modern Standby" functionality is currently only available in a small number of example products, but the IT industry is actively trying to encourage its development by ensuring that new hardware supports the functionality.

4.1.4.3 GPU efficiency

Identifying the power demand of iGfxs, and hence a BAT value, is a complex undertaking because they are normally included as an integral part of a CPU package. As such, as with CPUs, given the difficulty with identifying exact power demand levels, BAT for iGfxs needs to be defined in terms of the technologies included to improve energy efficiency. As most iGfxs are an integral part of the CPU package, the efficiency improvement technologies that could be viewed as BAT are much the same as those listed for CPUs.

Identifying a BAT line for dGfx is less challenging as power demand can either be measured directly or estimated. The power demands of dGfxs used within desktop and

[14] https://msdn.microsoft.com/en-us/library/windows/hardware/mt282515(v=vs.85).aspx

workstation computers can be measured directly using an oscilloscope, high-resolution current probes and a riser card placed between the motherboard and the dGfx. This approach to testing the power demand of dGfx is a complex undertaking and requires opening of the computer casing. The power demands of dGfx within desktop and workstation computers can also be estimated by identifying the difference in power demand when a dGfx is installed and when no dGfx is installed (N.B. this approach requires that the computer has a CPU with iGfx). Measuring the power demand of dGfxs included within mobile products could be conducted in a similar manner where the dGfx can be easily removed and replaced.

As previously discussed, dGfx manufacturers have taken a number of important steps to reduce the power demands of their products in recent years. Table 25 illustrates the performances and directly measured power demands of high performance dGfxs available on the EU market[15]. It is clear that dGfx manufacturers have been able to substantially reduce idle power demand in even their highest specification products to around 10W. The two dGfxs in bolded text could be assumed to represent idle mode BAT.

Table 25. Power Demands and Performances of high specification dGfxs

Discrete GPU Name	Date Launched to Market	Framebuffer Bandwidth (GB/s)	Idle Power Demand (W)	Power Demand (Furmark Test) (W)	Idle Efficiency (W/GB/s)	Active Efficiency (W/GB/s)
AMD Fury Nano	Aug-15	512.0	11.0	181.0	0.021	0.354
NVidia Geforce GTX 1080 FE	May-16	320.0	7.0	176.0	0.022	0.550
NVidia Titan X (Pascal)	Aug-16	480.0	11.0	252.0	0.023	0.525
NVidia GeForce GTX 1070 FE	Jun-16	256.0	9.0	150.0	0.035	0.586
MSI R9 390 Gaming 8G	Jun-15	384.0	15.0	309.0	0.039	0.805
MSI R9 390X Gaming 8G	Jun-15	384.0	15.0	367.0	0.039	0.956
MSI GTX 1060 Gaming X 3G	Aug-16	192.0	10.0	122.0	0.052	0.635
MSI GTX 1060 Gaming X 6G	Aug-16	192.0	10.0	130.0	0.052	0.677
AMD RX 480 8GB	Jun-16	256.0	16.0	168.0	0.063	0.656
MSI R9 380X Gaming 4G	Nov-15	182.4	13.0	251.0	0.071	1.376
MSI GTX 1050 Ti Gaming X 4G	Oct-16	112.0	8.0	71.0	0.071	0.634
MSI GTX 970 Gaming 4G	Sep-14	196.0	14.0	205.0	0.071	1.046
MSI GTX 980 Gaming 4G	Sep-14	224.0	16.0	209.0	0.071	0.933
Asus RX 470 StriX	Aug-16	211.0	16.0	145.0	0.076	0.687
Gigabyte GTX 960 Gaming G1	Jan-15	112.0	11.0	167.0	0.098	1.491

Whilst idle mode power demands for the high performance dGfxs shown in Table 4 are low, the same cannot be said for the power demands under load. It is clear that when these high-performance products are placed under load (e.g. running the Furmark benchmark) their power demands are likely to be higher than the rest of the computer combined. Despite these high power demand levels it is clear that the AMD Fury, which

[15] dGfx power demand measurements sourced from http://www.tomshardware.co.uk/nvidia-geforce-gtx-1050-ti,review-33685-6.html

utilises high bandwidth memory (HBM) in place of GDDR5 memory, and which provides the highest framebuffer bandwidth, is also the most efficient under this particular loading scenario. As such, the AMD Fury dGfx could be considered as reflecting BAT under this scenario.

As previously mentioned, hybrid graphics approaches, which are predominantly used in mobile and integrated desktop computers, can also provide a significant amount of energy savings when configured appropriately. In some hybrid graphics solutions, the dGfx is always powered on when a mobile product is connected to a mains power source. In more sophisticated hybrid graphics implementations, the dGfx is only utilised when higher graphics performances are required. The more sophisticated approach to hybrid graphics will likely lead to a dGfx being in an active state for less time and therefore save more energy. As such only hybrid graphics solutions that support performance based selection of a dGfx should be considered BAT.

4.1.4.4 Internal Power Supply efficiency

Efficiency data for IPSs used in personal computers is widely available through the 80PLUS programme and as such it is a straightforward process to identify BAT efficiency levels. Figure 4 illustrates the BAT efficiencies for IPS registered through the 80PLUS programme and compares these levels to the requirements listed in the EU ecodesign regulation on computers. It is clear from the results that the BAT efficiency levels are far in advance of the current EU ecodesign requirements.

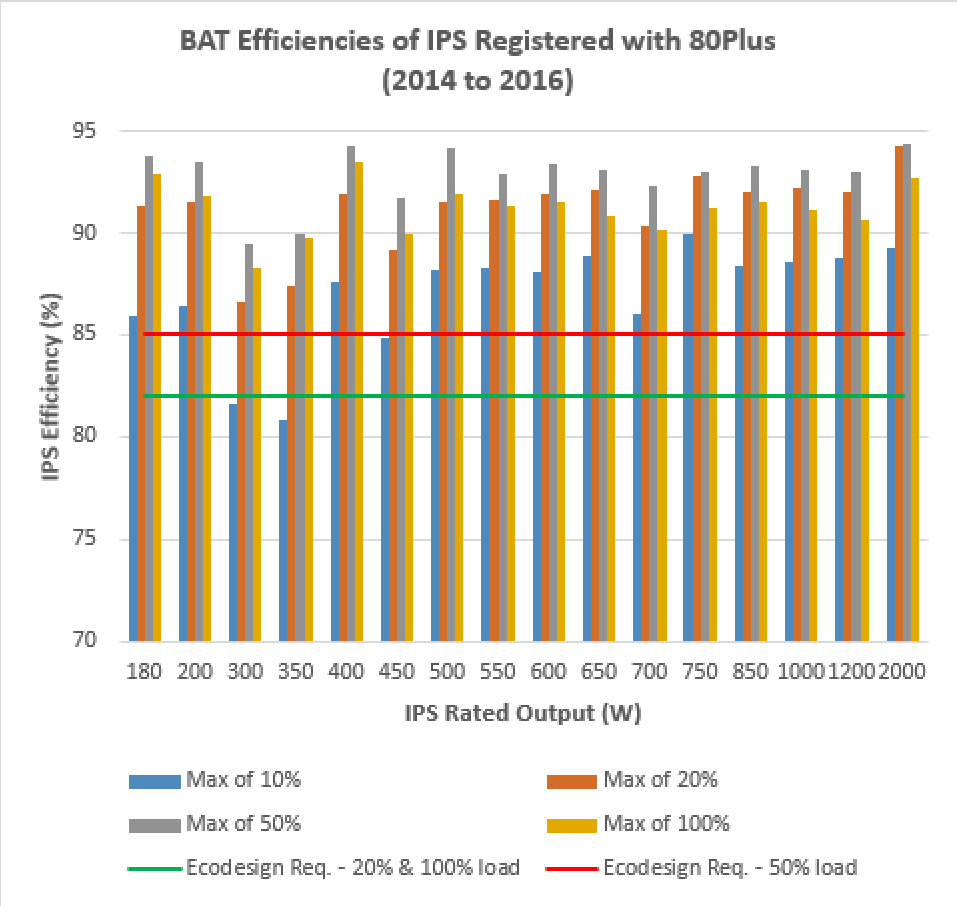

Figure 4. BAT Efficiencies of IPS Registered with the 80Plus Programme 2014 to 2016 [16].

Table 26 identifies the single highest efficiencies per loading state noted within the 80Plus registered IPS. The results show that the current EU ecodesign IPS efficiency requirements (85% efficiency at 50% load and 82% efficiency at both 20% and 100% loading) are significantly below BAT levels.

Table 26. Maximum efficiencies observed amongst 80PLUS Registered PSUs.

Maximum Observed Efficiency at loading profile			
10% load	20% load	50% load	100% load
89.9	94.3	94.3	93.5

4.1.4.5 Integrated display efficiency

Figure 5 and Figure 6 illustrate the minimum short-long idle deltas for integrated desktop and notebook computers, without any dGfxs installed, in the US ENERGY STAR database. The values show that estimated minimum display power demands vary considerably amongst each product type but some consistency is evident for notebook displays over 2.5 dm^2. The high degree of variability in BAT values is likely an artefact of estimating display power demand using the short-long idle delta as it does not take account of other components, such as the CPUs, which are also likely to have variable short-long idle deltas.

[16] Plugload Solutions, 80 PLUS® Certified Power Supplies and Manufacturers, available from https://www.plugloadsolutions.com/80PlusPowerSuppliesDetail.aspx?id=0&type=4

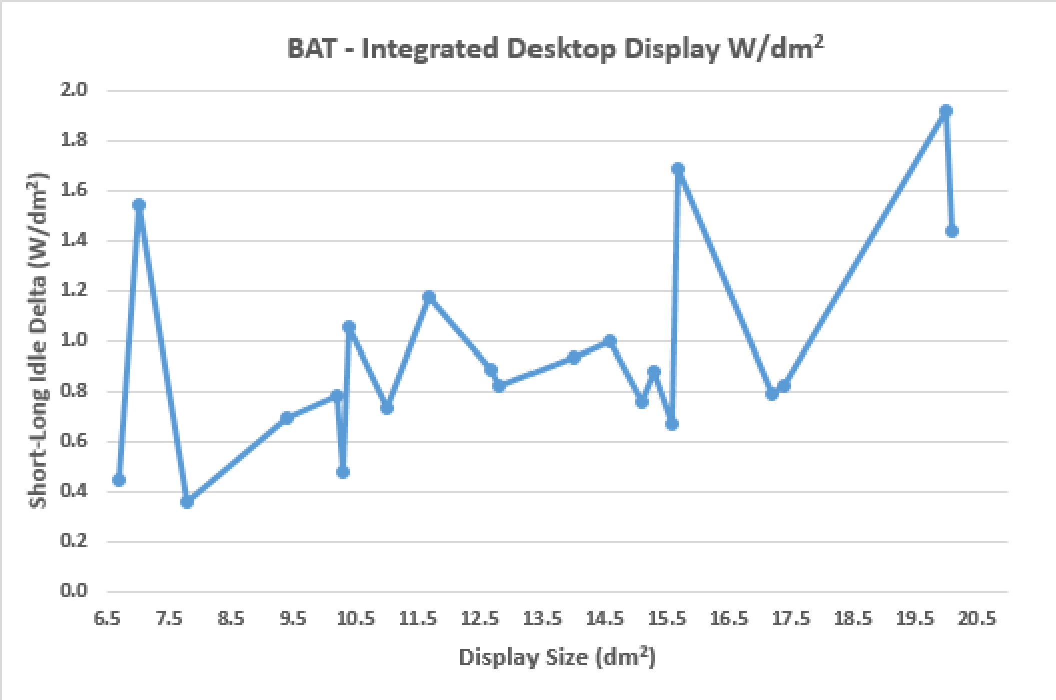

Figure 5. BAT Efficiencies of displays in ENERGY STAR registered Integrated desktop computers

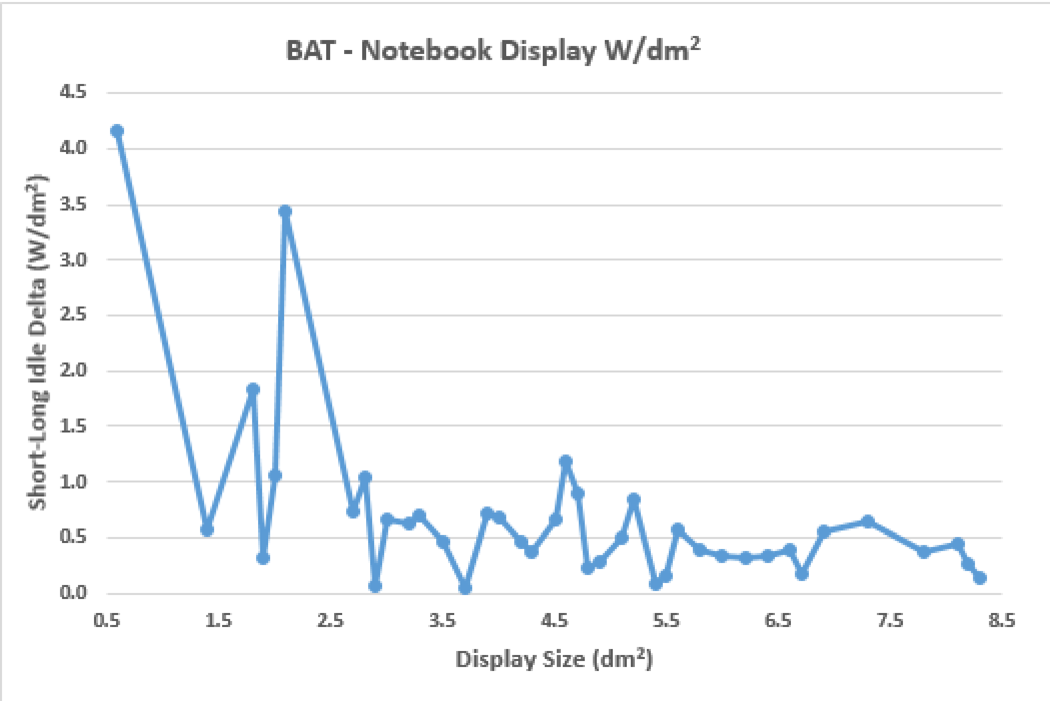

Figure 6. BAT Efficiencies of displays in ENERGY STAR registered notebook computers

Integrated display BAT levels are likely delivered through a combination of efficient technologies such as inclusion of reflective polarizing film, improved filters, more efficient LEDs and better control of backlighting.

Additional technologies such as automatic brightness control (ABC) may also help to deliver BAT levels. ABC functionality supports the adjustment of display brightness levels in response to ambient lighting conditions. That is, where displays are used in low ambient light levels ABC will support a reduction in display luminance as full display brightness is not required. Automatically reducing display luminance in low ambient light conditions could result in reduced energy usage but savings would be highly dependent on the distribution of ambient light conditions during product usage. Computers are typically used in a lower range of ambient light conditions than other devices, such as televisions, that also included ABC functionality. As such, energy savings from the inclusion and use of ABC technologies in computers may be lower than when used in other devices. Random Access Memory efficiency

The efficiency of RAM in personal computers has increased with each new iteration of RAM technology. DDR4, the latest iteration of RAM, operates at a lower voltage than older DDR3 RAM (1.2V compared to 1.35V) and also supports enhanced power management functionalities. These enhanced power management functionalities allow DDR4 memory to enter sleep modes without requiring refreshing of the memory which requires energy to undertake. DDR4 also supports the ability to refresh individual chips on a DIMM rather than requiring a refresh of the whole DIMM.

The actual savings estimates associated with DDR4 over DDR3 vary according to source but manufacturers estimate overall power demand savings to be around 40%.[17,18] Given these large potential power savings DDR4 memory should be described as BAT.

Further reductions in power demand can be achieved by using the smallest number of DIMMS possible to provide the required amount of RAM. That is, a single DDR4 RAM module of 16GB will have a lower power demand than two DDR4 RAM modules of 8GB.[19,20]

4.1.4.6 Storage technologies

Traditionally computer storage have had relatively higher power demands, especially during usage. This was largely as a result of the predominance of HDD which require mechanical force to spin platters. The advent of SSDs has resulted in the potential to significantly decrease energy use associated with storage. Table 27 provides a list of personal computer SSDs along with both power and performance data.[21] The idle power demand values are reported without Aggressive Link Power Management (ALPM) activated. ALPM is a power management protocol for Advanced Host Controller Interface-compliant (AHCI) Serial ATA (SATA) devices including SSDs. If ALPM were activated during test, then the idle power demand values would be noticeably lower. Under real-world usage scenarios SSDs would likely spend more time active than in a deeper sleep mode and so the values in Table 27 may be a more accurate reflection of real world power use. The data in Table 27 clearly show that the PCIe based SSDs have much higher active idle power demand levels than the traditional 2.5 inch SSDs, but remain efficient during active states due to their high levels of performance.

The bolded products in Table 27 provide both relatively high levels of read/write performance but also have low power demands in active idle and active states. Given these attributes these products are defined as BAT.

[17] http://www.samsung.com/global/business/semiconductor/file/media/DDR4_Brochure-0.pdf
[18] https://uk.crucial.com/wcsstore/CrucialSAS/pdf/product-flyer/ram/crucial-ddr4-sodimm-en.pdf
[19] https://www.kingston.com/en/memory/resources/power_benchmark
[20] https://h20195.www2.hpe.com/V2/getpdf.aspx/4AA6-2997ENW.pdf?ver=1.0
[21] http://www.anandtech.com/show/10328/the-toshiba-ocz-rd400-pcie-ssd-review/8

Table 27. BAT Efficiencies of Storage Devices.

Storage Product Name	Storage Product Type	Idle Power Demand (No ALPM) (W)	Mixed 4KB Random Read/ Write (W)	Mixed 4KB Random Read/ Write (MB/s)	Efficiency - (W/MB/s)
OCZ RD400 512GB	PCIe SSD	2.53	3.14	251.74	0.012
OCZ RD400 1TB	PCIe SSD	2.49	3.13	248.39	0.013
OCZ RD400 256GB	PCIe SSD	2.48	3.03	241.52	0.013
Samsung 950 Pro 512GB	PCIe SSD	1.64	2.83	218.34	0.013
Samsung 950 Pro 256GB	PCIe SSD	1.63	2.67	194.97	0.014
Samsung 850 Pro 1TB	SSD 2.5-Inch	0.36	2.30	171.46	0.013
Samsung 850 Pro 256GB	SSD 2.5-Inch	0.31	1.94	168.14	0.012
Samsung 850 Pro 512GB	SSD 2.5-Inch	0.30	1.93	167.9	0.011
Samsung 850 EVO 500GB	SSD 2.5-Inch	0.31	1.60	162.07	0.010
Samsung 850 EVO 250GB	SSD 2.5-Inch	0.31	1.55	149.63	0.010
Samsung 850 EVO 1TB	SSD 2.5-Inch	0.32	2.21	127.04	0.017
OCZ Vector 180 480GB	SSD 2.5-Inch	-	1.67	106.62	0.016
OCZ Vector 180 240GB	SSD 2.5-Inch	0.61	1.54	104.56	0.015
OCZ Vector 180 960GB	SSD 2.5-Inch	-	1.82	101.13	0.018
OCZ Trion 150 240GB	SSD 2.5-Inch	0.16	1.63	78.07	0.021
OCZ Trion 150 960GB	SSD 2.5-Inch	0.20	1.68	77.94	0.022
OCZ Trion 150 480GB	SSD 2.5-Inch	0.18	1.60	70.87	0.023

4.1.4.7 Advanced power management

The way in which low power modes have been implemented in common operating systems has evolved. Table 28 shows the evolution of these low power modes in the Windows operating systems. Power management functionality in some other operating systems, such as the Apple's macOS, has also evolved and improved in recent years. Power management functionality may not be so advanced in some minor operating systems.

The advent of S0iX states in new CPU chipsets along with the development of Modern Standby" are examples of advanced power management functionalities that may save significant amounts of energy going forward. Many of the failings of current power management functionality, such as the ability for users to disable, may be solved by the further use of "Modern Standby".

Table 28. The evolution of supported low power states in.

<table>
<tr><th>Operating System</th><th>Windows 7</th><th colspan="2">Windows 8</th><th colspan="2">Windows 10</th></tr>
<tr><td>Supported Sleep States</td><td>ACPI S3 & S4</td><td>ACPI S3 & S4</td><td>Connected Standby & ACPI S4</td><td>ACPI S3 & S4</td><td>Modern Standby & ACPI S4</td></tr>
<tr><td rowspan="4">Supported Devices</td><td colspan="5">Desktops</td></tr>
<tr><td colspan="5">Integrated Desktops</td></tr>
<tr><td colspan="5">Mobile computers</td></tr>
<tr><td colspan="4"></td><td>Smart phones</td></tr>
<tr><td>Architecture</td><td>X86/X64</td><td>X86/X64</td><td>X86/X64/ARM</td><td>X86/X64</td><td>X86/X64/ARM</td></tr>
</table>

The low power mode infrastructure has evolved in several ways within Windows 10. In particular, Modern Standby expands upon the Windows 8.1 Connected Standby power model to allow greater compatibility across component types. For example, Modern Standby supports systems based on a wide range of storage technologies (i.e. HDD, SSD and SSHD). Furthermore, network interface cards (NICs) that could not be supported under Connected Standby can be supported under Modern Standby. Modern Standby, is implemented through the S0 low power idle model. Network activity can also be more easily limited in Modern Standby has the flexibility to configure the default behaviour to limit which could help to reduce low power demand levels.

Modern Standby takes advantage of the more flexible power scaling within modern chipsets and can be implemented on a wide range of mobile and non-mobile computers. Computers using the Modern Standby functionality can be can be configured to be either connected or disconnected to a network. However, the computer remains in the S0 low power state irrespective of whether the product is connected or disconnected from to a network.

Modern Standby potentially provides several advantages over older low power state technologies, such as ACPI S3, including:

- Faster resume from a low power state. Microsoft claims that resume time from the low power states under Modern Standby is at least twice as fast as ACPI S3 resume[22]. These faster resume times could improve user experience with power management helping to ensure that the functionality is not disabled and provide more energy savings.
- Computers connected to a network can be programmed to wake based on specific network patterns. This can allow products to receive updates, emails and VoIP calls without the need to leave a computer turned on.
- Waking a computer from ACPI S3 requires the functionality to be integrated into the BIOS. The reliance on the BIOS aspect increases wake times and makes implementation more difficult. Modern Standby only requires a hardware interrupt and so may eliminate any need for firmware interaction.

Previous implementations of connected standby in Windows 8.1 required that the system woke at least once every thirty seconds to process work. Systems with Modern Standby implemented within Windows 10 only wake when necessary such as for OS maintenance updates or the user wakes the system. This has the potential to save further energy.

Modern Standby is supported in both Windows 10 desktop and Windows 10 Mobile. It is likely that growth of Modern Standby will mostly be centred on mobile computers but could extend to desktop computers where energy saving potentials are probably higher.

Panel self-refresh (PSR) technology is another example of an advanced power management functionality that offers the potential to save energy during short periods of user inactivity before a power down event occurs (i.e. the computer powers down to long idle, sleep mode or hibernate mode). This technology involves the inclusion of a small amount of memory that stores frames allowing GPUs to be powered down when a display doesn’t need to be refreshed.

4.1.5 BNAT – Best Not Available Technology

Identifying BNAT in computer components is a complex undertaking because the industry moves fast and what may appear as a future BNAT opportunity may be quickly superseded by a new emerging technology. This section of the report investigates some future BNAT opportunities within the main computer components.

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22 https://msdn.microsoft.com/en-us/library/windows/hardware/mt282186(v=vs.85).aspx

4.1.5.1 CPU Efficiency

CPU efficiency is likely to continue to evolve as reductions in process size continue (i.e. down to 7nm and 5nm). As the process size of CPUs and other components continues to reduce, leakage current will become an increasing concern for energy efficiency. New materials and architecture designs will be required to reduce leakage. This may include the development of improved node processes using new materials such as carbon nanofibers.

CPU power management opportunities are also likely to improve with the advent of better and wider implementation of SI0x states across CPUs and SoC designs. With the support of software based solutions such as Modern Standby computers could act much more like smart phones, in terms of power management functionality, and become significantly more efficient.

4.1.5.2 Software Efficiency

Microsoft are actively working with hardware manufacturers to ensure that Modern Standby is supported across more computer products. This holds the potential to significantly reduce energy usage in products that support this functionality.

4.1.5.3 Graphics Processing Unit Efficiency

The energy efficiency levels found in both iGfx and dGfx is likely to continue to increase in future, mirroring the improvements in CPUs and OS.

Usage of high band width memories (HBM) in future iGfX and dGfx will likely lead to significant improvements in performance whilst also offering reduced energy consumption.

4.1.5.4 IPS Efficiency

IPS efficiency is likely to further increase in future with the advent of two stage IPS which tackle inefficiencies at low load levels: the delta between active state power demand and idle power demand is growing, hence the load on the IPS is decreasing in idle mode which then results in further inefficiencies. Two stage IPSs will include a smaller IPS that provides power to computers at low loading levels and allowing the power management of the larger IPS. This new technology is currently being developed in the market and is likely to become more important going forward as loading levels on higher performance computers continue to fall.

4.1.5.5 Integrated Display Efficiency

Improvements in integrated display efficiencies will mirror improvements found in the external display and television products. This will likely include the development of quantum dot based integrated displays which hold the potential to significantly reduce the power needed for panel backlighting.

4.1.5.6 Memory Efficiency

Further power demand savings are expected from DDR4 memory as production moves to a 10nm process. It is estimated that a further power demand saving of between 10% to 20% per DIMM could be realised as a result of this shift to a smaller manufacturing process.[23]

[23] https://news.samsung.com/global/samsung-starts-mass-producing-industrys-first-10-nanometer-class-dram

HBM may also be used in RAM modules going forward, offering much greater performances with lower power demand levels.

4.1.5.7 Storage Technologies

New types of storage products such as the Intel Optane drives are due to start finding their way to market in the near future.[24] These products which provide non-volatile memory (NVM) will offer much faster retrieval of stored data, at RAM retrieval performance levels, whilst also purportedly offering improvements in energy efficiency.

4.1.5.8 Enhanced power management

It is expected that innovations such as Microsoft Modern Standby will continue to be adopted by manufacturers going forward and that this type of functionality will be supported in other OS available on the market.

4.2 Use of materials for average technologies and BAT

The life cycle of personal computers is represented by the production, distribution, use and end of life of personal computers. The geographical coverage of personal computers used in the European market through their life cycle is usually quite broad. Materials and components are primarily manufactured in Europe, the USA and Asia, shipped to China for assembly, then back to Europe for consumer use and disassembly at their end of life, and finally shipped to Asia, Africa or other countries for reuse, recycling and final disposal. Therefore, their life cycle is complex, covering many steps and involving many actors in the supply, use and disposal chain, and implying the use of a wide range of materials and resources and creating environmental impacts through the whole life cycle.

From previous studies[25,26,27,28] and what has been declared by some manufacturers, it is clear that the hot spots in the life cycle of computers in terms of material and resource use are the production and use stages, however if more reuse and recycling of personal computers happen at the end of life, the overall use of materials and the computers' overall environmental impacts can be reduced. Furthermore, by increasing the reuse and recycling of components and materials locally where the use of the computers takes place, more access to highly valuable materials is achieved within the EU. This also increases the amount of materials available for reuse and/or recycling which is necessary to make their recovery more economically attractive.

A detailed description of the use patterns and the paths of personal computers at their end of life has already been presented in the task 3. The focus of this chapter is on the manufacturing, specifically on product configuration and use of materials, of average technologies and BAT of personal computers.

The manufacturing of personal computers happens at different times and places, starting with the extraction of raw materials, the manufacturing of components and the assembly of the computer product. The places where these activities happen are different according to the sourcing of the parts to manufacture the components and the availability of raw materials to produce these parts. The components used in a personal

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[24] http://www.intel.com/content/www/us/en/architecture-and-technology/non-volatile-memory.html
[25] Lot 3 Preparatory study on personal computers (desktops and laptops) and computer monitors, 2007.
[26] Ecological and economic aspects when comparing workplace computers for use in public authorities, including user behavior. Öko-Institut e.V. and TU Berlin, 2016 (in German, summary in English).
[27] Paradigm Shift in Green IT – Extending the Life-Times of Computers in the Public Authorities in Germany. Prakash et al., 2016. Electronics Goes Green Conference Proceedings.
[28] Personal computer life cycle assessment study: the case of Western Australia. Sirait et al., 2012.

computer influence the computer's overall performance, as it has been discussed previously. In some cases, the materials used for manufacturing of the components also influence the performance of the computer. It is therefore that when assessing potential materials' substitution, the performance of the component and the overall performance of the computer need to be looked at by assessing how this substitution would affect them. These considerations need to be taken into account when suggesting changes of the design of the computer in order to reduce the use of materials and resources and the computers' overall environmental impact.

In order to get an overview of the components and parts used in personal computers currently on the market, the average Bill of Materials (BoM) for three of the product categories defined in task 1 are presented in the next sections (i.e. desktops incl. integrated desktops, notebooks and tablets). BoMs for workstations, thin clients, all-in-ones and small scale servers were not available, and thus this chapter focuses only on the three abovementioned product groups. The BoMs are presented as the average of products currently in the market, as well as for the Best Available Technology (BAT) identified for each product category. It is important to notice that the average BoMs were established based on information available in literature and product declarations from the manufacturers, and thus it may not reflect the whole range of products placed on the market. However, they are considered representative considering the information available.

4.2.1 Desktop computers

BoM data for desktop computers (excluding integrated desktop computers) was retrieved from six datasets, both from reviews of desktop computers available on the market[29,30,31,32] and from information available from manufacturers[33,34].

An average BoM was established from these datasets, which is shown at a component level (shown in Table 29). Data for materials is complex, since most of these components are formed by mixtures of many different materials. Due to this complexity is not possible to find BoM information at a material level, except for some of the key components. The average BoM was considered to represent the average technology on the market considering data availability limitations, and the BoM for BAT is based on the products identified in chapter 1.4. The BoMs are presented in Table 29.

Table 29. Bill of materials (BoM) of average and BAT desktop computers on the European market.

Component	Weight in average technology (kg)	Range of weight in average technology (kg)	Weight in BAT (kg)
Housing	4.94	0.78 – 8.70	0.78

[29] Sirait et al (2012). Personal Computer Life Cycle Assessment Study: The Case of Western Australia. 10th Global Conference on Sustainable Manufacturing, Oct 31-Nov 2 2012. Istanbul, Turkey: Middle East Technical University METU. Available at: http://espace.library.curtin.edu.au/R?func=dbin-jump-full&local_base=gen01-era02&object_id=190720

[30] JRC Technical Report (draft version, November 2016). Analysis of material efficiency aspects of personal computers product group.

[31] Teehan, Paul; Kandlikar, Milind (2013a): Comparing Embodied Greenhouse Gas Emissions of Modern Computing and Electronics Products. In: Environmental Science & Technology, 47(9), S. 3997–4003.

[32] Hischier and Wãger (2014). The Transition from Desktop Computers to Tablets: A Model for Increasing Resource Efficiency? Available at: http://publicationslist.org/data/patrick.waeger/ref-124/2014_Hischier_W%C3%A4ger_Transition_from_Desktop_Computers_AAM.pdf

[33] Mac Pro Environmental Report (2013). Available at: http://images.apple.com/environment/pdf/products/desktops/MacPro_PER_oct2013.pdf

[34] Mac mini Environmental Report (2014). Available at: http://images.apple.com/environment/pdf/products/desktops/Macmini_PER_oct2014.pdf

Component	Weight in average technology (kg)	Range of weight in average technology (kg)	Weight in BAT (kg)
Printed circuit board	1.18	0.33 – 2.77	0.33
Hard disk drive or Solid state drive*	0.33	0.11 – 0.55	0.10
Power supply unit	0.99	0.09 – 1.62	0.09
Cable	0.37	0.06 – 0.712	0.06
Fan	0.07	n.a.	*not present*
Radiator**	0.57	n.a.	*not present*
Total weight of desktop computer	8.45	1.36 – 13.50	1.36

*=most of the datasets contain HDD, with the newer and smaller models moving towards SSD; **=radiators are mainly used in high-end desktop computers for, e.g. gaming, as part of a liquid or fan-less air cooling system[35]; n.a.=only one dataset available for this component thus range not available.

The range of weight of each component differs greatly for desktop computers, as the designs include many sizes and ranges from mini-PCs[36] to tower desktop computers used for gaming. In spite of this variation, an average was established to define a representative from the market in terms of product configuration. This market representative of the average technology is then used to identify key components that present a potential for recovery and that contain materials that present an economic and/or environmental incentive for recovery. In the case of desktop computers, key components are HDD, PCB, CPU, graphic processing unit (GPU) and RAM. In some models, the CPU, GPU and RAM will be soldered to the PCB as it is the case of the new Apple Mac mini[37]. Cables are usually recovered at sorting stations at the end of life from conventional tower desktop computers and it is assumed they will be so as well for mini-PCs, due to their content of copper.

[35] http://www.digitaltrends.com/computing/heres-why-you-should-liquid-cool-your-cpu/
[36] A desktop computer in a small case that takes up very little desk space. There are numerous Windows mini PCs, and the Mac comes in a mini model as well. Configurable with the same CPUs and capacities as full-size desktop computers, a mini PC has no internal expansion (see http://www.pcmag.com/encyclopedia/term/64512/mini-pc).
[37] http://www.macworld.co.uk/how-to/mac/how-upgrade-processor-in-your-mac-3591567/

While carrying out this analysis it was acknowledged that several manufacturers are placing mini-PCs on the European market and based on information of the German public procurement of IT solutions[38], it can be assumed that the demand of these type of desktop computers will increase in the European market in the future. However, the accessibility of key components in conventional tower desktop computers at their end of life is, according to JRC[30], already largely implemented because it is relatively easy and cheaper to perform manual dismantling (according to JRC, key components are generally fastened with standard screws and full disassembly takes about 2-4 minutes). On the other hand, the still low presence of these products on the European market poses some challenges for their dismantling at the end of life, but it can be foreseen that it will be more challenging than that of conventional tower desktop computers. Furthermore, some newer tower desktop designs like the Mac Pro present some challenges to upgradeability for the storage modules (HDD or SSD)[39], because the SSD comes as built-in storage on the side of the computer (see Figure 8) which comes as one internal blade that has a limited third-party availability. Furthermore, the Peripheral Component Interconnect (PCI) slots require unique designs to fit additional hardware into the computer[40,41].

Figure 7:The naked Mac Pro (source MacWorld [37])

The material composition of HDD is based on information available from one of the most commonly found brands of HDDs found in desktop computers placed on the European market[42], and the relative material composition is shown in Figure 8. Due to lack of data availability, the composition herein presented of HDD is assumed to be the best available representative of what is found on the European market today.

[38] German Federal Ministry for the Environment, Nature Conservation, Construction and Reactor Safety (2016). Ecological and economic aspects when comparing workplace computers for use in public authorities, including user behavior (eco-APC). Available at: https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/endbericht_oko-apc_2016_09_27.pdf

[39] http://www.macworld.co.uk/review/mac-pro/mac-pro-review-apples-workstation-3455533/?p=2

[40] http://www.everymac.com/systems/apple/mac_pro/mac-pro-cylinder-faq/how-to-upgrade-mac-pro-cylinder-ssd-storage.html

[41] https://www.cnet.com/news/how-upgradable-is-the-new-mac-pro/

[42] Barracuda LP HDD Prodyct Life Cycle Analysis Summary (2011). Available at: http://www.seagate.com/files/www-content/global-citizenship/en-us/docs/final-barracuda-lca-summary-report-ams-3-24-14-10-1-2013.pdf

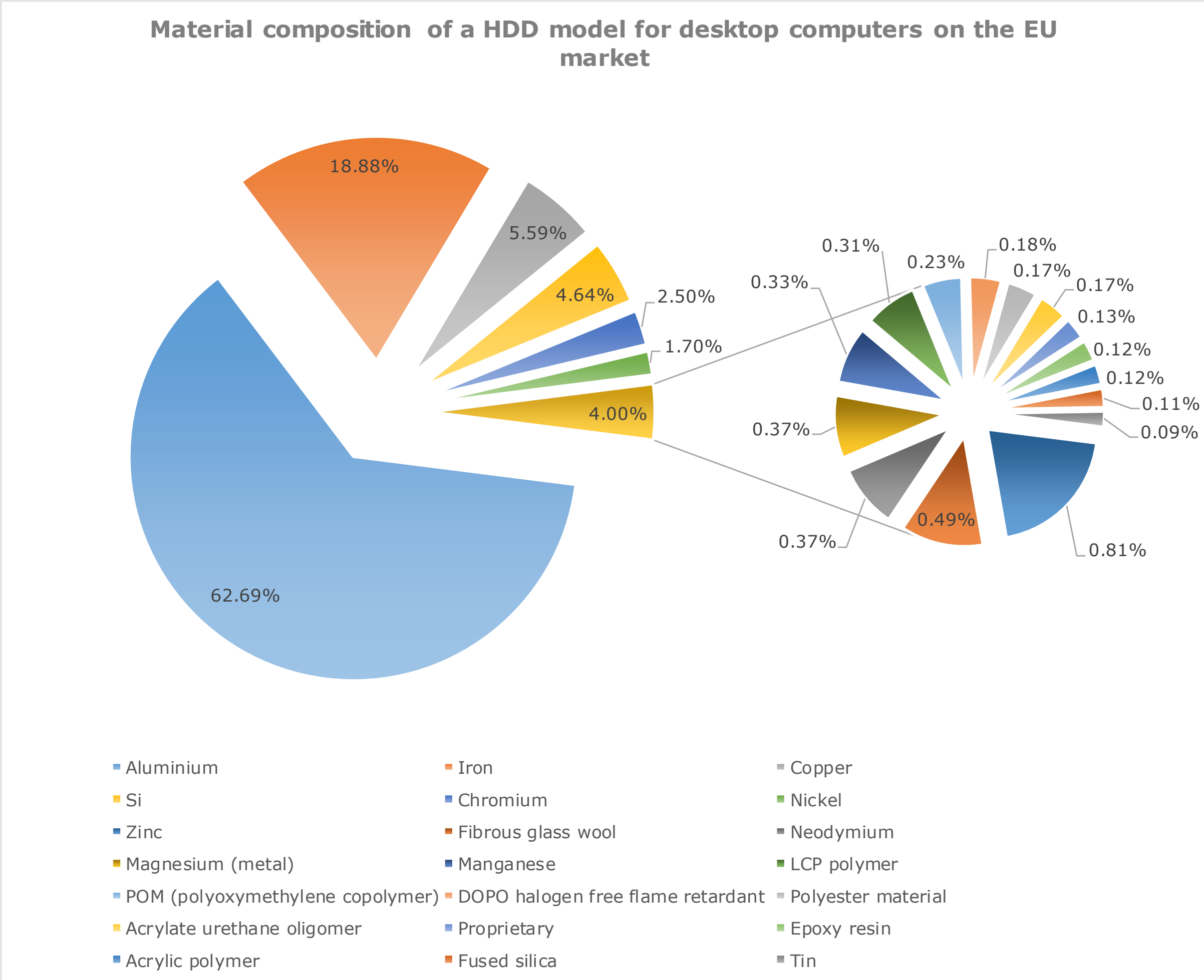

Figure 8. Material composition of a HDD model for desktop computers placed on the EU market[42].

Figure 8 shows that 82% of the HDD is made of highly recyclable metals (i.e. aluminium and iron), while other valuable metals such as copper, silicium, chromium and nickel form 16% of the HDD. The other 2% is formed by other metals such as zinc and a mixture of plastics. Neodymium, considered a rare earth element and listed as a critical raw material represents 0.36% of the total mass of the HDD. Considering the average weight of the HDD is 0.33kg, this would be about 1.2g of Neodymium in the whole storage drive.

4.2.1.1 Integrated desktop computers

The availability of BoM data for integrated desktop computers was limited to three product models on the EU market[43,44,45]. Due the few data points found, the BoM is shown for each of these products in Table 30. Furthermore, one of these products has been identified as the BAT for integrated desktops as seen in Table 30.

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[43] Product Water Footprint Report of Computer (2015). ThinkCentre X1 - Machine type: 10HT, 10JW, 10KE, 10JX, 10JY, 10KF, 10K0, 10HU. Lenovo. Available at: https://www.lenovo.com/social_responsibility/us/en/product_water_footprint/ThinkCentre_X1_Water_Footprint_Declaration.pdf

[44] 27-inch iMac with Retina 5K Display Environmental Report (2015). Available at: http://images.apple.com/environment/pdf/products/desktops/27inch_iMacR5K_PER_Oct2015.pdf

[45] 21.5-inch iMac and 21.5-inch iMac with Retina 4K Display Environmental Report (2015). Available at: http://images.apple.com/environment/pdf/products/desktops/21_5inch_iMac_PER_Oct2015.pdf

Table 30. Bill of materials (BoM) of identified integrated desktop computers on the European market (including BAT).

Component	Weight product 1[43] (kg)	Weight product 2[44] (kg)	Weight product 3 (BAT)[45] (kg)
Housing	3.66	4.05	2.56
Display unit	2.26	3.20	2.04
Printed circuit boards	0.17	0.52	0.31
Storage	0.09	0.42	0.10
CPU	0.01	*not declared*	*not declared*
RAM	0.02	*not declared*	*not declared*
Power supply unit	0.20	0.48	0.29
Cables	0.02	0.13	0.10
Speakers	0.07	0.48	0.26
LED backlight	0.01	*not declared*	*not declared*
Fans	0.04	*fanless*	*fanless*
Total weight of integrated desktop	6.50	9.29	5.68

Some of the components declared in product 1 are not declared in products 2 and 3. CPU and RAM are not declared for products 2 and 3 since it is assumed that they are mounted/soldered on to the mainboard (i.e. the PCB) and are, therefore, not declared separately. Furthermore, product 1 declares both CPU and RAM as part of the mainboard (i.e. the PCB), which confirms this assumption. Products 2 and 3 use a fanless, passive cooling system[46],. The LED backlight is an accessory offered by the models declared in product 1[47] (although it appears from internet search that only a few have it available), which is the same case for products 2 and 3. However, the manufacturer for products 2 and 3 does not declare this accessory in their BoMs. Due to the small size of this accessory and its relative low importance to the recovery of components and materials, the availability of this feature in products 2 and 3 was not pursued further.

Concerning key components, it is assessed that these are the display because of the mercury content, the PCB because of the valuable materials it contains such as copper and gold, and the HDD because of its content of Neodymium and highly recyclable materials. However, it is the understanding of the study team that the integrated desktops are treated exactly the same as electronic displays at the end of life, since no difference can be perceived by staff doing the sorting at the dismantling facilities. Furthermore, the design does not permit easy recovery of the key components that are unique to computers which were mentioned before. However, if ecodesign requirements are implemented for material efficiency of electronic displays, these may aid to the recovery of some of these components (e.g. the PCB).

[46] http://www.mactech.com/content/apple-patent-thin-passive-cooling-system
[47] http://shop.lenovo.com/us/en/itemdetails/10LLPAR6US/460/B13D3E47F9B14FE3B5B269DC4F6AA922

4.2.2 Notebook computers

BoM data for notebook computers was retrieved from ten datasets, both from reviews of notebook computers available on the market[30,32] and from information available from manufacturers[48,49,50,51,52,53,54].

An average BoM was established from these datasets, which is shown at a component level (shown in Table 31). BoM data at material level is presented for some of the key components in the next sections. The average BoM was considered to represent the average technology on the market considering data availability limitations, and the BoM for BAT is based on the products identified in chapter 1.4.

Table 31. Bill of materials (BoM) of average and BAT notebook computers on the European market.

Component	Weight in average technology (kg)	Range of weight in average technology (kg)	Weight in BAT (kg)
Housing	0.74	0.35 – 1.71	0.35
Printed circuit boards	0.24	0.05 – 0.78	0.05
Hard disk drive	0.08	0.07 – 0.10	*not declared*
Solid state drive	0.02	0.01 – 0.06	*not declared*
Optical disk drive	0.18	0.15 – 0.21	*not present*
Display unit	0.28	0.15 – 0.56	0.15
Power supply unit (incl. cable)	0.21	0.06 – 0.81	0.06
Fan	0.01	n.a.	*not present*
Speakers	0.005	n.a.	*not declared*
Keyboard and trackpad	0.14	0.11 – 0.15	0.11
Battery	0.31	0.19 – 0.45	0.19
Total weight of notebook computer	2.23	0.92 – 3.50	0.92

n.a.=only one dataset available for this component thus range not available

The range of weight of each component differs also for notebook computers, though not as much as for desktop computers. This is believed to be due to the higher homogeneity on designs of notebook computers placed on the market. The BAT presents component weights on the lowest range found from datasets available. Furthermore, this design does not declare five of the eleven components for average products. The HDD or SSD are believed to be mounted/soldered on the PCB in spite of the low weight of this component. The speakers are believed to be omitted in the declaration due to low weight. The ODD is assumed not to be present in this design, in spite it is declared by another product of the same manufacturer[50]. The reason is that the BAT is a newer product (introduced in 2016), whilst the other is older (introduced in 2012). It is

[48] 12-inch MacBook Environmental Report (2016). Available at: http://images.apple.com/environment/pdf/products/notebooks/MacBook_PER_April2016.pdf

[49] 13-inch MacBook AirnEnvironmental Report (2015). Available at: http://images.apple.com/environment/pdf/products/notebooks/13inch_MacBookAir_PER_march2015.pdf

[50] 13-inch MacBook PronEnvironmental Report (2012). Available at: http://images.apple.com/environment/pdf/products/notebooks/13inchMacBookPro_PER_june2012.pdf

[51] 13-inch MacBook Pro with Retina display Environmental Report (2015). Available at: http://images.apple.com/environment/pdf/products/notebooks/13inchMBP_wRetinaDisplay_PER_Oct2016.pdf

[52] 15-inch MacBook Pro with Retina display Environmental Report (2015). Available at: http://images.apple.com/environment/pdf/products/notebooks/15inchMBP_wRetinaDisplay_PER_2016.pdf

[53] 13-inch MacBook Pro with Thunderbolt 3 Environmental Report (2016). Available at: http://images.apple.com/environment/pdf/products/notebooks/13inchMBP_wTB3_PER_Oct2016.pdf

[54] 15-inch MacBook Pro with Thunderbolt 3 Environmental Report (2016). Available at: http://images.apple.com/environment/pdf/products/notebooks/15inchMBP_wTB3_PER_Oct2016.pdf

assumed that models from 2012 still offer the CD/DVD reading capability and thus need an ODD. However, it is expected that this component will be phased out from notebook computers in the European market, once older models are not placed on the market any longer.

In spite of the weight variation, an average was established to define the representative from the market in terms of product configuration. Key components of notebook computers for recovery are identified by JRC[30] as the battery, the PCB (larger than 10cm^2), the LCD panel (larger than 1dm^2) and the storage units (SSD and HDD). ODD is also mentioned but this is not considered relevant as it was explained before. It is expected that in the future more notebook computers come with SSD instead of HDD. Therefore, the relative composition of both storage options is presented in Table 32. Moreover, the material compositions of an HDD model and an SSD model from a brand found in notebooks placed on the European market are shown in Figure 9 and

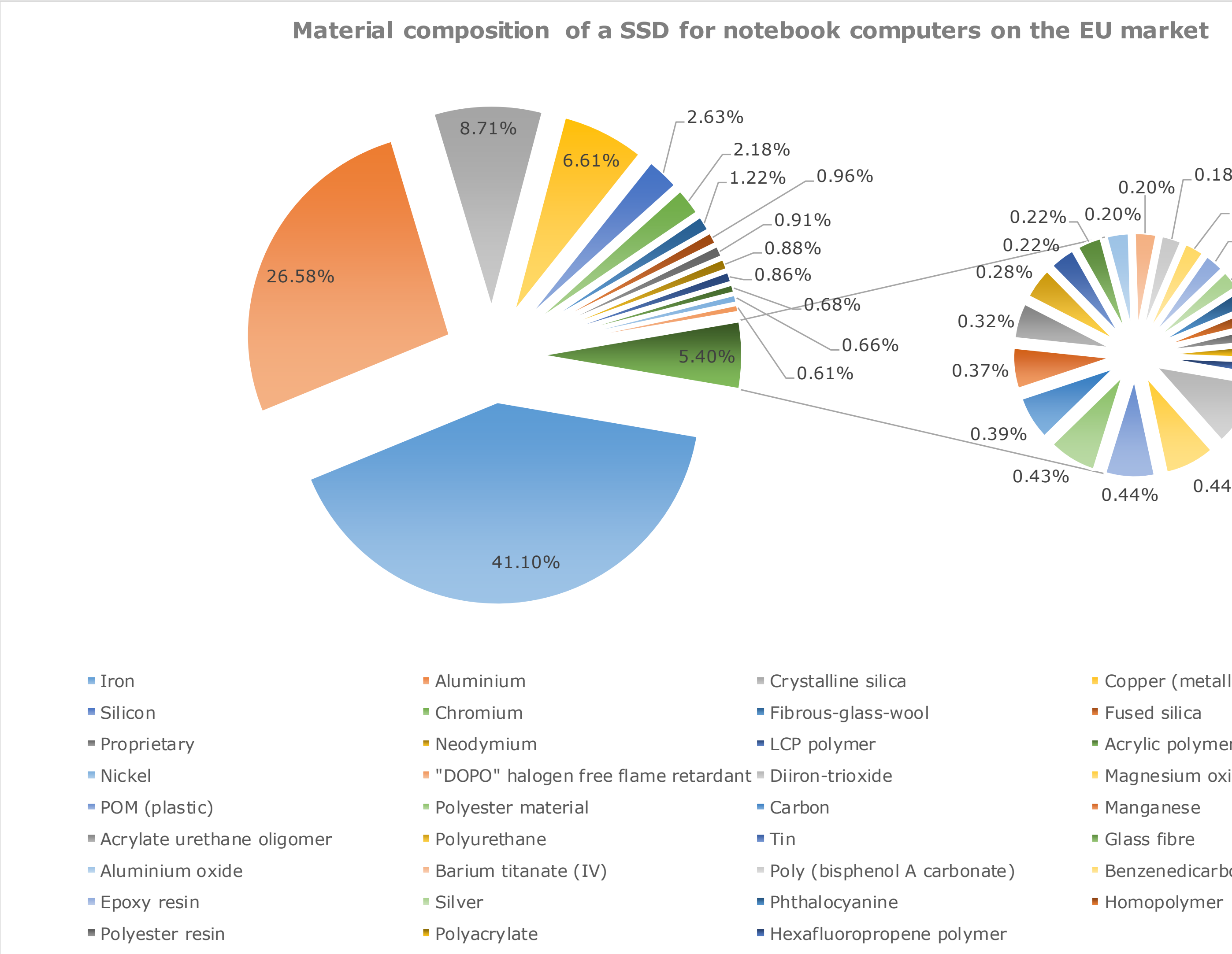

Figure 10.

Table 32. Material composition of HDD and SSD according to JRC review[30].

Material	HDD relative composition (%)	SSD relative composition (%)
Aluminium	45.0%	30.3%
Steel	31.2%	-

Material	HDD relative composition (%)	SSD relative composition (%)
Iron	8.7%	15.0%
Copper	0.4%	4.8%
Magnet	3.9%	-
Polychlorinated biphenyl	3.9%	-
Polycarbonate/ABS	3.9%	-
Polycarbonate/Glass fibre	3.0%	-
Fused silica	-	9.0%
Epoxy resin	-	6.1%
Aluminium oxide	-	4.8%
Magnesium silicate talc	-	3.2%
Silicon	-	3.1%
Tantalum	-	2.7%
LCP polymer	-	1.9%
Dioxygen	-	1.8%
Tin	-	1.8%
Vinyl silicone oil	-	1.7%
Fibrous-glass-wool	-	1.4%
C.I. pigment black 28	-	1.3%
Carbon	-	1.2%
Other materials	-	9.9%

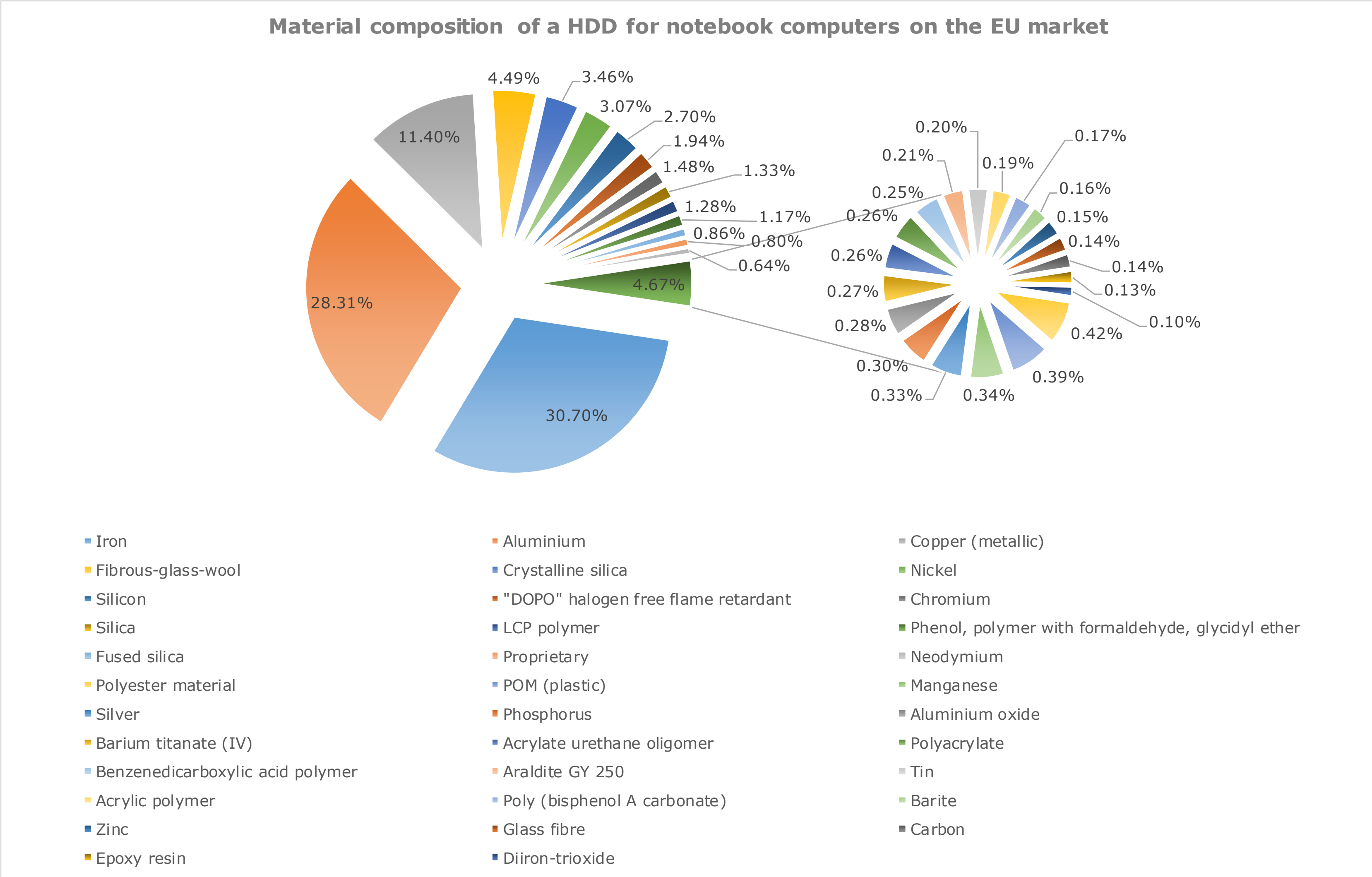

Figure 9. Material composition of a HDD model for notebook computers placed on the EU market[55].

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[55] Momentus HDD Product Life Cycle Analysis Summary (2011). Available at: http://www.seagate.com/files/www-content/global-citizenship/en-us/docs/momentus-lca-summary-report-9-26-2013.pdf

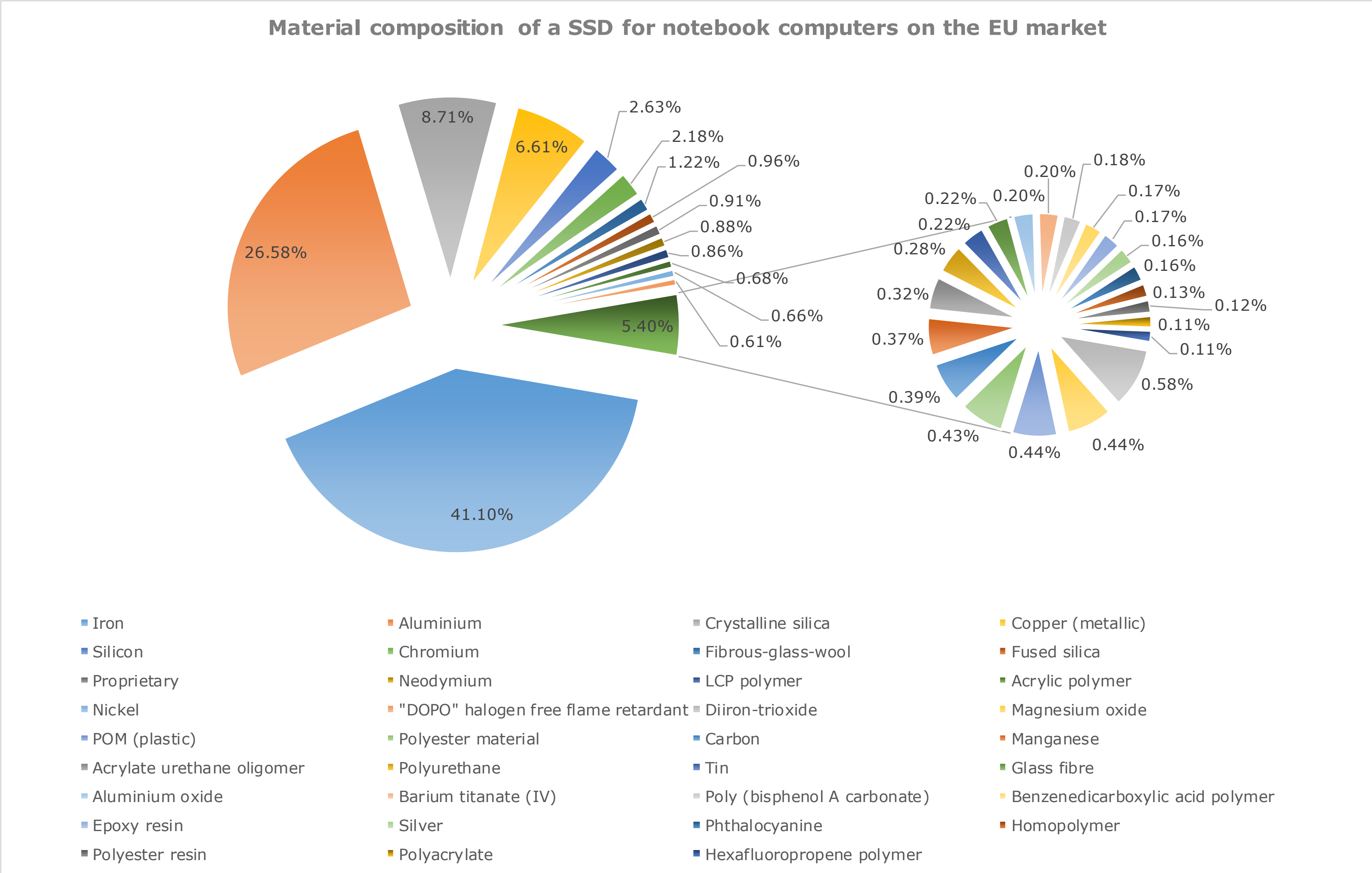

Figure 10. Material composition of a SSD model for notebook computers placed on the EU market[56].

[56] Momentus XT SSHD Product Life Cycle Analysis Summary (2011). Available at: http://www.seagate.com/files/www-content/global-citizenship/en-us/docs/final-momentus-xt-lca-summary-report-ams-3-12-14-10-1-2013.pdf

Concerning the material composition of HDD, Table 32 and Figure 9 agree on the amount of highly recyclable metals in the component (i.e. aluminium, iron and/or steel). It is assumed that iron substitutes steel and vice versa and that is why the composition of these metals differs in both datasets. However, three of the major differences are:

- The high difference in copper content, which is one of the metals that are looked at when recovering electronics at the end of life. This may be because the manufacturer's model is older than the dataset from the JRC review. It is known that one of the trends in electronics is to use less copper.
- The higher presence of plastics in the dataset from the JRC review, which may be due to the same reason as for the lower content of copper.
- The presence of Neodymium in the HDD from the manufacturer. This may be because the content is small and thus it is not declared by the studies reviewed by JRC.

Concerning the material composition of SSD, Table 32 and Figure 10 agree again on the high content of aluminium and iron (although it is much higher in the manufacturer's declared dataset). Furthermore, there is more alignment on the content of copper in both datasets as well as on the content of the other metals, polymers and elements. However, the same difference on the presence of Neodymium is observed as it is only declared by the manufacturer.

4.2.2.1 External power supply (EPS) units

As explained in previous tasks, there is an interest to know the amount of materials and resources saved by avoiding the use of product/model specific external power supply units and using universal types which can be used with several notebooks and/or computer products. Because of this interest, the material composition of the average EPS of the market for notebook computers was investigated by JRC[30]. An average composition is presented in Figure 11, which was updated to include a more recent analysis from 2014.

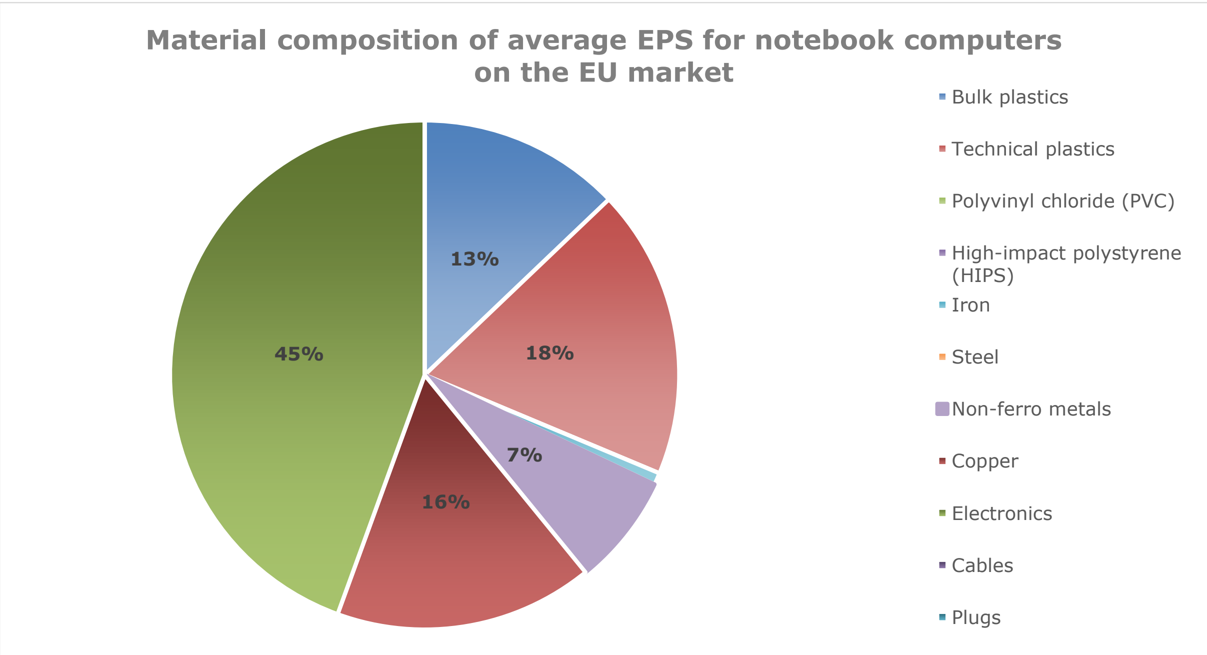

Figure 11. Average material composition of EPS for notebook computers with output powers from 60W to 90W[57].

Figure 11 shows that most of the materials in the average EPS are plastics, non-ferro metals, copper and electronics. This is expected since the metals are used for the conduction of electricity, the plastics for the construction and insulation and the electronics for the power adapter. This material composition includes both the power adapter and the cable.

4.2.3 Tablet/slate computers

BoM data for tablet/slate computers was retrieved from seven datasets, from a review of twenty tablets/slates available on the market[30], from a review of tablets used on the market during the year 2014[32] or from information available from manufacturers[58,59,60,61,62].

An average BoM was established from these datasets, which is shown at a component level (shown in Table 33). BoM data at material level is presented for some of the key components in the next sections. The average BoM was considered to represent the average technology on the market considering data availability limitations, and the BoM for BAT is based on the products identified in chapter 1.4.

Table 33. Bill of materials (BoM) of average and BAT tablet/slate computers on the European market.

Component	Weight in average technology (kg)	Range of weight in average technology (kg)	Weight in BAT (kg)
Housing	0.14	0.05 – 0.27	0.08
Printed circuit board	0.04	0.02 – 0.06	0.04
Display unit	0.17	0.1 – 0.3	0.17
Power supply unit (incl. cable)	0.05	0.02 – 0.06	0.03
Speakers	0.003	n.a.	*not declared*
Battery	0.13	0.09 – 0.17	0.13
Total weight of tablet/slate computer	0.53	0.30 – 0.72	0.45

n.a.=only one dataset available for this component thus range not available

The range of weight of each component is less than that for notebook and desktop computers as the design of these products across the European market are even more homogeneous. In the case of tablet/slate computers, the BAT does not represent the lowest range of components weight as for notebook computers. The only component not declared for BAT but declared for the average products in the market are the speakers, and it is assumed that they are not present in the declaration due to their very low weight and thus very little contribution to the material use. Storage units, RAM module and CPU are not declared in any BoM for tablets/slates indicating that all the products

57 Based on five review studies from 2003 to 2014.
58 12.9-inch iPad Pro Environmental Report (2015). Available at: http://images.apple.com/environment/pdf/products/ipad/12.9-inch_iPad_Pro_PER_nov2015.pdf
59 9.7-inch iPad Pro Environmental Report (2016). Available at: http://images.apple.com/environment/pdf/products/ipad/9.7-inch_iPadPro_PER_mar2016.pdf
60 iPad Air 2 Environmental Report (2014). Available at: http://images.apple.com/environment/pdf/products/ipad/iPadAir2_PER_oct2014.pdf
61 iPad Air 2 Environmental Report (2014). Available at: http://images.apple.com/environment/pdf/products/ipad/iPadAir2_PER_oct2014.pdf
62 iPad mini 2 Environmental Report (2013). Available at: http://images.apple.com/environment/pdf/products/ipad/iPadmini2_PER_sept2015.pdf

assessed in the datasets have these components mounted/soldered on to the PCB. Generally, it is noticed that there is no major difference in most components between the average product and the BAT, which implies that the technologies in the EU market for this product category are generally very similar in terms of material use.

In spite of the weight variation, an average was established to define the representative from the market in terms of product configuration. Key components of tablet computers for recovery identified by JRC[30] are the same as for the notebooks. However, in the case of tablets/slates the recovery of anything else than the battery and the LCD panel may be impossible, if there is no manual dismantling prior shredding as described in the task 3.