European Commission

JRC TECHNICAL REPORTS

Development of European Ecolabel and Green Public Procurement Criteria for Personal Computers & Notebook Computers

TECHNICAL REPORT, TASK 3

Technical analysis

(Draft) Working Document

Nicholas Dodd, Oliver Wolf (JRC-IPTS)

Kathrin Graulich, Rita Groß, Ran Liu, Andreas Manhart, Siddharth Prakash (Öko-Institut e.V. – Institute for Applied Ecology)

September 2013

Joint Research Centre

European Commission

Joint Research Centre

Institute for Prospective Technological Studies (IPTS)

Contact information

Nicholas Dodd

Address: Joint Research Centre, Edificion EXPO, Calle Inca Garcilaso 3, E-41092 Sevilla, Spain

E-mail: nicholas.dodd@ec.europa.eu

Tel.: +34 954 488 486

http://ipts.jrc.ec.europa.eu/

This publication is a Technical Report by the Joint Research Centre of the European Commission.

Table of Contents

List of Tables

List of Figures

3. LIFE CYCLE ANALYSIS OF DESKTOP COMPUTERS & NOTEBOOK COMPUTERS

The main requirement of the EU Ecolabel is that criteria should be based on scientific evidence and should focus on the most significant environmental impacts during the whole life cycle of products. The purpose of this Task Report is to respond to this requirement by using the best available scientific evidence to identify the environmental "hot spots" in the life cycle of desktop and notebook computers.

3.1 Overview of LCA studies on desktop and notebook computers

In the first step, relevant Life Cycle Assessment (LCA) literature regarding the environmental assessment and improvement potential of desktop and notebook computers, including their product sub-categories according to the scope of this revision study, was identified and critically reviewed for the robustness of the results (methodology, data quality, age etc.). Their compliance with the ISO standards for life cycle assessment (ISO 14040 and 14044) was also a consideration.

This section presents an overview of existing LCA studies together with an initial screening categorising them according to the following quality criteria:

- Subject of the studies: The analysed products should have representative features of the product group, sub-categories, technologies or specifications.
- Time-related coverage of data: This refers to the year the inventory data of the analysis is based on; studies should ideally be less than 4 years old
- Comprehensiveness and robustness: which environmental impacts are considered in the study? Impact Categories should be comprehensive, ideally reflecting the European Commission's Product Environmental Footprint (PEF) methodology or recognised LCA methodologies, and scientifically robust when considered against the evaluation provided in the JRC's ILCD Handbook. Studies should also be cradle-to-grave.

- Reliability: Information on data quality provided by the study authors; studies should ideally be subject to an external critical review. Detailed information on data sources and data quality requirements are described in section 3.4.1.5.

The following table provides an overview of the screening results regarding LCA studies on desktop and notebook computers including product sub-categories according to the scope of this revision study.

Table 1: Overview of selected LCA studies on desktop and notebook computers

Product category	Source	Title	Subject of the study	Functional Unit	System boundary	Time related coverage	Study type	Impact assessment	Reliability		
									Data quality	External critical review?	Notes
Desktop PC	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	Desktop PC with CRT (23%) and LCD Display (77%), keyboard and mouse	The functional unit for the study was one unit desktop PC system[1] (Dell), mainly produced in the mainland China, Japan, and USA, used during 8 years, 6.8 h/day in Macau and end in the Macau Incineration Plant.	From cradle to grave, i.e. from the extraction of a desktop PC to the final dismantling and recycling or disposal activities at the end of life.	2010	Traditional LCA from cradle to grave	Eco-Indicator'99 CML: -ADP, GWP, AP, EP, ODP, PCOP, HTP, TETP, FAETP, MAETP	Not specified	The manuscript was reviewed by Dr. Duan Huabo (Tsinghua University)	Paper in peer reviewed Journal of LCA
Desktop PC	Stutz 2011	Product Carbon Footprint (PCF) Assessment of a Dell OptiPlex 780 Desktop – Results and Recommendations	Dell OptiPlex 780 Desktop	A desktop Mini Tower with a lifespan of 4 years	The life-cycle phases taken into account include: Manu-facturing incl. extraction up to the final assembly; Transport; Use; Recycling.	2010	PCF	GWP	Not specified	Not specified	Paper in peer reviewed LCM 2011 conference

[1] The desktop PC considered in this study consists of four different subunits: the desktop computer itself, the screen (CRT 17-inch or LCD-17 inch), the standard keyboard, and the mouse.

Product category	Source	Title	Subject of the study	Functional Unit	System boundary	Time related coverage	Study type	Impact assessment	Reliability		
									Data quality	External critical review?	Notes
Desktop PC	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	Average desktop in China consisting of desktop computer itself; 50% a CRT and 50% a LCD screen, the keyboard and the mouse.	A desktop PC system which consists of four different subunits: desktop computer itself, the screen (CRT and LCD); the keyboard and the mouse. The lifespan is 6 years.	The complete life cycle ranging from manufacture (including extraction up to the final assembly); distribution; use and End-of-life	2006/2007	LCA	Eco-Indicator'99 CML: -ADP, GWP, AP, EP, ODP, PCOP, HTP, TETP, FAETP, MAETP	Not specified	Not specified	Paper in peer reviewed Science of the Total Environment
Desktop PC	IVF 2007	EuP Lot 3 - Personal Computers (desktops and laptops) and Computer Monitors	Desktop PC	A desktop PC[2] used in an office and a desktop PC used at home. The lifespan is 6.6 years	Production; distribution; use; end-of-life	The BOM is for an average com-puter in 2005.	Based on the LCA approach (MEErP)	GER, GWP, ODP, AP, EP, VOC, POP, Heavy metals in air and in water, PAHs in air	Not specified	Open stakeholder consultation	Commissioned by the EU COM
Notebook PC	St-Laurent et al. 2012	Green Electronics? – An LCA based study of Eco-labeling of laptop computers	Laptop computers	The use of a laptop computer for one year.	Life cycle analysis	The laptop stems from the Ecoinvent dataset, but updated to more accurately represent modern laptops.	Comparative analysis	ReCiPe: -Climate change -Human toxicity -Particulate matter formation -Terrestrial ecotoxicity -Fresh water ecotoxicity	Not specified	Not specified	Paper in peer reviewed EGG 2012 Conference

[2] characterized by 3 GHz processor (or equivalent), built-in graphics card, 512 MB RAM and 80 GB HDD

Product category	Source	Title	Subject of the study	Functional Unit	System boundary	Time related coverage	Study type	Impact assessment	Reliability		
									Data quality	External critical review?	Notes
								-Marine ecotoxicity -Metal depletion -Fossil depletion			
Notebook PC	Prakash et al. 2011	Timely replacement of a notebook under consideration of environmental aspects	1) EuP Lot 3 2) Ecoinvent 2.2 3) a fictive notebook based on data from UBA R&D project (UFOPLAN 2009) + Eco-invent 2.2	The functional unit is defined as 1 notebook over its entire useful lifetime. The lifetime of all notebooks studied was taken to be 5 years.	The complete life cycle ranging from manufacture (including extraction up to the final assembly); distribution; use and End-of-life	Different databases are used	Traditional LCA from cradle to grave	GWP	Not specified	No external critical review	Commissioned by the German Federal Environmental Agency
Notebook PC	Ciroth & Franze 2011	LCA of an Ecolabelled Notebook Consideration of Social and Environmental Impacts Along the Entire Life Cycle	ASUS UL50Ag: 15.6’’display with LED backlight	One unit of an ASUSTeK UL50Ag notebook for office use. The lifespan is 4 years.	The complete life cycle ranging from manufacture (including extraction up to the final assembly); distribution; use and End-of-life	2008	Traditional LCA from cradle to grave	ReCiPe: -Climate change human health -Climate change ecosystems -Ozone depletion -Terrestrial acidification -Freshwater eutrophication -Marine eutrophication -Human toxicity -Photo-chemical oxidant formation	Data quality was shortly described. There are no absolute, but only relative results.	No external critical review	Commissioned by the Belgian Government

Product category	Source	Title	Subject of the study	Functional Unit	System boundary	Time related coverage	Study type	Impact assessment	Reliability		
									Data quality	External critical review?	Notes
								-Particulate matter formation -Fresh water ecotoxicity -Marine ecotoxicity -Ionising radiation -Agricultural land occupation -Urban land occupation -Natural land transformation -Metal depletion -Fossil depletion -Terrestrial ecotoxicity			
Notebook PC	IVF 2007	EuP Lot 3 - Personal Computers (desktops and laptops) and Computer Monitors	Laptop	A Laptop[3]. The lifespan is 5.6 years.	Production; distribution; use; end-of-life	The BOM is for an average com-puter in 2005.	Based on the LCA approach (MEErP)	GER, GWP, ODP, AP, EP, VOC, POP, Heavy metals in air and in water, PAHs in air	Not specified	Open stakeholder consultation	Commissioned by the EU COM
Notebook PC	Connell & Stutz 2009	Product Carbon Footprint (PCF) Assessment of a	Dell Latitude E6400	A Dell Latitude E6400. The lifespan is 4	Manufacturing; Logistics; Use; End-of-life	2009	PCF	GWP	Not specified	Not specified	Sustainable Systems and Technology

3 characterized by mobile 1.7 GHz processor (or equivalent), good 3-dimensional graphic performance, 15”-screen, 512 MB RAM and 60 GB HDD

Product category	Source	Title	Subject of the study	Functional Unit	System boundary	Time related coverage	Study type	Impact assessment	Reliability		
									Data quality	External critical review?	Notes
		Dell OptiPlex 780 Desktop – Results and Recommendations		years.							(ISSST), 2010 IEEE, ISBN 978-1-4244-7094-5
Thin client computing	Maga et al. 2012	Comparison of two ICT solutions: desktop PC versus thin client computing	Thin client model IGEL UD3	The functional unit is defined as the supply of a computer workstation with two or three applications simultaneously for a time period of 5 years with 220 working days per year using SBCTC or DPC, respectively.	The life cycle analysis includes the whole life cycle (material extraction and production, manufacturing, distribution, use, and end of life stage) for both ICT solutions, a desktop PC and server-based computing in combination with thin clients	2007	LCA	GWP and MIPS indicators: MIPS: -abiotic materials, -biotic materials, -water, -air, -earth movements in agriculture and forestry	Data quality was shortly described	Not specified	Paper in peer reviewed LCA Journal
Tablet according to EU Ecolabel	Apple 2012a	iPad Environmental Report	iPad (third generation) • Mercury-free LED-backlit display • Arsenic-free display glass • BFR-free • PVC-free • Recyclable aluminium enclosure • Power	A iPad. The lifespan is 3 years.	The life cycle: production; use; Transport; Recycling	2012	PCF	GWP	Not specified	It is mentioned at the Apple website that the data and life cycle model used in the tool are checked for quality and accuracy by the Fraunhofer Institute in	

Product category	Source	Title	Subject of the study	Functional Unit	System boundary	Time related coverage	Study type	Impact assessment	Reliability		
									Data quality	External critical review?	Notes
			adapter that outperforms strictest global energy-efficiency standards							Germany. However, there is no detailed information on which studies were reviewed.	
Tablet	Shuttle 2012	Environmental Product Declaration (EPD): Slate-Tablet PC V08CN01	Slate-Tablet PC V08CN01	One unit of tablet	The product lifecycle stage: raw materials acquisition, product manufacturing, distribution/ marketing, use and final disposal	2011	EPD based on Product category rules for preparing an EPD for Slate-Tablet PC,PCR 2011:1.0	GWP, ODP, POCP, AP, EP	quality was shortly described	Externally reviewed	
Computer Display	IVF 2007	EuP Lot 3 - Personal Computers (desktops and laptops) and Computer Monitors	17" LCD-Display 17" CRT-Display	For monitors two functional units are used, impact per product and impact per screen area. -LCD display, 17”, -CRT display, 17”.	Production; distribution; use; end-of-life	The BOM is for an average display in 2005.	Based on the LCA approach (MEErP)	GER, GWP, ODP, AP, EP, VOC, POP, Heavy metals in air and in water, PAHs in air	Not specified	Open stakeholder consultation	Commissioned by EU COM
Computer Display	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	CRT Display LCD Display	One 17-inch CRT screen and one 17-inch LCD screen	From cradle to grave, i.e. from the extraction of a desktop PC to the final dismantling and recycling or disposal activities at the end of life.	2010	Traditional LCA from cradle to grave	Eco-Indicator'99 CML: -ADP, GWP, AP, EP, ODP, PCOP, HTP, TETP, FAETP, MAETP	Not specified	The manuscript was reviewed by Dr. Duan Huabo (Tsinghua University)	Paper in peer reviewed Journal of LCA

Product category	Source	Title	Subject of the study	Functional Unit	System boundary	Time related coverage	Study type	Impact assessment	Reliability		
									Data quality	External critical review?	Notes
Computer Display	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	CRT Display LCD Display	No description on the size of screen	The complete life cycle ranging from manufacture (including extraction up to the final assembly); distribution; use, End-of-life	2006/2007	LCA	Eco-Indicator'99.	Not specified	Not specified	Paper in peer reviewed Science of the Total Environment
Small-scale server	Stutz et al. 2012	Carbon Footprint of a Dell Rack Server	Dell PowerEdge R710 2U Rack Server	A typical high-volume, next-generation Intel Xeon processor-based 2U Rack Server. The lifespan is 4 years (7 days a week and 24 hours a day)	Manufacturing; Transport; Use; Recycling	2011	PCF	GWP	Not specified	Not specified	Paper in peer reviewed EGG 2012 Conference
Workstation	Apple 2012b	Mac Pro Environmental Report	Model MD770, MD771 • Brominated flame retardant-free • PVC-free • Highly recyclable aluminium enclosure	A workstation with Model MD770, MD771. A lifespan is 4 years.	The life cycle: production; use; Transport; Recycling	2012	PCF	GWP	Not specified	Not specified	

Note: GER: total energy; ADP: abiotic resource depletion; GWP: global warming potential; ODP: stratospheric ozone depletion; PCOP: photochemical oxidation potential; AP: acidification potential; EP: eutrophication potential; HTTP: human toxicity potential; FAETP: fresh-water aquatic ecotoxicity potential; MAETP: marine aquatic ecotoxicity potential; TETP terrestrial ecotoxicity potential

3.2 Evaluation of the comprehensiveness of the LCA studies

The following Table 2 and Table 3 evaluate the studies identified in Table 1 for their comprehensiveness against the European Commission's PEF methodology (Table 2 [4]). The impact categories and methodologies used in the PEF form the basis for the evaluation, with an overall score derived for each study then allowing for a qualitative comparison of the comprehensiveness of each study.

[4] Table 2: Default EF impact categories (with respective EF impact category indicators) and EF impact assessment models for PEF studies

Table 2: Evaluation of comprehensiveness based on the PEF methodology: studies on desktop PCs and notebook PCs

The Product Environmental Footprint (PEF) (Table 2)				Desktop PC				Notebook PC				
EF Impact Category	**EF Impact Assessment Model**	**EF Impact Category indicators**	**Source**	**Song et al. 2013**	**Stutz 2011**	**Duan et al. 2009**	**IVF 2007**	**St-Laurent et al. 2012**	**Prakash et al. 2011**	**Ciroth & Franze 2011**	**IVF 2007**	**Connell & Stutz 2009**
Climate Change	Bern model - Global Warming Potentials (GWP) over a 100 year time horizon.	kg CO2 equivalent	Intergovern-mental Panel on Climate Change, 2007	+[5]	+[6]	- IPCC 2001	- IPCC 2001	+	+	+[7]	- IPCC 2001	+[8]
Ozone Depletion	EDIP model based on the ODPs of the World Meteorological Organization (WMO)	kg CFC-11 equivalent	WMO, 1999	+	0	+	- Based on the Regulation (EC) No 2037/2000[9]	0	0	- ODP is taken into account, but based on ReCiPe method.	- Based on the Regulation (EC) No 2037/2000[11]	0
Ecotoxicity for aquatic fresh water	USEtox model	CTUe (Comparative Toxic Unit	Rosenbaum et al., 2008	- FAETP is taken into	0	- FAETP is taken into	0	- FAETP is taken into	0	- FAETP is taken into	0	0

[5] Although a 100 year time horizon is not explicitly mentioned, we assume that GWP100 is investigated

[6] Although a 100 year time horizon and IPCC 2007 are not explicitly mentioned, we assume that it is compliant with PEF method.

[7] The midpoint in kg CO_{2e} was calculated and further calculated into "Human health damage" and "Ecosystem Damage". The ILCD handbook states that there is a fine consistency between midpoint and endpoint methods, since the endpoint default method builds directly on the recommended midpoint default method.

[8] Although a 100 year time horizon and IPCC 2007 are not explicitly mentioned, we assume that it is compliant with PEF method.

[9] REGULATION (EC) No 2037/2000 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 29 June 2000 on substances that deplete the ozone layer

The Product Environmental Footprint (PEF) (Table 2)				Desktop PC				Notebook PC				
EF Impact Category	**EF Impact Assessment Model**	**EF Impact Category indicators**	**Source**	**Song et al. 2013**	**Stutz 2011**	**Duan et al. 2009**	**IVF 2007**	**St-Laurent et al. 2012**	**Prakash et al. 2011**	**Ciroth & Franze 2011**	**IVF 2007**	**Connel l & Stutz 2009**
		for ecosystems)		considerati on, but the source is based on CML method.		consideration, but the source is based on CML method.		account, but based on ReCiPe method		account, but based on ReCiPe method		
Human Toxicity - cancer effects	USEtox model	CTUe (Comparativ e Toxic Unit for humans)	Rosenbaum et al., 2008	- HTP is taken into considerati on, but the source is based on CML method. (no difference between cancer and non-cancer effects)	0	- HTP is taken into consideration, but the source is based on CML method. (no difference between cancer and non-cancer effects.)	0	- HTP is taken into account, but based on ReCiPe method.	0	- HTP is taken into account, but based on ReCiPe method.	0	0
Human Toxicity – non-cancer effects	USEtox model	CTUe (Comparativ e Toxic Unit for humans)	Rosenbaum et al., 2008		0		0	0	0	0	0	0
Particulate Matter/ Respiratory Inorganics	RiskPoll model	kg PM2.5 equivalent	Humbert, 2009	0	0	0	0	- is taken into account, but based on ReCiPe method	0	- is taken into account, but based on ReCiPe method	0	0
Ionising Radiation – human health effects	Human Health effect model	kg U235 equivalent (to air)	Dreicer et al., 1995	0	0	0	0	0	0	- is taken into account, but based on ReCiPe method	0	0
Photochemical Ozone Formation	LOTOS-EUROS model	kg NMVOC equivalent	Van Zelm et al., 2008 as applied in ReCiPe	- POCP is taken into considerati on, but the	0	- POCP is taken into consideration, but the source	0	0	0	+	0	0

The Product Environmental Footprint (PEF) (Table 2)				Desktop PC				Notebook PC				
EF Impact Category	**EF Impact Assessment Model**	**EF Impact Category indicators**	**Source**	**Song et al. 2013**	**Stutz 2011**	**Duan et al. 2009**	**IVF 2007**	**St-Laurent et al. 2012**	**Prakash et al. 2011**	**Ciroth & Franze 2011**	**IVF 2007**	**Connell & Stutz 2009**
				source is based on CML method.		is based on CML method.						
Acidification	Accumulated Exceedance model	mol H+ eq	Seppälä et al.,2006; Posch et al., 2008	- AP is taken into consideration, but the source is based on CML method.	0	- AP is taken into consideration, but the source is based on CML method.	- AP is taken into account, based on European Community legislation and the Gothenburg Protocol	0	0	- AP is taken into consideration, but the source is based on ReCiPe method.	- AP is taken into account, based on European Community legislation and the Gothenburg Protocol	0
Eutrophication – terrestrial	Accumulated Exceedance model	mol N eq	Seppälä et al.,2006; Posch et al., 2009	- EP is taken into consideration, but the source is based on CML method (no difference between aquatic and terrestrial eutrophication)	0	- EP is taken into consideration, but the source is based on CML method (no difference between aquatic and terrestrial eutrophication)	0	0	0	0	0	0
Eutrophication – aquatic	EUTREND model	fresh water: kg P equivalent marine: kg N equivalent	Struijs et al., 2009 as implemented in ReCiPe		0		- EP is taken into account, but based on CML1992	0	0	- EP is taken into consideration, but the source is based on ReCiPe method.	- EP is taken into account, but based on CML1992	0
Resource Depletion – water	Swiss Ecoscarcity model	m3 water use related to local scarcity of water	Frischknecht et al., 2008	0	0	0	- Water used, not related to local scarcity	0	0	0	- Water used, not related to local scarcity	0
Resource Depletion –	CML2002	kg antimony (Sb)	van Oers et al.,	+	0	-	0	-	0	-	0	0

The Product Environmental Footprint (PEF) (Table 2)				Desktop PC				Notebook PC				
EF Impact Category	**EF Impact Assessment Model**	**EF Impact Category indicators**	**Source**	**Song et al. 2013**	**Stutz 2011**	**Duan et al. 2009**	**IVF 2007**	**St-Laurent et al. 2012**	**Prakash et al. 2011**	**Ciroth & Franze 2011**	**IVF 2007**	**Connel l & Stutz 2009**
mineral, fossil	model	equivalent	2002			Based on old version of CML model		Is taken into account, but based on ReCiPe Method.		Is taken into account, but based on ReCiPe Method.		
Land Transformation	Soil Organic Matter (SOM) model	Kg (deficit)	Milà i Canals et al., 2007	0	0	0	0	0	0	- Agricultural land occupation , Urban land occupation, Natural land transformation are taken into account, but based on ReCiPe method.	0	0
The number of environmental impacts categories that are investigated within the studies				10 (CML)	1	10 (CML)	10 (incl. emissions)	8	1	17	10 (incl. emissions)	1
The number of impact categories that are the same as PEF but don't use the same methodology				5	0	7	5	4	0	9	5	0
The number of impact categories compliant with the PEF methodology, i.e. use the same methodology				3	1	1	0	1	1	2	0	1

* CFC-11 = Trichlorofluoromethane, also called freon-11 or R-11, is a chlorofluorocarbon.

** PM2.5 = Particulate Matter with a diameter of 2.5 µm or less.

*** NMVOC = Non-Methane Volatile Organic Compounds

**** Sb = Antimony

+ = compliant with the requirements of the PEF methodology

- = not compliant with the requirements of the PEF methodology

0 = not taken into account

Table 3: Evaluation of comprehensiveness based on PEF methodology: studies on Thin Clients, Tablet PCs, Computer Displays, Small Scale Server and Workstations

The Product Environmental Footprint (PEF) (Table 2)				Thin client computing	Tablet	Computer Display			Small-scale server	Workstation
EF Impact Category	**EF Impact Assessment Model**	**EF Impact Category indicators**	**Source**	**Maga et al. 2012**	**Apple 2012a**	**IVF 2007**	**Song et al. 2013**	**Duan et al. 2009**	**Stutz et al. 2012**	**Apple 2012b**
Climate Change	Bern model - Global Warming Potentials (GWP) over a 100 year time horizon.	kg CO2 equivalent	Intergovernmental Panel on Climate Change, 2007	+	+[10]	- IPCC 2001	+[11]	- IPCC 2001	+ [10]	+[9]
Ozone Depletion	EDIP model based on the ODPs of the World Meteoro-logical Organi-zation (WMO)	kg CFC-11 equivalent	WMO, 1999	0	0	- Based on the Regulation (EC) No 2037/2000[11]	+	+	0	0
Ecotoxicity for aquatic fresh water	USEtox model	CTUe (Comparative Toxic Unit for ecosystems)	Rosenbaum et al., 2008	0	0	0	- FAETP is taken into consideration, but the source is based on CML method.	- FAETP is taken into consideration, but the source is based on CML method.	0	0
Human Toxicity - cancer effects	USEtox model	CTUe (Comparative Toxic Unit for humans)	Rosenbaum et al., 2008	0	0	0	- HTP is taken into consideration, but the source is based on CML method. (no difference between cancer	- HTP is taken into consideration, but the source is based on CML method. (no difference between cancer	0	0
Human Toxicity – non-cancer effects	USEtox model	CTUe (Comparative Toxic Unit for	Rosenbaum et al., 2008	0	0	0			0	0

[10] Although IPCC 2007 is not explicitly mentioned, we assume that it is compliant with PEF method.

[11] Although a 100 year time horizon is not explicitly mentioned, we assume that GWP100 is investigated

The Product Environmental Footprint (PEF) (Table 2)				Thin client computing	Tablet	Computer Display			Small-scale server	Workstation
EF Impact Category	**EF Impact Assessment Model**	**EF Impact Category indicators**	**Source**	**Maga et al. 2012**	**Apple 2012a**	**IVF 2007**	**Song et al. 2013**	**Duan et al. 2009**	**Stutz et al. 2012**	**Apple 2012b**
		humans)					and non-cancer effects.)	and non-cancer effects.)		
Particulate Matter/Respiratory Inorganics	RiskPoll model	kg PM2.5 equivalent	Humbert, 2009	0	0	0	0	0	0	0
Ionising Radiation – human health effects	Human Health effect model	kg U235 equivalent (to air)	Dreicer et al., 1995	0	0	0	0	0	0	0
Photochemical Ozone Formation	LOTOS-EUROS model	kg NMVOC equivalent	Van Zelm et al., 2008 as applied in ReCiPe	0	0	0	- POCP is taken into consideration, but the source is based on CML method.	- POCP is taken into consideration, but the source is based on CML method.	0	0
Acidification	Accumulated Exceedance model	mol H+ eq	Seppälä et al.,2006; Posch et al., 2008	0	0	- AP is taken into account, based on European Community legislation and the Gothenburg Protocol	- AP is taken into consideration, but the source is based on CML method.	- AP is taken into consideration, but the source is based on CML method.	0	0
Eutrophication – terrestrial	Accumulated Exceedance model	mol N eq	Seppälä et al.,2006; Posch et al., 2009	0	0	0	0 - EP is taken into consider-ation, but the source is based on CML method (no difference between aquatic and terrestrial eutrophication)	EP is taken into consideration, but the source is based on CML method (no difference between aquatic and terrestrial eutrophication)	0	0
Eutrophication – aquatic	EUTREND model	fresh water: kg P equivalent marine: kg N equivalent	Struijs et al., 2009 as implemented in ReCiPe	0	0	- EP is taken into account, but based on CML1992			0	0
Resource Depletion – water	Swiss Ecoscarcity model	m3 water use related to local scarcity of water	Frischknecht et al., 2008	0	0	- Water used, not related to local scarcity	0	0	0	0

The Product Environmental Footprint (PEF) (Table 2)				**Thin client computing**	**Tablet**	**Computer Display**			**Small-scale server**	**Workstation**
EF Impact Category	**EF Impact Assessment Model**	**EF Impact Category indicators**	**Source**	**Maga et al. 2012**	**Apple 2012a**	**IVF 2007**	**Song et al. 2013**	**Duan et al. 2009**	**Stutz et al. 2012**	**Apple 2012b**
Resource Depletion – mineral, fossil	CML2002 model	kg antimony (Sb) equivalent	van Oers et al., 2002	0	0	0	+	- Based on old version of CML model	0	0
Land Transformation	Soil Organic Matter (SOM) model	Kg (deficit)	Milà i Canals et al., 2007	0	0	0	0	0	0	0
The number of environmental impacts categories that are investigated within the studies				2 (GWP and MIPS method)	1	10 (including emissions)	(CML)	10 (CML)	1	1
The number of impact categories that are the same as PEF but don't use the same methodology				0	0	5	5	7	0	0
The number of impact categories compliant with the PEF methodology, i.e. use the same methodology				1	1	0	3	1	1	1

* CFC-11 = Trichlorofluoromethane, also called freon-11 or R-11, is a chlorofluorocarbon.

** PM2.5 = Particulate Matter with a diameter of 2.5 µm or less.

*** NMVOC = Non-Methane Volatile Organic Compounds

**** Sb = Antimony

+ = compliant with the requirements of the PEF methodology

- = not compliant with the requirements of the PEF methodology

0 = not taken into account

3.3 Selection of comprehensive LCA studies for further analysis

The existing LCA studies on computers (see Table 1) generally cover all relevant sub-categories, different technologies (CRT and LCD displays) as well as innovative market developments (tablet computers, thin clients). Several of the studies provide a broader range of impact categories. On the other hand, there are studies with focus on relevant specific aspects, e.g. Global Warming Potential, hazardous substances, which will also be taken into account.

To decide which of the studies in Table 1 were to be analysed in detail (see section 3.4), we assessed and compared them regarding their quality. The first precondition for a further detailed analysis – besides the fact that they should not be older than four years – was that the LCA studies had to provide at least 5 different impact categories to ensure a broad focus. Hence, certain Product Carbon Footprint (PCF) studies were excluded from the further detailed analysis.

Furthermore, the impact categories investigated in the LCA studies should, as far as possible, be prescribed by the PEF methodology (see Table 2). The LCA studies had to provide at 5 of the same impact categories as the PEF. A further consideration of the PEF methodology for each impact category allowed for further comparison of the studies shortlisted for analysis.

3.3.1 LCA studies selected for further detailed analysis

Against this background, the following studies passed the quality check and were further analysed. The findings are presented in the next section 3.4:

- Desktop PC / Computer Displays:
  - **Song et al. 2013**: Song et al. (2013) conducted a LCA study of desktop PCs in Macau (China). The assessment of the PC was based on the ISO 14040/44. Eco-indicator 99 (EI 99) and CML methods were used for the assessment of environmental impacts. The study reveals absolute values of environmental impacts differentiated by life cycle phases and the relative values of environmental impacts on the component level. For displays, the study conducted by Song et al. (2013) compares CRT and LCD display

technologies. The results are demonstrated based on the Eco-indicator 99 method and are differentiated by the life cycle phases (i.e. manufacturing, distribution, use and end-of-life). Furthermore, the environmental impacts in the manufacturing phases of the CRT and LCD screen are shown in percentages on the component level based on the CML method.

  - **Duan et al. 2009**: Complementarily, the study by Duan et al. (2009) provides absolute results associated with the manufacturing phase of a desktop PC based on EI 99 on the component level. Interestingly, the study provides additionally a comparison between computers used in China and computers used in other regions (e.g. Europe), which takes country/region-specific electricity production into account. This observation shows that the main contributors to the environmental impact can be influenced depending on where the computer is used.

- Notebook PC:
  - **St-Laurent et al. 2012**: A non-labelled generic laptop was compared with an EPEAT-labelled laptop and a TCO-labelled laptop concerning their environmental impacts. The results showed that there was no clear difference between the environmental impact of the labelled laptops and other laptops on the market. This is partly based on the fact that current laptops are already energy efficient and partly due to the short lifetime of laptops. Although this study does not reveal the hot spots at component level or the most relevant impacts, it is interesting to demonstrate the difference of the non-labelled and labelled laptops with regard to the environmental impacts.
  - **Ciroth & Franze 2011**: A study on social and environmental impacts of an ecolabelled laptop along the entire life cycle was conducted. As for the impacts of the environmental analysis, ReCiPe with comprehensive impact and resource consideration was used. Although the results are only reported in percentages, the conclusive findings reveal which components contribute mainly to which environmental impacts.

3.3.2 LCA studies chosen for supplementary evidence on environmental impacts

The following LCA studies were *excluded from a further detailed analysis* in section 3.4. Although they have a different focus and targets, some findings and conclusions regarding environmental hotspots in the life cycle of computers may still be considered relevant for the purpose of this study. Thus, *specific results* of these studies are briefly highlighted in section 3.5 based on their relevance to the development of ecolabel criteria for computers and their complementarity to the results of the detailed LCAs.

- *The DELL studies, which cover desktop PCs (Stutz 2011), notebook PCs (Connell & Stutz 2009) and small-scale server (Stutz et al. 2012)* focus on PCF and thus will not be investigated in depth. However, the GWP values resulting from these studies can be compared to the detailed LCA studies to show the variety of results.
- *The study on Thin Client Computing (Maga et al. 2012)* will be excluded from the further detailed analysis due to a limited number of impact categories. However, the results will be briefly discussed in section 1.5. To date, there are only a few LCA studies addressing thin clients due to their relatively new emergence on the market. Based on a literature review, we found a comparative analysis of two ICT solutions: Desktop PC versus thin client computing. As a thin client needs a terminal server, a thin client model in combination with a terminal server was analysed. A share of the impact of the terminal server is allocated to the thin client. The MEErP Tool was used to assess the environmental impacts (Note: the environmental impacts in the manufacturing phase under MEErP methodology might be underestimated (this will be described more detailed in the further analysis). The study calculates GWP values and additionally a material intensity based on the MIPS (material input per service unit) method.
- *The Apple datasheet on Tablet PCs (Apple 2012a)* will be excluded from the further detailed analysis due to a limited number of impact categories. However, the results will be briefly discussed in section 3.5.5. Tablet PCs are new

emerging products coming onto the market at a rapid increasing rate. Apple published its environmental report for iPad (third generation) in terms of GWP value. The absolute and relative GWP results are performed based on the life phases. Although there are only GWP values available, the main contributions of other environmental impacts associated mainly from the manufacturing phase can be estimated to be the same compared to a notebook computer. Moreover, the iPad possesses the following features related to ecodesign and hazardous substances which are interesting for the purpose of revising the ecolabel criteria:

– Mercury-free LED-backlit display
– Arsenic-free display glass
– BFR (Brominated Flame Retardants)-free
– PVC (Polyvinylchloride)-free
– Recyclable aluminium enclosure
– Power adapter that outperforms strictest global energy-efficiency standards

- *The Environmental Product Declaration (EPD) of a Tablet PC from the Shuttle Company* will be briefly discussed in section 3.5.5. The EPD was conducted based on a comprehensive lifecycle approach according to Product Category Rules (PCR's). The shuttle EPD provides only the aggregate values of a unit tablet of all life stages concerning global warming, ozone layer depletion, photochemical oxidation, acidification and eutrophication.
- *The Apple datasheet on workstations* will be excluded from the further detailed analysis due to a limited number of impact categories. However, the results will be briefly discussed in section 1.5. Workstation computers enable high intensity software to be run, which leads to a high need for comprehensive hardware configurations and intensive usage time. They are characterised by a large range of configurations, e.g. number of hard drives or processor types, which consequently results in different power consumption. Consequently, the absolute environmental impacts associated with a workstation throughout the

whole life cycle are likely to be larger compared to a desktop PC. LCA literature research on workstations only revealed an environmental report for “Mac Pro” by Apple, which provides an overview on the absolute and relative GWP values throughout the life cycle. Workstation computers

- *Teehan & Kandlikar (2012) assessed the quality of various LCA studies on desktop computers (excluding displays and peripherals)* based on a literature review. Their focus was on the GWP values and primary energy demand. They considered only the manufacturing and use phase, as distribution and end-of-life have relatively smaller impacts in terms of GWP and energy consumption and therefore were excluded. They also provided the GWP and energy values at the component level and uncertainties in light of the various literatures. The individual LCA literature sources cited by Teehan & Kandlikar (2012) have already been included in the screening review (see Table 1). The overall results of the study will be compared to the key findings of the detailed LCA evaluation in case there is additional valuable information concerning environmental hot spots.
- *Prakash et al. (2011) carried out a PCF study for a notebook computer* based on different secondary datasets. The study provides absolute GWP values and percentage proportions of life cycle phases. Furthermore, two scenarios referring to end-of-life management called “best practice” and “business-as-usual” were analysed. In the best-practice variant, precious metals such as Au, Ag and Pd are recovered with greater efficiency than in the business-as-usual scenario. The study is limited to the evaluation of GWP. Therefore, it will be excluded from the further detailed analysis. However, the GWP values resulting from these studies might be compared to the detailed LCA studies to show the variety of results.
- *Dell (Stutz et al. 2012) conducted a PCF study for a typical high volume, 2U rack server, in 2011*. The server was modelled as running 24 hours a day and 7 days a week. The use phase related to the cooling systems or back-up battery in the data centre was taken out of the scope of the study. The study showed

that the use phase dominates the whole life cycle, since the server operates all the time. As for the contributors in the manufacturing phase, there is no further breakdown on the component level available. However, it is likely that the percentage proportions of life cycle phases in terms of other environmental impacts have a similar trend to a desktop.

Finally, studies being older than 4 years will generally not be included in the further research. The ICT technology has been developing rapidly. Hence, the outdated studies are not considered to reflect current technology, e.g. a more than 10 year old LCA study on desktop computer displays by US EPA (Socolof et al. 2001), or James & Hopkinson (2009), whose analysis on environmental impacts is based on the EuP preparatory study Lot 3 (IVF 2007).

3.4 Detailed analysis of the selected LCA studies

3.4.1 Base parameters of the selected LCA studies

The corresponding products investigated in each of the different LCA studies are outlined in the following table.

Table 4: Description of objects investigated and their characterisations

Product	Studies	Title of the studies	Products investigated	Characterisation
Desktop	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	One unit desktop PC (Dell) system	Not specified
Desktop	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	A desktop PC system assembled in China	Desktop PC based on a Pentium IV processor.
Notebook	St. Laurent et al. 2012	Green Electronics? – An LCA based study of Eco-labeling of laptop computers	A HP omnibook	The laptop has a 12.1" LCD, a lithium-ion battery, an expansion base containing CD/DVD drive and a power adapter. The weight of the kit is 3.51kg. The laptop has one cold cathode fluorescent lamp (CCFL) backlight unit containing 0.558 mg of mercury.
Notebook	Ciroth & Franze 2011	LCA of an Ecolabeled Notebook Consideration of Social and Environmental Impacts Along the Entire Life Cycle	ASUS Tek UL50Ag for office use	The notebook has a 15.6''display with LED backlight. It weighs 2.3kg and contains an 8 cell lithium-ion battery which has a battery life up to 12 hours. Integrated is an Intel® CoreTM 2 Duo processor with 2*1.3 GHz, 4096 MB RAM, and 500 GB hard drive space. The computer provides 3 USB 2.0 ports, an optical DVD drive as well as a 5 in 1 card reader. Further, it provides W-LAN, Bluetooth, and a 0.3 mega pixel webcam.
Display	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	One unit desktop PC (Dell) system including CRT and LCD screen	17 inch CRT and 17 inch LCD
Display	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	A desktop PC system including CRT and LCD screen	Not specified

3.4.1.1 Goal and scope

The goal and scope of the selected studies are described in the Table 5. The definitions of goal and scope should be compliant with the goal and scope of Task 3 in our study. As described at the beginning of this chapter, "*The purpose of this Task Report is to respond to this requirement by using the best available scientific evidence to identify the environmental "hot spots" in the life cycle of desktop and notebook computers."*

The selected LCA studies have to be based on the ISO standards for life cycle assessment (ISO 14040 and 14044). A life cycle assessment analyses the environmental impacts of products from cradle to grave.

Table 5: Goal and Scope of the studies

Product	Studies	Title of the studies	Goal of the studies	Scope	Study Type
Desktop	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	To establish a scientific baseline that evaluates the key environmental impacts related to desktop PCs	A traditional LCA from cradle to grave	LCA
Desktop	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	To conduct a LCA study according to the ISO 14040 series.	A traditional LCA from cradle to grave	LCA
Notebook	St. Laurent et al. 2012	Green Electronics? – An LCA based study of Eco-labeling of laptop computers	To analyse the difference concerning environmental impacts between eco-labelled laptops and baseline laptop	A traditional LCA from cradle to grave	LCA (comparative analysis)
Notebook	Ciroth & Franze 2011	LCA of an Ecolabeled Notebook Consideration of Social and Environmental Impacts Along the Entire Life Cycle	To identify social and environmental hot spots in the life cycle of the considered notebook in order to improve and ensure respectively the sustainable performance over its entire life cycle.	A traditional LCA from cradle to grave	E-LCA and S-LCA
Display	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	To do an initial comparison of the two competing graphical interface technologies (CRT and LCD)	A traditional LCA from cradle to grave	LCA (comparative analysis)
Display	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	Although the focus is on the whole PC system, environmental life-cycle impacts of CRT and LCD desktop computer displays are also identified	A traditional LCA from cradle to grave	LCA (comparative analysis)

3.4.1.2 Functional units and system boundaries

According to ISO 14040/44, the functional unit refers to a quantified performance of a product system for use as a reference unit in LCA studies. The system boundary describes which processes are taken into account in the LCA analysis and which processes are not.

Table 6: Functional units and system boundaries

Product	Studies	Title of the studies	Functional Unit	System boundary
Desktop	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	One unit desktop PC system (Dell) that consists of four different subunits: the desktop computer itself, the screen (23% of CRT 17-inch and 77% of LCD-17 inch), the standard keyboard, and the mouse, mainly produced in the mainland China, Japan, and USA, used during 8 years, 6.8 h/day in Macau and end in the Macau incineration plant.	From cradle to grave, i.e. from the extraction of a desktop PC to the final dismantling and recycling or disposal activities at the end of life.
Desktop	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	A desktop PC system that consists of four subunits: the desktop computer itself, the screen (50% CRT and 50% LCD), the keyboard and the mouse. It is 4.2h per day active and 2.6h per day in either standby or sleep mode (assuming a 40% office and 60% home use of the PC system) during 6 years.	The complete life cycle, ranging from manufacture, distribution, use, up to the EoL treatment.
Notebook	St. Laurent et al. 2012	Green Electronics? – An LCA based study of Eco-labeling of laptop computers	The use of a laptop computer for one year	From cradle to grave
Notebook	Ciroth & Franze 2011	LCA of an Ecolabeled Notebook: Consideration of Social and Environmental Impacts Along the Entire Life Cycle	One recent, lightweight laptop of the Taiwanese company ASUSTeK that is certified according to the EU Ecolabel.	From cradle to grave, i.e. from the extraction of a desktop PC to the final dismantling and recycling or disposal activities at the end of life.
Display	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	One 17” CRT screen and one 17” LCD screen	From cradle to grave, i.e. from the extraction of a screen to the final dismantling and recycling or disposal activities at the end of life.
Display	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	One CRT screen and one LCD screen	From cradle to grave, i.e. from the extraction of a screen to the final dismantling and recycling or disposal activities at the end of life.

3.4.1.3 *Cut-off criteria*

According to the ISO 14040/44:2006 and the ILCD Handbook, cut-off criteria should be documented in an LCA study, the reasons should be stated and the effect of cut off decisions on results should be estimated.

Table 7: Cut-off criteria

Product	Studies	Title of the studies	Cut-off Criteria (inclusion of mass, energy and environmental cut-off criteria)	Estimation of the effect of cut-off
Desktop	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	Not specified	Not specified
Desktop	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	Not specified	Not specified
Notebook	St. Laurent et al. 2012	Green Electronics? – An LCA based study of Eco-labeling of laptop computers	Not specified	Not specified
Notebook	Ciroth & Franze 2011	LCA of an Ecolabeled Notebook; Consideration of Social & Environmental Impacts Along the Entire Life Cycle	Out of consideration are sundries as screws, speakers, webcam, and plugs also due to lack of data. Further, the informal recycling in China was not part of the E-LCA because of data gaps.	Not specified
Display	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	Not specified	Not specified
Display	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	Not specified	Not specified

3.4.1.4 *Allocation*

The results of our analysis show that none of the studies documented any allocation rules, at least in their published papers. However, it is difficult to judge whether no allocation has been conducted, or if it has not been documented.

Table 8: Allocation applied

Product	Studies	Title of the studies	Allocation parameter
Desktop	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	Not specified
Desktop	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	Not specified
Notebook	St. Laurent et al. 2012	Green Electronics? – An LCA based study of Eco-labeling of laptop computers	Not specified
Notebook	Ciroth & Franze 2011	LCA of an Ecolabeled Notebook; Consideration of Social and Environmental Impacts Along the Entire Life Cycle	Not specified
Display	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	Not specified
Display	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	Not specified

3.4.1.5 Data quality requirements and data sources

Data quality level and sources of primary and secondary data should be documented. The time-related, geographical and technological representativeness of the selected LCA studies are summarised in Table 9. Furthermore, the information on the data source including primary and secondary data is described in Table 10.

Table 9: Data quality requirements

Product	Studies	Title of the studies	Time-related representativeness	Geographical representativeness	Technological representativeness
Desktop	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	Primary data: 2010 Secondary data: Ecoinvent 2.2	Production phase: primarily mainland China, Hong Kong and the USA. Use phase: Macau	One of the most prevalent desktop PC in Macau was chosen, corresponding up-to-date technology
Desktop	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	Ecoinvent 1.3(2006)	Production phase: Assembly (China); Upstream processes (China/Global). Upstream processes: Global Use phase: Consumption pattern (China); Electricity consumption (Global); Electricity mixes (Europe Global)	Desktop generation with Pentium IV processor
Notebook	St. Laurent et al. 2012	Green Electronics? – An LCA based study of Eco-labeling of laptop computers	Secondary data: Ecoinvent 2007	Production phase: Dataset from Ecoinvent for the production of laptop is global Use phase: The average European electricity mix is applied	RoHS-compliant laptop and the Ecoinvent dataset was updated to more accurately represent modern laptops
Notebook	Ciroth & Franze 2011	LCA of an Ecolabeled Notebook Consideration of Social and Environmental Impacts Along the Entire Life Cycle	Primary data: 2008/2009 Secondary data: Ecoinvent 2.2	Production phase: Mainboard, HDD, fan, the power supply, keyboard, touchpad (China); battery, RAM (Korea); display (produced in Taiwan; assembled in China); drive (Philippines). Use phase: Belgium	The investigated computer is a recent laptop available in Europe, including Belgium, and is certified according to the EU ecolabel corresponding up-to-date technology
Display	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	Primary data: 2010 Secondary data: Ecoinvent 2.2	Production phase: Primarily mainland China, Hong Kong and the USA. Use phase: Macau	One of the most prevalent desktop PC in Macau was chosen, corresponding up-to-date technology
Display	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	Ecoinvent 1.3(2006)	Production phase: Assembly (China); Upstream processes (China/Global). Upstream processes: Global Use phase: Consumption pattern (China); electricity consumption (Global); electricity mixes (Europe Global)	Desktop generation with Pentium IV processor

Table 10: Data sources

Product	Studies	Title of the studies	Data sources of primary data	Data sources of secondary data
Desktop	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	Composition data is based on dismantling at EoL. Use pattern and end-of-life are based on field survey.	Ecoinvent 2.2 databases
Desktop	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	No primary data	Ecoinvent 1.3 databases; Empa-internal database (=pre-version of the Ecoinvent 2.0); Chinese statistics
Notebook	St. Laurent et al. 2012	Green Electronics? – An LCA based study of Eco-labeling of laptop computers	No primary data	Ecoinvent (2007); Energy Star 5.0
Notebook	Ciroth & Franze 2011	LCA of an Ecolabeled Notebook Consideration of Social and Environmental Impacts Along the Entire Life Cycle	Disassembly of the notebook and also from information about the location of the process	Ecoinvent 2.2 databases
Display	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	Composition data is based on dismantling at EoL. Use pattern and end-of-life are based on field survey.	Ecoinvent 2.2 databases
Display	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	No primary data	Ecoinvent 1.3 databases; Empa-internal database (=pre-version of the Ecoinvent 2.0); Chinese statistics

3.4.1.6 Impact categories and impact assessment methods

The environmental impacts considered and assessment methods applied are described in the following table.

Table 11: Impact categories and Impact assessment methods

Product	Studies	Title of the studies	Impact assessment methods	Impact categories
Desktop	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	CML and Eco-Indicator 99	<u>Eco-Indicator'99:</u> Resources; Ecosystem Quality; Human Health <u>CML:</u> ADP, GWP, AP, EP, ODP, PCOP, HTP, TETP, FAETP, MAETP
Desktop	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	CML and Eco-Indicator 99	<u>Eco-Indicator'99:</u> Resources; Ecosystem Quality; Human Health <u>CML:</u> ADP, GWP, AP, EP, ODP, PCOP, HTP, TETP, FAETP, MAETP

Product	Studies	Title of the studies	Impact assessment methods	Impact categories
Notebook	St. Laurent et al. 2012	Green Electronics? – An LCA based study of Eco-labeling of laptop computers	ReCiPe 2008	ReCiPe: -Climate change -Human toxicity -Particulate matter formation -Terrestrial ecotoxicity -Fresh water ecotoxicity -Marine ecotoxicity -Metal depletion -Fossil depletion
Notebook	Ciroth & Franze 2011	LCA of an Ecolabeled Notebook Consideration of Social and Environmental Impacts Along the Entire Life Cycle	ReCiPe (hierarchist) and Eco-Indicator 99	Eco-Indicator'99: Resources; Ecosystem Quality; Human Health ReCiPe: -Climate change human health -Climate change ecosystems -Ozone depletion -Terrestrial acidification -Freshwater eutrophication -Marine eutrophication -Human toxicity -Photochemical oxidant formation -Particulate matter formation -Fresh water ecotoxicity -Marine ecotoxicity -Ionising radiation -Agricultural land occupation -Urban land occupation -Natural land transformation -Metal depletion -Fossil depletion -Terrestrial ecotoxicity
Display	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	CML and Eco-Indicator 99	Eco-Indicator'99: Resources; Ecosystem Quality; Human Health CML: ADP, GWP, AP, EP, ODP, PCOP, HTP, TETP, FAETP, MAETP
Display	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	CML and Eco-Indicator 99	Eco-Indicator'99: Resources; Ecosystem Quality; Human Health CML: ADP, GWP, AP, EP, ODP, PCOP, HTP, TETP, FAETP, MAETP

3.4.1.7 Assumptions

Whilst modelling, a series of assumptions have to be made. Documentation of these assumptions is crucial to ensure the transparency and reproducibility of the results to some extent. The important assumptions are therefore summarised in the following table.

Table 12: Assumptions made while modelling

Product	Studies	Title of the studies	Production	Distribution	Use	End-of-life
Desktop	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	-	Only the ocean freight and the transportation in Macau considered	8 years used in Macau; 6.8h/day (4.2h active; 2.6h stand-by) 150 W active, 20W stand-by	-
Desktop	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	-	Standard distances and means used	-40% office use; 60% home use -UCTE-mix as European mix used -China-Mix for other Asian countries used	Worst case recycling: 100% of hazardous substances from PC & LCD screen to air; hazardous substances from CRT screen to air, solid and water (each 33%) Best case recycling: metal recycled and plastic 100% incinerated
Notebook	St. Laurent et al. 2012	Green Electronics? – An LCA based study of Eco-labeling of laptop computers	All PWBs were lead-free (RoHS legislation). The PWBs were assumed to contain 45g of bromine per kg of glass fibre board. For ecolabelled product: The only change was that PVC was replaced by HIPS in the power adapter.	Not specified	Operational modes: Off (43.5%); Sleep (33.5%); Idle (19%); Load (4%). Electricity based on the average European (UCTE) production mix is applied. Energy Star is applied for the ecolabelled product. No change was modelled regarding electricity use since the average power consumption of modern laptops is already lower than the Energy Star.	For generic laptop: 10% are recycled. For ecolabelled product: 20% of laptops recycled
Notebook	Ciroth & Franze 2011	LCA of an Ecolabeled Notebook Consideration of Social and Environmental Impacts Along the Entire Life Cycle	All components are compliant with the RoHS Directive and do not contain solder with lead. The composition of the notebook case is 50% Polycarbonate and 50% Acrylnitril-Butadien-Styrol (ABS) The notebook needs 2 batteries during the entire use phase	Not specified	4 years use The office use phase: 2200h active use, 800h standby, 6600h off. The reuse phase with further 2 years in a private household: 2550h active, 1020h standby, 1530h off	After the use phase, 20% of the collected laptops are transported for reuse to China for 2 years, the remaining 80% are recycled in Belgium
Display	Song et al. 2013	Life cycle assessment of desktop PCs in Macau	-	Only the ocean freight and the transportation in Macau considered	8 years; 6.8h/day (4.2h active; 2.6h stand-by) CRT: 80W active, 5W stand-by LCD:35W active, 2W stand-by	-

Product	Studies	Title of the studies	Production	Distribution	Use	End-of-life
Display	Duan et al. 2009	Life cycle assessment study of a Chinese desktop personal computer	-	Standard distances and means used	40% office use; 60% home use UCTE-mix as European mix used China-Mix for other Asian countries used	Worst case recycling: 100% of hazardous substances from PC & LCD screen to air; hazardous substances from CRT screen to air, solid and water (each 33%) Best case recycling: metal recycled and plastic 100% incinerated

3.4.2 Quality of assessment of the methods applied in the selected LCA studies

To provide an overall picture of the scientific robustness of the indicator sets used in the selected LCA studies, this chapter evaluates the assessment methods applied in the selected LCA studies based on the ILCD handbook (ILCD 2011).

The ILCD handbook on recommendations for life cycle impact assessment in the European context evaluates different impact methods and provides the following six criteria:

- Scientific criteria
  - Completeness of scope
  - Environmental relevance
  - Scientific robustness & Certainty
  - Documentation & Transparency & Reproducibility
  - Applicability
- Stakeholder acceptance criterion
  - Degree of stakeholder acceptance and suitability for communication in a business and policy contexts

The first five science based criteria are applied as a basis for the evaluation of the impacts methods. The rating used is based on the ILCD handbook (2011) as listed below:

- A: Full compliance
- B: Compliance in all essential aspects
- C: Compliance in some aspects
- D: Little compliance
- E: No compliance

To facilitate the calculation of scores, we assume that A=5; B=4; C=3; D=2; E=1.If there is B/C as the evaluation result, the average data (in this case: 3.5) is used.

Table 13: Evaluation of the scientific robustness of the impact methods used

	Product	**Desktop / Display**		**Notebook**	
	Studies	**(Song et al. 2013): Life cycle assessment of desktop PCs in Macau** **(Duan et al. 2009): Life cycle assessment of a Chinese desktop personal computer**		**(St-Laurent et al. 2012): Green Electronics? – An LCA based study of Eco-labelling of laptop computers**	**(Ciroth & Franze 2011): LCA of an Ecolabelled Notebook** **Consideration of Social and Environmental Impacts Along the Entire Life Cycle**
Score based on the Tables in ILCD hand-book 2011	**Impact methods**	**CML**	**Ecoindicator 99**	**ReCiPe**	**ReCiPe**
Based on Table 3	Climate change	24	18	23	23
Based on Table 5	Ozone depletion	24	19	Not applicable	21
Based on Table 7	Human toxicity	22	Not evaluated in the ILCD handbook	21	21
Table 11	Particulate matter/respiratory inorganics	Not evaluated in the ILCD handbook	Not evaluated in the ILCD handbook	Not evaluated in the ILCD handbook	Not evaluated in the ILCD handbook
Table 13	Ionizing radiation	Not evaluated in the ILCD handbook	Not evaluated in the ILCD handbook	Not evaluated in the ILCD handbook	Not evaluated in the ILCD handbook
Table	Photochemical ozone	18.5	Not evaluated in	Not applicable	19.5

	Product	Desktop / Display		Notebook	
	Studies	**(Song et al. 2013): Life cycle assessment of desktop PCs in Macau** **(Duan et al. 2009): Life cycle assessment of a Chinese desktop personal computer**		**(St-Laurent et al. 2012): Green Electronics? – An LCA based study of Eco-labelling of laptop computers**	**(Ciroth & Franze 2011): LCA of an Ecolabelled Notebook Consideration of Social and Environmental Impacts Along the Entire Life Cycle**
14 and Table 15	formation		the ILCD handbook		
Table 16 and Table 17	Acidification	20.5	17	Not applicable	20
Table 18	Aquatic eutrophication	16.5	Not evaluated in the ILCD handbook	Not applicable	21.5
Table 19	Terrestrial eutrophication	16.5	19	Not applicable	Not evaluated in the ILCD handbook
Table 21	Ecotoxicity	Not evaluated in the ILCD handbook	Not evaluated in the ILCD handbook	22.5	22.5
Table 24	Land use	Not evaluated in the ILCD handbook	not applicable[12]	not applicable	2
Table 27	resources	21	18	20	20
Total score		**163**	**91**	**86.5**	**170.5**
Possible maximum score = maximum score of scientific criteria (25) x number of categories covered in the corresponding methods		**=25x8=200**	**=25x5=125**	**=25x4=100**	**=25x9=225**
Share $= \frac{\text{total score}}{\text{possible maximum score}}$		**81.5%**	**72.8%**	**86.5%**	**75.8%**

[12] "Not applicable" refers to the impact category under the corresponding method is evaluated in the ILCD handbook, but the impact category is not considered in the studies.

3.4.3 Results of the selected LCA studies

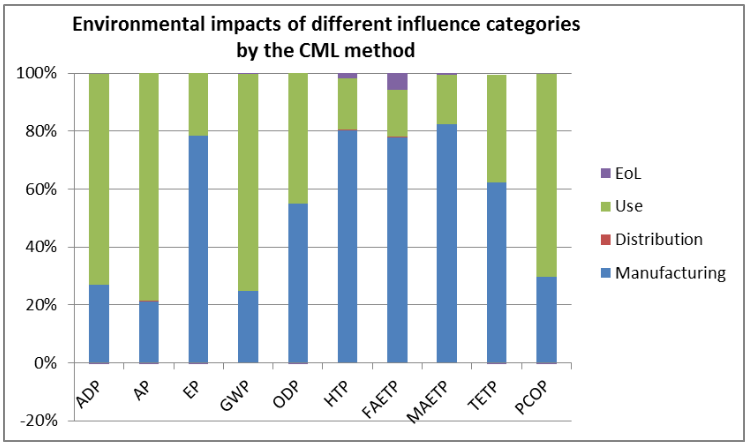
3.4.3.1 Desktop computers

<u>*Results from the study by Song et al. 2013 and Duan et al. 2009*</u>

The following tables summarise the results from the contribution analysis and differentiates the impacts by life phase and at a component level.

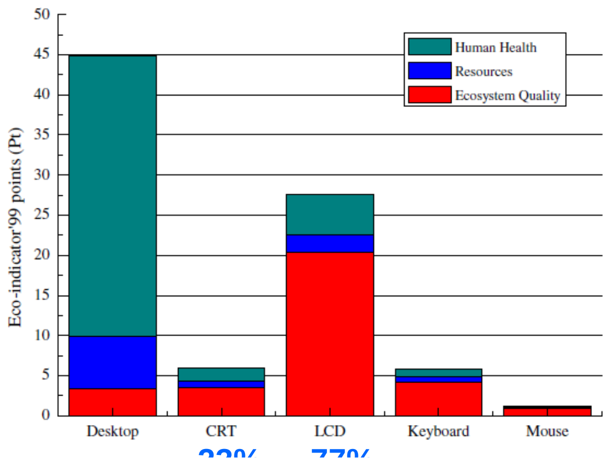
Both studies concluded that manufacturing and use have a clearly higher environmental impact overall compared to the distribution and EoL. The environmental hot spots have also been identified by both studies (Table 14). There is a slight deviation between the conclusions on the hot spots. Song et al. 2013 identified that with the regard to freshwater aquatic ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity, the manufacturing phase has larger impacts than the use phase, while Duan et al. 2009 drew a converse conclusion.

Table 14: Comparison of environmental impacts differentiated by life cycle phases

Sources	Life cycle phases	Environmental impacts of the life cycle phases
Life cycle assessment of desktop PCs in Macau (Song et al. 2013)	Manufacturing and use have a clearly higher environmental impact compared to the distribution and EoL.	 Environmental impacts dominating in the manufacturing phase: • Eutrophication • Ozone layer depletion • Human toxicity • Freshwater aquatic ecotoxicity • Marine aquatic ecotoxicity • Terrestrial ecotoxicity Environmental impacts dominating in the use phase:

		• Abiotic resources • Global warming • Acidification • Photochemical oxidation
Life cycle assessment of a Chinese desktop personal computer (Duan et al. 2009)	Manufacturing and use have a clearly higher environmental impact compared to the distribution and EoL.	Environmental impacts dominating in the manufacturing phase: • Eutrophication • Ozone layer depletion • Human toxicity Environmental impacts dominating in the use phase: • Abiotic resources • Global warming • Acidification • Photochemical oxidation • Terrestrial ecotoxicity • Marine aquatic ecotoxicity (slightly more than in production phase) Environmental impacts dominating in the EoL phase: • Freshwater aquatic ecotoxicity

Table 15: Comparison of environmental impacts of the manufacturing phase of the PC system

Sources	Production	Environmental impacts of the manufacturing phase
Life cycle assessment of desktop PCs in Macau (Song et al. 2013)	The desktop unit of the PC has the greatest contribution to environmental impacts. Compared to the results by Duan et al. 2009, the Eco-Indicator points show a difference of factor 2. Moreover, the human health dominates the impacts of the desktop production. As for LCD screen, the ecosystem quality is of main importance.	 Fig. 4 Environmental impacts of the manufacturing phase

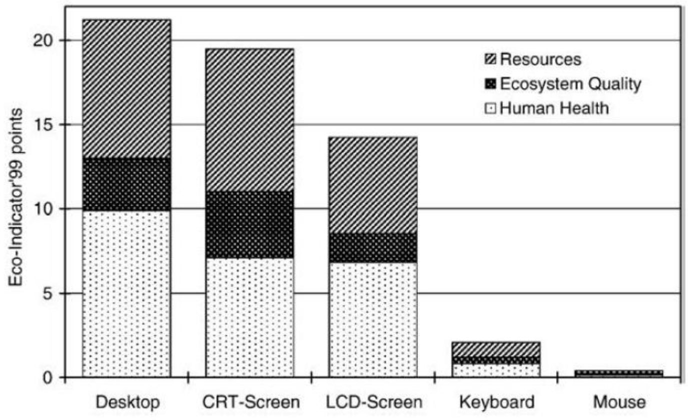
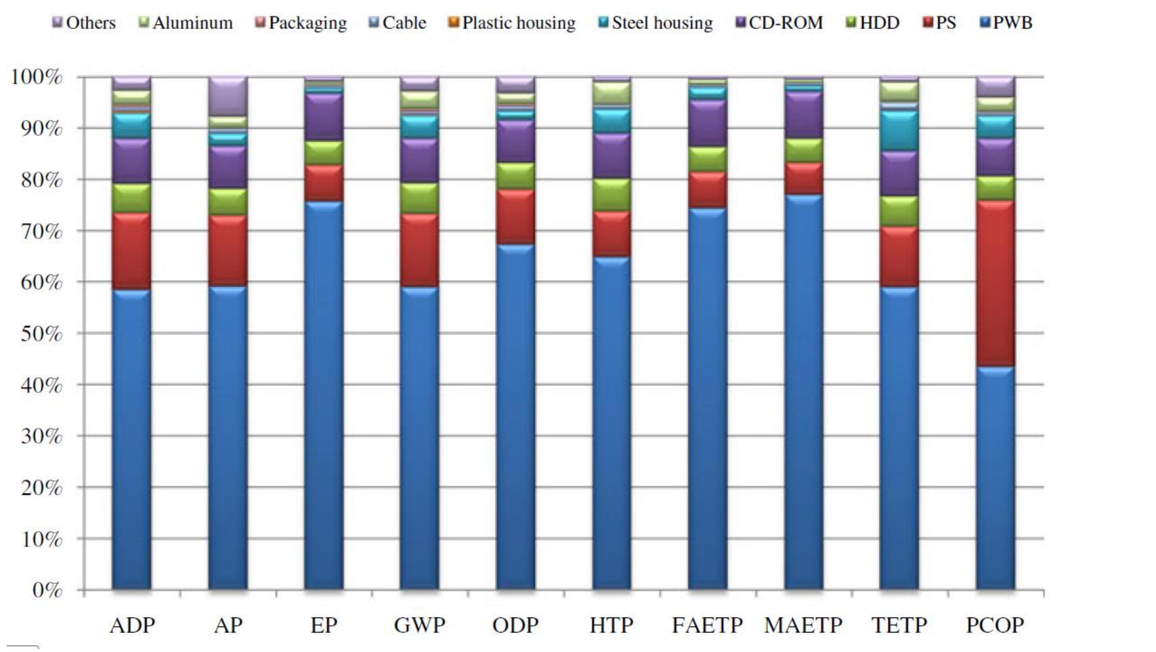
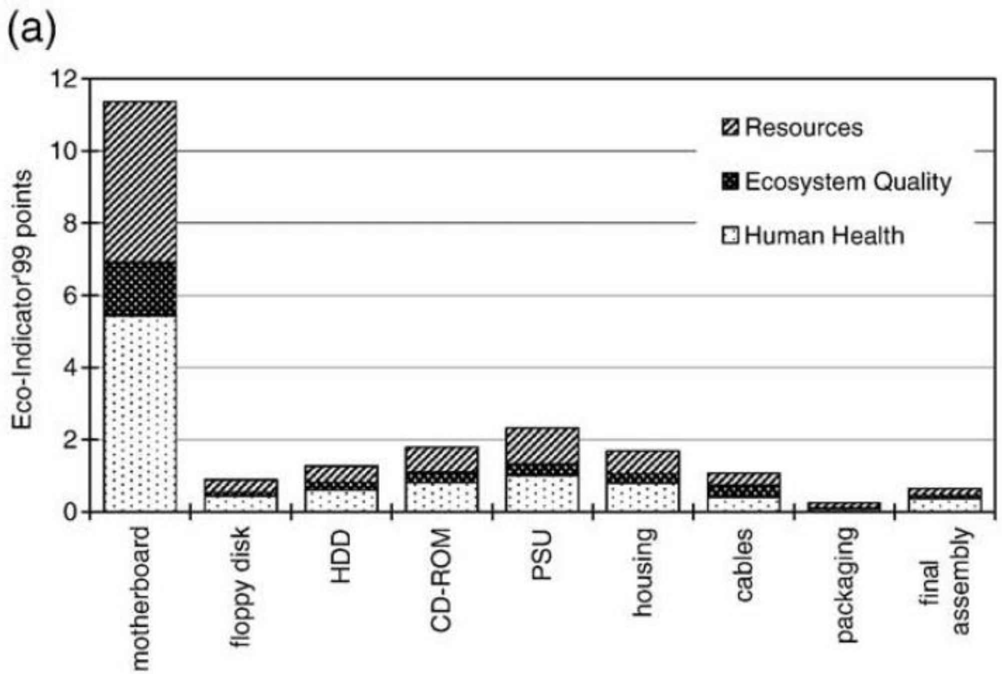
Life cycle assessment of a Chinese desktop personal computer (Duan et al. 2009)	The desktop unit of the PC has the greatest contribution to environmental impacts, followed by the screens, while keyboard and mouse are of minor importance. Environmental impacts, such as resources and human health play a more important role than ecosystem quality.	 **Fig. 6 – Environmental impacts caused by the production of the various parts of the here examined PC system, expressed with the method of Eco-Indicator'99.**

Table 16: Desktop computer: Comparison of environmental impacts of the manufacturing phase at component level

Sources	Production	Environmental impacts of the manufacturing phase
Life cycle assessment of desktop PCs in Macau (Song et al. 2013)	The environmental impacts of a desktop PC are clearly dominated by the PWB, which has an impact ranging from 44% (PCOP) up to 77% (MAETP) of the manufacturing phase. The second contributor was the power supply (PS) with an impact between 6% (MAETP) and 32% (PCOP). These are followed by the CD-ROM, the HDD and aluminium components.	

Sources	Production	Environmental impacts of the manufacturing phase
Life cycle assessment of a Chinese desktop personal computer (Duan et al. 2009)	It can be seen that the environmental impacts of a desktop PC are clearly dominated by the motherboard accounting for 54% of the impacts of the complete desktop PC, or about 11.5 EIP. The actual weight of a motherboard accounts only for 8.1%. This is followed by the PSU (Power Supply Unit), CD-ROM, housing and HDD.	

Furthermore, three scenarios on the sensitivity to End of Life (EoL) treatment regarding best case, worst case and landfill were conducted by Duan et al. 2009. The results show that taking care of toxic substances during recycling processes allows an overall benefit for the EoL treatment.

In summary, the findings were as follows:

- Manufacturing and use have a clearly higher environmental impact compared to the distribution and EoL. The environmental impact in the manufacturing phase can be reduced, if EoL treatment is in a sound management, since the secondary resources from recycling can avoid primary production. The impact of the use phase is caused by the energy consumption of the PC system. Electricity mix, use pattern and power consumption of PC determine the impact calculation.
- Within the PC system analysed, the desktop unit of the PC has the greatest contribution to environmental impacts, followed by the screens, while the keyboard and mouse are of minor importance. Furthermore, the environmental hotspots are human health and resources.
- At component level, the production of the motherboard has the largest impact regarding all environmental impacts investigated, followed by the power supply, CD-ROM and HDD.
- Within the EoL, sound management of toxic substances during the recycling process results in ca.75% reduction of impacts.

Although both analysed desktop studies examined computers in China, the results are representative for Europe as well. Duan et al. 2009 analysed the use phase in China, Europe, America, Asia and world average compared to the manufacturing phase, see Figure 1.

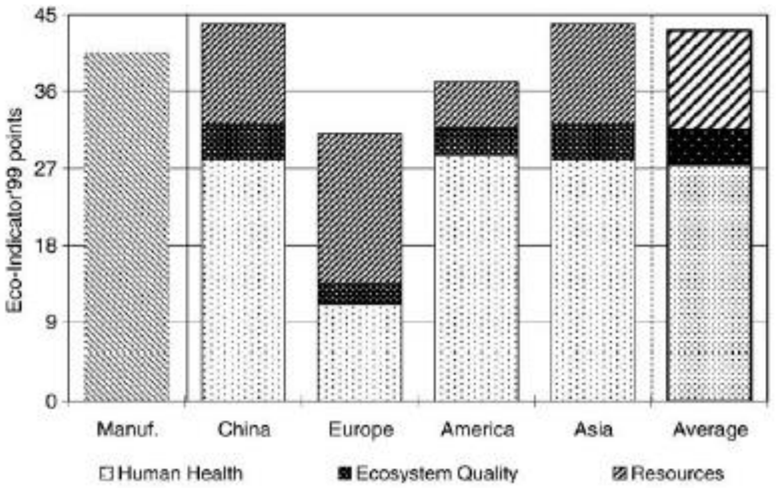


Figure 1: Split of the environmental impacts of the use phase into the amounts from the different markets plus the resulting average (according to the respective market shares) (Source: Duan et al. 2009)

If e.g. European electricity mix instead of Chinese electricity mix is used for the calculation, the dominating life stage is switched from the use phase into manufacturing. This shows that the electricity mix, consumption pattern and power consumption in the use phase determine the share of the life stages. As for the end-of-life phase (EoL), three scenarios for EoL – EU, China and USA were analysed: Recycling best case; Recycling worst case and landfilling worst case. These scenarios, however, do not change the summary of the study: Within the EoL, sound management of toxic substances during the recycling process results in approximately a 75% reduction of impacts.

3.4.3.2 Computer displays

A comparison between a 17-inch CRT screen and a 17-inch LCD screen was made by Song et al. 2013 (Figure 2). For the entire life cycle of CRT and LCD screens, the impact points based on EcoIndicator99 are similar, 44.32 Points and 44.92 Points respectively. The CRT technology shows rather similar impact points in the manufacturing and use phase due to its higher weight and power requirement.

In contrast, the LCD technology dominates the impacts in the manufacturing phase. Within the manufacturing phase, LCD technology has higher impacts than CRT, while within the use phase, CRT technology shows higher impacts.

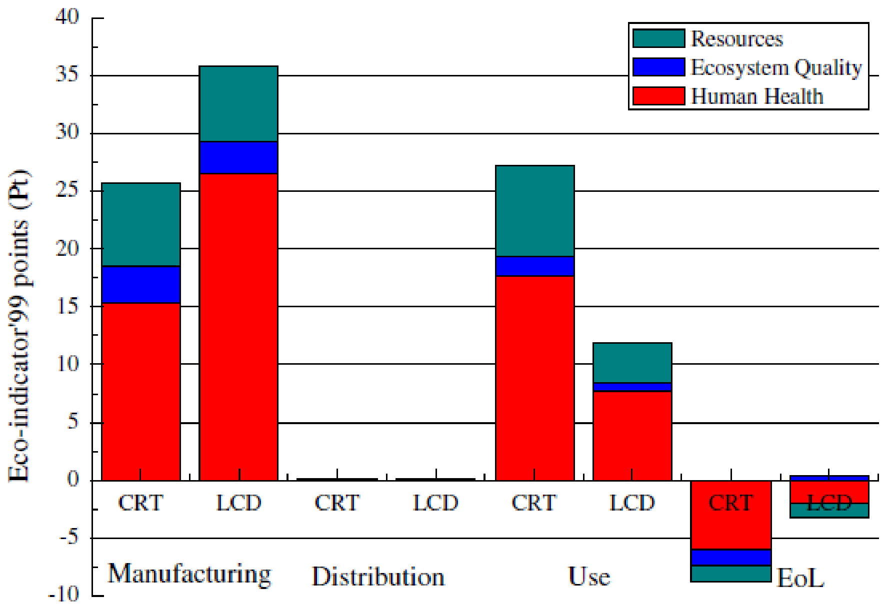
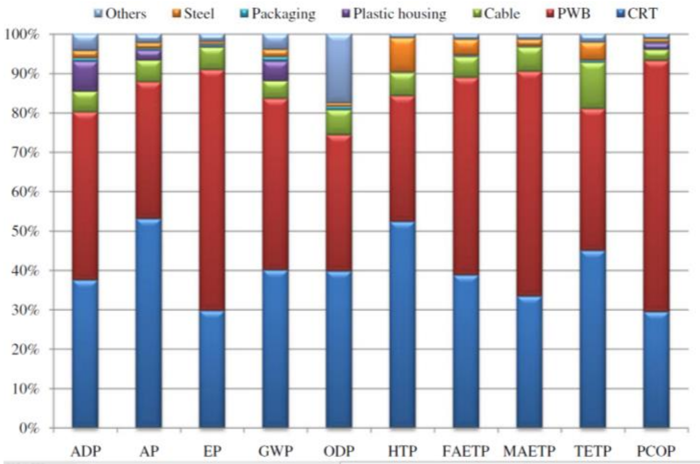
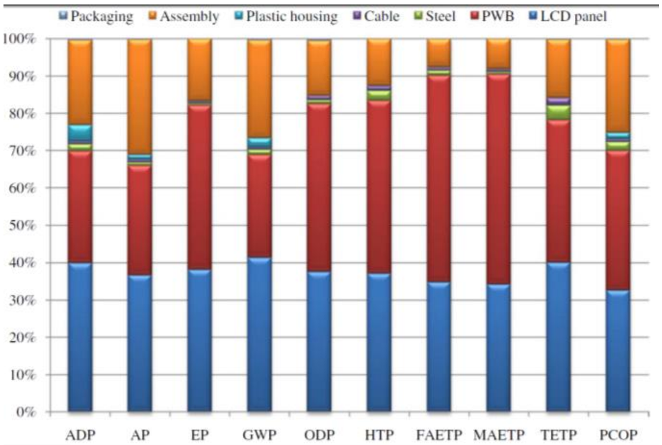
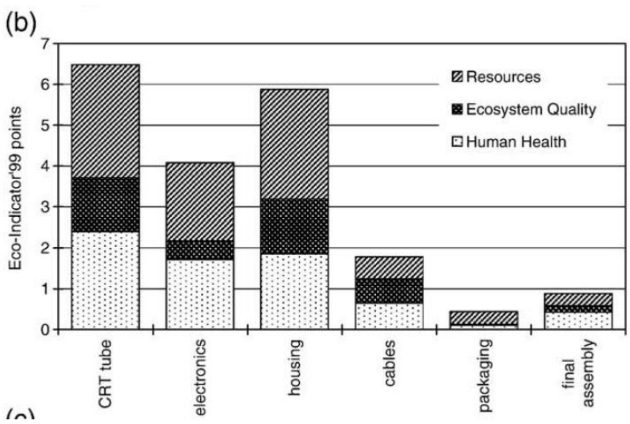
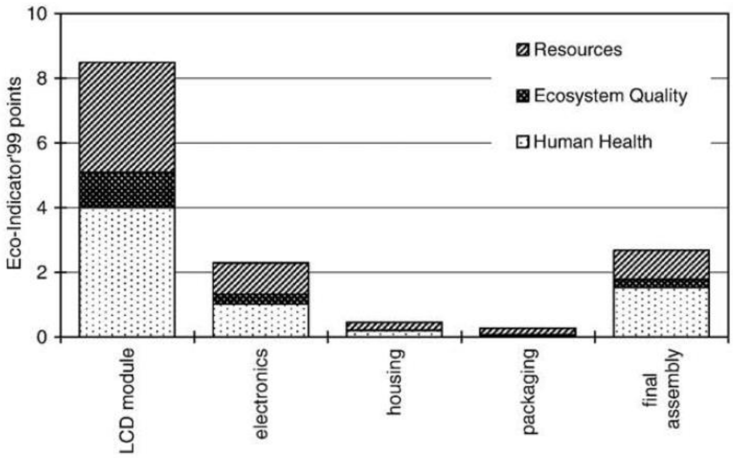


Figure 2: Comparison between CRT and LCD technologies (taken from Song et al. 2013 Fig. 13)

Table 17: Displays: Comparison of environmental impacts of the manufacturing phase at component level

<table>
<tr><th>Title of the studies</th><th>Display type</th><th>Environmental impacts at component level</th></tr>
<tr><td rowspan="2">Life cycle assessment of desktop PCs in Macau (Song et al. 2013)</td><td><u>CRT:</u>
The cathode ray tube and the Printed Wiring Board (PWB) together are responsible for more than 80% of the manufacturing phase.
The glass in the CRT is responsible for the major part.</td><td>
</td></tr>
<tr><td><u>LCD:</u>
The PWB has the greatest contribution to the environmental impact between 27% (GWP) and 56% (MAETP), followed by the LCD panel and the assembly process.</td><td>
</td></tr>
<tr><td>Life cycle assessment of a Chinese desktop personal computer (Duan et al. 2009)</td><td><u>CRT:</u>
CRT tube and housing are the dominating impacts in the manufacturing phase, followed by electronics. These three components together are responsible for more than 80% of the environmental impact.</td><td>
</td></tr>
</table>

Title of the studies	Display type	Environmental impacts at component level
	LCD: The LCD module dominates the manufacturing phase, accounting for about 60% of the total impacts, while the assembly process and electronic components account for about 16%.	

In summary, the findings were as follows:

- Within the manufacturing phase, LCD technology has a higher impact than CRT, while within the use phase, CRT is dominating the impacts.
- Within the manufacturing of the LCD screen, all investigated environmental impacts are dominated by the LCD panel and PWB, followed by assembly.
- Within the manufacturing of the CRT screen, the CRT tube is the dominating component based on Duan et al 2009, while Song et al. 2013 concluded that both the PWB and CRT tube have a higher environmental impact.

3.4.3.3 Notebook computers

<u>*Results from the study by Ciroth & Franze 2011*</u>

The results from Ciroth & Franze 2011 are only presented in percentages. The following figures are taken directly from their study. The results show that the production of the notebook dominates the environmental impacts throughout all 17 impact categories. The use phase including the reuse phase is the second contributor to the overall environmental burden. This is based on the fact that the notebook investigated is a high energy efficiency computer. Besides that, the relative short use time and the place, where the computer is used due to the electricity mix, have also an influence on the shares between the life cycle phases concerning environmental impacts.

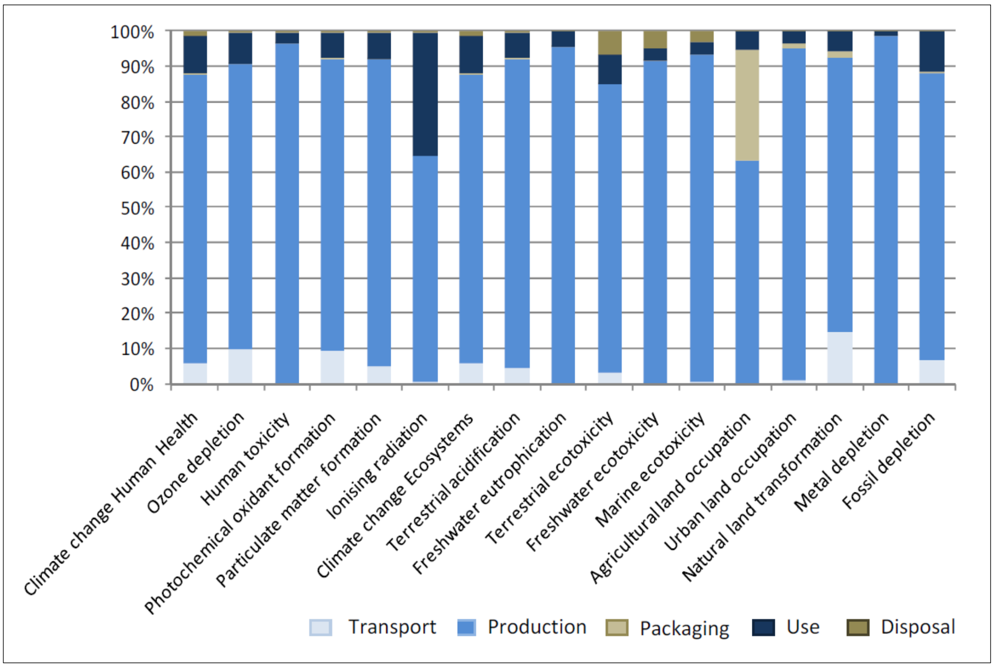


Figure 3: Environmental impacts along the life cycle phase of a notebook based on ReCiPe method (taken from Ciroth & Franze 2011, Figure 15)

Furthermore, the environmental hot spots through normalisation based on “World ReCiPe H/H” revealed that the most relevant impact categories are climate change (human health and ecosystems), human toxicity, particulate matter formation, and fossil depletion (see Figure 4).

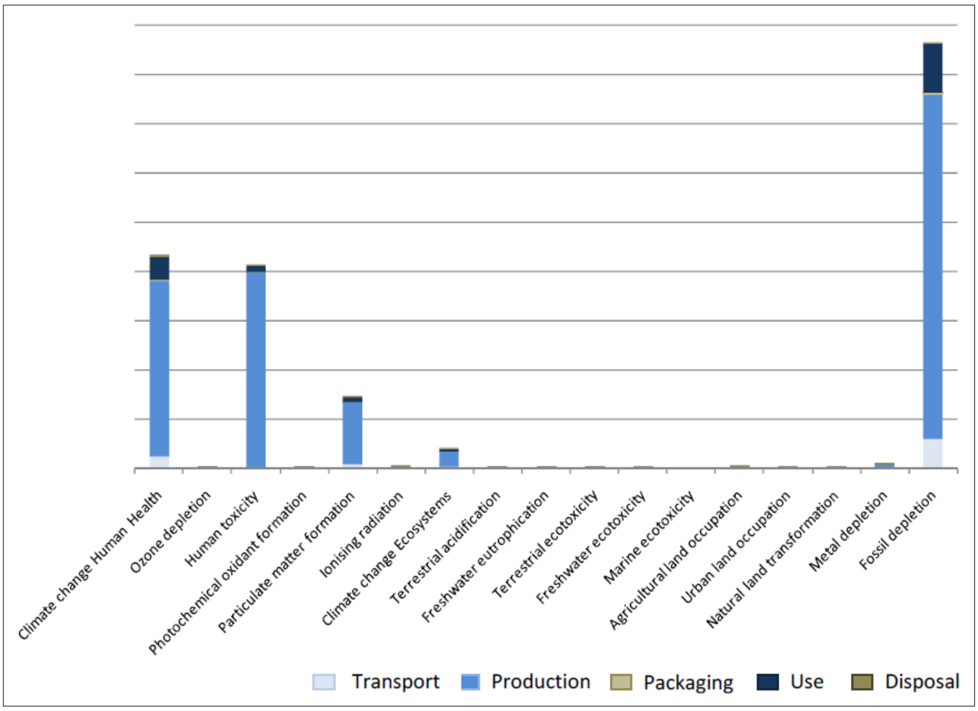


Figure 4: Normalised environmental impacts along the life cycle phase of a notebook based on ReCiPe method (taken from Ciroth & Franze 2011, Figure 16)

Within the production phase, the authors also revealed which components contribute most to which environmental impacts. This is summarised in the following table. The symbol "√" means that the components are identified as a major contributor to the impacts. Moreover, the information in the parentheses describes the proportion of the impacts. For instance, 52% of human toxicity is caused by the motherboard production. The symbol "x" means that the components are not identified as major contributors in Ciroth & Franze's study.

Table 18: Major contributors in the production phase

Environmental impacts	**Major contributors**		
	LCD display production	**Mainboard production**	**Battery production**
Climate change human health	√ (45%)	√ (23%)	x
Climate change ecosystem	√ (45%)	√ (23%)	x
Human Toxicity	√ (27%)	√ (52%)	√ (6%)
Particulate matter formation	√ (43%)	√ (27%)	x
Fossil Depletion	√ (45%)	√ (22%)	√ (3%)
Metal Depletion	√ (36%)	√ (37%)	√ (16%)

In summary, the main findings were:

- On the level of overall life cycle phases, production of a notebook PC has a large environmental impact.
- On the component level, the production of the display and motherboard of a notebook PC has a rather large environmental impact, followed by battery production.

Results from the study by St-Laurent et al. 2012

Figure 5 shows the comparative results of generic and labelled notebooks concerning the environmental impacts evaluated by the ReCiPe 2008 method. The study concludes that the application of ecolabel criteria into the life cycle model influences the environmental impact only to a minor degree for the indicators. The EPEAT Gold-labelled notebook shows even no difference compared to the generic notebooks. The TCO notebook contributes to about a 10% reduction in human, freshwater and marine toxicity potential, since 20% of TCO-labelled notebooks are recycled instead of 10% for a generic notebook model.

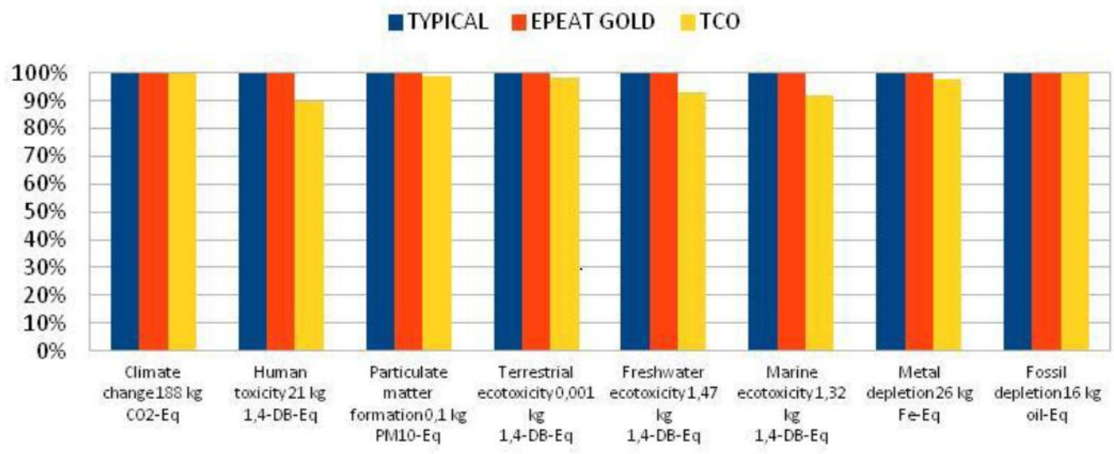


Figure 5: Life cycle impacts results of generic and ecolabelled notebooks (taken from St-Laurent et al. 2012, Figure 1)

As a result, key messages from this study are compiled as below (St-Laurent et al. 2012):

- Label criteria should be tightened to make sure that labelled notebooks have less environmental impacts and are clearly environmentally preferable compared to non-labelled notebooks.
- Typical current label criteria still avoid the worst product designs and corporate practices but are not sufficient to push the industry to improve.
- The impacts can be reduced directly by improving design and production techniques or indirectly by extending notebooks' use life or by reusing parts.

St-Laurent et al. 2012 indicated that the labels do not impose criteria targeting directly impacts during production, such criteria could preferably be added, since a large part of laptop's impact originates from the production phase.

3.5 Findings from further studies

In this section, studies that do not comply with the quality criteria for LCA studies to be analysed as described in sections 3.1 and 3.2 are reviewed if they provide particular insight, e.g. because of the methodology or data used, or certain additional aspects on environmental hotspots not provided by the full LCA studies.

3.5.1 Overview of the GWP impacts resulting from the manufacturing phases of computers investigated

Teehan & Kandlikar 2013 conducted a study to make LCA results for ICT products easier to derive and more useful in supporting decisions, both by contributing a new primary dataset of product inventories and impact estimates and by exploring linear regression-based models that could approximate impact assessment using a limited set of easily collected inputs. They analysed ICT products and compared their results with other studies. The following table taken from their paper provides an overview of the embodied GWP values in the manufacturing phase. It can be summarised as below. That means, as for stationary computers such as desktop PCs, rack server and switches, circuit boards, ICs and power supply are the dominating components regarding the environmental impacts.

Table 19: Main contributors of GWP in the manufacturing phase

Product group	Products	Main contributor (GWP)
Stationary computers	Desktop PCs, rack server and switch	Circuit boards, ICs and power supply
Display	LCD display	LCD module
Portable computers	Laptop, netbook, iPad	Circuit boards, ICs and display

Note that this study was conducted from a GWP perspective. Batteries could also play a role, if other environmental impacts were taken into consideration.

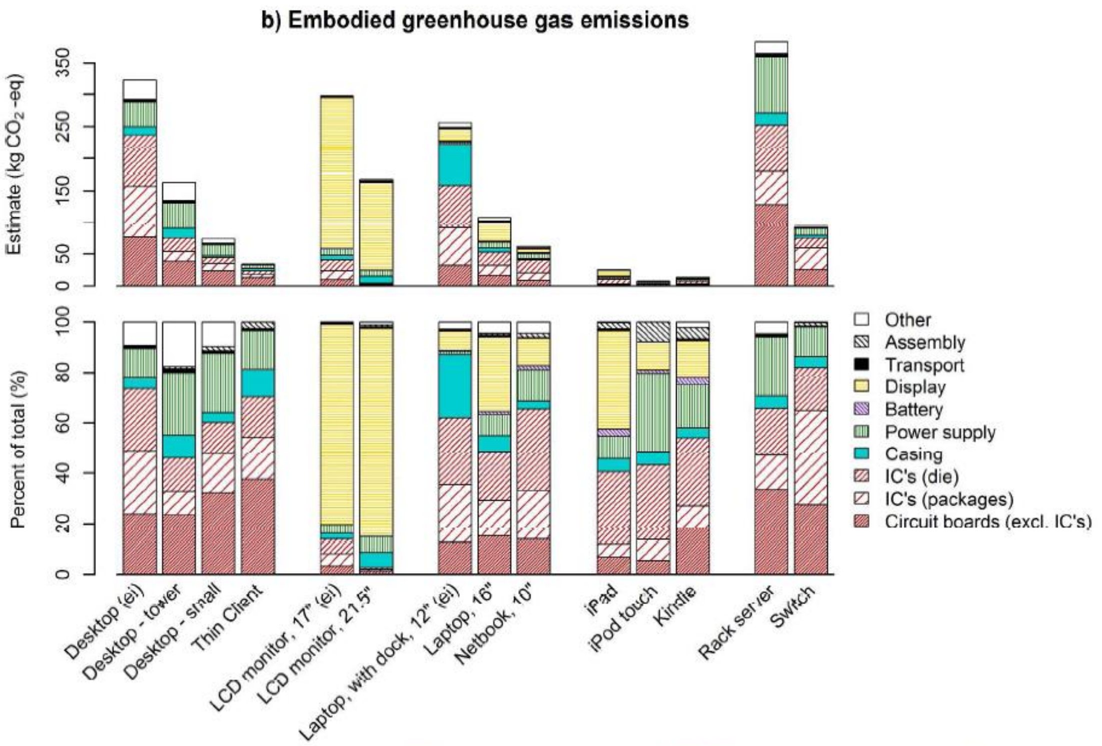


Figure 1: Results showing product mass (a) and embodied emissions (b). (ei) denotes adjusted studies from ecoinvent database.

Figure 6: GWP-Values on the component level (taken from Teehan & Kandlikar 2013, Fig. 1)

3.5.2 Desktop PCs and workstations

Table 20 shows the proportion of GWP values differentiated by life phase, as well as the absolute total value resulting from different studies. As mentioned in section 3.3.2, Apple Max Pro is a workstation. The sole investigation on GWP shows that the use phase dominates the GWP. Depending on the different configuration of computers, the share of manufacturing on the overall GWP impact is different. However, based on the previous detailed analysis using diverse impact categories, the manufacturing phase has a larger impact compared to the use phase (Table 14). This confirms that solely PCF investigation is not sufficient enough to obtain a whole picture on the environmental hot spots. Note that the comparability of these studies is limited, since life times, products, and assumptions in the modelling are different in the individual analyses.

Table 20: Comparison of GWP values of desktops resulting from different studies

GWP	**Song et al. 2013**	**Stutz 2011**	**Duan et al. 2009**	**IVF 2007 (EuP Lot 3)**	**Apple Mac Pro**
Functional unit	**A desktop PC with CRT (23%) and LCD Display (77%), keyboard and mouse**	**A desktop PC without screen, keyboard and mouse**	**A desktop PC with CRT (50%) and LCD Display (50%), keyboard and mouse**	**A desktop PC without display, keyboard and mouse. Used in office - used at home**	**Workstation (without display)**
Life time	8a	4a	6a	6,6a	4a
1. Manufacturing	25%	Approximately 10%-20%	29%	18%-23%	44%
2. Distribution /transportation	0%	-	0%	4%-5%	3%
3. Use phase	75%	Approximately 90%-80%	64%	78%-72%	52%
4. End of Life	0%	-	-7%	0%	1%
Absolut value of GWP	1788 kg CO2e	-800 kg CO2e (when used in the US) -720 kg CO2e (when used in Europe) -1230 kg CO2e (when used in Australia)	Not specified	761-603 kg CO2e	1790 kg CO2e

3.5.3 Notebooks

Table 21 shows the comparison of GWP values of notebook PCs resulting from different studies. Most of them indicate that the manufacturing phase has a greater contribution to GWP than the use phase, which confirm the results of the previous detailed analysis. Deviating from this is the EuP study. As mentioned before, the manufacturing phase of the EuP studies is underestimated. O'Connell&Stutz 2010 and Prakash et al. 2011 revealed that the motherboard (especially ICs) and displays are the dominating components from a GWP point of view.

Table 21: Comparison of GWP values of notebook PCs resulting from different studies

GWP	Ciroth & Franze 2011	Prakash et al. 2011	IVF 2007 (EuP Lot 3)	Apple 2010	Apple 2010	O'Connell&Stutz 2010
Functional unit	**15.6"**	**15"**	**15" (Used in office - used at home)**	**17" MacBook Pro**	**13" MacBook Pro**	**14" with EPEAT Gold registered**
Life time	4a	5a	5.6 a	4a	4a	4a
1. Manufacturing	81%	56%	23%-32%	65%	59%	42% (in China); 50% (in Europe)
2. Distribution/ transportation	7%	8%	3%-4%	6%	8%	Not specified
3. Use phase	11%	36%	74%-65%	28%	32%	65% (in China); 47% (in Europe)
4. End of Life	1%	0%	0%	1%	1%	Not specified
Absolut value of GWP	Not specified	382 kg CO2e	348-251 kg CO2e	700 kg CO2e	440 kg CO2e	-320 kg CO2e (when used in Europe) -370 kg CO2e (when used in China)

3.5.4 Thin client computing

The object investigated by Maga et al. 2012 is a thin client model IGEL UD3 in combination with a terminal server abbreviated as SBCTC. A standard office PC (abbreviated as DPC) is described in the "EuP Lot 3 Personal Computers" study. The goal of this study was to compare and evaluate two ICT solutions (thin client and desktop PC) using the MEErP and MIPS methodologies[13].

[13] MEErP: Methodology for ecodesign of energy-related products; MIPS: Material input per service unit

The study was based on the life cycle approach. The impacts analysed are GWP and material input (abiotic material, water and air). The following tables describe the framework of this study and data quality requirements as well as data sources.

Table 22: Description of framework by Maga et al. 2012

Functional Unit	System boundary	Cut-off Criteria	Allocation parameter
The functional unit is defined as the supply of a computer workstation with two or three applications simultaneously for a time period of 5 years with 220 working days per year using SBCTC or DPC, respectively. Each working day comprises nine working hours.	The life cycle analysis includes the whole life cycle (material extraction and production, manufacturing, distribution, use, and end of life stage) for both ICT solutions.	Not specified	The impact of the terminal server in the datacentre is allocated proportionally to the thin client. One blade running virtualized terminal servers can supply 130 users. The factor of 1/130 is therefore used for the allocation of energy consumption.

Table 23: Data quality requirements and data sources

Time-related representativeness	Geographical representativeness	Technological representativeness	Data sources of primary data	Data sources of secondary data
Primary data: 2010 Secondary data: GEMIS 4.6 and EuP lot 3 (IVF 2007)	Production phase: Not specified Use Phase: Germany	Up-to-date thin client used in the Fraunhofer UMSICHT	The detailed material composition of the thin client was provided by the producer. The electricity demand during the use phase was measured by Fraunhofer UMSICHT	Gemis 4.6 databases MEErP Tool EuP Lot 3 Personal computers study (IVF 2007)

Table 24: Assumptions made while modelling

Production	Distribution	Use	End-of-life
Due to missing data, it is assumed that the composition of the server is the same as that of PC systems, scaled on the basis of their weight.	Not specified	5 years used. 9 working hours 220 days per year. The thin client is switched at night. 30% of DPC users switch off the DPC overnight (scenario 1). 30% of DPC users switch off (scenario 2). Besides annual consumption of server, additional energy consumption for monitor and cooling has also been included.	The material and energy demand in the end of life stage is estimated via the MEErP tool. The standard values for reuse, recycling, recovery, incineration, and landfilling given in the MEErP report are used

The following figure (Maga et al. 2012) shows greenhouse gas emissions in the life cycle of DPC and SBCTC with a use phase of 5 years.

The GWP resulting from the desktop PC is more than two times higher than the GWP of thin client computing amounting to 141 kg CO_{2e}. The use phase dominates the GWP of the entire life cycle. Note that the production phase could be underestimated, as the MEErP Tool was applied for modelling the production of components. The study by Prakash et al. 2011 demonstrated that the EuP study underestimated the production phase.

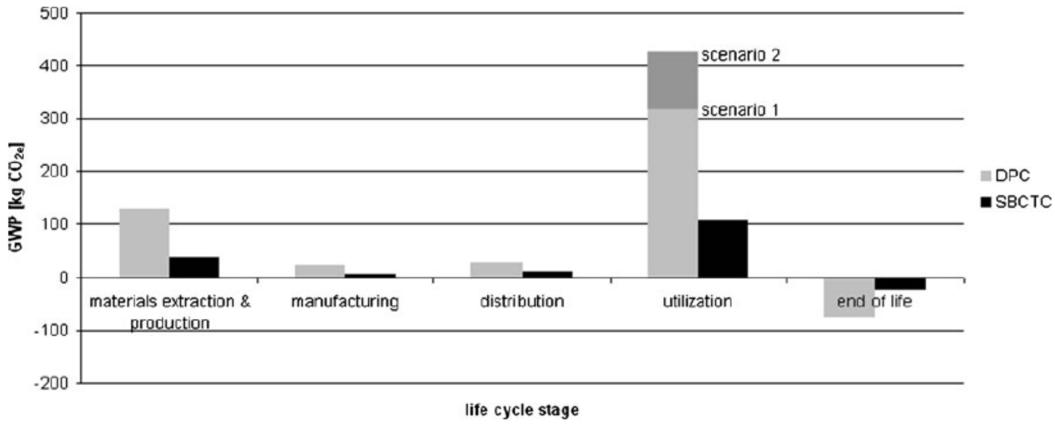


Figure 7: Greenhouse gas emissions in the life cycle of DPC and SBCTC with a using time of 5 years (taken from Maga et al. 2012 Fig. 3)

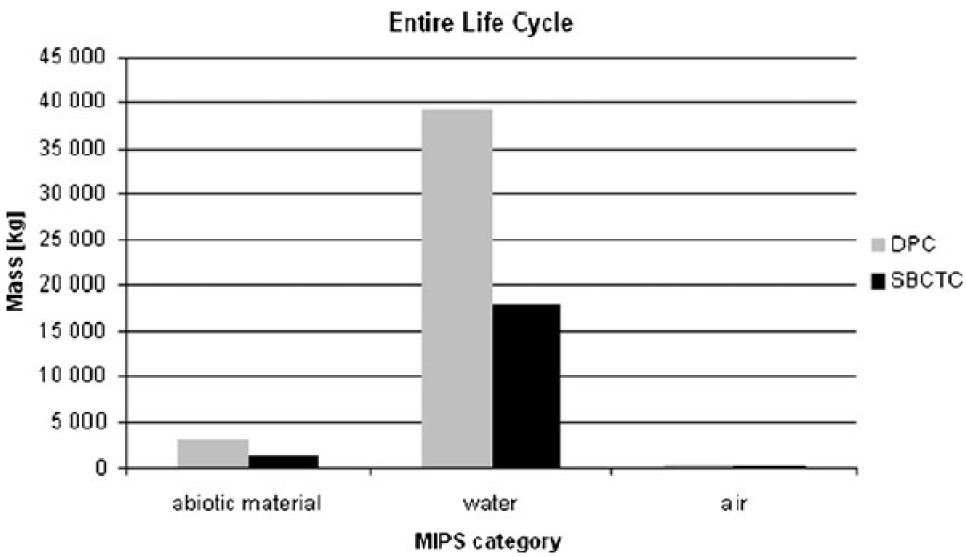


Figure 8: Resources demand in the categories abiotic material, water, and air of a DPC and SBCTC based on MIPS assessment method (taken from Maga et al. Fig. 6)

Maga et al. (2012) discussed the data quality and indicated that the worst case estimates were used in case of doubt. They reported that concrete data on terminal servers provided by the industry would improve the LCI data quality.

3.5.5 Tablets

Overall, an iPad 3rd Generation results in 180 kg CO_2e over the entire life cycle. The greatest proportion of GWP emissions arises in the production phase with 67%, followed by the use phase with 25%. The outcomes of the use phase were calculated assuming a useful lifetime of 3 years. Transport and recycling generates 8% of the total GWP emissions.

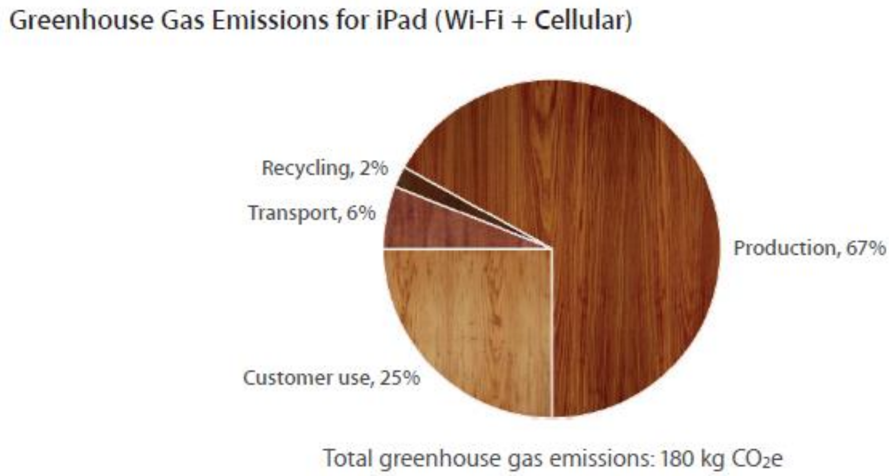


Figure 9: Absolute GWP values of life cycle phases of iPad (taken from the Apple environmental datasheet)

To determine roughly the difference between notebook PCs and tablet PCs with respect to the material used, below we make a simplistic comparison of the bill of materials based on the Apple environmental datasheets. Table 25 shows that notebooks comprise hard drive and optical drive, keyboard and track pad, while tablets do not have them. Hence, the share of battery, aluminium, display and glass account for the main part of the tablet. It can be assumed that the main contributor of environmental impacts of a tablet stems from the battery and the display.

Table 25: Comparison of material use between tablet and notebook (source: Apple reports)

	iPad (9.7")		MacBook Air (11")		MacBook Pro (13")		MacBook Pro (15")	
Components	**Weight (g)**	**in %**	**Weight (g)**	**in %**	**Weight (g)**	**in %**	**Weight (g)**	**in %**
Battery	205	31%	230	21%	355	17%	440	18%
Aluminium	135	20%	425	39%	520	25%	625	25%
Display	132	20%	145	13%	290	14%	420	17%
Glass	112	17%	-	-	103	5%	132	5%
Circuit boards	40	6%	100	9%	195	9%	250	10%
Other metals	28	4%	40	4%	121	6%	175	7%
Plastics	10	2%	25	2%	-	-	-	-
Hard drive and optical drive	-	-	15*	1%	240	11%	240	10%
Keyboard and trackpad	-	-	100	9%	154	7%	154	6%
Others	-	-		-	121	6%	58	2%
Total	**662**	**100%**	**1080**	**100%**	**2099**	**100%**	**2494**	**100%**

*Solide state drive

Another study, in which an Apple iPad 1st generation is investigated, stems from Teehan & Kandlikar (2013). Figure 10 shows the contributors of components regarding GWP and primary energy with the help of the data based on Teehan & Kandilikar 2013. The overall GWP value embodied from the manufacturing phase is 25.5 kg CO2eq. Display and Integrated Circuits (ICs, die) together are responsible for about 67% of the GWP impact resulted from the manufacturing phase. Surprisingly the battery has only a proportion of 2.7% concerning the GWP value. This may be due to the light weight of a battery of iPad 1st generation, which weights 129 gram and accounts for 17% of the total weight. In contrast, the battery of iPad 3rd generation weights 205 gram and has a share of 31% of the total weight.

Although there are no detailed LCA studies for tablets so far, it can be assumed that the manufacturing phase and use phase account for the large proportion of other impact categories within the entire life cycle phases, similar to notebooks. Tablets are lighter and have fewer components compared to notebooks; however the power consumption in the use phase of tablets is lower than that of notebooks. Due to the short lifetime of tablets the manufacturing phase might have a larger share than the use phase.

On the component level, battery[14], display and motherboard can be the contributions of great significance to the overall product environmental impacts (see Figure 6).

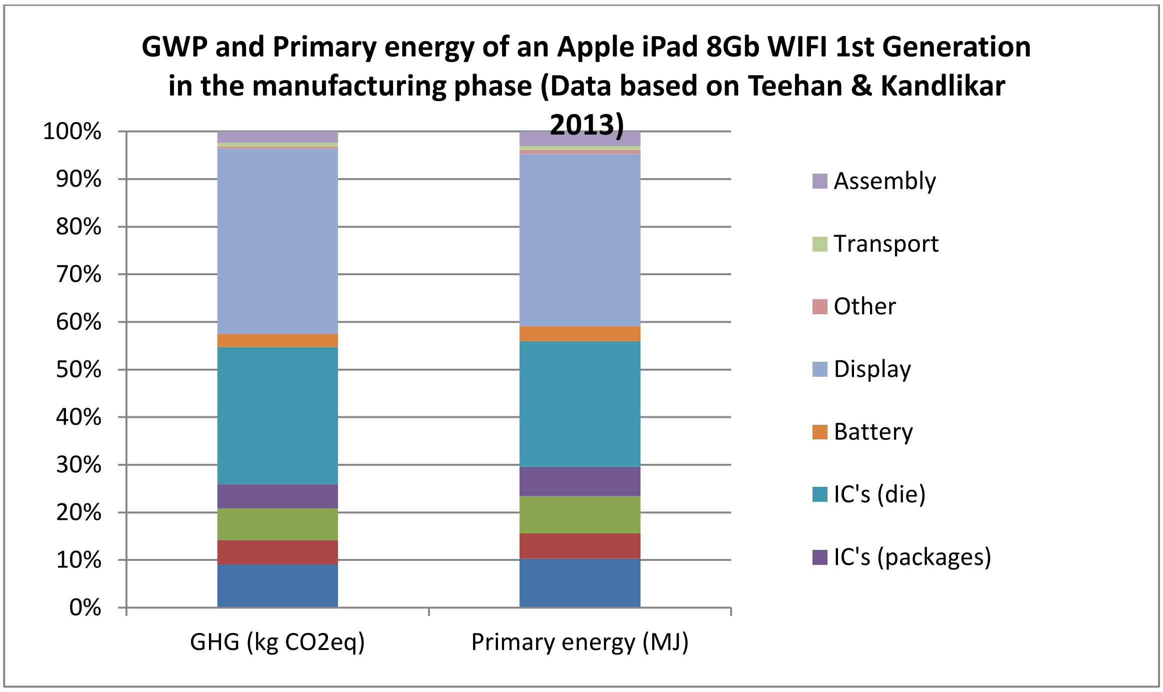


Figure 10: GWP and primary energy of an Apple iPad 1st Generation based on the Teehan & Kandlikar 2013

The third available study on Tablet PCs refers to the Environmental Product Declaration (EPD) from the Shuttle Company (Shuttle 2012). The functional unit is one unit of Tablet PC with a lifetime of two years. The size of the touch screen display is 8 inch. The weight without packaging and power supply unit accounts for 570 grams. The EPD, however, provides only the aggregate values of a unit tablet of all life stages (see Table 11), so that the proportion of different life stages and the hot spots at the component level cannot be identified.

---

[14] Although battery is of minor importance (2.7%) regarding GWP value based on the Teehan & Kandlikar (2013), we still believe that further in-depth studies including other environmental impacts are necessary in the future.

The analysed tablets are produced in China, the location of the use phase is not specified so it remains unclear on which country-specific electricity grid the analysis is based.

Table 26: Results of one unit of Tablet PC of all lifecycle stages based on EPD from Shuttle (2012)

Sum of all lifecycle stages	Equivalent
Global warming (kg CO_2eq)	9.11E+01
Ozone layer depletion (kg CFC-11eq)	6.74E-05
Photochemical oxidation(kg C_2H_4)	3.81E-02
Acidification (kg SO_2eq)	6.54E-01
Eutrophication (kg PO_4^{3-}eq)	4.85E-02

The EPD provides a list of major materials and components with power supply unit and packaging. Table 27 shows the weight of them. To facilitate comparison with the values provided in Table 25, the weight of packaging and power supply unit is excluded in this table. It shows that battery of this tablet with 8" accounts for a less weight (18%) compared to the Apple iPad with 9.7" (31%). On the contrary, the share of the LCD module (33%) is larger than that of the iPad (20%).

Table 27: The weight of major materials and components of one unit of tablet PC (8") without packaging (Shuttle 2012)

Materials/Components	Weight (g)	Share (%)
LCD	190	33%
PCBA	44	8%
Battery	104	18%
Metals	35.5	6%
Plastics	103.5	18%
Touch panel	77.5	14%
Electronic components	15.5	3%
Total (without packaging and power supply unit)	570	100%

Concerning data quality, primary data were obtained from Shuttle's Suzhou Plant in China for the product assembly and motherboard SMT operations. As for the product's main components, including LCD module, rear cover and product chassis, on-site audits were conducted on the suppliers' sites (Shuttle 2012). According to the EPD, the number of measured values accounts for 88%, the number of calculated values 8% and the number of estimated values 4%. This shows that the data stems mainly from primary sources.

3.5.6 Servers

Stutz et al. 2012 conducted a PCF study for a Dell server. The specific configuration of the server investigated was described in Stutz et al. 2012. The lifetime of the server was estimated to be 4 years, running 24 hours a day and 7 days a week.

The overall GWP value was approximately 6360 kg CO_2e when used in the US. The GHG emissions from use phase account for more than 90% of the total results.

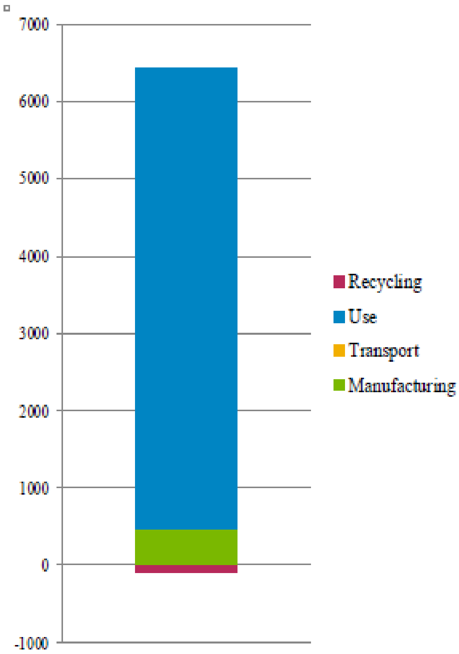


Figure 2: Total product carbon footprint [kg CO2eq] of the Dell PowerEdge R710 in the US

Figure 11: Product carbon footprint of Dell PowerEdge R710 used in the US (taken from Stutz et al. 2012, Fig. 2)

3.6 Summary of key environmental issues identified by the detailed LCA analysis and further studies

Desktop PCs

- Within the entire life cycle phases, manufacturing and use phase have a larger impact on the environment. The share of these two phases can vary due to product lifespan, electricity grid mixes and power consumption, which determine the environmental impacts in the use phase. As for products with a shorter lifetime, such as notebook PCs, the production phase has a larger environmental impact compared to the use phase.
- For LCD displays, the environmental impacts of the manufacturing phase are clearly dominating over the impacts of the use phase.
- The environmental impact in the manufacturing phase can be reduced, if EoL treatment receives better management, since the secondary resources from recycling can avoid primary production. Within the EoL, sound management of toxic substance during recycling process results in ca.75% reduction of impacts.
- The main contributors to the environmental impacts during the manufacturing phase at component level were identified as follows:
  - Desktop unit: PWB, power supply, CD-ROM, and HDD.
  - LCD screen: LCD panel, PWB, and the final assembly process.
- Further studies based only on the investigation of GWP gave the result that the use phase dominates the GWP. However, the previous detailed LCA analyses showed that the manufacturing phase has a larger impact compared to the use phase taking into account diverse impact categories. It confirms that solely PCF investigation is not sufficient enough to obtain a whole picture.

Notebook PCs

- The detailed LCA studies as well as most of the further analysed studies show that the production of a notebook PC clearly dominates the environmental impacts in comparison to the use phase.
- The main contributors of the manufacturing phase at component level were: Production of the LCD display and motherboard, followed by battery production.
- Regarding notebooks, the study by St. Laurent et al. 2012 indicated that there is no clear difference with regard to environmental impacts between ecolabelled and non-labelled generic products. In conclusion it can be summarised that the current ecolabel criteria still avoid the worst product designs and corporate practices but seem not stringent enough to push the industry to improve.
- The impacts can be reduced directly by improving design and production techniques or indirectly by extending notebooks' use life or by reusing parts.

Workstations, servers, thin clients and tablet PCs,

To date, there are few robust science-based LCA studies due to the recent emergence of some of these products. Some further, less comprehensive and non LCA studies revealed, however, the following:

- For servers and workstations, the use phase dominates the total results with regard to GHG emissions.
- For thin clients, the differentiation of the life cycle phases regarding their environmental impacts are similar to that of a desktop PC with the use phase dominating the GWP of the entire life cycle, but being more than two times lower than the GWP of a desktop PC. However, the production phase could have been generally underestimated in that study because the MEErP Tool was applied to modelling the production of components and another study demonstrated that the EuP study using the MEErP Tool underestimated the production phase.

- For tablet PCs the greatest proportion of GWP emissions arises in the production phase with 67%, followed by the use phase with 25%. Compared to notebooks, the manufacturing phase might be more relevant due to the short lifetime and the lower power consumption of tablets. Regarding the difference between tablets and notebook PCs with respect to the materials used, a simplistic comparison of the bill of materials shows that the share of battery, aluminium, display and glass account for the main parts of the tablet PC. At component level, the main contributors of a tablet PC to GHG emissions and primary energy consumption are the display and the mainboard.

LITERATURE

Apple 2012a	Datasheet Tablet
Apple 2012b	Datasheet Workstation
Ardente et al. 2011	Ardente F.; Wolf M-A.; Mathieux F.; Pennington D.; Joint Research Centre. Institute for Environment and Sustainability. Deliverable 1 of the project “Integration of resource efficiency and waste management criteria in the implementing measures under the Ecodesign Directive”. July 2011.
Andrae & Andersen 2010	Anders S.G. Andrae, Otto Andersen, Life cycle assessments of consumer electronics – are they consistent? Int J Life Cycle Assess (2010) 15:827–836, DOI 10.1007/s11367-010-0206-1
Buchert et al. 2012	Buchert M.; Manhart A.; Bleher D.; Pingel D.; Recycling critical raw materials from waste electronic equipment, Commissioned by the North Rhine-Westphalia State Agency for Nature, Environment and Consumer Protection, 2012
Ciroth & Franze 2011	Ciroth A., Franze J., LCA of an Ecolabeled Notebook, Consideration of Social and Environmental Impacts, Along the Entire Life Cycle, 2011
Duan et al. 2009	Duan H.; Eugster M.; Hischier R.; Streicher-Porte M.; Li J.H.; Life cycle assessment study of a Chinese desktop personal computer, Science of the Total Environment 407, 1755-1764, 2009
Götze&Rotter 2012	Götze R.; Rotter V.S.; Challenges for the recovery of critical metals from waste electronic equipment – A case study of Indium in LCD Panels, Paper in EGG 2012 conference.
ILCD 2011	Recommendations for life cycle impact assessment in the European context, - based on existing environmental impact assessment models and factors, first edition, 2011, http://lct.jrc.ec.europa.eu/assessment/pdf-directory/Recommendation-of-methods-for-LCIA-def.pdf
IPCC 2007	Fourth Assessment Report: Climate Change 2007, Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing. 2007, http://www.ipcc.ch/ipccreports/ar4-wg1.htm 11.2007
ISO 14040:2006	Environmental management - Life cycle assessment – Principles and framework

ISO 14044:2006	Environmental management - Life cycle assessment - Requirements and guidelines
IVF 2007	IVF Industrial Research and Development Corporation. Lot 3, personal computers (desktops and laptops) and computer monitors. 2007.
James & Hopkinson 2009	James P.; Hopkinson L.; Energy and Environmental Impacts of Personal Computing, A Best Practice Review prepared for the Joint Information Services Committee (JISC)http://www.goodcampus.org/files/files/57-LCA_of_computing_equipment_v7_final_June_2011.pdf
James & Hopkinson 2011	James P.; Hopkinson L.; Life Cycle Energy and Environmental Impacts of Computing Equipment - A June 2011 Update to a 2009 SusteIT Report
Maga et al. 2012	Maga D.; Hiebel M.; Knermann C.; Comparison of two ICT solutions: desktop PC versus thin client computing, Int J Life Cycle Assess (2012), DOI 10.1007/s11367-012-0499-3 https://www.igel.com/fileadmin/user/upload/documents/PDF_files/White_Paper_DE/thinclients2011-de-2.pdf
Manhart et al. 2010	Top 100: PROSA Thin clients – Developing the award criteria for a climate label. Component of the overall project "Top 100 – Ecolabel for climate-relevant products"; Manhart, A.; Brommer, E.; Prakash, S.; Gröger, J.; 2010
O'Connell&Stutz 2010	Product Carbon Footprint (PCF) Assessment of Dell Laptop – Results and Recommendations, 2009; Sustainable Systems and Technology (ISSST), 2010 IEEE, ISBN: 978-1-4244-7094-5
Prakash et al. 2011	Prakash S.; Liu R.; Schischke K.; Stobbe L.; Timely replacement of a notebook under consideration of environmental aspects, on behalf of the Federal Environment Agency (Germany), Project No. (FKZ) 363 01 322; Report No. (UBA-FB) 001666/E
Prakash et al. 2011a	Top 100: PROSA Personal desktop computers – Developing the award criteria for a climate label. Component of the overall project "Top 100 – Ecolabel for climate-relevant products"; Prakash, S.; Brommer, E.; Gröger, J.; 2011
Prakash et al. 2011b	Top 100: PROSA Computer monitors – Developing the award criteria for a climate label. Component of the overall project "Top 100 – Ecolabel for climate-relevant products" Prakash, S.; Brommer, E.; Gröger, J.; 2011

Prakash et al. 2010a	Top 100: PROSA Nettops – Developing the award criteria for a climate label. Component of the overall project "Top 100 – Ecolabel for climate-relevant products"; Prakash, S.; Brommer, E.; Gröger, J.; 2010
Prakash et al. 2010b	Top 100: PROSA Mobile computers – Developing the award criteria for a climate label. Component of the overall project "Top 100 – Ecolabel for climate-relevant products"; Prakash, S.; Brommer, E.; Gröger, J.; 2010
Quack et al. 2009	PROSA Netbooks – Developing the award criteria for a climate label. Quack, D.; Brommer, E.; Grether, S.; Grießhammer, R.; Lüders, B.; 2009
Shuttle 2012	Environmental Product Declaration, Slate-Tablet PC V08CN01, Shuttle, Inc. 2012
Song et al. 2013	Song Q.B.; Wang Z.S.; Li J.H.; Yuan W.Y.; Life cycle assessment of desktop PCs in Macau, Int J Life Cycle Assess (2013) 18:553-566, DOI 10.1007/s11367-012-0515-7
St-Laurent et al. 2012	St-Laurent J.; Hedin D.; Honée C.; Fröling M.; Green Electronics? – An LCA based study of Eco-labeling of laptop computers, Paper in EGG 2012+ conference in Berlin
Stutz et al. 2012	Stutz M.; O'Connell S.; Pflueger J.; Carbon Footprint of a Dell Rack Server, Paper in EGG 2012.
Teehan & Kandlikar 2013	Teehan P.; Kandlikar M.; Comparing embodied greenhouse gas emissions of modern computing and electronics products, Environ. Sci. Technol., DOI: 10.1021/es303012r, http://pubs.acs.org/doi/abs/10.1021/es303012r and supporting information: http://pubs.acs.org/doi/suppl/10.1021/es303012r/suppl_file/es303012r_si_001.pdf
Teehan & Kandlikar 2012	Teehan P.; Kandlikar M.; Sources of Variation in Life cycle assessments of desktop computers, Journal of Industrial Ecology, DOI: 10.1111/j.1530-9290.2011.00431.x, 2012 http://onlinelibrary.wiley.com/store/10.1111/j.1530-9290.2011.00431.x/asset/supinfo/JIEC_431_sm_suppmatS1.pdf?v=1&s=3962fa7ede04478e03ac446c1ce0bcb6aa169f9d