TEXTE
45/2012

Timely replacemet of a notebook under consideration of environmental aspects

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| TEXTE | 45/2012

ENVIRONMENTAL RESEARCH OF THE
FEDERAL MINISTRY OF THE ENVIRONMENT,
NATURE CONSERVATION AND NUCLEAR SAFETY

Project No. (FKZ) 363 01 322
Report No. (UBA-FB) 001666/E

Timely replacement of a notebook under consideration of environmental aspects

by

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UMWELTBUNDESAMT

ISSN 1862-4804

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Study completed in: October 2011

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Edited by: Section III 1.1 General Aspects of Product-related Environmental Protection,
Sustainable Consumption,Innovation Programme

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Dessau-Roßlau, September 2012

Kurzbeschreibung

Die Herstellung von Notebooks ist mit großen Umweltauswirkungen verbunden. Trotzdem spielen diese bei den Kaufentscheidungen selten eine Rolle. Vor diesem Hintergrund hat das Umweltbundesamt das Öko-Institut e.V. und das Fraunhofer IZM mit einer Studie beauftragt, die folgende Fragen klären sollte: (1) Welchen Anteil haben verschiedene Lebenszyklusphasen an Gesamttreibhausgasemissionen eines Notebooks? (2) Wann amortisieren sich die Umweltauswirkungen von Production, distribution and disposal eines energieeffizienten Neu-geräts? (3) Wie viel effizienter muss das neue Notebook sein, damit sich der Ersatz des alten und weniger energieeffizienten Geräts aus ökologischen Gesichtspunkten lohnt? Die Ergebnisse zeigen, dass die Herstellungsphase mit knapp 56% (214 kg CO_2e in 5 Jahren) einen höheren Beitrag an den Gesamttreibhausgasemissionen eines Notebooks leistet als die Nutzungsphase. Die Analyse der Amortisationszeiten hat belegt, dass der Umweltaufwand bei der Herstellung eines Notebooks so hoch ist, dass er sich durch eine erhöhte Energieeffizienz in der Nutzung nicht in realisierbaren Zeiträumen amortisieren lässt. Bei einer 10%igen Energieeffizienzsteigerung des neuen Notebooks im Vergleich zum alten liegen die Amortisationszeiten zwischen 33 und 89 Jahre. Die Studie weist nach, dass der Beitrag der Herstellungsphase an Gesamttreibhausgasemissionen mit einer Erhöhung der Lebensdauer der Notebooks erheblich reduziert wird. Deswegen schlägt die Studie vor, den Fokus der verpflichtenden produktpolitischen Ökodesign-Maßnahmen für IKT-Geräte auf Aspekte wie Möglichkeiten der Auf- und Nachrüstung, modularer Aufbau, recyclinggerechte Konstruktion, Ersatzteilverfügbarkeit, Standardisierung von Komponenten und Mindestgarantie auszuweiten.

Abstract

The production of notebooks induces significant environmental impacts. However, these impacts are seldom considered by consumers in their purchasing decisions. Against this background, the Federal Agency of Environment in Germany commissioned the Öko-Institut e.V. and the Fraunhofer IZM with a study to address following questions: (1) What is the share of different life cycle phases in the total greenhouse gas emissions of a notebook, (2) When are the environmental impacts, which are associated with the production, distribution and disposal of a new notebook, compensated as a result of energy efficiency gains in the use-phase of the new notebook, (3) Which energy efficiency gains should be possessed by a new notebook, if the replacement of the older and less energy efficient notebook can be justified under the consideration of environmental concerns. The results show that production phase, with about 56% (214 kg CO_2e in 5 years) of the total greenhouse gas emissions of a notebook, casts a significantly higher impact than the use phase. Moreover, the environmental impacts of the production phase of a notebook are so high, that they cannot be compensated in realistic time-periods by energy efficiency gains in the use phase. In case of a 10% increase in the energy efficiency of a new notebook as compared to the older one, replacement of the older notebook can only be justified after 33 to 89 years, if environmental concerns are considered. The study concludes that the share of the production phase in the total greenhouse gas emissions of a notebook can be significantly reduced by taking measures to extend the useful life-time of a notebook. Therefore, the study recommends that the focus of mandatory product policy for ICT should be expanded to measures related to possibilities of hardware upgrading, modular construction, recycling-friendly design, availability of spare parts, standardisation of components and minimum warranty periods.

Contents

Figures

Tables

Abbreviations and acronyms

Figures

Tables

Abbreviations and acronyms

ACPI	Advanced Configuration and Power Interface
AUO	AU Optronics Corporation
CMO	Chi Mei Optoelectronics
DDR3	Double Data Rate 3
DRAM	Dynamic Random Access Memory
ECN	Energy Centre of the Netherlands
EPD	Environmental Product Declaration
ETH	Swiss Federal Institute of Technology Zurich (*Eidgenössische Technische Hochschule*)
FBGA	Fine Pitch Ball Grid Array
FC	Fluorinated Compounds
GHG	Greenhouse Gas
GHz	Gigahertz
GWP	Global Warming Potential
HDD	High Definition Device
HFCs	Hydrofluorocarbons
IC	Integrated Circuits
IEEE	Institute of Electrical and Electronics Engineers
IERC	International Electronics Recycling Congress
ICT	Information and Communication Technology
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ISSST	International Symposium on Sustainable Systems and Technology
KBA	German Federal Motor Transport Authority (*Kraftfahrt-Bundesamt*)
LCA	Life Cycle Assessment
LCD	Liquid Crystal Display
LED	Light Emitting Diode
MEEuP	Methodology for the Ecodesign of Energy-using Products
MHz	Megahertz
OEMs	Original Equipment Manufacturers

PCF	Product Carbon Footprint
PFCs	Perfluorocarbons
ProBas	Process-specific data repository for environmental management tools, maintained by UBA (*Prozessorientierte Basisdaten*)
PWB	Printed Wiring Board
RAM	Random Access Memory
RFI	Radiative Forcing Index
SMD	Surface-Mounted Device
TEC	Typical Energy Consumption
TFT	Thin-Film Transistor
UBA	German Federal Environment Agency (*Umweltbundesamt*)
WEEE	Waste Electrical and Electronic Equipment Directive

1 Introduction

The German federal government has set itself the target of reducing ICT-related energy consumption in federal administrations by 40 percent by the year 2013 from the 2009 baseline.[1] This is to be achieved by reducing the electricity consumption caused by the operation of IT systems in federal administrations, and by producing guidance for the public-sector procurement of environmentally sound ICT products. As a part of the second approach, replacement of the present stock of end-user computers by new, more efficient notebooks is now being discussed.

The production of ICT devices – such as notebooks – is highly energy-intensive and generates major environmental impacts. Depending upon how long and how intensively a notebook is utilised in the use phase, the production phase can even account for the bulk of environmental impacts. The available statements on the apportionment of energy consumption between notebook production and use vary widely. A study performed in the context of the EcoTopTen project found that if a computer is used for four hours each day over a period of four years in private homes, about 40% of the associated environmental impact is attributable to the production phase and around 60% to the use phase (www.ecotopten.de). Other studies even estimate that the contribution of manufacturing to the overall greenhouse gas emissions of a notebook amount to 57–93% (Prakash et al. 2010, Andrae and Anderson 2010). Such statements, however, are still subject to a certain degree of imprecision, as very little data is available on resource consumption in upstream chains. For instance, it has not yet been determined sufficiently what impact sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3), which are used to produce semiconductor components and liquid crystal displays, have upon the overall greenhouse gas balance of a notebook. Over a period of 100 years 1 kg SF_6 gas has the same global warming impact as 22,800 kg CO_2; the radiative forcing of NF_3 is 17,200 times that of CO_2 (IPCC 2007).

A further key aspect is that the extremely short product life cycles of notebooks, in combination with the high rate of innovation in the sector and the falling prices for new units, is causing the actual lifetime of notebooks to become ever shorter. There is, for instance, empirical evidence that notebooks often have a useful lifetime of less than 3 years (Deng et al. 2011, Williams and Hatanka 2005). This very short lifetime of notebooks is often not caused by any physical fault, but rather by a lack of practicable options to expand performance, such as by upgrading the main memory or bulk storage device. As a result, more and more consumers decide to buy a new device although the old and still functioning one could in principle be upgraded.

The new generations of notebooks are indeed becoming increasingly efficient in terms of their energy consumption in the use phase, and the level of electricity consumption is taken with a certain regularity as an indicator for new purchase. Unfortunately, however, purchasing decisions do not take account of the environmental impacts arising in the production phase. To

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[1] ICT Strategy of the German Federal Government: Digital Germany 2015, www.bmwi.de

gain a full picture of the environmental impacts attributable to notebooks, it would be essential to include the material consumption and appropriation of environmental carrying capacity arising in both the upstream and downstream phases. Such a perspective would give policy-makers, public procurers and private final consumers greater certainty when taking decisions on the extension of lifetime or new purchase of notebooks. Furthermore, such a life cycle analysis makes it possible to determine with greater accuracy and predictive certainty when and under which conditions it makes environmental sense to replace an old device with a new one.

To achieve those goals, the German Federal Environment Agency (UBA) has commissioned the Öko-Institut e.V. and the Fraunhofer IZM to perform a study to identify the optimal replacement period for notebooks in terms of environmental outcomes.

2 Purpose and scope of the study

2.1 Goal and task

In the context of this study, the following questions were to be addressed:

- Which contributions do the different life cycle phases make to the overall greenhouse gas emissions attributable to a notebook?
- When is the optimum time to replace an old notebook by a new model in environmental terms?[2]

Two further questions were addressed by the study concerning the calculation of the point in time for optimum replacement of an old notebook by a new model:

- When are the environmental impacts generated by the production, distribution (incl. shopping trip) and disposal of the new device compensated by the savings delivered by energy-efficient devices in the use phase?
- How much more efficient must the new notebook be in order that replacement of the old and less energy-efficient device is worthwhile in environmental terms?

2.2 Scope and scenario formulation

It would not have been expedient in the context of this study to separately collect and analyse life cycle data for an old and a new notebook. While notebooks are subject to major market dynamics and constantly changing technological innovations (which would speak in principle for separate data collection), on the other hand primary collection of life cycle data for an old and a new notebook would be very costly and time-consuming, and would go well beyond the resources available to this project. Moreover, Prakash et al. (2011) have shown that the data uncertainties are larger than the differences between production processes for different

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[2] This study did not examine the question of the replacement of a stationary workplace computer by a notebook.

notebook generations. Not least, the decisions relevant to the replacement of a notebook generally must be taken relatively quickly and cannot always be supported by a comprehensive life cycle analysis. For the above reasons this study delivers results that are based on methodological considerations which, while less complex, are tailored to the purpose of the study. To that end, the study takes recourse to various existing data sources to determine the material and energy inputs needed to produce a notebook and identifies in that way the best replacement period in environmental terms. In addition, sensitivity analyses are carried out that verify the outcome from various perspectives and indicate points of leverage to shift life cycle outcomes.

2.2.1 Characterisation of the scenarios analysed

As set out in Section 2.1, the question of the optimum replacement time for a notebook is examined comparatively using three different data sources. These are the following:

1. EuP Lot 3 – PCs (desktops and laptops) and Computer Monitors[3] (Scenario 1)
2. EcoInvent 2.2 (Scenario 2)
3. **UBA UFOPLAN 2009** project (Scenario 3)

UBA **UFOPLAN 2009** project data for ICT components were generated within the UFOPLAN 2009 environmental research programme of the German Federal Environment Agency (Umweltbundesamt, UBA). The overall project was titled “Resource conservation in the field of information and communication technologies (ICT)” (*Ressourcenschonung im Aktionsfeld Informations- und Kommunikationstechnik (IKT*)), under which sub-project C, titled “Establishing a data base for the evaluation of ecological effects of ICT products” (*Schaffung einer Datenbasis zur Ermittlung ökologischer Wirkungen der Produkte der IKT)* generated the dataset in question.[4] These data are publicly accessible in the ProBas database[5] at www.probas.uba.de.

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[3] European Commission DG TREN, Preparatory studies for Eco-design Requirements of EuPs (Contract TREN/D1/40-2005/LOT3/S07.56313): Lot 3 Personal Computers (desktops and laptops) and Computer Monitors Final Report (Task 1-8)

[4] Prakash, S.; Liu, R.; Schischke, K.; Stobbe, L.: *Establishing a data base for the evaluation of ecological effects of ICT products,* in cooperation with Gensch, C.-O. within the UBA Ufoplan 2009 project *“Resource conservation in the field of information and communication technologies (ICT)”* – FKZ 3709 95 308, Öko-Institut e.V. in cooperation with the Fraunhofer Institute for Reliability and Microintegration (IZM, Berlin) (2011)

[5] The UBA database “ProBas – *Prozessorientierte Basisdaten für Umweltmanagement-Instrumente*” [Process-specific data repository for environmental management tools] www.probas.umweltbundesamt.de contains several thousand datasets with environmentally relevant material flow data for material extraction, manufacturing, transport and service processes. The data come from a diverse array of sources; the

Production phase

The production phase of a notebook is modelled in the present study in three scenarios, each based on one of the above data sources. The production-related data generated by the UBA-funded UFOPLAN 2009 project were only compiled for two notebook components, namely the display module and integrated circuits (ICs). No further datasets for other notebook components are as yet available in ProBas. The datasets lacking for an inventory analysis of the overall notebook were therefore taken from EcoInvent 2.2 in Scenario 3.

Transport (distribution)

For Scenarios 2 (EcoInvent 2.2) and 3 (UBA UFOPLAN 2009 project), the same assumptions were made for the transport of notebooks from production sites to wholesalers and further fine distribution from wholesalers to retainers. For Scenario 1 (EuP Lot 3) the data were taken from the EuP Lot 3 preparatory study.

Shopping trip

A shopping trip by final consumers for the new purchase of a notebook was assumed equally in all scenarios.

Use phase

Calculation of the use phase was based on the TEC approach of Energy Star Version 5.0 for computers. TEC stands for “Typical Energy Consumption”, and is a value used to check and compare the energy efficiency of computers, reflecting the typical energy consumption of a product in normal operation over a representative period. For notebooks, the key criterion used in the TEC approach is the typical annual electricity consumption of a computer measured in kilowatt-hours (kWh/a), using measurements of the average levels of power consumption in various operational modes, adjusted to an assumed typical pattern of utilisation (operating time).

The Energy Star Version 5.0 database for computers is the data source for energy consumption in the use phase.[6] The same pattern of utilisation in the use phase was assumed in all scenarios.

End-of-life

For Scenario 1 (EuP Lot 3) the dataset for notebook disposal was taken from the EuP Lot 3 preparatory study. Scenarios 2 and 3 were based on the corresponding dataset from EcoInvent 2.2: This characterises manual pretreatment followed by mechanical aftertreatment (shredding) of a notebook plus refining the metal fractions in metallurgical facilities. This combination of process steps recovers base metals such aluminium (Al), copper (Cu) and iron (Fe), and also recovers around 40% of the precious metals gold (Au), silver (Ag) and palladium (Pd).

ProBas database is not a citable source, but is rather designed to provide a library giving interested users the simplest possible access to the datasets via the Internet.

[6] http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=CO; accessed August 2010

A fourth scenario was defined for the disposal phase in addition to the other three scenarios. The only difference from Scenario 3 is in the recovery rate of the three precious metals (gold, silver and palladium).[7] It is assumed here that the precious metals can be recovered with substantially greater efficiency by optimising recycling technology and infrastructure. The reason for defining a fourth scenario is that primary extraction of precious metals is associated with far greater environmental impacts than their secondary extraction (Prakash and Manhart 2010, Hagelüken and Buchert 2008). The rising demand for resources – driven partly by the ever shorter lifetimes of consumer goods – increases the pressure on primary extraction and leads to many adverse environmental effects. If it were possible to recover the bulk of the precious metals by optimising recycling technology and infrastructure, the pressure on primary extraction could be reduced to a certain extent. This prevention of environmental impacts arising from primary extraction is assigned a credit in the inventory analysis. The purpose of the fourth scenario is to determine what influence optimised recovery rates have upon the optimal notebook replacement period.

The fourth scenario is based on the same data for production, transport, shopping trip and use as Scenario 3. End-of-life management in the fourth scenario is termed “Best practice” in the present study, and that in the second and third scenario is termed “Business-as-usual”.[8]

Section 3 describes the detailed modelling of the individual life cycle phases for all scenarios.

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[7] See Section 3.5.2

[8] It should be noted that the term “Best practice”, which is used here to refer to highly efficient recovery of the three precious metals gold, silver and palladium, is used in a very specific sense for the purposes of this study and only has orientative character. In reality, high-tech facilities are capable of recovering up to 17 different precious and rare metals from electroscrap. The study is restricted to gold, silver and palladium recovery solely for reasons of data availability. It can therefore be assumed that the potential to reduce global warming impact by means of secondary extraction of notebook metals in high-tech facilities is in fact significantly greater than the figures calculated in this study. Moreover, a comprehensive analysis would need to also take account of further environmental effects such as acidification, eutrophication, biodiversity loss etc., as well as social impacts.

The following Table 1 summarises the four scenarios:

Table 1: Overview of data sources and assumptions for the scenarios studied[9]

Scenario No.	Production	Transport (distribution to wholesalers + to retailers)	Shopping trip	Use	End-of-life
1	Calculated following EuP Lot 3	Calculated following EuP Lot 3	Assumptions: 10 km round trip by car	In accordance with the utilisation profile of Energy Star Version 5.0	Calculated following EuP Lot 3
2	Calculated in accordance with data from EcoInvent 2.2	Assumptions: 1) Production sites -> airport: truck: 500 km 2) Flight: Shanghai -> Warsaw: 8000 km 3) Distribution to retailers: truck: 1000 km			Business-as-usual
3	Calculated in accordance with data from UBA R&D project (UFOPLAN 2009) (for display module and ICs) + EcoInvent 2.2 (other components)[10]				Business-as-usual
4	Calculated in accordance with data from UBA R&D project (UFOPLAN 2009) (for display module and ICs) + EcoInvent 2.2 (other components)[8]				Best practice

2.2.2 Function and functional unit

The functions of the system studied reflect the functional properties expected of a product. The functions were to be equivalent for all variants studied.[11] The data sources used in the present study (EuP Lot 3, EcoInvent 2.2 and UBA R&D project (UFOPLAN 2009)) to determine the optimal replacement period for a notebook refer to different notebook configurations and technical specifications (see Table 2). However, the function of different notebook variants is considered to be equivalent.

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[9] A uniform use phase was taken for all scenarios, in order to gain a clearer picture of differences in the assessment of the production phase.

[10] Including consumption in production processes

[11] Deviations must be explained and compensated where appropriate. According to ISO 14040 2006, a functional unit provides a quantified reference to which the inputs and outputs in an LCA can be related and on the basis of which different variants can be compared.

Table 2: Notebook specifications in EuP Lot 3, EcoInvent 2.2 and UBA R&D project (UFOPLAN 2009)

	EcoInvent 2.2	**EuP Lot 3**	**UBA R&D project (UFOPLAN 2009)**
CPU	Pentium 3, 600 MHz	1.7 GHz	Pentium 3, 600MHz[12]
HDD	10 GB HDD	60 GB HDD	10 GB HDD[9]
Memory IC	128 MB RAM	512 MB RAM	8 GB
Display size	12.1″	15″	15.4″
Weight	3.15 kg (with packaging) 2.17kg (without packaging)	3.7 kg (with packaging) 2.8 kg (without packaging)	3.3 (with packaging) 2.4 (without packaging)[13]
Reference year	2005	2005	2000-2010

It should be stressed that the goal of the study is not to produce a comparative LCA of different notebooks, but rather to determine, on the basis of a range of data sources, the best point in time in environmental terms to replace a notebook. The configuration of the notebook in Scenarios 3 and 4 is therefore a fictitious assumption – it does, however, correspond to the configuration of a typical notebook. The procedure adopted for this LCA study follows ISO 14040/44 (2006), but only examines one impact category, namely Global Warming Potential (GWP). This is purposeful because GWP correlates directly with energy consumption in both the use and production phases. Due to poor data availability, it was not possible in the context of the present study to consider further impact categories such as acidification and eutrophication potential, photochemical oxidant formation and ecotoxicity. A previous LCA study of the recycling of Ni-MH batteries has shown that recycling makes only a modest contribution to reducing climate impact (Öko-Institut 2010). That study found that recycling, on the other hand, makes a very major contribution to reducing acidification and eutrophication. Toxic emissions of mining and ore upgrading are also prevented. These effects can also be expected for the Li-ion rechargeable batteries used in mobile ICT devices such as notebooks.

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. It was assumed that during this period the notebooks operate without malfunction and without replacement of spare parts, and that no repairs are necessary.

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[12] Taken from EcoInvent 2.2

[13] The weight of the display and memory ICs (from UBA R&D project UFOPLAN 2009) and the weight of other components (from EcoInvent 2.2) were added.

2.2.3 Definition of system boundaries

The system boundary of the four scenarios examined in this study is characterised as follows (Figure 1):

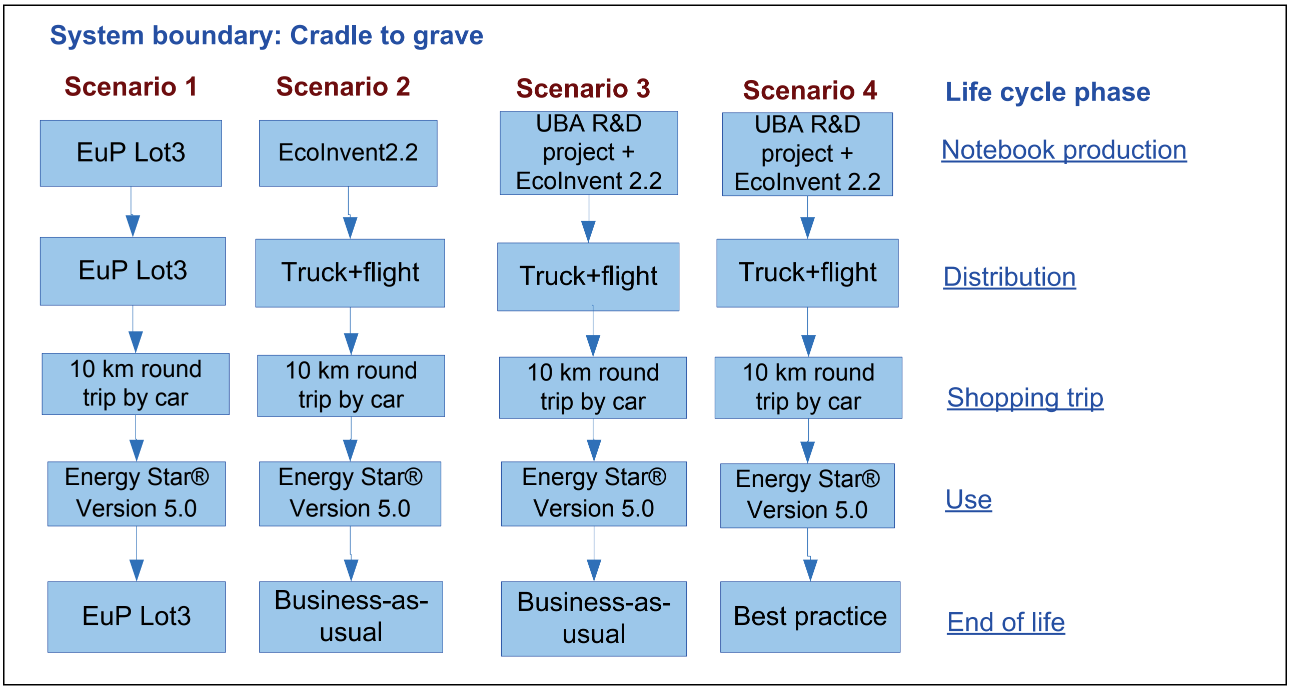

Figure 1: System boundary of the scenarios examined

Aspects not taken into account are described in the following:

- Different specifications and functions of the new notebook are beyond the scope of the study.
- The production and disposal of capital equipment is generally not covered (e.g. energy and material required to produce facilities or trucks).
- Furthermore, the secondary data taken from EcoInvent 2.2 (2010) and EuP Lot 3 (2005) as well as the UBA R&D project (UFOPLAN 2009) (Prakash et al. 2011) are not documented in detail in the present study. The detailed documentation of these data can be found in the corresponding original sources.
- For the end-of-life phase, only disposal and metal recycling are considered. Reuse is beyond the system boundary of this study.
- This study does not consider other environmental effects such as acidification, eutrophication, other resource consumption, biodiversity loss and social impacts.

2.2.4 Impact categories considered

In accordance with the purpose and scope of this study, the impact assessment only considers Global Warming Potential (GWP).

3 Data sources

3.1 Production phase

The production phases of the four scenarios characterised are modelled on the basis of three different data sources (Table 3).

Table 3: Data sources used for production phases

Scenario	Data sources for notebook production
1	EuP Lot 3
2	EcoInvent 2.2
3	UBA R&D project (UFOPLAN 2009) (for production of display module and ICs) + EcoInvent 2.2 (other components+ production inputs of a notebook)
4	UBA R&D project (UFOPLAN 2009) (for production of display module and ICs) + EcoInvent 2.2 (other components + production inputs of a notebook)

EuP Lot 3

In the context of the Energy-using Products (EuP) Directive 2009/125/EC process, the European Commission generally contracts a preparatory study for each product group stipulated in the Working Plan.[14] The purpose of the studies is to create a basis (statutory setting, technical data, sales figures, environmental performance etc.) for designing suitable implementing measures. One of these preparatory studies (Lot 3) was concerned with desktop and notebook PCs and monitors, and was published in 2007.[15] Table 4 lists the material composition examined in the EuP Lot 3 preparatory study. The list applies to the notebooks sold most in 2005, with 15 ″ LCD displays and a weight of 2.8 kg (without packaging) (EuP 2007). The reference unit of this dataset is 1 produced notebook with a weight of 3.8 kg (including packaging).

Table 4: Material composition for notebooks (2007 EuP study)

Materials (incl. packaging)	Weight [g]
LDPE	43
PP	4
PS	3
EPS	50

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[14] In preparation for a Working Plan, the contractors of the study contracted by the European Commission draft a list of product groups which, in their view, should be treated next within the EuP Directive process. The Commission published the Working Plan for 2009–2011 in October 2008. The study for the new post-2011 Working Plan commenced in November 2010 (www.eup-network.de).

[15] European Commission DG TREN, Preparatory studies for Eco-design Requirements of EuPs (Contract TREN/D1/40-2005/LOT3/S07.56313): Lot 3 Personal Computers (desktops and laptops) and Computer Monitors Final Report (Task 1-8)

Materials (incl. packaging)	Weight [g]
PVC	23
ABS	142
PA 6	281
PC	267
PMMA	36
Epoxy	3
Steel sheet galvanised	489
Al sheet /extrusion	38
Cu wire	60
Cu tube /sheet	15
MgZn5 cast	122
LCD screen m^2 (viewable screen size)	63
Big caps & coils*	501
Slots / ext. Ports	133
Integrated circuits, 5% silicon, Au	47
Integrated circuits, 1% silicon	31
SMD & LEDs avg.	50
PWB 1/2 lay 3.75 kg/m^2	5
PWB 6 lay 4.5kg/m^2	77
Solder SnAg4Cu0.5	7
Glass for lamps	1
Cardboard	921
Glass for LCD	362
Total	3774

* "Big Caps & Coils" were modelled in the EuP Lot 3 preparatory study as a simplified reference for the production of the rechargeable lithium-ion battery. The weight thus refers to the weight of the lithium-ion battery.

EcoInvent 2.2

The EcoInvent database characterises an Omnibook 500 notebook from Hewlett Packard (HP) for the period from 2001 to 2006 (Lehmann and Hischier 2007). The datasets of the associated lithium-ion battery and the LCD display module were updated in 2010 (EcoInvent 2.2 Report No.16 2010). The production of the notebook considered here comprises the entire production chain, i.e. the production of the individual components, the upstream material production and processing chains, assembly, the associated transportation and the packaging. This production dataset includes the disposal of a notebook and of its packaging. Therefore, to determine production input for the purposes of the present study, the share of disposal and transportation of the final product was deducted in order to arrive at the purely production-related GWP value (Section 4.1.2). The reference unit of this dataset is 1 produced notebook. As EcoInvent is a commercial database whose use incurs a charge, the detailed input and output data cannot be presented in publicly accessible publications.

UBA R&D project (UFOPLAN 2009)

A project (funding code: FKZ 3709 95 308) conducted within the UFOPLAN 2009 research programme of the German Federal Environment Agency (Umweltbundesamt, UBA)[4] generated datasets for two components – a display module and integrated circuits (memory ICs) of a notebook – with the aim of publishing these in the ProBas database (Prakash et al. 2011).

The dataset for the display module is based on an Environmental Product Declaration (EPD) of the Taiwanese company CMO.[16] The copper production data reported in that EPD were corrected by Prakash et al. 2011.

The system boundary of the dataset of this display module is cradle to gate. This means that it comprises resource extraction, production of materials and intermediate products, fabrication processes and the transport of goods to the CMO factory. Along this life cycle chain, the display module generates 35.11 kg CO_2e emissions per display with a size of 15.4″ and a weight of 530 g.

To calculate the transportation associated with a display module ex works to the final assembly of a notebook, 6,250 km by air is assumed. This distance is the average between Asia-Asia transport (approx. 2,500 km) and USA-Asia transport (10,000 km).

The dataset for integrated circuits (ICs) is limited to their direct production phases. The direct production input of energy and materials was determined in Prakash et al. (2011) without the related upstream chains. Furthermore, presentation of the IC datasets in ProBas differentiates between front-end and back-end processes. The IC datasets are therefore presented in ProBas with different reference units (Table 5).

Table 5: Overview of the IC datasets published in ProBas (Prakash et al. 2011)

No.	Dataset name in ProBas	Reference unit	Notes
1.	*Silizium Wafer Herstellung* (Silicon wafer production)	1 cm^2 polished silicon wafer	Partly with upstream chains. The upstream chains of hydrogen chloride, graphite and electrical energy are not included.
2.	*IC-Fertigung Front-End-Prozess|"Wafer Out"* (IC fabrication front-end process \ "wafer out")	1 cm^2 finished wafer out	Without upstream chain. However, the additional input factors for the production of high-purity process chemicals are characterised.
3.	*IC-Fertigung Front-End-Prozess|"Good Die Out"* (IC fabrication front-end process \ "good die out")	1 cm^2 defect-free die out	Without upstream chain. However, the additional input factors for the production of high-purity process chemicals are characterised.

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[16] Chi Mei Optoelectronics (CMO) is a part of the Chi Mei Corporation. CMO achieved a turnover of 9.9 billion US dollars in 2007. In March 2010, several companies – Innolux Display Corp., Chi Mei Optoelectronics and TPO Displays Corp. – merged to form the new company named Chimei Innolux Corporation. Its key products are liquid crystal displays (LCD) and panels for televisions and desktop and notebook PCs, which are assembled by OEMs worldwide in their products. Alongside AU Optronics Corporation (AUO), LG Display and Samsung, Chimei Innolux numbers among the largest manufacturers of liquid crystal displays using thin film transistor (TFT) technology.

4.	*IC-Fertigung Back-End-Prozess* (IC fabrication back-end process)	1 memory IC	Without upstream chain

The IC dataset generated by the UBA R&D projects (UFOPLAN 2009) and imported into ProBas relates to a specific IC from the Samsung company with 1 GB (gigabyte) DDR3 (Double Data Rate 3) Dynamic Random Access Memory (DRAM) with a FBGA (Fine Pitch Ball Grid Array) packaging type. The unencapsulated area is 43 mm^2 and the encapsulated finished product weighs 0.162 g (Prakash et al. 2011). In order to link the front-end processes and silicon wafer production, the principal material flows (silicon flows) are required. Figure 2 illustrates the principal processes and flows.

In consequence, the upstream chain used for IC datasets in the present study is documented and explained in the following sequence:

1. Silicon wafer production
2. Front-end processes for IC fabrication
3. Back-end processes for IC fabrication
4. Transport of IC between silicon wafer production and front-end process; between front-end process and back-end process; between back-end process and notebook assembly.

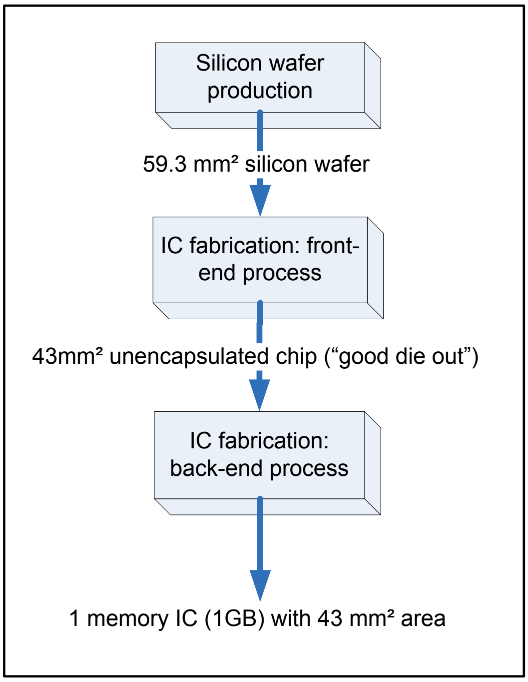

Figure 2: Principal material flows (silicon flows) associated with IC fabrication

Silicon wafer production

As Table 5 shows, the silicon wafer production dataset contains the upstream chains associated with the supply of the respective intermediate products, with the exception of electricity supply and graphite and hydrogen chloride production. Because energy consumption is the critical factor for the purposes of the present study, the average electricity mix is determined on the basis of the worldwide distribution of silicon wafer production. According to our own estimates, production is distributed among countries as shown in Table 6. The country-specific emission factors are attached as an annex (Table 42) to this report. The input and output data for silicon wafer production are listed in Table 43. The sources of these data are documented in Prakash et al. (2011).

Table 6: Distribution of silicon wafer production among countries (own estimates)

Distribution of silicon wafer production among countries	Proportion
Japan	66%
Germany	12.5%
USA	8.5%
Korea	8.5%
Singapore	4%
Total	100%

Table 7: Secondary data used for the upstream chain of silicon wafer production

Description of inputs	Processes	Database	Datasets	Spatial reference	Temporal reference
Silicon dioxide	Upstream chain: extraction from silica	GEMIS 4.6	Xtra mining\silica DE-2010	Germany	2010
Electrode material	Upstream chain: production	ProBas[17]	Graphite	Europe	2000–2004
Hydrogen chloride (HCl)	Upstream chain: production	EcoInvent 2.2	Hydrogen chloride from the reaction of chlorine with hydrogen, ex works	Europe	1997–2000

Front-end processes for IC fabrication

The dataset generated by the UBA R&D projects (UFOPLAN 2009)and imported into ProBas for the front-end process exclusively comprises direct production processes, i.e. starting from the silicon wafer as source and extending to the final production of a defect-free unencapsulated IC ("good die out"). The electricity mix is determined and modelled using a worldwide average

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[17] Öko-Institut 2005, http://www.probas.umweltbundesamt.de/php/volltextsuche.php?&prozessid={5F5B8E83-F37B-4B7E-A4C5-A33A19A64F0B}&id=1&step=1&search=Graphit&b=1

according to the distribution of front-end processes among countries (Table 8). The country-specific emission factors are listed in an annex (Table 42) to this report.

Table 8: Distribution of front-end processes among countries (own estimates)

Distribution of front-end processes among countries	Proportion
USA	15%
Europe	8%
Japan	23%
Korea	14%
Taiwan	23%
China	8%
Singapore	9%
Total	**100%**

Many high-purity chemicals are used in IC fabrication. Higgs et al. (2010) have examined the additional energy consumption attributable to the purification processes. The factors thus determined are compiled in Prakash et al. (2011) and are listed in the annex to this report (Table 47). The following Table 9 documents the secondary data used in the present study to model the front-end processes.

Table 9: Secondary data used for IC front-end processes

Processes	Database	Datasets + source	Spatial reference	Temporal reference
Silicon wafer	ProBas	Silicon wafer production	World mix	2000–2002
Elementary gases and chemicals				
N2 (high-purity)	GEMIS 4.6	Xtra-generic\N2 (gaseous) + factor for high-purity (Higgs et al. 2010)	Germany	2000
O2 (high-purity)	GEMIS 4.6	Xtra-generic\O2 (gaseous) + factor for high-purity (Higgs et al. 2010)	Germany	2000
Ar (argon) (high-purity)	GEMIS 4.6	Xtra-generic\Argon-DE-2005 + factor for high-purity (Higgs et al. 2010)	Germany	2005
H2 (high-purity)	GEMIS 4.6	Chem-inorg\H2 chemical + factor for high-purity (Higgs et al. 2010)	Germany	2000
Sulphuric acid (high-purity)	EcoInvent 2.2	Sulphuric acid, liquid, ex works + factor for high-purity (Higgs et al. 2010)	Europe	2001
Phosphoric acid (high-purity)	GEMIS 4.6	Chem-inorg\phosphoric acid + factor for high-purity (Higgs et al. 2010)	Germany	2000
Hydrogen peroxide (high-purity)	GEMIS 4.6	Chem-inorg\hydrogen peroxide + factor for high-purity (Higgs et al. 2010)	Germany	2000
2-propanol (C_3H_8O)/isopropyl alcohol (IPA) (high-purity)	GEMIS 4.6	Chem-org\2-propanol + factor for high-purity (Higgs et al. 2010)	Germany	2005
Ammonium hydroxide (high-purity)	GEMIS 4.6	Chem-inorg\ammonia-DE-2010 + factor for high-purity (Higgs et al. 2010)	Germany	2010
Hydrofluoric acid (high-purity)	EcoInvent 2.2	Hydrofluoric acid, ex works + factor for high-purity (Higgs et al. 2010)	Germany	1979–2006

Processes	Database	Datasets + source	Spatial reference	Temporal reference
PFC chemicals				
Chem-org\CF$_4$	ProBas[18]	Chem-org\CF$_4$	Germany	2005
Chem-org\C$_2$F$_6$	ProBas[19]	Chem-org\C$_2$F$_6$	Germany	2005
CHF$_3$	EcoInvent 2.2	Trifluoromethane, ex works	World mix	2000–2005
Chem-inorg\NF$_3$	ProBas[20]	Chem-inorg\NF$_3$	Germany	2005
Chem-inorg\SF$_6$	ProBas[21]	Chem-inorg\SF$_6$	Germany	2005
Water	ProBas[22]	Xtra potable water\DE-general	Germany	2000
NaOH (for effluent treatment)	ProBas[23]	Chem-inorg\NaOH-mix-DE	Germany	2000
Energy consumption				
Electricity mix (average based on distribution of production sites)	see Table 8		Electricity mix average based on distribution of production sites	2005–2010
Gas	GEMIS 4.6	Gas-boiler-DE-2010 (final energy)	Germany	2010

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[18] Öko-Institut 2005, http://www.probas.umweltbundesamt.de/php/volltextsuche.php?&prozessid={3BF953E5-B516-4B48-8D11-52AD3FEB862F}&id=1&step=1&search=Chem-Org\CF4&b=1

[19] Öko-Institut 2005, http://www.probas.umweltbundesamt.de/php/volltextsuche.php?&prozessid={AE1AD576-FD7E-46B6-ACAE-00D61BAEEFFB}&id=1&step=1&search=Chem-Org\C2F6&b=1

[20] Öko-Institut 2005, http://www.probas.umweltbundesamt.de/php/volltextsuche.php?&prozessid={C59A04E2-4887-4C4B-B397-301354829378}&id=1&step=1&search=Chem-Anorg\NF3&b=1

[21] Öko-Institut 2005, http://www.probas.umweltbundesamt.de/php/volltextsuche.php?&prozessid={045519F2-13CD-43A0-8EE9-9B452FEAE0ED}&id=1&step=1&search=Chem-Anorg\SF6&b=1

[22] Öko-Institut 2000, http://www.probas.umweltbundesamt.de/php/volltextsuche.php?&prozessid={611FF321-CDF7-456E-B8AE-A3016C1163B4}&id=1&step=1&search=Xtra-Trinkwasser\DE-allgemein&b=1

[23] Öko-Institut 2000, http://www.probas.umweltbundesamt.de/php/volltextsuche.php?&prozessid={0E0B2AC5-9043-11D3-B2C8-0080C8941B49}&id=1&step=1&search=Chem-Anorg\NaOH-mix-DE&b=1

Back-end processes for IC fabrication

The dataset for the back-end process that was generated as an outcome of the UBA R&D project (UFOPLAN 2009)and imported into ProBas exclusively comprises the direct production processes, i.e. the defect-free unencapsulated chip ("good die out") as initial input to the output of one finished and encapsulated memory IC.[24] The electricity mix is determined and modelled using a worldwide average according to the distribution of back-end processes among countries (Table 10). The country-specific emission factors are listed in an annex (Table 42) to this report. The input and output data of the back-end processes (Prakash et al. 2011) are listed in Table 46 of the annex. The secondary datasets used are listed in Table 11.

Table 10: Distribution of back-end processes among countries (own estimates)

Distribution of back-end processes among countries	Proportion
USA	10%
Europe	0%
Japan	10%
Korea	10%
Taiwan	15%
China	15%
Singapore	15%
Malaysia	15%
Philippines	10%
Total	100%

Table 11: Secondary datasets used for IC back-end processes

Production processes	Database	Datasets	Spatial reference	Temporal reference
Defect-free unencapsulated chip	ProBas	IC fabrication front-end process\"good die out"	World mix	2002–2010
Polymers	ProBas[25]	Polystyrene thermo-forming	Europe	no data
Silicon dioxide	GEMIS 4.6	Xtra-mining\silica-DE-2010	Germany	2010
Gold	ProBas/IFEU[26]	Gold	World mix	2000–2004
Carbon Black	ProBas[27]	Graphite	Europe	2000–2004

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[24] In this case SAMSUNG DRAM DDR3 with packaging type K4B1G0846E-HCH9

[25] PlasticsEurope 2005, http://www.probas.umweltbundesamt.de/php/volltextsuche.php?&prozessid={4B7D42FE-0847-4A31-B5A8-8F5C9E16D2B2}&id=1&step=1&search=Polystyrene thermoforming&b=1

[26] IFEU (Institut für Energie- und Umweltforschung Heidelberg) 2011

Production processes	**Database**	**Datasets**	**Spatial reference**	**Temporal reference**
Silver (Ag)	ProBas/IFEU[28]	Silver	Europe	2000–2005
Copper (Cu)	ProBas/IFEU	Copper	World mix	2000–2004
Tin (Sn)	ProBas/IFEU	Tin	World mix	2000–2004
BT-Core (bismaleimide-triazine) + Cu + Au + Ni	EcoInvent 2.2: Triazine compounds, ex regional distribution centre ProBas/IFEU for other metal production processes		World mix	2000–2010
Electricity mix (average based on distribution of production sites)	see Table 10		Electricity mix average based on distribution of production sites	2005–2010
Gas	GEMIS 4.6	Gas-boiler-DE-2010 (final energy)	Germany	2010

The material composition of DDR3 memory ICs stated by Samsung gives the mixture of BT-Core + Cu + Au + Ni as an aggregate total. In order to be able to model production broken down by individual materials, in the present study we make an estimate of our own (Table 12).

Table 12: Proportions of BT-Core + Cu + Au + Ni assumed for modelling purposes (own estimates)

BT-Core (bismaleimide-triazine) + Cu + Au + Ni	**Proportion**
BT(bismaleimide-triazine)-core	78%
Cu	20%
Ni	1.50%
Au	0.50%
Total	100%

Transport

IC transport comprises the following segments:

- from silicon wafer production to the front-end process,
- from the front-end to the back-end process,
- from the back-end process to the final assembly of the notebook.

As already indicated in Table 6, Table 8 and Table 10, production sites are spread around the world. Jain (2011) reports that in many cases chips are mounted at two different locations and are then tested at two further locations. It is not possible in the scope of the present study to

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[27] Öko-Institut 2005, http://www.probas.umweltbundesamt.de/php/volltextsuche.php?&prozessid={5F5B8E83-F37B-4B7E-A4C5-A33A19A64F0B}&id=1&step=1&search=Graphit&b=1

[28] IFEU (Institut für Energie- und Umweltforschung Heidelberg) 2011

model the entire logistics chain. It is therefore assumed that transport by air covers a distance of 6,250 km (this being the average of Asia–Asia: (approx. 2,500 km and USA–Asia: approx. 10,000 km)).

Table 13: Dataset used for freight transport by air

Input	Database	Datasets	Spatial reference	Temporal reference
Transport by air	EcoInvent 2.2	Transport, airfreight, intercontinental	Europe	2000

3.2 Distribution of finished products to wholesalers and retailers

The data for the inventory analysis of distribution to wholesalers and to points of sale are based on assumptions made by O'Connell and Stutz (2010) and own estimates. O'Connell and Stutz (2010) make the following assumptions concerning the European distribution network:

- Air transport from China to Poland and
- further land carriage by truck from Poland to the final customers.

Proceeding from these assumptions, the overall distribution chain has three phases (Figure 3):

1. From the production sites to the airport (16-32 t truck) → 500 km and 80% capacity utilisation
2. From Shanghai PuDong airport to Warsaw airport → 8,000 km
3. Fine distribution from Poland to retailers (7.5–16 t truck) → 1,000 km and 80% capacity utilisation.

The capacity utilisation rate and the truck type were estimated in the present study and applied to the round trip. For LCA purposes, both the outward and return journey of truck carriage should be taken into account. This means that if the truck is fully loaded during the outward journey (100% capacity utilisation) and carries other goods with a capacity utilisation of 60% on the return journey, capacity utilisation for the round trip is 80%. Only 40% of the environmental impact attributable to the return journey is allocated to the notebooks, while the remaining 60% is allocated to the other goods transported.

Figure 3: Schematic of distribution chain

Freight transport is weighted according to the respective delivery weight. This means that, due to their different weights, the three notebooks studied contribute different proportions to the environmental impacts arising during the distribution phase. The datasets used are listed in Table 14.

Table 15 shows the corresponding emission factors. It should be noted that the emission factor of air transport does not take account of the Radiative Forcing Index (RFI). In the sensitivity analysis transport by air is calculated with RFI in order to identify the full range of outcomes (Section 5.4).

Table 14: Datasets for modelling distribution to wholesalers and retailers

Input	Datasets	Temporal reference	Spatial reference	Source
Transport from production sites to airport	Transport, truck 16–32 t, EURO3	2005	Europe	EcoInvent 2.2
Air transport (from Shanghai to Warsaw)	Transport, airfreight, intercontinental	2000	Europe	EcoInvent 2.2
Fine distribution (from airport to retailers)	Transport, truck 7.5-16t, EURO3	2005	Europe	EcoInvent 2.2

Table 15: Emission factors of truck and air transport (EcoInvent 2.2)

Input	Emission factors (GWP values)	Unit
Transport, truck 16–32 t, EURO3	0.15	kg CO_2e/tkm
Airfreight (intercontinental)	1.04	kg CO_2e/tkm
Transport, truck 7.5–16 t, EURO3	0.20	kg CO_2e/tkm

3.3 Shopping trip

It is assumed in all scenarios that the user makes a shopping trip by car for the sole purpose of purchasing the notebook. Therefore not just a proportion of the shopping trip (depending upon the total weight of the goods purchased) is attributed to the notebook, but 100% of the trip. A shopping trip of 5 km (one way) with an average car is assumed. In accordance with the car fleet in Germany as of January 2010, a proportion of 26% cars with diesel engine and 74% cars with petrol engine was taken for the calculation (KBA 2010).[29] The datasets used are from

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[29] The original statistics compiled by the German Federal Motor Transport Authority (Kraftfahrt-Bundesamt, KBA) record the following breakdown of the car fleet: 73% petrol, 26% diesel and a further 1% running on liquefied petroleum gas, natural gas or electricity and hybrid. For the purposes of the present study, these 1% are neglected and the proportions of petrol and diesel vehicles are adjusted accordingly.

EcoInvent 2.2[30] (see Table 16). The reference units of the datasets correspond to 1.6 persons and 1 km. The resulting emission factor is 143 g/pkm.

Table 16: Datasets for modelling the shopping trip

Input	Datasets	Temporal reference	Spatial reference	Source
Diesel car (26%)	Transport, car, diesel, fleet average of 2010	2010	Europe	EcoInvent 2.2
Petrol car (74%)	Transport, car, petrol, fleet average of 2010	2010	Europe	EcoInvent 2.2

3.4 Use phase

The database of Energy Star Version 5.0 for computers provides the data on energy consumption in the use phase.[31]

As the electricity consumption of a notebook depends greatly upon the way it is used, the sensitivity analysis examines a different weighting of operational states (Section 5.3). Depending upon their configuration, notebooks are classed in three categories. The precise definitions are set out in Energy Star Version 5.0 for computers.

The following Table 17 shows the weighting of the three operational states:

Table 17: Weighting of the operational states of a notebook (Energy Star® Version 5.0)

Operational state	Proportion
T-Off	60%
T-Sleep	10%
T-Idle	30%

Table 18 shows the number of models that were selected for the respective Energy Star category, and their electricity consumption. The average electricity consumption of a notebook with a lifetime of 5 years is derived from these values; it figures 231 kWh per year. The emission factor was taken from GEMIS 4.6 and is based on data for the German electricity mix (low voltage). It figures 0.599 kg CO_2e/kWh and is used in all scenarios.

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[30] ProBas (www.probas.umweltbundesamt.de) also contains recent datasets for the shopping trip. The datasets from EcoInvent 2.2 are only used because of agreements made between the client and the study contractor concerning scenario formulation.

[31] http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=CO; accessed August 2010

Table 18: TEC values (kWh/a) of the notebooks[32], as of August 2010 (Energy Star® Version 5.0)

	Category A[33]	Category B	Category C
Number of models measured, base configuration (n)	1190	264	9
TEC: Annual average electricity consumption	30.1 kWh	40.2 kWh	68.5 kWh
TEC: Annual average over the three categories	46.3 kWh		
Average electricity consumption over a period of 5 years (according to assumed lifetime)	**231.3 kWh**		

3.5 End-of-life

Disposal processes were already characterised for Scenario 1 in detail in EuP Lot 3 (2005) and are not explained further here. For the other scenarios, a distinction is made in the "End-of-life" phase between business-as-usual and best practice.

3.5.1 Business-as-usual

"End-of-life" comprises disposal and recycling processes. The datasets of EcoInvent 2.2 were used to model the disposal of a notebook. The dataset titled *"Entsorgung, Laptop Computer, in E-Schrott-Aufbereitung"* (disposal, laptop computer, in e-scrap processing) captures the disposal situation in Switzerland in 2005. In accordance with the WEEE Directive, e-scrap is first pretreated manually, whereby the components and materials stipulated in Annex II to the Directive, such as batteries and displays, must be removed. The next step is mechanical treatment (in a shredder). The EcoInvent 2.2 dataset comprises

- collection,
- detoxification (manual removal of batteries and display modules),
- mechanical pretreatment (shredder facility)
- transport to the processing works,
- treatment and processing, and extraction of secondary metals,

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[32] Devices in base configuration of the relevant categories

[33] Category A: All portable computers that do not meet the definition of Category B or Category C can qualify for Category A.

Category B: To qualify for Category B, portable computers must have the following attributes:
- a discrete graphics processing unit (GPU).

Category C: To qualify for Category C, portable computers must have the following attributes:
- at least two physical processor cores
- at least 2 gigabyte (GB) system memory and
- a discrete graphics processing unit (GPU) with a frame buffer above 128 bit

- landfilling of residues.

The non-precious metal fractions acquired by those processes are listed in Table 19.

Table 19: Metal fractions acquired after shredding, in relation to 1 kg notebook (Hischier 2007)

Fraction	Quantity	Unit
Al fraction, mechanical treatment, laptop computer, at plant [GLO]	0.067	kg
Cu fraction, mechanical treatment, laptop computer, at plant [GLO]	0.101	kg
Fe fraction, mechanical treatment, laptop computer, at plant [GLO]	0.162	kg
Dismantling, laptop, mechanically, at plant [GLO]	1	kg

To calculate the precious metals extracted, first the precious metal contents of a notebook need to be specified. It was not possible in the context of this study to produce a complete compilation of the materials contained in a notebook. A project conducted by Berlin Technical University and the Fraunhofer IZM has studied the material composition of an assembled printed wiring board (Gref et al. 2008). Table 20 lists the mass percentages of silver and gold contained in the wiring board as identified by that study. The proportions of silver contained in other components were taken from EuP Lot 3, and the proportion taken from Gref et al. 2008 was added. The proportion of silver in a notebook taken for the present study is thus on a scale similar to that of a desktop PC (Gmünder 2007).

The proportion of gold, however, differs greatly between the two studies. The present study uses the gold proportion taken from Gref et al. 2008.[34]

As no further sources are available that state the proportion of palladium contained in a notebook, the figure given by Gmünder (2007) was used and extrapolated to the weight of the notebook. The values printed bold in Table 20 were used for the present study.

Table 20: Estimated Ag, Au and Pd proportions in the notebook

Precious metal	EuP Lot 3 (excl. printed wiring board)	Gref et al. 2008 (only printed wiring board)	Total (EuP Lot 3; Gref et al.)	Gmünder 2007
Ag	0.01%	0.005%	**0.015%**	0.017%
Au	0%	0.010%	**0.010%**	0.003%
Pd	no data	no data	no data	**0.001%**

Table 21 lists the recycling rates for the precious metals. Scenarios 2 and 3, which model the end-of-life phase as business-as-usual, proceed from these recycling rates and precious metal fractions extrapolated on the basis of the weight of the notebook studied. Table 49 lists the detailed outcomes for the metals extracted. It is to be noted in this context that the additional

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[34] The assumption by Gref et al is the best-practice assumption for the proportion of gold contained in the printed wiring board of a notebook. The figure reported by Gmünder (2007) relates to a desktop PC, while the EuP study reports 0%.

treatment input required is taken into account in a first approximation using a general dataset for secondary precious metal extraction taken from EcoInvent 2.1. A credit is allocated through the corresponding primary metal production. The emission factors used are listed in Table 48 in the annex.

Table 21: Recycling rates for business-as-usual scenario

Precious metals	Business-as-usual	Source
Ag	40%	Personal communication[35]
Au	40%	Chancerel 2010
Pd	40%	Chancerel 2010

3.5.2 Best practice

In the best-practice variant, precious metals such as Au, Ag and Pd are recovered with greater efficiency than in business-as-usual (Table 22). These efficiency improvements can be achieved mainly through optimised manual pretreatment that largely avoids subsequent mechanical processing by shredding. The credit is allocated through the corresponding primary metal production. The emission factors used are listed in Table 48 in the annex.

Table 22: Recycling rates for best practice[36]

Precious metal	Best practice	Source
Ag	87%	Prakash and Manhart 2010
Au	93%	Prakash and Manhart 2010
Pd	91%	Prakash and Manhart 2010

4 Presentation and interpretation of outcomes

The following Section 4.1 presents the GWP outcomes of the individual scenarios that were calculated on the basis of the assumptions and methodology set out in the previous sections and the system boundaries defined in Section 2.2.3. Section 4.2 then gives an overview of the aggregate greenhouse gas emissions of all scenarios, while Section 4.3 discusses the amortisation periods of the individual scenarios. Section 5 then examines four sensitivity

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[35] Dr.-Ing. Perrine Chancerel, staff scientist at the Fraunhofer Institute for Reliability and Microintegration (IZM, Berlin Technical University), Dept. Environmental Engineering

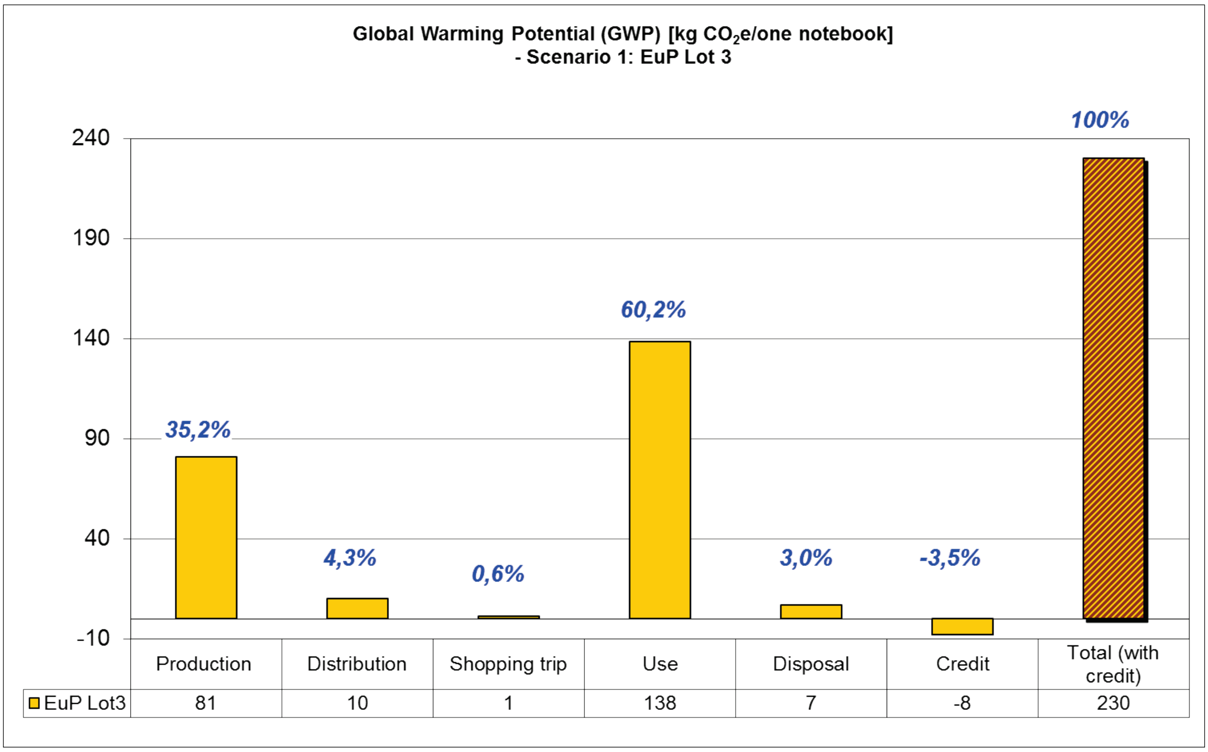
[36] In Prakash and Manhart (2010) the recycling rates in Best-Available-Technologies were determined on the basis of deep manual dismantling of a desktop PC to the level of subcomponents.

analyses in which key parameters or the methodology were varied in order to examine the effects of such changes upon the outcomes.

4.1 Presentation of the outcomes of the individual scenarios

4.1.1 Scenario 1: EuP Lot 3

Overall, the EuP Lot 3 scenario results in 230 kg CO_2e over the entire life cycle of a notebook. Figure 4 shows both the absolute GWP emissions and the percentage shares of the individual life cycle phases of a notebook. The greatest proportion of GWP emissions arises in the use phase with 60.2%, followed by the production phase with 35.2%. The outcomes of the use phase were calculated assuming a useful lifetime of 5 years. Distribution to wholesalers and fine distribution to retailers generates 4.3% of the total GWP emissions. “End-of-life” additionally identifies the credits arising in the notebook disposal process. Due to the credits (from recycling) the total GWP emissions are reduced. With a contribution of just under one percent (0.6%) the shopping trip has scarcely any impact.



	Production	Distribution	Shopping trip	Use	Disposal	Credit	Total (with credit)
■ EuP Lot3	81	10	1	138	7	-8	230

Figure 4: Absolute GWP values and percentage proportions of life cycle phases in Scenario 1: EuP Lot 3

The GWP values for production, distribution and end-of-life are based on EuP Lot 3. The absolute GWP values generated by the shopping trip and the use phase are equal in all scenarios, as they were inventoried on the basis of the same assumptions (Sections 3.3 and 3.4).

4.1.2 Scenario 2: EcoInvent 2.2

Overall, the EcoInvent 2.2. scenario results in 362 kg CO_2e over the entire life cycle of a notebook.

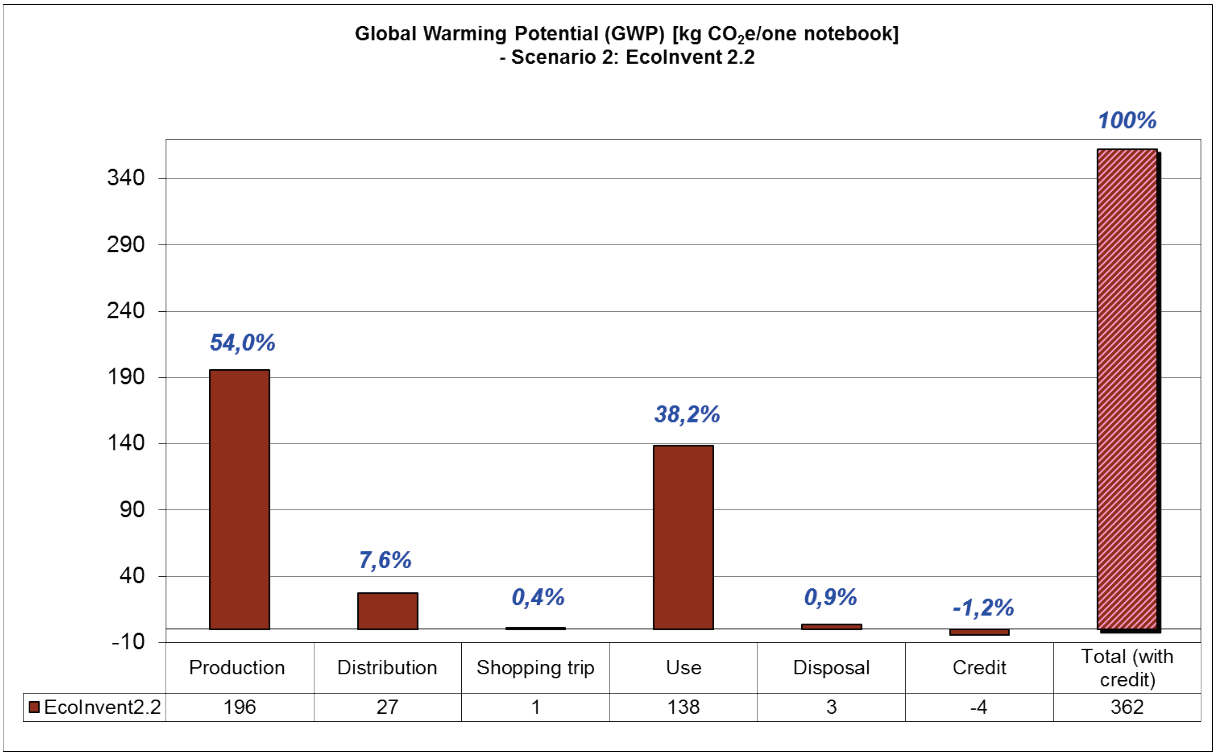


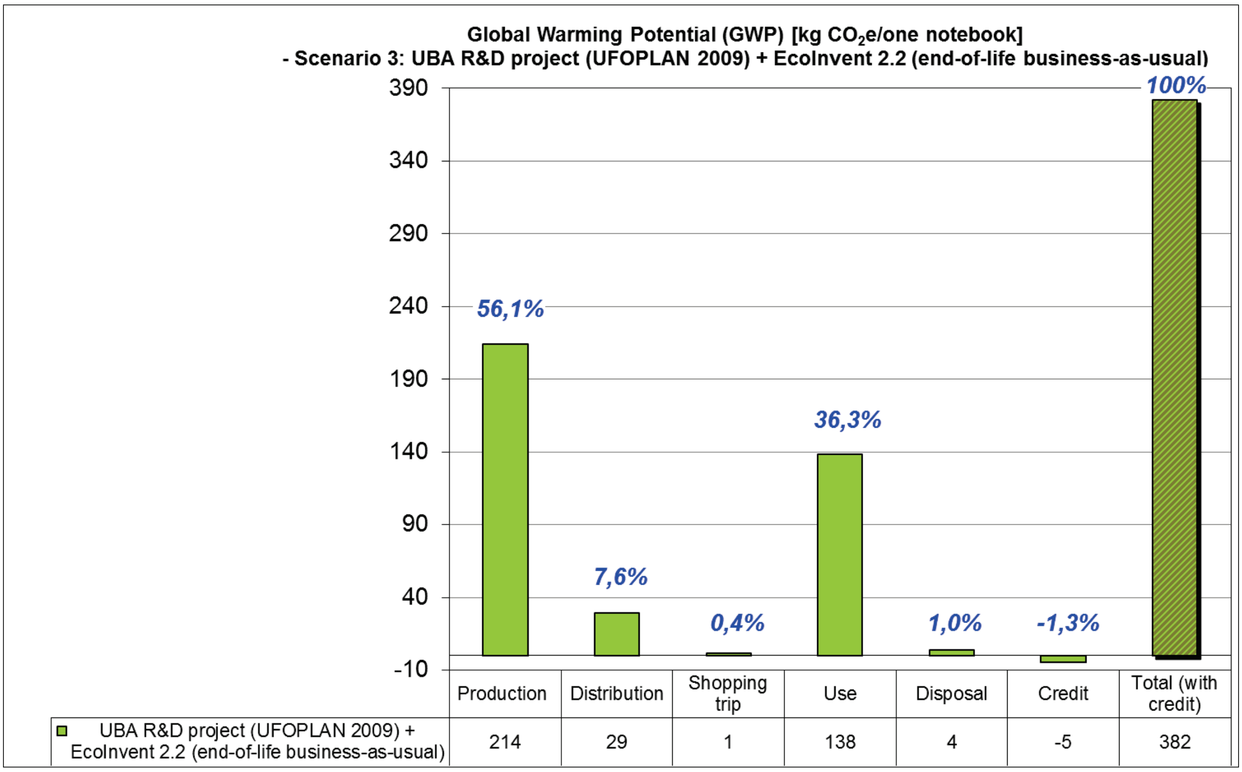
Figure 5: Absolute GWP values and percentage proportions of life cycle phases in Scenario 2: EcoInvent 2.2

Figure 5 shows both the absolute GWP emissions and the percentage shares of the individual life cycle phases of a notebook. Production accounts for the largest proportion of GWP emissions with 54%, followed by the use phase with 38.2%. The outcomes of the use phase were calculated assuming a useful lifetime of 5 years. Distribution to wholesalers and fine distribution to retailers generates 7.6% of the total GWP emissions. “End-of-life” additionally identifies the credits arising in the notebook disposal process. The credit (Al, Cu and Fe secondary metal production through primary metal production) has a positive effect upon the overall GWP outcome. As a result, the emissions arising in the disposal process are compensated fully by the recycling credits. With a contribution of just under one percent (0.4%) the shopping trip has scarcely any impact.

The notebook production and disposal phases are based on datasets from EcoInvent 2.2. For distribution to wholesalers and fine distribution to retailers the same assumptions were made as in Scenarios 3 and 4. The absolute GWP values generated by the shopping trip and the use phase are equal in all scenarios, as they were inventoried on the basis of the same assumptions (Sections 3.3 and 3.4).

4.1.3 Scenario 3: UBA R&D project (UFOPLAN 2009) + EcoInvent 2.2 (end-of-life business-as-usual)

Overall, this scenario results in 382 kg CO_2e over the entire life cycle of a notebook. Figure 6 shows both the absolute GWP emissions and the percentage shares of the individual life cycle phases of a notebook. Production accounts for the largest proportion of GWP emissions with 56%, followed by the use phase with 36%. The outcomes of the use phase were calculated assuming a useful lifetime of 5 years. Distribution to wholesalers and fine distribution to retailers generates 7.6% of the total GWP emissions. “End-of-life” additionally identifies the credits arising in the notebook disposal process. The credit (Al, Cu and Fe secondary metal production through primary metal production) in business-as-usual has a positive effect upon the overall GWP outcome. With a contribution of just under one percent (0.4%) the shopping trip has scarcely any impact.



	Production	Distribution	Shopping trip	Use	Disposal	Credit	Total (with credit)
🟩 UBA R&D project (UFOPLAN 2009) + EcoInvent 2.2 (end-of-life business-as-usual)	214	29	1	138	4	-5	382

Figure 6: Absolute GWP values and percentage proportions of life cycle phases in Scenario 3: UBA R&D project (UFOPLAN 2009) + EcoInvent and end-of-life as business-as-usual

The data for the production of a display module and a memory IC are taken from Prakash et al. (2011). In Prakash et al. (2011), the datasets for the display module and the memory IC were imported into the ProBas database. The resulting GWP values are listed in Table 23 together with the GWP values of the other components from EcoInvent 2.2, with 1 notebook as reference unit. The production and transport of the display module account for just under 18% of the GWP emissions of the entire production of a notebook. Production of the memory IC accounts for just under 5%. Table 50 in the annex lists the absolute and percentage distribution of the GWP values of memory IC fabrication. Figure 7 illustrates that the front-end process, with around 66%, accounts for the largest contribution to the GWP emissions of memory IC fabrication, followed by the back-end process with 20% and silicon wafer production with 14%. Although transport is by air, the three trips have only a minimum impact on the overall outcome, as the ICs are very light.

Table 23: Specific outcomes for the display module and memory ICs from the UBA R&D project (UFOPLAN 2009) (kg CO_2e/notebook)

Outcomes	GWP (kg CO_2e/notebook)	Proportion
Display module: Production (Prakash et al. 2011)	35.1	16.4%
Display module: Transport	3.4	1.6%
Memory ICs (8GB): Fabrication (Prakash et al. 2011)	7.6	3.5%
Memory ICs (8GB): Transport (silicon wafer -> front-end process -> back-end process -> notebook assembly)	0.03	0.01%
Other components (EcoInvent 2.2)	168	78.5%
Total	**214**	**100%**

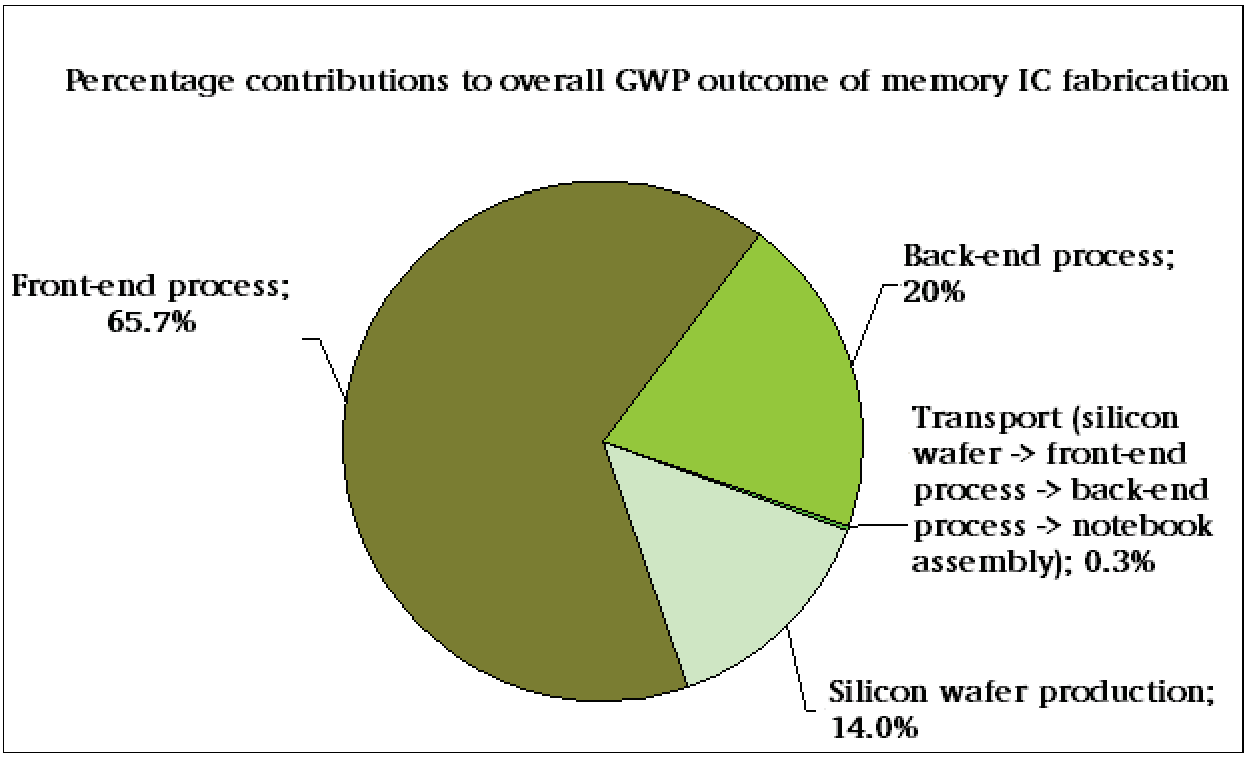


Figure 7: Percentage contributions to overall GWP outcome of memory IC fabrication

Disposal is identical to that in Scenario 2. For distribution to wholesalers and fine distribution to retailers, the same assumptions were made as in Scenarios 2 and 4. The absolute GWP values generated by the shopping trip and the use phase are equal in all scenarios, as they were inventoried on the basis of the same assumptions (Sections 3.3 and 3.4).

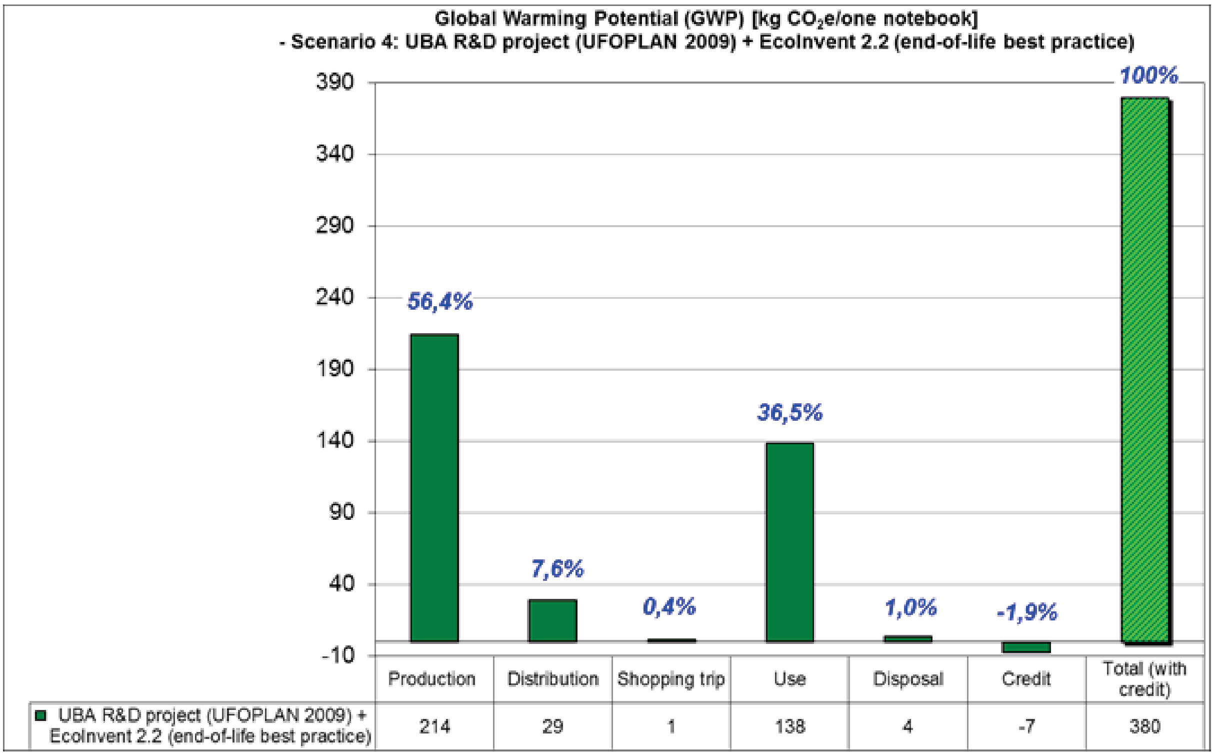
4.1.4 Scenario 4: UBA R&D project (UFOPLAN 2009) + EcoInvent 2.2 (end-of-life best practice)

Overall, this scenario results in 380 kg CO_2e over the entire life cycle of a notebook. Figure 8 shows for the breakdown among the phases an outcome similar to that of Scenario 3. Production accounts for the largest proportion of GWP emissions with 56%, followed by the use phase with 36.5%. The outcomes of the use phase were calculated assuming a useful lifetime of

5 years. Distribution to wholesalers and fine distribution to retailers generates 7.6% of the total GWP emissions.

The outcomes for the notebook display module and memory IC that were taken from the study by Prakash et al. (2011) are already described in Scenario 3 (Section 4.1.3).

The only difference between Scenario 4 and Scenario 3 is the modelling of the “End-of-life” phase. As Table 48 shows, the GWP outcomes of primary metal production and secondary metal production differ enormously, which impacts particularly on the precious metal outcomes. Table 49 lists the metal fractions calculated in the inventory analysis, in relation to the functional unit. The additional consideration of credits for Au, Ag and Pd has a positive effect upon the overall GWP outcome. This results in a negative CO_2e value.

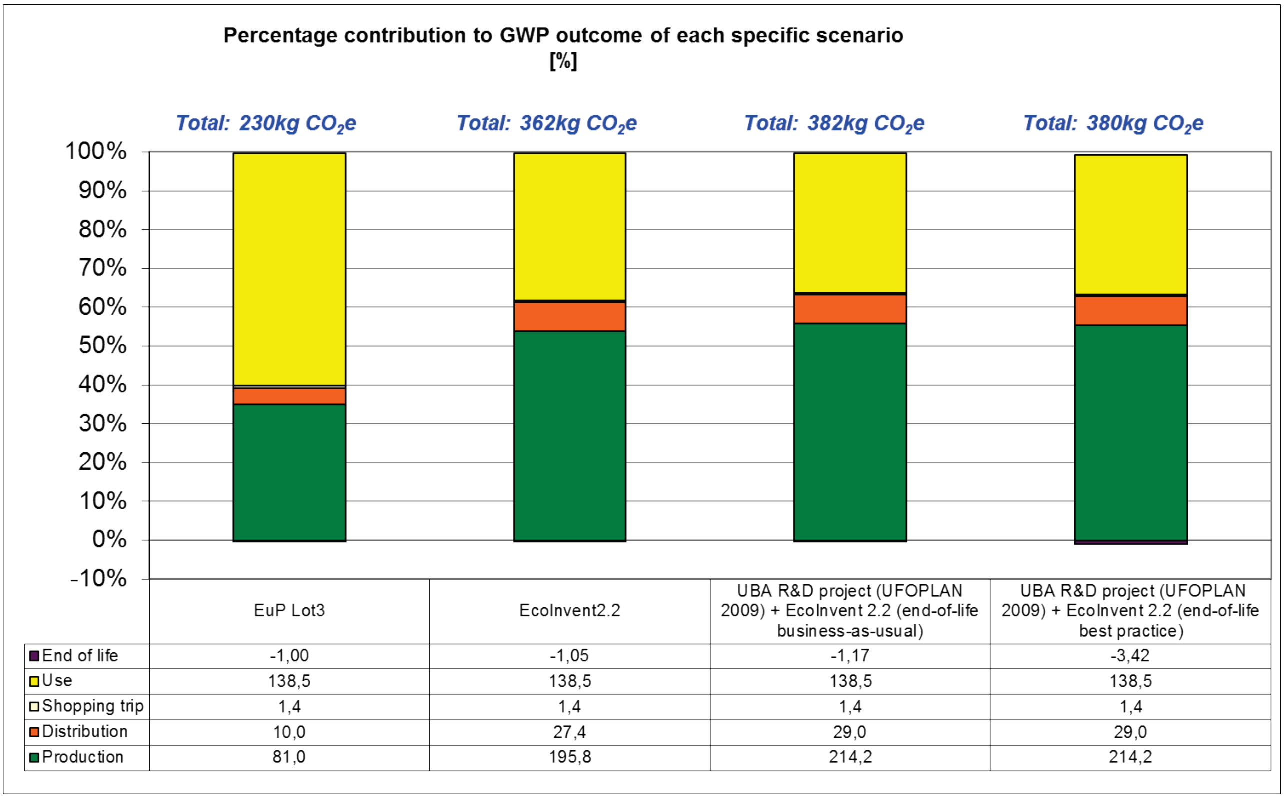


	Production	Distribution	Shopping trip	Use	Disposal	Credit	Total (with credit)
■ UBA R&D project (UFOPLAN 2009) + EcoInvent 2.2 (end-of-life best practice)	214	29	1	138	4	-7	380

Figure 8: Absolute GWP values and percentage proportions of life cycle phases in Scenario 4: UBA R&D project (UFOPLAN 2009) + EcoInvent and end-of-life as best practice

4.2 Overview of all scenarios studied

Figure 9 provides an overview of the GWP values resulting from all scenarios studied. The GWP emissions of Scenario EuP Lot 3 are the lowest. Furthermore in Scenario EuP Lot 3 the use phase is dominant, while in other three scenarios the production phase makes the greatest contribution to the overall outcome. The reason for the minor difference in the distribution phase of Scenarios 2, 3 and 4 is that the notebooks studied have different weights (Table 2) and the environmental impact resulting from transport is calculated according to the weight of the freight (with the same assumptions regarding kilometres travelled, truck size and truck capacity utilisation). The results for the use phase (assuming a useful lifetime of 5 years) and the shopping trip are the same in all scenarios. Due to their small proportion, the shares of the shopping trip and of the end-of-life phase are not visible in the figure. Together, they account for just under 1 percent of the total GWP emissions.



	EuP Lot3	EcoInvent2.2	UBA R&D project (UFOPLAN 2009) + EcoInvent 2.2 (end-of-life business-as-usual)	UBA R&D project (UFOPLAN 2009) + EcoInvent 2.2 (end-of-life best practice)
🟪 End of life	-1,00	-1,05	-1,17	-3,42
🟨 Use	138,5	138,5	138,5	138,5
☐ Shopping trip	1,4	1,4	1,4	1,4
🟧 Distribution	10,0	27,4	29,0	29,0
🟩 Production	81,0	195,8	214,2	214,2

Figure 9: Absolute GWP emissions outcome for all scenarios studied, differentiated according to life cycle phase (kg CO_2e/notebook)

Figure 10 shows the GWP emissions resulting from a PCF study conducted by O’Connell and Stutz (2010). The total GWP values are between 320 kg CO_2e in Europe and 370 kg CO_2e in China, the reference unit being 1 notebook with a lifetime of 4 years. In Europe, the production phase accounts for 47% of emissions (150 kg CO_2e) and the use phase also accounts for 47% of the emissions, while in China the use phase accounts for 65% of total emissions. This is due to the Chinese electricity mix, which has a higher emission factor than the European electricity mix (O’Connell and Stutz 2010).

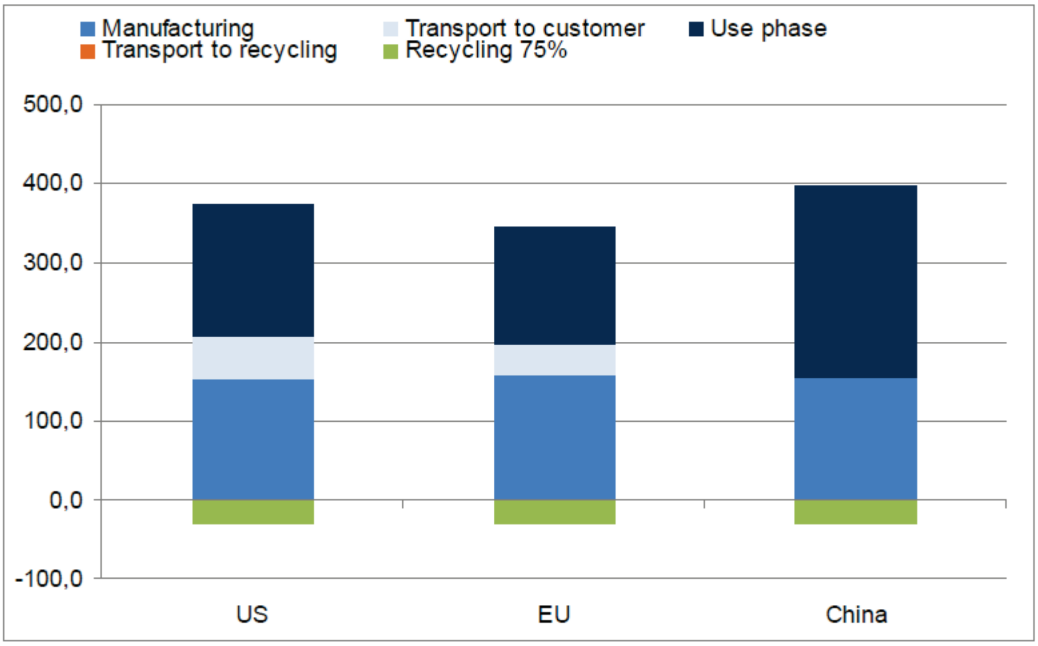


Figure 10: GWP emissions of a notebook (kg CO_2e/notebook). Lifetime 4 years (O'Connell&Stutz 2010)

If we compare the findings of O'Connell and Stutz (2010) with the outcomes of the individual scenarios in the present study, we find the following differences:

The outcomes for notebook production of O'Connell and Stutz (2010) are approx. 85% higher than those of Scenario 1 EuP Lot 3 and approx. 33% below those of Scenario 2 EcoInvent. Compared to Scenarios 3 and 4, the outcomes for notebook production are also lower in O'Connell and Stutz (2010), namely by approx. 45%.

4.3 Amortisation calculation

To calculate amortisation periods (in years) it was assumed that the new notebook is more energy-efficient in use than the old one. To model different scenarios for different levels of energy efficiency improvement of new notebooks compared to old ones, energy efficiency improvement classes were formed with intervals of 10 percent. This means that the new notebooks improve by 10% energy efficiency increments in the use phase (compared to the base scenarios 1 to 4), until an energy efficiency improvement of 50% is reached. A further calculation is performed for an increase by 70%. In other words, the GWP outcomes of the new notebooks in the use phase always develop in step with the energy efficiency improvements. This results in different GWP outcomes over the entire life cycle of the new notebook, whereby the GWP values of production, distribution (incl. shopping trip) and disposal always remain the same. The saving potential in the use phase that results from energy efficiency improvement compared to the old device (base scenarios) can be calculated as follows:

$$GWP_{\text{Saving potential}} = GWP\__{\text{Use}}\ [kg\ CO_2e/year/notebook] * x[\%])$$

whereby

- GWP $_{Use}$ (kg CO_2e/year/notebook) represents the annual greenhouse gas emissions of the old notebook in the use phase
- x is the energy efficiency improvement (in %) of the new notebook.

The corresponding amortisation periods (years) can be calculated as follows: the GWP value of production, distribution (incl. shopping trip) and disposal is divided by the GWP values saved due to energy efficiency improvement (savings in use compared to the old notebook) of the new notebook.

$$= \frac{GWP_{\Pr oduction,\, distribution,\, disposal}}{GWP_{Saving\ \ potential}}$$

It is to be noted here that possible changes in the framework conditions are not taken into account, such as changes in the emission factor of the electricity mix that might arise from the substitution of an energy carrier, energy efficiency improvement of electricity supply, or changes in utilisation patterns over time. The analysis is therefore a static one.

The following tables (Table 24 to Table 27) list the amortisation periods of the four scenarios studied. As a general principle, the higher the energy efficiency improvement is, the shorter is the amortisation period.

Table 24: Amortisation calculation with energy efficiency improvement in the use phase in Scenario 1: EuP Lot 3

		Energy efficiency improvement					
EuP Lot 3	**Initial situation**	**10%**	**20%**	**30%**	**40%**	**50%**	**70%**
GWP: Production, distribution[37] and disposal) (kg CO_2e/one notebook)	91.4	91.4	91.4	91.4	91.4	91.4	91.4
GWP: Only use phase (kg CO_2e/year and notebook)	27.7	24.9	22.2	19.4	16.6	13.8	8.3
GWP: Saving potential in the use phase compared to the old device (kg CO_2e/year and notebook)	-	2.8	5.5	8.3	11.1	13.8	19.4
Amortisation period (years) $= \frac{GWP_{\Pr oduction,\, distribution,\, disposal}}{GWP_{Saving\ \ potential}}$	**-**	**33**	**17**	**11**	**8**	**7**	**5**

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[37] In the Tables 24 to 27 distribution includes the shopping trip.

Table 25: Amortisation calculation with energy efficiency improvement in the use phase in Scenario 2: EcoInvent 2.2

EcoInvent 2.2\“Business as-usual“	**Initial situation**	**Energy efficiency improvement**					
		10%	**20%**	**30%**	**40%**	**50%**	**70%**
GWP: Production, distribution and disposal) (kg CO_2e/one notebook)	223.7	223.7	223.7	223.7	223.7	223.7	223.7
GWP: Only use phase (kg CO_2e/year and notebook)	27.7	24.9	22.2	19.4	16.6	13.8	8.3
GWP: Saving potential in the use phase compared to the old device (kg CO_2e/year and notebook	-	2.8	5.5	8.3	11.1	13.8	19.4
Amortisation period (years) $= \frac{GWP_{Production,\ distribution,\ disposal}}{GWP_{Saving\ potential}}$	-	**81**	**40**	**27**	**20**	**16**	**12**

Table 26: Amortisation calculation with energy efficiency improvement in the use phase in Scenario 3: UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life business-as-usual)

UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life business-as-usual)	**Initial situation**	**Energy efficiency improvement**					
		10%	**20%**	**30%**	**40%**	**50%**	**70%**
GWP: Production, distribution and disposal) (kg CO_2e/one notebook)	243.4	243.4	243.4	243.4	243.4	243.4	243.4
GWP: Only use phase (kg CO_2e/year and notebook)	27.7	24.9	22.2	19.4	16.6	13.8	8.3
GWP: Saving potential in the use phase compared to the old device (kg CO_2e/year and notebook	-	2.8	5.5	8.3	11.1	13.8	19.4
Amortisation period (years) $= \frac{GWP_{Production,\ distribution,\ disposal}}{GWP_{Saving\ potential}}$	-	**89**	**44**	**29**	**22**	**18**	**13**

Table 27: Amortisation calculation with energy efficiency improvement in the use phase in Scenario 4: UBA R&D project (UFOPLAN 2009) +EcoInvent (end-of-life best practice)

UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life best practice)	**Initial situation**	**Energy efficiency improvement**					
		10%	**20%**	**30%**	**40%**	**50%**	**70%**
GWP: Production, distribution and disposal) (kg CO_2e/one notebook)	241.2	241.2	241.2	241.2	241.2	241.2	241.2
GWP: Only use phase (kg CO_2e/year and notebook)	27.7	24.9	22.2	19.4	16.6	13.8	8.3
GWP: Saving potential in the use phase compared to the old device (kg CO_2e/year and notebook	-	2.8	5.5	8.3	11.1	13.8	19.4
Amortisation period (years) $= \frac{GWP_{Production,\ distribution,\ disposal}}{GWP_{Saving\ potential}}$	**-**	**87**	**44**	**29**	**22**	**17**	**12**

Tables 24 to 27 show that if the new notebook is 10% more energy-efficient in use, depending upon the data source the amortisation period is between 33 and 89 years. This means that the old notebook would have had to be used between 33 and 89 years to compensate the greenhouse gas emissions attributable to the production, distribution and disposal of the new notebook. If the energy efficiency of the new notebook increases by 70%, the amortisation period shortens to values between 6 and 13 years depending upon data source.

The additional consideration of increased precious metal recovery has only a marginal impact on the overall outcome (cf. Scenarios 3 and 4).

Figure 11 gives an overview of the amortisation periods of all scenarios studied:

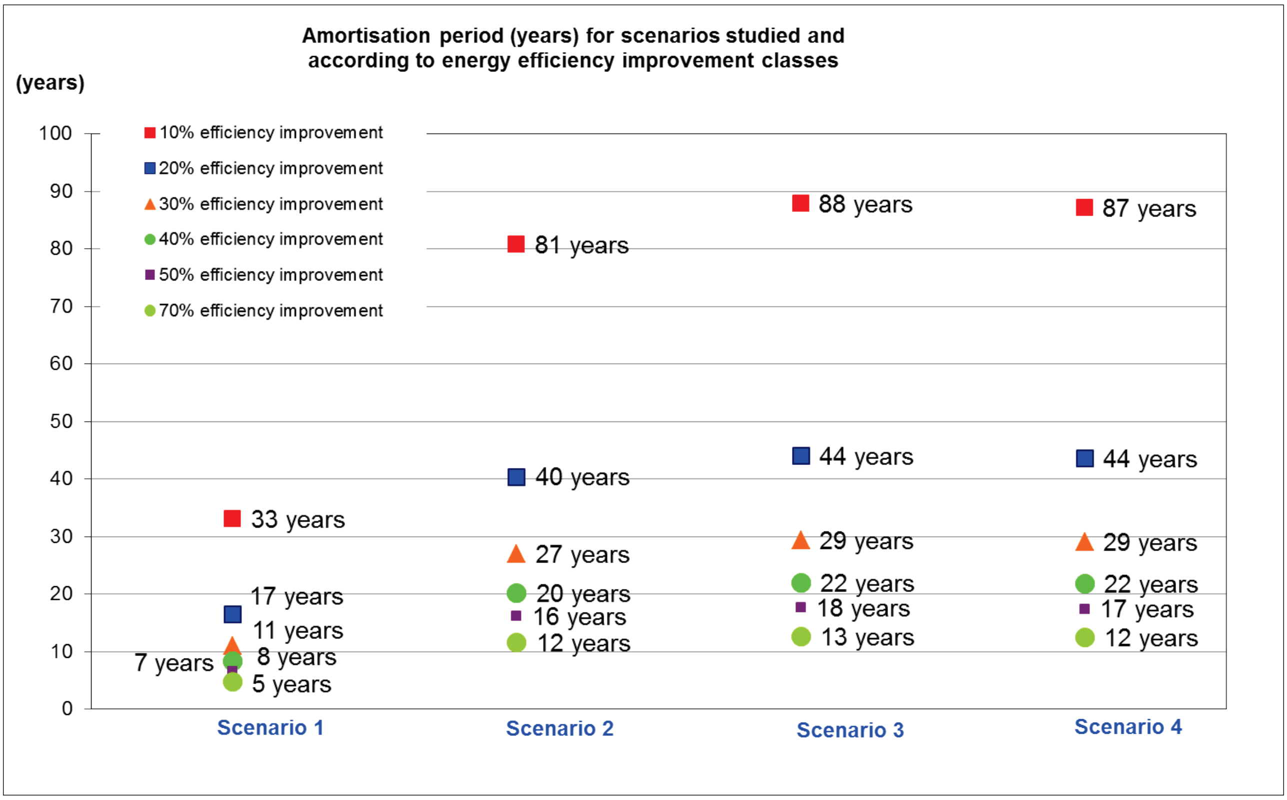

Figure 11: Overview of amortisation period as a function of energy efficiency improvement in the use phase, for all scenarios

5 Sensitivity analysis

The principal input quantities for the calculation of GWP emissions are:

- the quantity of electricity consumed,
- the operational modes in the use phase and
- methodological uncertainties.

Inaccuracies attaching to these quantities can therefore significantly influence the GWP outcome. The following sections examine systematically the influence that the input quantities can have upon GWP emissions. This is done by performing sensitivity analyses examining those parameters that involve uncertainties or which were estimated.

The sensitivity analyses are carried out for the following cases:

- Adjustment of electricity consumption values in the use phase according to the limits set under Energy Star® Version 5.0 for computers (Section 5.1)
- Adjustment of electricity consumption values and of operational modes in the use phase according to EuP Lot 3 (Section 5.2)
- Adjustment of the weighting of the operational modes in the use phase (Section 5.3)
- Consideration of the Radiative Forcing Index (RFI) (Section 5.4) in air transport
- Consideration of the emissions of fluorinated compounds (FCs)[38] from display production (Section 5.5) and
- Adjustment of useful lifetime to 2.9 years (Section 5.6)

The impacts of varying the parameters upon the overall greenhouse gas emissions of the four scenarios are examined. The results of the analyses present the absolute GWP values and the percentage deviations from the base values of the respective scenario as listed in the previous sections. It must be noted that, in line with the base scenarios, the sensitivity analyses were all calculated with a lifetime of 5 years.

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[38] In accordance with the Kyoto Protocol, “fluorinated greenhouse gases” comprises three groups of substances: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). In terms of chemistry there are further groups of substances that belong to fluorinated gases, such as the fluorinated ethers and nitrogen trifluoride (NF_3). These substances are not yet listed by the Kyoto Protocol, but their inclusion is under debate. Fluorinated greenhouse gases (F-gases) have a global warming impact that is 100 to 24,000 times greater than that of CO_2. The share of fluorinated greenhouse gases in the overall emissions of global warming gases is expected to grow threefold worldwide from its present proportion of just under 2% to around 6% by the year 2050. F-gases such as SF_6 and NF_3 are used in applications such as etching and cleaning gases for flat screen display, semiconductor and printed wiring board production (Umweltbundesamt 2010).

5.1 Sensitivity analysis 1: Adjustment of electricity consumption values in the use phase according to the limits set under Energy Star® Version 5.0 for computers

This sensitivity analysis applies the baseline requirements of Energy Star® TEC Version 5.0 to electricity consumption in the use phase. The baseline requirement is a limit that must be complied with in order that a device qualifies for the Energy Star® label. The electricity consumption in the base analysis represents an average for all devices bearing the Energy Star® label. The consumption of the base scenarios is therefore lower than that of the average of the devices found on the market. The purpose of this analysis is to examine the effect that a change in the assumed electricity consumption of the notebook would have upon the outcome. Table 28 compiles the data used to calculate electricity consumption in the base analysis (Section 3.4) and the sensitivity analysis. The sensitivity analysis conducted with the Energy Star® limit values arrives at an electricity consumption and GWP value in the use phase that is increased by approx. 31%.

The deviations of the individual scenarios from the base analysis are between 11 and 19% (Table 29). Scenario 1 EuP Lot 3 has the largest deviation of 19%, as in this scenario the use phase plays a major role.

Section 5.7 provides an overview of all sensitivity analyses.

Table 28: Compilation of electricity consumption in the use phase in the base analysis and sensitivity analysis according to Energy Star® TEC 2009 Version 5.0

Energy Star®	Category A	Category B	Category C	Average over all categories per year	5 years lifetime	GWP values in the use phase
Base analysis (average values)	30 kWh/a	40 kWh/a	69 kWh/a	46 kWh/a	231.3 kWh/5a	138.5 kg CO_2e/notebook within 5 years
Sensitivity analysis 1 (limit values)	40 kWh/a	53 kWh/a	88.5 kWh/a	61.5 kWh/a	302.5 kWh/5a	181.1 kg CO_2e/notebook within 5 years
Deviation from base analysis in %	+32.9%	+31.8%	+29.2%	+30.8%	+30.8%	+30.8%

Table 29: Results of sensitivity analysis 1 compared to the base analyses of all scenarios examined

Total GWP values of a notebook (kg CO_2e/notebook)	EuP Lot3 (Scenario 1)	EcoInvent 2.2 (Scenario 2)	UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life business-as-usual) (Scenario 3)	UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life best practice) (Scenario 4)
Base analysis	230	362	382	380
Sensitivity analysis 1	273	405	425	422
Deviation from base analysis in %	+19%	+12%	+11%	+11%

It follows from Tables 28 and 29 that in Scenarios 3 and 4, despite the increased electricity consumption over the useful lifetime of 5 years, the use phase only accounts for 43% of overall greenhouse gas emissions.[39]

Sensitivity 1 for Scenarios 3 and 4 (Section 0) has the following effect upon the amortisation calculation:

- If a new notebook is 10% more energy-efficient than an old one, the greenhouse gas emissions arising from production, distribution and disposal would only pay back after 67 years of use.
- If the energy efficiency improvement of the new notebook is 70%, the amortisation period in Scenarios 3 and 4 shortens to 10 years.

5.2 Sensitivity analysis 2: Adjustment of electricity consumption values and of operational modes according to EuP Lot 3

For the purposes of this sensitivity analysis, electricity consumption levels and the weighting of operational modes were taken from EuP Lot 3 (Table 30).

Table 30: Electricity consumption according to EuP Lot 3

Operational mode	According to EuP Lot3	Hours per year (h)	Power absorbed (kW/h)	Electricity consumption (kWh/year)
T_{Off}	36%	3153	0.0015	4.73
T_{Sleep}	34%	2995	0.003	8.99
T_{Idle}	30%	2613	0.032	83.62
Total	100%	8761	-	97.33

Table 31 shows the electricity consumption under the terms of the sensitivity analysis, as compared to the base scenario. Electricity consumption and GWP values in the use phase are 110% higher. The increased GWP values in the use phase cause the overall outcome to change by 40% to 66%. This high deviation is due to the circumstance that the use phase has a major influence upon overall GWP emissions.

Section 5.7.1 provides a synoptic overview of all sensitivity analyses.

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[39] Sensitivity analysis 1: (GWP values in use phase / overall GWP values of a notebook in CO_2e/one notebook within 5 years)*100%. Example of Scenario 3: (181 kg CO_2e/one notebook / 425 kg CO_2e/one notebook)*100% = 42.7%

Table 31: Compilation of electricity consumption in the use phase of the base analysis and sensitivity analysis, according to different data sources

	Electricity consumption/ 5 years lifetime	GWP values in the use phase
Base analysis (after Energy Star® Version 5.0)	231.3 kWh	138.5 kg CO_2e/one notebook within 5 years
Sensitivity analysis 2 (after EuP Lot3)	486.7 kWh	291.4 kg CO_2e /one notebook within 5 years
Deviation from base analysis in %	+110.4%	+110.4%

Table 32: Results of sensitivity analysis 2 compared to the base analyses of all scenarios examined

Total GWP values of a notebook (kg CO2e/notebook)	EuP Lot3 (Scenario 1)	EcoInvent 2.2 (Scenario 2)	UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life business-as-usual) (Scenario 3)	UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life best practice) (Scenario 4)
Base analysis	230	362	382	380
Sensitivity analysis 2	383	515	535	535
Deviation from base analysis in %	+66%	+42%	+40%	+41%

It follows from Tables 31 and 32 that, due to the higher electricity consumption in use, the use phase of 5 years accounts for approx. 54% of overall greenhouse gas emissions in Scenarios 3 and 4.[40] Sensitivity 2 for Scenarios 3 and 4 (Section 0) has the following effect upon the amortisation calculation:

- If a new notebook is 10% more energy-efficient than an old one, the greenhouse gas emissions arising from production, distribution and disposal would only pay back after 41 years of use.
- If the energy efficiency improvement of the new notebook is 70%, the amortisation period in Scenarios 3 and 4 shortens to 6 years.

5.3 Sensitivity analysis 3: Adjustment of the weighting of the operational modes in the use phase

User behaviour has a major impact on calculations in the use phase. The weighting of operational modes in the base analysis is based on Energy Star® Version 5.0 for computers. For the purposes of this sensitivity analysis, the weighting of operational modes was varied by

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[40] Sensitivity analysis 2: (GWP values in use phase / overall GWP values of a notebook in CO_2e/one notebook within 5 years)*100%. Example of Scenario 3: (291.4 kg CO_2e/one notebook / 535 kg CO_2e/one notebook)*100% = 54.5%

increasing the shares of the idle and sleep modes.[41] The sensitivity analysis estimates and examines two weighting alternatives according to different operational modes (Table 33).

Table 33: Compilation for parameter: Weighting of operational modes in base and sensitivity analysis

Operational mode	Baseline situation (Energy Star®)	Sensitivity analysis: Alternative 1 (own assumption)	Sensitivity analysis: Alternative 2 (own assumption)
TOff	60%	30%	20%
TSleep	10%	40%	40%
TIdle	30%	30%	40%

Table 34 lists the underlying electricity consumption levels in relation to the two weighting alternatives.

Section 5.7 provides a synoptic overview of all sensitivity analyses.

Table 34: Compilation of electricity consumption levels in the use phase in the base and sensitivity analysis, according to the different weighting of operational modes

Electricity consumption in use phase	Categories A	Categories B	Categories C	Average value	5 years lifetime	GWP values in use phase
Baseline value	30 kWh/a	40 kWh/a	69 kWh/a	46 kWh/a	231.3 kWh/5a	138.5 kg CO_2e/ notebook within 5 years
Sensitivity analysis: Alternative 1	31 kWh/a	41 kWh/a	68 kWh/a	47 kWh/a	234.5 kWh/5a	140.4 kg CO_2e/ notebook within 5 years
Sensitivity analysis: Alternative 2	39 kWh/a	52 kWh/a	88 kWh/a	60 kWh/a	299.2 kWh/5a	179.1 kg CO_2e/ notebook within 5 years
Sensitivity analysis: Alternative 1 Deviation from base analysis in %	+3.3%	+3.1%	-0.5%	+1.4%	+1.4%	+1.4%
Sensitivity analysis: Alternative 2 Deviation from base analysis in %	+29.4%	+30.2%	+28.8%	+29.3%	+29.3%	+29.3%

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[41] Idle state: This is the state in which the operating system and other software have completed loading, a user profile has been produced, the machine is not asleep, and activity is limited to those basic applications that the system starts by default.
Sleep mode: A low power state that the computer is capable of entering automatically after a period of inactivity or by manual selection. A computer with sleep capability can quickly “wake” in response to network connections or user interface devices. It reaches full functionality, including display, within a maximum of 5 seconds after initiation of the waking event. Sleep mode correlates to ACPI System Level S3 (suspend to RAM) state, where applicable.

Alternative 1 has a limited impact, as the power absorbed by notebooks in the sleep and standby states[42] is generally very low, and there is minimal scope to influence it by shifts in operation times between these states without changing the operating time in idle state. Alternative 2, in contrast, causes electricity consumption and GWP values in the use phase to increase by 29%. Therefore in the present study only Alternative 2 is examined. Increasing duration of the idle and sleep states causes the overall GWP values of the life cycle to increase by 11–18% (Table 35).

Table 35: Outcomes of sensitivity analysis 3 compared to the base analyses of all scenarios examined

Total GWP values of a notebook (kg CO2e/notebook)	**EuP Lot3 (Scenario 1)**	**EcoInvent 2.2 (Scenario 2)**	**UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life business-as-usual) (Scenario 3)**	**UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life best practice) (Scenario 4)**
Base analysis	230	362	382	380
Sensitivity analysis 3: Alternative 2	271	403	423	420
Deviation from base analysis in %	+18%	+11%	+11%	+11%

It follows from Tables 34 and 35 that, despite adjusting the weighting of the operational modes or increasing the duration of the idle state, the use phase of Scenarios 3 and 4 still accounts for approx. 42% of overall greenhouse gas emissions[43] (Alternative 2). Sensitivity 2 for Scenarios 3 and 4 (Section 0) has the following effect upon the amortisation calculation:

- If a new notebook is 10% more energy-efficient than an old one, the greenhouse gas emissions arising from production, distribution and disposal would only pay back after 68 years of use.
- If the energy efficiency improvement of the new notebook is 70%, the amortisation period in Scenarios 3 and 4 shortens to 10 years.

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[42] Standby state: The power consumption level in the lowest power mode which cannot be switched off (influenced) by the user and that may persist for an indefinite time when the appliance is connected to the main electricity supply and used in accordance with the manufacturer's instructions. Standby correlates to ACPI System Level S5 state, where applicable.

[43] Sensitivity analysis 3 (Alternative 2): (GWP values in use phase / overall GWP values of a notebook in CO_2e/one notebook within 5 years)*100%. Example of Scenario 3: (291.4 kg CO_2e/one notebook / 535 kg CO_2e/one notebook)*100% = 42.3%

5.4 Sensitivity analysis 4: Consideration of the Radiative Forcing Index (RFI) in air transport

This sensitivity analysis is only carried out for Scenarios 3 and 4. The purpose is to take account for air transport of the additional climate impacts that this generates, using the Radiative Forcing Index (RFI). RFI is a constant that is used to capture the presently still prevailing uncertainties with regard to the radiative forcing of greenhouse gases as a function of flight altitude, the state of the atmosphere, and physical-chemical interactions with condensation trails, ice clouds, ozone etc. The method used is documented in detail in a reference study (Atmosfair 2008). According to an update by the Intergovernmental Panel on Climate Change (IPCC) the RFI is between 1.9 and 4.7 (Grassl and Brockhagen 2007). An estimated mean RFI of 2.7 was used for the present sensitivity analysis calculations (IPCC 1999). This is also the factor recommended by the Öko-Institut in its “PCF Memorandum” produced on behalf of the German Federal Environment Ministry (BMU) and Federal Environment Agency (UBA) (Memorandum Product Carbon Footprint 2009).

However, this approach results in a deviation from ISO 14064-1 and from the GHG Protocol, as neither of the two envisages consideration of an RFI factor. The analysis was carried out nonetheless in order to determine how large the contribution of the RFI to overall greenhouse gas emissions is.

Table 36 shows the emission factors used and the corresponding GWP values. The trips concerned are the transport by air of a display module, the transport by air of the ICs and the distribution of a final product by air and by truck.

Table 36: Compilation of the relevant trips for the purposes of the base and sensitivity analysis, with and without consideration of RFI

Trips	Emission factor	Total of trips concerned
Base analysis: without RFI	1.04 kg CO_2e/tkm	32.47 kg CO_2e/notebook
Sensitivity analysis: with RFI = 2.7	2.58 kg CO_2e/tkm	78.72 kg CO_2e/notebook
Deviation from base analysis in %	+148.3%	+142.4%

If the RFI is taken into account, the GWP value increases by 142% in relation to the greenhouse gas emissions of all transportation. The percentage deviations of emission factors and total GWP is not identical. This is because some of the transportation is performed by truck. The GWP sum in Table 36 relates to the above-mentioned three trips, and not only to transport by air. In this sensitivity analysis, changes in the emission factors changes the overall outcome of Scenarios 3 and 4 by 12% (Table 37).

Section 5.7 provides a synoptic overview of all sensitivity analyses.

Table 37: Results of sensitivity analysis 4 compared to the base analyses of Scenarios 3 and 4

Total GWP values of a notebook (kg CO_2e/Notebook)	UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life business-as-usual) (Scenario 3)	UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life best practice) (Scenario 4)
Base analysis	382	380
Sensitivity analysis 4: with RFI	428	426
Deviation from base analysis in %	12%	12%

It follows from Tables 36 and 37 that, due to the consideration of the RFI factor, in Scenarios 3 and 4 the distribution phase accounts for almost 18% of total greenhouse gas emissions[44], which is considerable. The use phase of Scenarios 3 and 4 accounts for 32% of total greenhouse gas emissions. Sensitivity 2 for Scenarios 3 and 4 (Section 5.7) has the following effect upon the amortisation calculation:

- If a new notebook is 10% more energy-efficient than an old one, the greenhouse gas emissions arising from production, distribution and disposal would only pay back after 104 years of use.
- If the energy efficiency improvement of the new notebook is 70%, the amortisation period in Scenarios 3 and 4 shortens to 15 years.

5.5 Sensitivity analysis 5: Consideration of the emissions of fluorinated compounds (FCs) from display production

This sensitivity analysis is only carried out for Scenarios 3 and 4.

Prakash et al. (2011) estimate that in fabs without fluorinated compound (FC) emissions treatment the GWP values of display production may be even higher than generally assumed. The GWP value calculated in Prakash et al. (2011) is therefore used to calculate this sensitivity analysis. The additional consideration of FC emissions results in the GWP values of display production increasing substantially by 22% (Table 38), while the resulting increase in the overall greenhouse gas emissions of a notebook is only approx. 2% (Table 39).

Section 5.7 provides a synoptic overview of all sensitivity analyses.

Table 38: Compilation of the GWP values of display production of the base and sensitivity analyses, with consideration of FC emissions as compared to the base analyses of Scenarios 3 and 4

Production of display module	**kg CO_2e/notebook display**
Base analysis	35.1
Sensitivity analysis 5	42.7
Deviation from base analysis in %	+21.7%

Table 39: Results of sensitivity analysis 5 compared to the base analyses of Scenarios 3 and 4

Total GWP values of a notebook (kg CO_2e/notebook)	**UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life business-as-usual) (Scenario 3)**	**UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life best practice) (Scenario 4)**
Base analysis	382	380
Sensitivity analysis	390	387
Deviation from base analysis in %	+2%	+2%

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[44] Sensitivity analysis 4: (GWP values in the distribution phase with consideration of the RFI factor / overall GWP values of a notebook in CO_2e/one notebook within 5 years)*100%. Example of Scenario 3: (78.72 kg CO_2e/one notebook / 428 kg CO_2e/one notebook)*100% = 18.3%

It follows from Tables 38 and 39 that if FC emissions are taken into account, production of the display module accounts for 11% of total greenhouse gas emissions.[45] If FC emissions are not additionally considered, production of the display module accounts for only 9% of total greenhouse gas emissions.

The use phase accounts for 35% of total greenhouse gas emissions in Scenarios 3 and 4.[46] Sensitivity 2 for Scenarios 3 and 4 (Section 0) has the following effect upon the amortisation calculation:

- If a new notebook is 10% more energy-efficient than an old one, the greenhouse gas emissions arising from production, distribution and disposal would only pay back after 90 years of use.
- If the energy efficiency improvement of the new notebook is 70%, the amortisation period in Scenarios 3 and 4 shortens to 13 years.

5.6 Sensitivity analysis 6: Adjustment of useful lifetime to 2.9 years

This sensitivity analysis is only carried out for Scenarios 3 and 4. It is assumed that the lifetime is 2.9 years and not 5 years as was assumed for the base analysis. This figure of 2.9 years follows from a study by Williams and Hatanka (2005). In that study a survey was carried out among 1,000 Japanese households to determine the length of time that a notebook is used as primary device. In this sensitivity analysis the question of amortisation period cannot be addressed, because here the lifetime is a variable and is not identical to the lifetime assumed in the other scenarios.

Table 40 shows the electricity consumption in the use phase if the lifetime is 2.9 years. Electricity consumption and GWP in the use phase drop by 42%. The reduced GWP values in the use phase cause the overall outcome to drop by between 25 and 15% (Table 41).

Section 5.7 provides a synoptic overview of all sensitivity analyses.

Table 40: Compilation of electricity consumption in the use phase of the base and sensitivity analysis, for different lifetimes

Lifetime	Electricity consumption/lifetime	GWP values in the use phase
Base analysis (lifetime of 5 years)	231.3 kWh/5a	138.5 kg CO_2e/notebook within 5 years
Sensitivity analysis 6 (lifetime of 2.9 years)	134.2 kWh/2.9a	80.3 kg CO_2e/notebook within 2.9 years
Deviation from base analysis in %	-42%	-42%

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[45] Sensitivity analysis 5: (GWP values of display production in fabs without FC treatment / overall GWP values of a notebook in CO_2e/one notebook within 5 years)*100%. Example of Scenario 3: (42.7 kg CO_2e/one notebook / 390 kg CO_2e/one notebook)*100% = 10.9%

[46] Sensitivity analysis 5: (GWP values in use phase / overall GWP values of a notebook in CO_2e/one notebook within 5 years)*100%. Example of Scenario 3: (138.5 kg CO_2e/one notebook / 390 kg CO_2e/one notebook)*100% = 35.5%

Table 41: Results of sensitivity analysis 6 compared to the base analyses of all scenarios examined

Total GWP values of a notebook (kg CO_2e/notebook)	**EuP Lot3 (Scenario 1)**	**EcoInvent 2.2 (Scenario 2)**	**UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life business-as-usual) (Scenario 3)**	**UBA R&D project (UFOPLAN 2009) + EcoInvent (end-of-life best practice) (Scenario 4)**
Base analysis	230	362	382	380
Sensitivity analysis 6	172	304	324	322
Deviation from base analysis in %	-25%	-16%	-15%	-15%

It follows from Tables 40 and 41 that, due to the reduced lifetime of the notebook, the use phase of Scenarios 3 and 4 only accounts for approx. 24% of total greenhouse gas emissions.[47] If this analysis is compared to the base scenario, in which the lifetime was taken to be 5 years, the share of the use phase increases to 36% of the total greenhouse gas emissions of a notebook. In other words, if the lifetime of notebooks is extended, the share of the production, distribution and disposal phases in total greenhouse gas emissions is reduced.

5.7 Synoptic overview of all sensitivity analyses examined

Figure 12 illustrates the outcomes in absolute terms of the sensitivity analyses in combination with the outcomes of the base analysis. Figure 13 compiles the percentage deviations from the respective base analysis. The detailed breakdown of the overall outcome illustrates, as set out in the previous sections, that the data on which EuP Lot 3 is based over-rate the use phase and under-rate the production phase.

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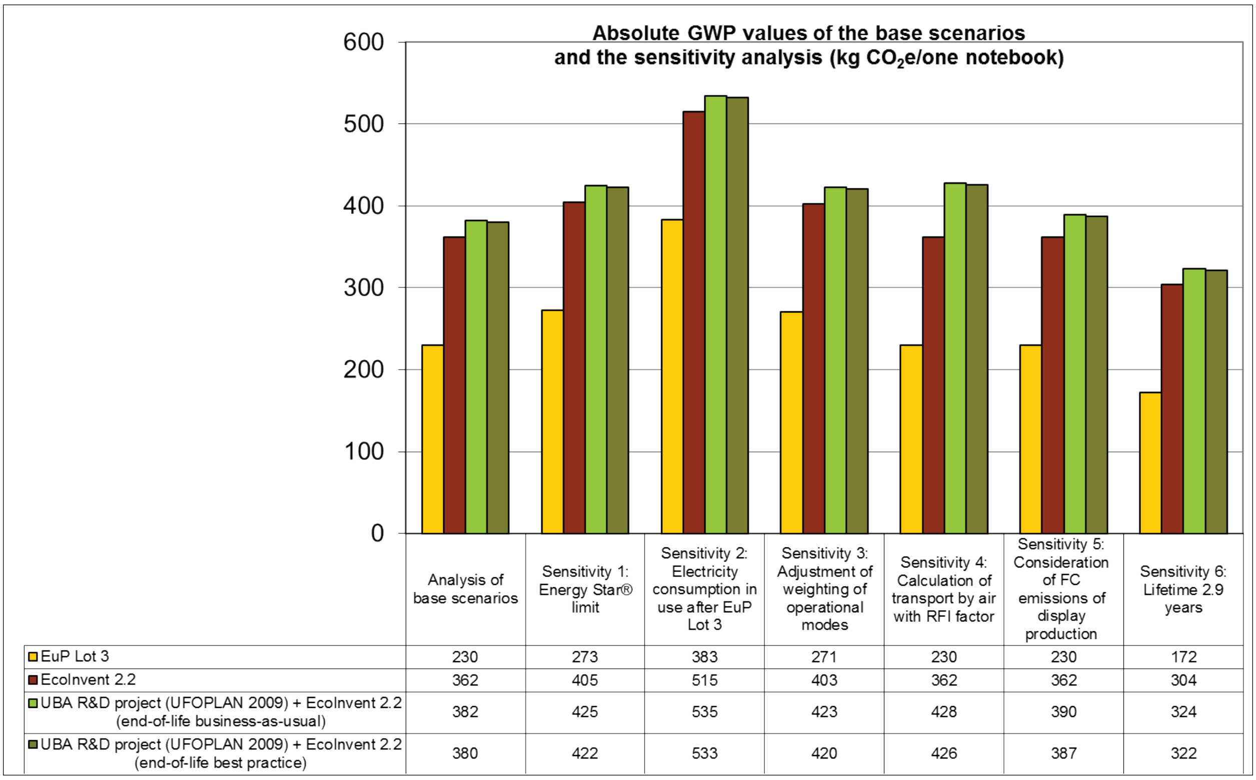
[47] Sensitivity analysis 6: (GWP values in use phase / overall GWP values of a notebook in CO_2e/one notebook within 5 years)*100%. Example of Scenario 3: (80.3 kg CO_2e/one notebook / 324 kg CO_2e/one notebook)*100% = 24.8%



	Analysis of base scenarios	Sensitivity 1: Energy Star® limit	Sensitivity 2: Electricity consumption in use after EuP Lot 3	Sensitivity 3: Adjustment of weighting of operational modes	Sensitivity 4: Calculation of transport by air with RFI factor	Sensitivity 5: Consideration of FC emissions of display production	Sensitivity 6: Lifetime 2.9 years
🟨 EuP Lot 3	230	273	383	271	230	230	172
🟥 EcoInvent 2.2	362	405	515	403	362	362	304
🟩 UBA R&D project (UFOPLAN 2009) + EcoInvent 2.2 (end-of-life business-as-usual)	382	425	535	423	428	390	324
■ UBA R&D project (UFOPLAN 2009) + EcoInvent 2.2 (end-of-life best practice)	380	422	533	420	426	387	322

Figure 12: Absolute GWP outcomes of the base and sensitivity analyses for the four scenarios examined

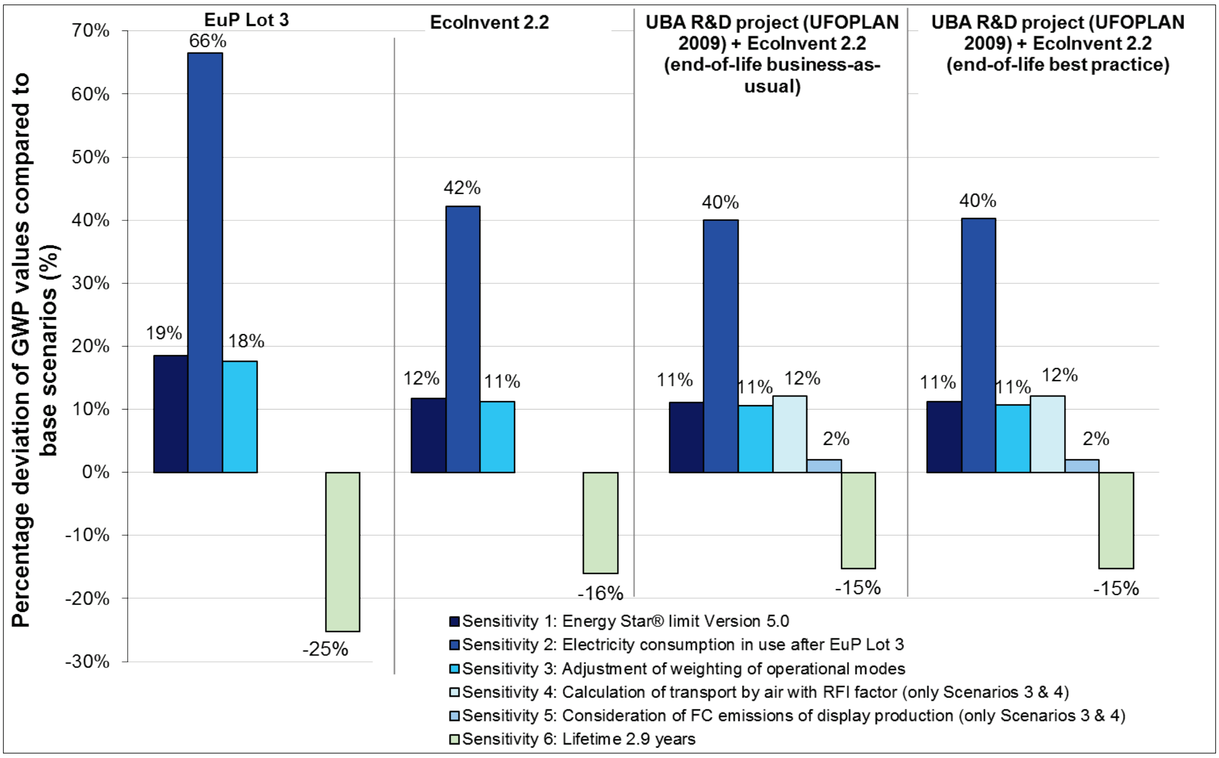


Figure 13: Percentage deviations of the sensitivity analysis from the base analysis for the four scenarios examined

5.7.1 Amortisation calculation on the basis of the sensitivity analyses

Figure 14 shows the amortisation calculation for Scenario 4 compared to the base scenario outcomes.

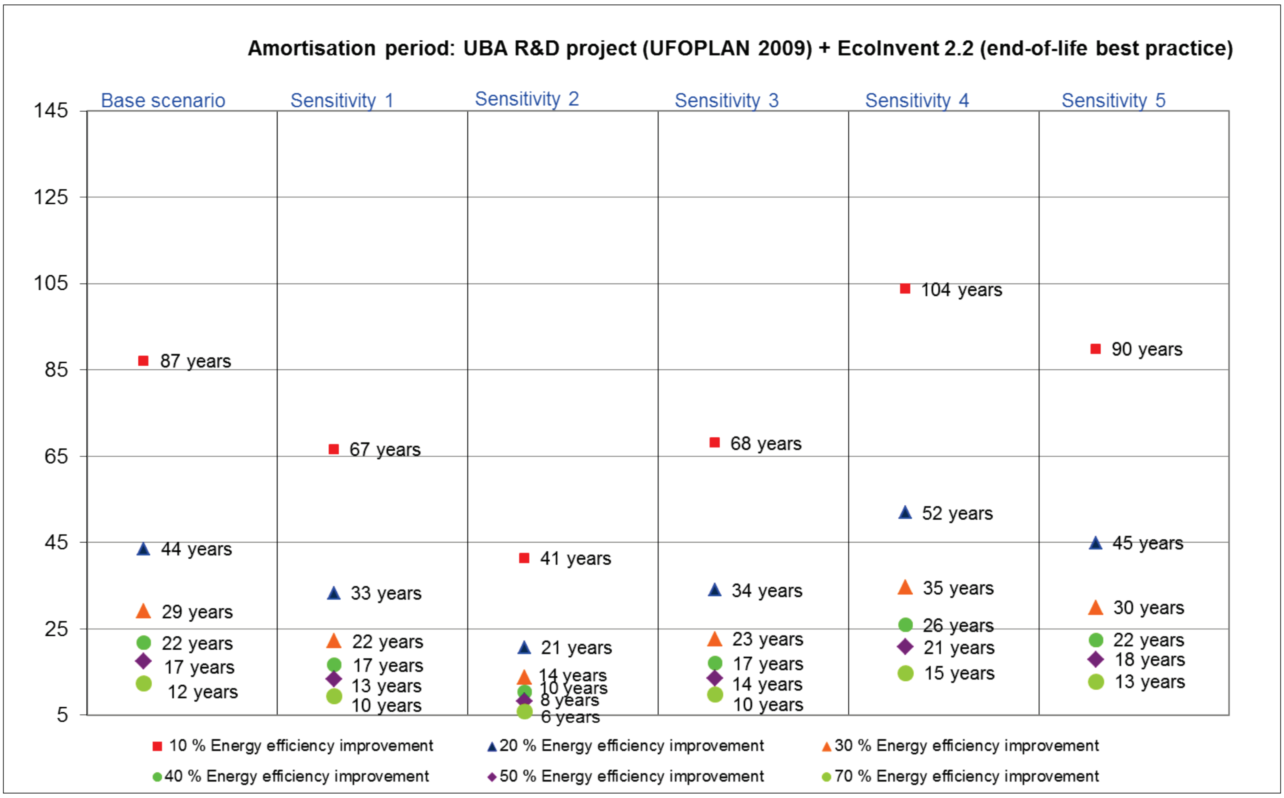


Figure 14: Amortisation period of base and sensitivity analyses for Scenario 4 UBA R&D project (UFOPLAN 2009) + EcoInvent 2.2 (end-of-life best practice)

Sensitivity analyses 1, 2 and 3 examine the results of increased electricity consumption in the use phase, either through consumption at the maximum limit or an increase in idle and sleep phases. In these cases the increase of electricity consumption leads to an increase of the saving potential. The amortisation periods are therefore generally shorter than those in the base analysis.

The outcomes of sensitivity analyses 4 and 5, in contrast, lead to a lengthier amortisation period than in the base analysis. This is due to increased GWP values in either the production phase or in other phases such as distribution.

It is furthermore important to note that specific uncertainties attach to the individual inventories. The sensitivity analyses presented here, however, serve to appraise these uncertainties and overall deliver a greater predictive certainty of the study findings. Such uncertainties can result from the methodological approach (e.g. Sensitivity 4, 5), the difficulties in modelling user behaviour (Sensitivity 1, 2, 3) or the framework conditions considered, such as consideration of fabs with or without FC emissions treatment (Sensitivity 5).

6 Discussion

With a useful lifetime of 5 years, the overall greenhouse gas emissions attributable to an average notebook are between 230 and 382 kg CO_2e, depending upon the data source used to calculate emissions from the production phase of a notebook. The lowest greenhouse gas emissions (230 kg CO_2e per notebook) are calculated if the data of EuP Lot 3 (Scenario 1) are used. The greenhouse gas emissions calculated on the basis of EcoInvent 2.2 amount to 362 kg CO_2e per notebook. Emissions are highest (382 kg CO_2e per notebook) if the data are taken from the UBA R&D project UFOPLAN (2009) for the production of the display module and memory IC and data from EcoInvent 2.2 are taken for the production of other notebook components (Scenario 3).

Relative contributions of the production and use phases to the overall greenhouse gas emissions of a notebook

In terms of the distribution of the greenhouse gas emissions attributable to a notebook among the individual life cycle phases, if the data of EuP Lot 3 are taken the use phase (60.2%) has a much greater impact than the production phase (35.2%). In contrast, the production phase of a notebook carries a greater weight if the data of EcoInvent 2.2 and UBA R&D project UFOPLAN 2009 (Prakash et al. 2011) are taken: Taking EcoInvent 2.2 data, 54% of all greenhouse gas emissions are generated by the production phase and only 38.2% by the use phase. If the data from the UBA R&D project UFOPLAN 2009 (Prakash et al. 2011) are taken, around 56% of all greenhouse gas emissions are attributable to the production phase and only 36% to the use phase. In absolute terms, the production of a notebook is the source of only 81 kg CO_2e in the case of EuP Lot 3. In the case of EcoInvent 2.2 the figure is approx. 195 kg CO_2e and in the case of the UBA R&D project UFOPLAN 2009 (Prakash et al. 2011) it is approx. 214 kg CO_2e per notebook.

It is possible that the use scenario on which the present study is based no longer corresponds to the latest developments in user behaviour, especially in the business sector. The use scenario, which was taken from Energy Star® Version 5.0 for computers, is indeed the most commonly applied standard used worldwide to determine the energy consumption of end-user computers. On the other hand, this standard does not take account of the active use (higher CPU load than in idle mode) of end-user computers that may possibly play a decisive role in office uses. It can furthermore be assumed that the increase in data quantities and data traffic in the web driven by media digitalisation leads to a significantly different weighting of operational modes than has previously been assumed. Processor capacity and the associated power absorbed by computers is an aspect that has not been taken into account at all in assessments of electricity consumption in the active use phase.

Despite the above reservations, the sensitivity analyses 1, 2 and 3 show that even if electricity consumption in the use phase is increased or doubled the greenhouse gas emissions arising from the production phase remain substantial. Moreover, the comparison of different data sources confirms that EuP Lot 3 significantly under-rates the material and energy inputs required to produce a notebook. Other studies find that the production-related emissions for the motherboard of a notebook alone are on the order of 70 kg CO_2e (PE International 2008; O'Connell and Stutz 2010) to 85 kg CO_2e (Tekawa et al. 1997). Prakash et al. (2011) found the greenhouse gas emissions associated with the production of a notebook display module to amount to 35.1 kg CO_2e and those arising from memory IC fabrication to be approx. 7.6 kg CO_2e per notebook. O'Connell and Stutz (2010) similarly find the production of the notebook display to be associated with greenhouse gas emissions of just under 41.0 kg CO_2e per notebook.

Sensitivity analysis 6, in which the lifetime of a notebook was reduced to a period of 2.9 years, which is realistic under present market and consumption patterns (Williams and Hatanka 2005), confirms that the use phase of a notebook only accounts for 25% of all greenhouse gas emissions (Prakash et al. 2011). If notebook lifetime is increased to 5 years, as assumed in the base scenarios, the use phase accounts for 36% of all greenhouse gas emissions.

Relative contributions of recycling or of the end-of-life phase to the overall greenhouse gas emissions of a notebook

Analysis of the end-of-life phase in this study distinguishes between business-as-usual (see Section 3.5.1) and best practice (see Section 3.5.2). The difference between the greenhouse gas emissions of the two scenarios is minimal, being only 2 kg CO_2e. The two recycling practices differ only in terms of the recovery rates of gold, silver and palladium. Business-as-usual takes a recovery rate of 40% each for gold, silver and palladium, while best practice takes 93% for gold, 87% for silver and 91% for palladium. The reason why the high recovery rates with best practice recycling deliver only a minor reduction in greenhouse gas emissions compared to business-as-usual recycling is that the proportions of gold, silver and palladium contained in a notebook are small. If, however, we consider the overall number of notebooks present in Germany (stock in the residential and business sectors in 2009/2010: approx. 47 million notebooks) the potential for reduced environmental impact would be significantly greater if all notebooks in Germany were recycled in accordance with the best practice scenario. Moreover, the potential to reduce impact could be further increased if the following aspects were considered:

- Environmental effects such as acidification, eutrophication, resource consumption, biodiversity loss, toxicity etc.
- Social impacts, such as safe and healthy living conditions of the people living in the vicinity of extraction sites.
- Consideration of the secondary recovery of further precious and special metals. Existing high-tech facilities can in fact recover up to 17 different precious and special metals from e-scrap. Data availability is the sole reason why only the recovery of gold, silver and palladium was considered.
- Consideration of extreme scenarios such as notebook recycling and disposal in developing and newly industrialising countries where recycling infrastructures and technologies are under-developed. No dataset considering this aspect is yet available in the existing databases.

Amortisation calculation

The second part of the chapter on LCA outcomes examined the question of how efficient a newly purchased notebook would need to be in order that the greenhouse gas emissions generated by its production, distribution and disposal are compensated by its improved energy efficiency in the use phase. A further aim in that connection was to determine the environmentally optimal periods for the utilisation or replacement of a notebook. The purpose of that analysis was to provide robust environmental decision-making support for final consumers, providing an answer to the following question: “If the new notebook is X% more energy-efficient during the use phase than the old one, how long would the new notebook need to be used in order to compensate for the environmental impacts of its production, distribution and disposal?”

The analysis of environmental amortisation periods has shown that the environmental impact associated with the production of a notebook is so great that it cannot be compensated in a realistic period of time by its improved energy efficiency during the use phase – regardless of which data source is used. Compared to the other data sources, EuP Lot 3 Scenario 1 clearly delivers the shortest amortisation period for the same energy efficiency rate. Proceeding from an assumed lifetime of 5 years, this means that a replacement of the notebook only pays in environmental terms if the EuP Lot 3 data are used, but even then only if energy efficiency is improved by 70%. Such an efficiency improvement between two notebook generations of similar configuration and functionality is unrealistic. For notebooks are already designed to have high levels of energy efficiency, as this permits longer running times of the rechargeable batteries – a key precondition for mobile use. If we assume a realistic energy efficiency improvement of 10% between two notebook generations, the amortisation periods are between 33 and 88 years, while if energy efficiency improves by 20% the period is between 17 and 44 years, depending upon the data source used to analyse notebook production. Evidently no notebook has such a useful lifetime.

It is therefore clear that the greenhouse gas emissions generated by the production, distribution and disposal of a new notebook can only be compensated to a limited extent by the energy saving or energy efficiency improvements of the new notebook in the use phase. Even if energy efficiency in the use phase is improved by 70%, the production of the new device only pays back in environmental terms after 13 years if calculated with the data from the UBA R&D projects UFOPLAN 2009 (Prakash et al. 2011).

It therefore follows from this study that it is not environmentally purposeful (with regard to global warming potential) to purchase a new notebook after a period of only a few years, even if the assumed energy efficiency of the new device exploits the full scope of cutting-edge technology.

7 Conclusion

The findings of this study confirm that the production phase makes a significant contribution to the overall greenhouse gas emissions of a notebook and should therefore be placed in the focus of sustainable product policy. Until now, however, European ecodesign policy for energy-using products (EuP) has focussed on improving energy efficiency or reducing energy consumption in the use phase. For the notebook product group this focus is of only limited usefulness in achieving policy goals, as notebooks are already designed to have high levels of energy efficiency in order to achieve long running times and long lifetimes of the rechargeable batteries for mobile applications. European ecodesign policy should therefore address Original Equipment Manufacturers (OEMs) and the component manufacturers of ICT devices in a manner that embraces the entire produce life cycle. The focus of mandatory product policy measures for ICT devices should be placed on the following aspects that lead to an extension of device lifetimes:

- Possibilities of hardware upgrading,
- Modular construction,
- Recycling-friendly design,
- Availability of spare parts,
- Standardisation of components and
- Extension of minimum warranty periods.

Not least, the focus of assessments of the environmental impacts of ICT devices should not be limited to greenhouse gas emissions, but should be broadened to include other impact categories such as acidification and eutrophication potential, resource consumption, biodiversity loss, toxicity etc.

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9 Annex

Table 42: Country-specific emission factors of electricity supply (electricity mix)

Data source	Dataset	GWP emission factor used in the present study: kg CO_2e/kWh	Spatial reference	Temporal reference
GEMIS 4.6	*Netz-el-DE-Verteilung-MS-2010*	0.591	Germany	2010
GEMIS 4.6	*El-KW-Park-JP-2005*	0.502	Japan	2005
GEMIS 4.6	*El-KW-Park-US-2010*	0.638	USA	2010
GEMIS 4.6	*El-KW-Park-EU-30-2010*	0.377	EU25+BG+RO+TR+CH+NO	2010
Wang 2009		0.997	China	2008
Personal communication by ITRI Taiwan		0.810	Taiwan	2009
CarbonNeutral Company 2010		0.673	Singapore	no data
		0.532	Korea	no data
		0.678	Malaysia	no data
		0.608	Philippines	no data

Table 43: Input and output data for the silicon wafer production dataset (Prakash et al. 2011)

Input			Output		
Electricity	3,85E-01	kWh	Polished wafer	1	cm^2
Silicon dioxide	4,87E-03	kg	CO_2	8,33E-03	kg
Woodchips	1,83E-03	kg	CO	1,67E-04	kg
Dry wood	3,98E-03	kg	NO_x	1,38E-05	kg
Petroleum coke	5,97E-04	kg	Methanol	8,51E-05	kg
Electrode material	1,63E-04	kg	Methane	6,88E-05	kg
Hydrogen chloride (HCl)	6,75E-03	kg	Ethane	2,90E-05	kg
			Particulates	2,01E-04	kg
			H_2O	1,88E-03	kg
			SO_2	3,44E-05	kg
			SiO_2	1,63E-05	kg
			Hydrogen	1,25E-04	kg
			Metal chloride	7,87E-04	kg
			Co-products: Silicon residues	4,50E-03	kg

Table 44: Input and output data for the IC fabrication front-end process/Wafer Out dataset (Prakash et al. 2011)

Input			Output		
Silicon wafer	1.14	cm2	Finished wafer out	1	cm^2
Electricity	1.05	kWh	HFC-23 trifluoromethane)	1.86E-06	kg
Gas	0.13	kWh	Perfluoroethane (C_2F_6)	3.16E-06	kg
Water	6.5	kg	Tetrafluoromethane (CF_4)	2.68E-06	kg
N_2 (high-purity)	5.00E-01	kg	Perfluoropropane (C_3F_8)	1.86E-06	kg

Input			**Output**		
O_2 (high-purity)	3.41E-03	kg	SF_6	1.86E-06	kg
Ar (argon) (high-purity)	1.93E-03	kg	Nitrogen trifluoride (NF_3)	1.29E-05	kg
H_2 (high-purity)	5.23E-05	kg			
Sulphuric acid (high-purity)	6.04E-03	kg			
Hydrogen peroxide (high-purity)	1.68E-03	kg			
Hydrofluoric acid (high-purity)	4.56E-04	kg			
Phosphoric acid (high-purity)	2.74E-03	kg			
2-propanol (C_3H_8O)/ Isopropyl alcohol (IPA) (high-purity)	2.30E-03	kg			
Ammonium hydroxide (high-purity)	8.95E-04	kg			
CF_4	4.89E-05	kg			
CHF_3	4.67E-06	kg			
NF_3	2.49E-04	kg			
C_2F_6	5.68E-05	kg			
SF_6	7.39E-06	kg			
NaOH (for effluent treatment)	1.68E-03	kg			

Table 45: Input and output data for the IC fabrication front-end process\"good die out" dataset (Prakash et al. 2011)

Input			**Output**		
Silicon wafer	1.38	cm2	Good die out	1	cm^2
Electricity	1.27	kWh	HFC-23 (trifluoromethane)	2.26E-06	kg
Gas	0.16	kWh	Perfluoroethane (C_2F_6)	3.84E-06	kg
Water	7.88	kg	Tetrafluoromethane (CF_4)	3.25E-06	kg
N_2 (high-purity)	6.06E-01	kg	Perfluoropropane (C_3F_8)	2.26E-06	kg
O_2 (high-purity)	4.13E-03	kg	SF_6	2.26E-06	kg
Ar (argon) (high-purity)	2.34E-03	kg	Nitrogen trifluoride (NF_3)	1.56E-05	kg
H_2 (high-purity)	6.34E-05	kg			
Sulphuric acid (high-purity)	7.33E-03	kg			
Hydrogen peroxide (high-purity)	2.04E-03	kg			
Hydrofluoric acid (high-purity)	5.53E-04	kg			
Phosphoric acid (high-purity)	3.32E-03	kg			
2-propanol (C3H80)/ Isopropyl alcohol (IPA) (high-purity)	2.78E-03	kg			
Ammonium hydroxide (high-purity)	1.09E-03	kg			
CF_4	5.94E-05	kg			
CHF_3	5.66E-06	kg			
NF_3	3.02E-04	kg			
C_2F_6	6.89E-05	kg			
SF_6	8.96E-06	kg			
NaOH (for effluent treatment)	2.04E-03	kg			

Table 46: Input and output for the IC fabrication back-end process dataset (Prakash et al. 2011)

Input			**Output**		
Electricity	0.5476	kWh	Memory IC	1	Piece (0.162 g)
Natural gas	0.0678	kWh			
Unencapsulated chip (silicon)	0.024	g			
Polymer	0.011	g			
SiO_2	0.048	g			
Au	0.000	g			
Carbon Black	0.000	g			
Ag	0.001	g			
Cu	0.0001	g			
Sn	0.026	g			
BT-core (bismaleimide-triazine) + Cu + Au + Ni	0.053	g			

Table 47: Factors for high-purity chemicals to normal chemicals (Higgs et al. 2010)

Elementary gases	**Factors for high-purity chemicals to normal chemicals**
N_2	1.8
O_2	1.9
Argon, Ar	3
Hydrogen, H_2	9
Chemicals	**Factors for high-purity chemicals to normal chemicals**
Sulphuric acid	10
Phosphoric acid	1.45
Hydrogen peroxide	1.17
2-propanol (C_3H_8O)/Isopropyl alcohol (IPA)	1.39
Ammonium hydroxide	1.17
Hydrofluoric acid	1.21

Table 48: Emission factors for primary and secondary metal production (EcoInvent 2.1)

GWP [kg CO_2e/kg]	**Fe (steel)**	**Al**	**Cu**	**Ag**	**Au**	**Pd**
Primary production	2.04	10.20	2.81	112.14	17,879.75	9,284.30
Secondary production	0.40	1.32	0.10	14.31	835.40	437.57

Table 49: Metal fractions inventoried in kg in relation to the notebook examined

kg/notebook	**Scenario 2: EcoInvent 2.2 (End-of-Life Business-as-Usual)**	**Scenarios 3 and 4: UBA R&D project (UFOPLAN 2009) + EcoInvent**
Al	1.5E-01	1.6E-01
Cu	2.2E-01	2.4E-01
Fe	3.5E-01	3.8E-01
Ag	1.3E-04	3.1E-04
Au	8.7E-05	2.2E-04
Pd	8.7E-06	2.1E-05

Weight of the respective notebook	2.17	2.4

Table 50: Absolute GWP outcomes and percentage shares of memory IC fabrication

Processes	kg CO_2e/memory IC (1 GB)	Share
Silicon wafer production	0.13	14.0%
Front-end process	0.62	65.7%
Back-end process	0.19	20.0%
Transportation (silicon wafer -> front-end process -> back-end process -> notebook assembly)	0.003	0.3%
Total (kg CO_2e/memory IC)	0.95	100%