DEVELOPMENT OF NEW ECOLOGICAL FOOTPRINT TECHNIQUES APPLICABLE TO CONSUMER ELECTRONICS

A thesis submitted for the degree of Doctor of Philosophy

by

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ABSTRACT

In order to extend ecological footprint analysis (EFA) to electronic products, new methods had to be developed which associate the world average bioproductive space per capita and year – the fair Earth share - with an individual product. The problem analysed in this thesis is the need for an environmental assessment tool for electronic products, which uses natural capital accounting. This need arose because so far, electronic products were mainly assessed using life cycle analysis with a focus on toxicity.

Since the ecological footprint (EF) is a sustainability indicator, the sustainability discussion and in particular its relevance and implications with regard to the EF is reviewed.

The electronic products assessed in this thesis are a personal computer (PC) in an exploratory study, and three mobile phones (two main case studies and one updated case study). To establish the land areas used by the mined materials used in electronic products, a database was developed based on site specific data found in the literature, and on approximations from the density of materials and their overburden. A life cycle energy approach was used to determine the burdens from producing and using a mobile phone. In order to estimate energy requirements for materials for which no data was available, the relationship between abundance and rucksack / overburden values was used in a regression analysis. Direct land use data and results from the energy analysis were used as an inventory for the subsequent EFA.

An EF time series was applied to represent a more accurate picture of PC and phone use. This was also necessary since the EF reflects the instantaneous rate (a snapshot) of resource consumption. Key results are that the EF of electronic products are much larger than their actual size and that different electronic products have different EF. Our methodology proved sensitive enough to reveal differences even in small electronic products, given the high benchmark of a fair Earth share, and useful in monitoring space-efficient technology.

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Acknowledgements

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"The problem with land is that they stopped making it some time ago"

(Mark Twain)

CHAPTER 1: INTRODUCTION

The ecological footprint (EF) has mainly been known for its application to geographical levels, from whole nations to small regions. As a measurement of ecological sustainability, the EF illustrates the consequences of consumption on a finite planet. Inherent to the EF method used in this study is an ecological benchmark, the principle of fair Earth shares. The world's EF changes with global population size, global average consumption, and technology. Shrinking land space must be divided by an increasing population.

More recently, EF analysis (EFA) has also been applied to some household consumption items. Certain components around transport, energy, house and garden have been incorporated into software [Chambers et al., 2000]. In this study, EFA was applied to complex electronic products.

1.1. Goal, scope and purpose of this study

Most, if not all environmental assessments of electronic products are based on life cycle analysis (LCA), and most of them focus on the toxicological aspects of either the entire product or its components. Although LCA results in a range of different environmental indicators (for example, toxicity, global warming potential, acidification and eutrophication potentials), LCA cannot measure sustainability since it does not address how much "nature" is needed to provide or absorb all the measured material and substance flows. However, this is where EFA begins.

This thesis analyses the need for natural capital accounting in electronic products, and assesses how much natural capital a single electronic product requires - during its lifetime and as a snapshot. Subsequently, this demand is compared with the currently available bioproductive space per capita, the ecological benchmark. Since electronic products contain a plethora of different materials, new methods had to be developed in order to extend EFA to electronic products and to associate a single electronic product with the ecological benchmark, or fair Earth share.

In order to relate the EF results to a sustainability framework outlined in [Holmberg et al., 1999], consequently the following research questions were addressed:

- Can emissions of an electronic product adequately be transformed into a corresponding land area?
- Can the degree to which an electronic product contributes to the deterioration of long-term bioproductivity or threatens biodiversity be measured and its impacts adequately transformed into land space (for example, through mining activities)?
- Can a product's demand for biocapacity be compared with the biocapacity available?
- Can the technological change of an electronic product be measured, indicating and monitoring trends of future product developments?

This research will establish whether EFA makes a suitable assessment tool for electronic products, providing a new context in which to view the use of certain electronic products and their use of biophysical services.

1.2. The structure of the thesis

The literature review in chapter 2 consists of six parts. The first part briefly reviews the literature on biochemical cycles and perturbations by humans. The second part is a critical discussion of the sustainability debate, its roots, and implications. The third part addresses the main strategies for using natural capital sustainably (Factor X and Eco-efficiency). In contrast to the mainstream sustainability discussion, the Gaia theory is revisited in the fourth part, reminding us that in our own self-interest humans have to live within the means of nature. Part five contains the focal theory on the EF, its methodology and the summarised results from some geographical applications. This was included to illustrate the nature, implications, and the potential of the EF, and to clarify its underlying principle of fair Earth shares:

Worldwide, humanity exceeds available biocapacity by more than a third [Wackernagel et al., 2001].

Part five moves on to examine the sustainability implications of the EF and to discuss their relevance for electronic products. Core aspects of sustainability – carrying capacity, overshoot and biophysical limits - are addressed from an EF perspective as well as the role of technology and trade.

The EF concept has found many applications, but also its critics. Advantages and limitations of the EF found in the literature are discussed.

Part six gives a literature review on environmental assessments of electronic products. Key conclusions from the literature review are that although efforts to reduce resource flows are an important factor to achieve sustainability, these efforts may be in vain in the absence of a biophysical benchmark. Without such a benchmark, resource-efficiency efforts may dangerously head into the wrong direction of overshoot. It also became clear that monetary analysis cannot measure the ecological dimension of sustainability. By comparing how much natural capital is available, and how much of it humans use, the EF reveals global and regional dependence on ecosystems and provides an ecological bottom line. This sets the EF apart from most other tools that aim to assess sustainability.

Chapter 3 presents the EF methodology, which is divided into estimating direct land use and the actual EF aggregation and calculation procedure including carbon sequestration.

Chapter 4 contains an exploratory EF study of a personal computer (PC), of which some results have already been published [Frey, Harrison, Billett, 2000a, b]. Main conclusions from the study were that a PC's total area used is more than a thousand fold larger than its actual size (7 per cent of the fair Earth share) and that small amounts of resources extracted can have a high land use. Although not comprehensive, the study gave a first approximation of the demand for land space by a single product. The PC study [ibid.] has been updated by equivalence factors and a time series.

Chapter 5 estimates energy for raw material extraction for elements used in mobile phones for which no data could be obtained (beryllium, gallium, lanthanum, samarium, neodymium, indium). Based on the assumption that energy requirements in extraction increase with rucksack values, the relationship between abundance and rucksack values for known elements was used in a regression analysis.

Chapter 6 assesses the total primary energy requirements and CO_2 emissions for two mobile phone case studies with different manufacturing energy based on life cycle energy analysis. For both cases, a sensitivity analysis with 95 per cent confidence limits, based on the results from the regression analysis, was included for the raw material extraction phase. This is featured in three scenarios for each case. The energy and carbon analysis serves as an inventory for the subsequent EFA.

Chapter 7 presents the EFA for two mobile phone case studies and their 95 per cent confidence limits, plus an additional scenario with lower energy consumption for the charger. A time series analysis is included for all cases. Key conclusions from this chapter are that despite the limitations of EFA, the method is sensitive enough to detect small differences on small product scales. Useful approximations for the appropriation of bioproductive space by a small product could be obtained.

The final chapter is a brief summary of the main arguments in this thesis and the conclusions drawn from these. It also addresses future work.

1.3. Contribution to knowledge

The EF is still a fairly new indicator of sustainability; its use is not widespread (yet) but seems to be increasing. Significant contributions of this thesis have been:

- Applying EFA to a PC (exploratory study based on an existing LCA).
- Energy and CO_2 analysis of different mobile phone generations with the focus on raw material extraction, manufacture, and use phase.
- Regression analysis between rucksack and abundance values of minerals to estimate energy requirements and CO_2 emissions for "unknown" elements in mobile phones, including their 95 per cent confidence limits (sensitivity analysis). The outcome of this analysis was used in the mobile phone

scenarios (raw material extraction) to explore the influence of the upper and lower confidence limits for six elements on the overall results.

- Analysis and ranking of 90 phone components with regard to CO_2 emissions. This part of the analysis was traced down to the material contents level of a component.
- Applying EFA to a range of different mobile phone cases, using results from the energy analysis in the EF - inventory.
- EF-time series analysis for mobile phones and suggestions for future product improvements.

Further significant research areas were:

- Association of a single complex electronic product with a global systems level (the fair Earth share).
- Understanding and clarification of biophysical limits and translating these down to the product level.

CHAPTER 2: LITERATURE REVIEW

The first four sections of this chapter are a general literature review, whereas sections five and six contain the focal theory on the Ecological Footprint and a review on environmental assessments for electronic products.

2.1. Biochemical cycles

Natural ecosystems provide a variety of services that are essential for life on Earth. One major service is regulating the atmospheric balance, such as stabilising the climate. The natural greenhouse effect, regulated through clouds, water vapour, CO_2 and other trace gases in the atmosphere, keeps the planet habitable. If these mechanisms were absent, the Earth's surface temperature would be about 33 degrees Celsius higher. Life on Earth can have both negative and positive feedback on climate by influencing absolute or relative amounts of trace gases. Life is linked to climate through a variety of interacting cycles and feedback loops. Changes in atmospheric processes, such as through deforestation and fossil fuel burning, are feared to disturb many essential ecosystem functions [Alexander, Schneider and Lagerquist, 1997].

The so-called ***grand cycles*** of carbon, nitrogen, sulphur and phosphorous are most important from a biological view. Without efficient cycling of these elements, life on Earth would be impossible [Graedel and Allenby, 1995]. The Earth's inventory of these and all the other elements of which the surface biosphere consists, has accumulated over the aeons and been cycled and recycled over the past four and a half billion years via geological processes [Nisbeth, 1991].

Although nature has long-term cycles for all elements, their time scales vary. Only between 15 to 20 elements cycle rapidly enough between reservoirs on time scales that can be analysed [Alexander, Schneider, Lagerquist, 1997; Graedel and Allenby, 1995]. For some elements, modest cycling is important to provide the biologically essential trace elements. These quantities are generally dispersed through the hydrological processes [Alexander, Schneider, Lagerquist, 1997].

2.1.1. The carbon cycle

The carbon cycle includes five main reservoirs for storing carbon: As CO_2 in the atmosphere, as organic compounds in living or recently dead organisms, dissolved in water bodies as CO_2, and as $CaCO_3$ in limestone and buried organic matter (such as peat, coal and oil) [Alexander, Schneider, Lagerquist, 1997]. Plants trap CO_2 from the atmosphere, and through photosynthesis, convert it into plant tissue [Nisbeth, 1991]. Animals consume plants and use them for their metabolism. When plants and animals die and decay, the greater part is formed again as CO_2 as organic compounds are oxidised. A small part is redeposited as sediment where it can form peat, petroleum or coal again [Alexander, Schneider, Lagerquist, 1997]. Because CO_2 dissolves in sea and other water bodies, aquatic plants also use it for photosynthesis while marine animals use it for $CaCO_3$ in their shells. Shells of dead organisms accumulate on the seabed, forming limestone as part of the sedimentary cycle [Nisbeth, 1991]. These different processes have varying time scales, from million of years for rock cycles and plate tectonics to days and seconds for processes like photosynthesis and exchange between air and sea [Nisbeth, 1991; Alexander , Schneider, Lagerquist, 1997]. CO_2 in the atmosphere has a strong influence on the Earth's heat balance as it absorbs infrared radiation. CO_2, N_2O, H_2O vapour and CH_4 are strong greenhouse gases; the CH_4 cycle is also an important mechanism for recycling carbon [ibid.]. In the Earth's pristine state, the exchange of CO_2 from land biosphere and the oceans with the atmosphere is a balanced two-way flux of about 60 Gigatonnes of carbon per year in both directions. This, however, is an annual average not considering seasonal inequalities in the northern hemisphere [Andrews et al., 1996]. During the growing seasons in temperate climates, CO_2 decreases as plants increase their CO_2 uptake. During the cooler and darker winter months, CO_2 is added to the atmosphere because increased plant respiration and decay occur faster than photosynthesis [Alexander, Schneider, Lagerquist, 1997; Andrews et al. 1996]. Since the landmass in the northern hemisphere is greater than in the southern hemisphere, atmospheric CO_2 concentrations in the North reflect seasonal changes in terrestrial vegetation better than in the South [Figure 1].

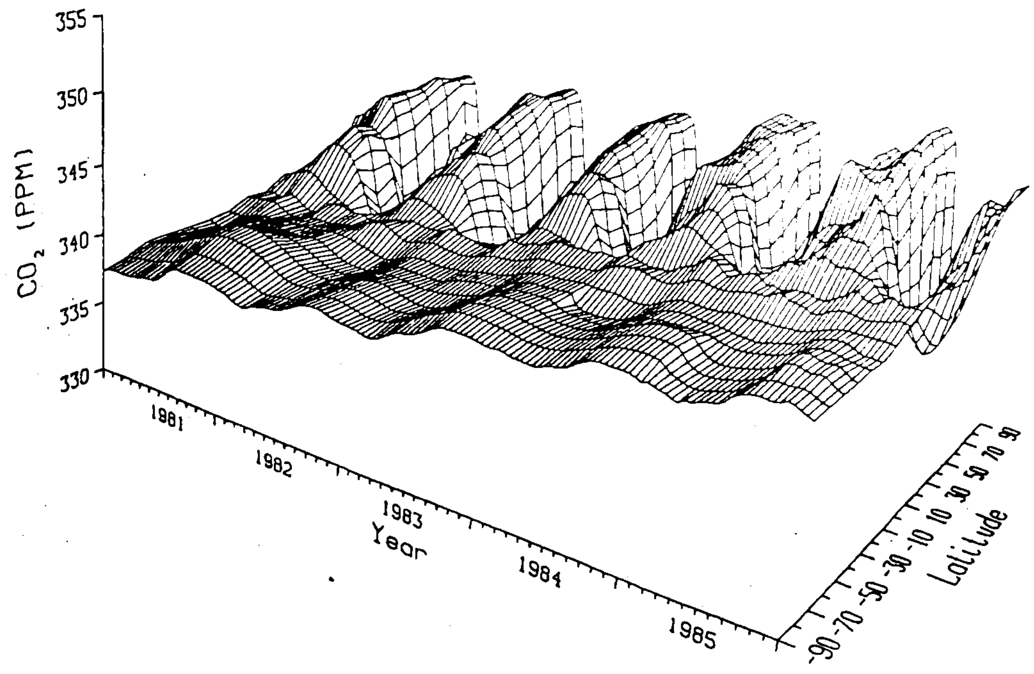

Figure 1. The saw tooth nature of atmospheric CO_2 [from U.S. National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory, in Nisbeth, 1991].

Life affects atmospheric CO_2 through photosynthesis, respiration, and oceanic absorption. Altering ecosystems will alter the balance of these processes. Human activities disturb the carbon balance in the atmosphere by burning fossil fuels and clearing of forests [Alexander, Schneider, Lagerquist, 1997; Nisbeth, 1991; Andrews et al., 1996]. Hence, human activities control primarily the year-to-year increase in atmospheric CO_2, but biological exchanges control its seasonal pattern [Andrews et al., 1996].

2.1.2. The nitrogen cycle

With a nitrogen (N) concentration of 78 per cent, the atmosphere is the major storage pool for gaseous nitrogen. Atmospheric N is inorganically made available by lightning, resulting in nitrate (NO_3-), or organically by bacteria (resulting in ammonium, NH_4+) [Graedel and Allenby, 1995]. In soils and waters, some N is fixed as ammonia (NH_3), ammonium (NH_4+), nitrates (NO_3-) and other N- compounds. N- fixation is the primary source of N in all living organisms. Once fixed in soil or aquatic systems, N can either be oxidised for energy production (nitrification) or assimilated by an organism into biomass. After conversion into amino acids and fixed as proteins, denitrification by bacteria starts when plants are either eaten or die, resulting in N_2 and to a lesser degree, nitrous oxide (N_2O). N finally returns as nitrogen gas into the atmosphere [ibid., Alexander, Schneider, Lagerquist, 1997]. Human activities play a major role in the disruption of the N-cycle. N_2O is a greenhouse gas that traps heat near the Earth's surface. It also destroys stratospheric ozone as UV light splits it into NO_2 and NO, which catalytically reduces ozone. Finally, N-compounds precipitate to the Earth's surface where they can enter the cycle again. Nitrate rain is acidic and can cause ecological problems, but it is also a fertiliser for plants [Alexander, Schneider, Lagerquist, 1997].

2.1.3. The sulphur cycle

The gas sulphur dioxide (SO_2) or particles of sulphate (SO_4^{2-}) compounds in the air precipitate from the atmosphere and are incorporated in plant tissues. In very low levels, sulphur (S) is an essential trace element for living organisms, forming part and structure of proteins. After plants die or are consumed by animals, S-compounds are returned to land and water [Alexander, Schneider, Lagerquist, 1997]. Bacteria convert organic S into hydrogen sulphide gas (H_2S). These gases can enter the atmosphere, hydrosphere, and geosphere to continue the cycle [ibid.]. In the sea, phytoplankton can produce dimethyl sulphide (DMS) that may be important in cloud formation [Nisbeth, 1991]. DMS is the major component of maritime, volatile S [Andrews et al., 1996]. As sulphate (SO_4^{2-}), S causes increased acidity in natural and polluted rainwater, linking it to geochemical, atmospheric, and biological processes such as the natural weathering of rocks, acid precipitation, and denitrification rates [ibid.]. By placing enormous amounts of S-aerosol into the atmosphere, volcanic eruptions can sometimes rapidly change the global environment [Nisbeth, 1991]. However, volcanic emissions of S, natural sea-to air fluxes or emissions of sulphur gases from land sources are important components in sulphur cycling. Global S-budgets could not be balanced without these natural fluxes [Andrews et al., 1996].

2.1.4. Human influence

The CH_4-cycle has deviated so much from pre-human norms that it cannot be described as normal [Nisbeth, 1991] while the increase in CO_2 during the industrial era has been dramatic: Climate scenarios suggest that global average temperatures could rise between 1.4 and 5.8 degrees Celsius during 1990 and

2100. For year 2100, projections for CO_2 concentrations range between 540 to 970 parts per million (ppm) which is 90 to 250 per cent above the pre-industrial level of 280 ppm [IPCC, 2001a]. Current (1999) CO_2 levels are at 367 ppm; around 75 per cent of this increase is a consequence of fossil fuel use. Since 1980, the annual average increase has been 0.4 per cent [ibid.; IPCC, 2001b]. Overall, the Intergovernmental Panel on Climate Change, IPCC [2001a] concludes that "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities" and that anthropogenic global warming is likely to be between 0.1 and 0.2 degrees Celsius per decade.

With regard to N, industrial activity strongly influences the N-cycle by fixing about the same amount of nitrogen as nature - mostly through inorganic chemicals and fossil fuel combustion [Graedel and Allenby, 1995].

The sulphur (S) cycle is one of the most seriously perturbed elemental cycles by human activity [Alexander, Schneider, Lagerquist, 1997], changing the S-balance between the atmosphere, ocean and land surface. Although natural atmospheric S - emissions from terrestrial and marine sources are about 70 per cent of the amount of anthropogenic S emitted into the atmosphere, the total balance of sulphur flows between continental and maritime atmosphere is different: In comparison to the sulphur cycle 150 years ago, today there is a six times greater net flow of S flowing towards the sea [Andrews et al., 1996]. The most significant impact has been input of SO_2 to the atmosphere from fossil fuel use, metal smelters and other industrial activities. However, anthropogenic S-fluxes from dust particles, S- deposits on land and sea surface, from river run-off also exceed natural fluxes manifold [ibid.; Alexander, Schneider, Lagerquist, 1997].

The phosphorus cycle in surface and ground water has been perturbed on regional and local scales through the mining of phosphate rock, and by the use of phosphates in detergents (although the latter practice has largely been abandoned today) [Graedel and Allenby, 1995].

Humans are perturbing significantly all of these biochemical cycles, and other Earth system processes [Alexander, Schneider, Lagerquist, 1997]. In addition, the chemical industry has synthesised several million different chemicals, mainly organic, never previously seen on Earth [Andrews et al., 1996]. For virtually all metals and metalloids, except for iron, silicon and calcium, the global cycles (not the budgets) are exceeded by human activities [Graedel and Allenby, 1995]. Biologically, the existence of the traditional cycles is crucial, their disruption is of concern, and introducing new cycles is a danger signal [ibid.]. Sustainable development may therefore be defined as the "avoidance of serious perturbations to the materials cycles of nature" [Graedel and Allenby, 1995, p. 106]. The atmosphere is especially important with regard to perturbations as it mediates all energy that enters and leaves the planet. The biochemical cycles are embedded in this system, regulating on different time and space scales the flows of energy and materials through the Earth's system [Figure 2]. Although the functioning of the separate system parts is largely understood, feedback and linkages that allow the interconnected parts to function as a whole must still be discovered, as well as their response to human modification [Alexander, Schneider, Lagerquist, 1997].

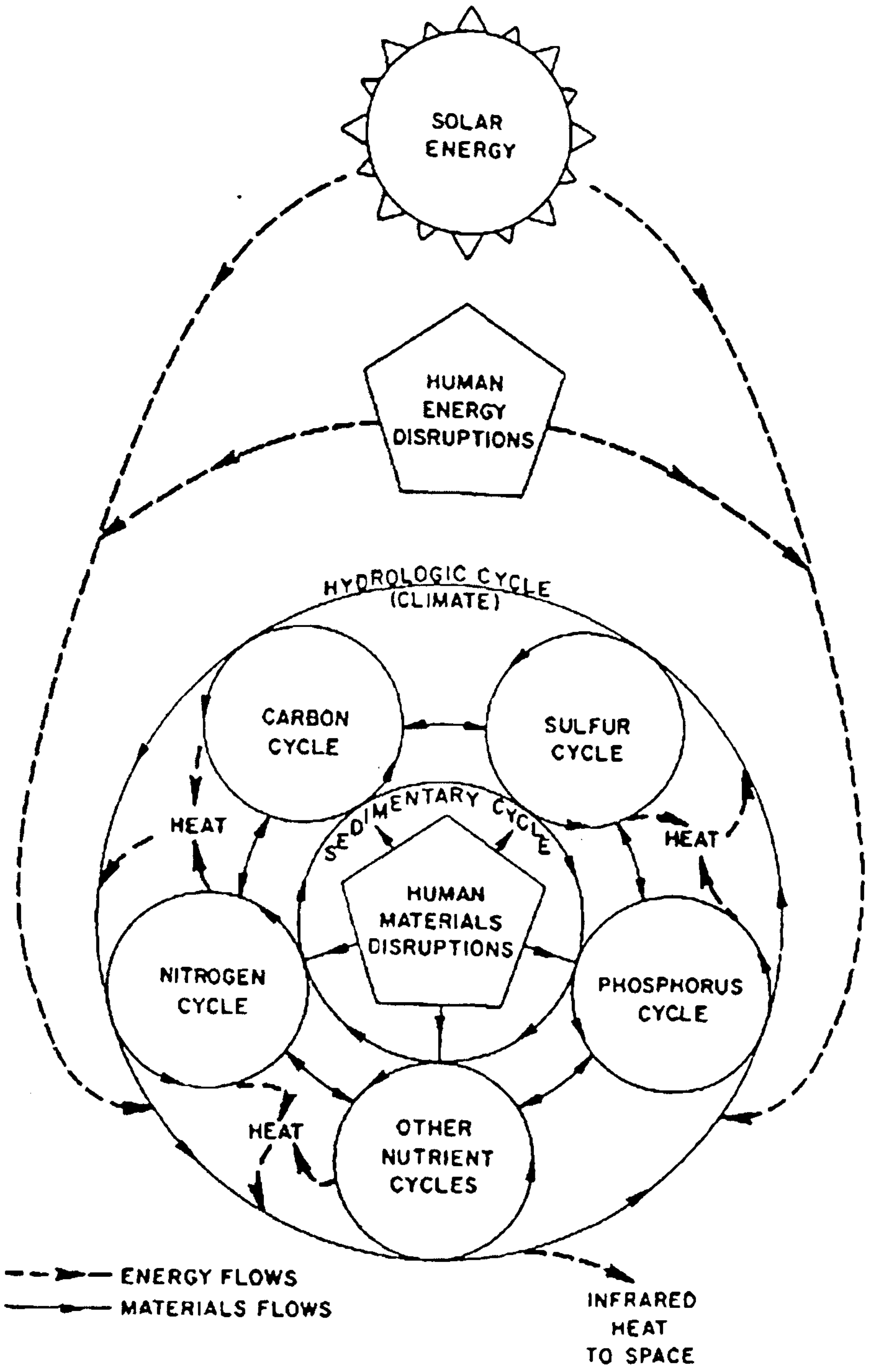

Figure 2. Biochemical cycles and human influence [Schneider and Morton, 1981, in Daily, 1997]

2.2. *The development of sustainability concepts*

There have been many attempts to define sustainability, and it is easy to get lost in the vast literature on sustainable development (SD). Pearce, Barbier and Markandya [1989, in Ryan, 1995] found more than twenty different definitions ranging from ecological sustainability to sustaining economic growth. The meaning of sustainability can be divided into economic, political, social, and ecological dimensions of sustainability. This study is more concerned with the latter dimension. Here, the aim is to outline the problem of sustainability and to set the boundaries of this thesis.

Concepts of SD are deep rooted. Attempts to trace back its origins reach as far as Thomas Malthus (1766-1834) although they only began to blossom in the 1980s [Mather and Chapman, 1998]. The 1960s and 1970s were concerned with the shortage of non-renewable resources, but also with rising population. In his classic essay *"The Tragedy of the Commons"*, Hardin [1968] stressed that technological solutions to increase resource production will only delay the problem of overpopulation (a no-win-situation) and that freedom (especially to breed) implies the recognition of necessity – responsible citizenship for the common good. A few years later, Meadows et al. [1972] popularised the idea that the Earth's non-renewable resources would be the "limits to growth", thus being the constraining factor in traditional economic policies[1] [Markandya and Richardson, 1992]. It was the Stockholm Conference in 1972 which is usually seen as the birthplace of global environmentalism since it made environmental issues legitimate in international relations [Thomas, 1992; in Mather and Chapman, 1998]. However, at that time, environmental and development problems were still treated separately [Mather and Chapman, 1998]. After Stockholm, the discussion had shifted towards reconciling economy and environment, marked by the formation of the World Conservation Strategy (WCS) in 1980. Here, for the first time, a compromise was sought to combine conservation with development, and the mentioning of "needs" [IUCN, 1980]. This was also the birth of the term "sustainable development" [Markandya and Richardson, 1992; Mather and Chapman, 1998]. In 1987 however, the Brundtland Report *"Our Common Future"* [WCED, 1987], based on the International Union for the Conservation of Nature (IUCN) report from 1980, brought "sustainable development" onto the international agenda and into the political mainstream [Markandya and Richardson, 1992]. Compared to the first strategy in 1980, the second WCS in 1991, *"Caring for the Earth"*, placed the major emphasis on development and distributional aspects and the promotion of ethics [Mather and Chapman, 1998]. The Rio *"Earth Summit"* in 1992, held by

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[1] Here quite rightly, economists were the first to criticise their book "Limits to Growth", asking "why it should matter all that much whether we do run out of some material" [Beckermann, 1972, in Mather and Chapman, 1998].

the United Nations Conference on Environment and Development (UNCED) was the largest conference staged by the UN [ibid.] so far. Compared to the Stockholm Conference, the Rio declaration gives greater emphasis to development than environmental issues. Despite this, major agreements such as the Agenda 21 and the Framework Convention on Climate Change were reached, but the conference was also marked by major disputes about North-South issues, funding, and sovereignty (for example, creating forests in the South as carbon sinks for developed northern countries). Although legally binding conventions were not agreed, the concept of sustainable development had diffused "far and wide" [ibid.].

2.2.1. Brundtland definition of sustainability

Today, sustainable development is mainly associated with the Brundtland Report. Numerous interpretations of the report exist, with varying degrees of precision and specificity. For example, [Pezzey, in Mather and Chapman, 1998] identified more than 60 definitions by 1989. Some have argued that the bland vagueness of the concept has been the key to being accepted by a wide range of political settings [ibid.].

The Brundtland Commission [WCED, 1987] understands two key concepts of sustainable development:

- Needs: in particular the essential needs of the world's poor, to which overriding priority should be given, and
- The idea of limitations imposed by the state of technology and social organisation on the environment's ability to meet present and future needs [ibid.].

To achieve SD, population size should be consistent with the productive capacity of the ecosystem, challenging lower population growth rates especially in developing countries [ibid.]. The Brundtland Report further recognises that in most developing countries the dependence on natural resources and the environment is higher than the input in production and economic growth, and that these two problems are linked [Markandya and Richardson, 1989; Nisbeth, 1991]. The report does not reject economic growth per se but underlines that alternative development strategies and technologies are needed to sustain and expand environmental resources. Benefits from development must be equitably distributed [Markandya and Richardson, 1989].

2.2.2. Implications of sustainable development

However, the Brundtland Report also raises many questions, especially how the environmental, social and economic dimensions of the principle "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [WCED, 1987] can be reconciled [Howes, Skea and Whelan, 1997]:

- How the equity issues between present and future generations should be addressed, and whether this includes higher needs such quality of life, landscape and wilderness [ibid.].
- Whether there is an acceptable rate of global warming [Pearce, 1991].
- How an effective structure of global incentives for co-operation can be designed [Pearce, 1991].

Some controversial points are:

- The concept is distinctly anthropocentric, other life is only considered as it contributes to its end [Pearce, 2000; Allenby, 1999].
- It is not known how a sustainable society might look like, sustainable development is one possibility among many for a sustainable future, and might not be the most probable [Allenby, 1999].
- The social rather than scientific approach obscures the fact that a sustainable subsystem (for example a company, product or an individual) in an unsustainable global system is profoundly contradictory [ibid.].
- It is not clear whether equity is necessary for a physically sustainable world, although it might be desirable. Because historically, equity was never present, it can be argued that if sustainability has to wait on equity, sustainability might never be achieved - or that the human species can achieve sustainability sooner than sustainable development [ibid.].

The Brundtland concept is still ambiguous, difficult to implement and lacks a systemic approach: The sustainability of a subsystem in a global system can only be defined in terms of a global system – it cannot exist without links to the greater whole. Sustainability must address aggregate human activity plus all levels of biological, chemical and physical systems. It is not known whether a system is sustainable until this state has already been achieved. Sustainability is a science, technology and a social challenge [Allenby, 1999]. However, the Brundtland Commission also crystallised and publicised sustainable development concepts [Mather and Chapman, 1998]. In conclusion, although the Brundtland Report lacks many essential criteria, it gave an important impulse for bringing sustainable development closer to mainstream policies. The danger may lie in moving too far away from the ecological dimension of sustainability in the future.

2.2.3. Weak and strong sustainability

"Weak" or "strong" sustainability, termed by Daly [1991, in Mather and Chapman, 1998], can be distinguished as the two main orientations of sustainability [GUA, 2000]. Both forms imply that the total amount of capital must be kept constant, but both address different types of capital [Pearce, 2000]. As capital consists of man-made capital and natural capital, ***weak*** sustainability implies that natural capital can be replaced by man-made capital through investment and technology [Solow, 1993, in Ryan, 1995], while in ***strong*** sustainability, natural capital cannot be replaced with man-made capital – both are not substitutable, but complement each other [Daly, 1991; Perrings, 1987, in Ryan, 1995]. However, there is also much confusion in this debate. Pearce [2000] stressed that having strong sustainability without having weak sustainability is not possible, since it makes no sense to set constraints on one form of capital unless there is an overall constraint on the total stock. This would falsely imply that only one form of capital creates well-being. The debate is split over the question whether man-made capital can replace natural capital, with ecological economists who generally do not believe in substitution, and environmental economists who mainly do [ibid.]. However, since renewable/replenishable resources are critical for life supporting processes they are generally not substitutable [Rees, 1996]. For non-renewable resources, depletion can be compensated through investment in renewable natural capital [ibid.] or should be "no greater than the rate at which substitutes become available" [Mather, Chapman, 1998, p. 253].

Applying standard economic arguments of man-made capital to a stock of "natural capital" has been criticised because:

- Putting prices on non-quantifiable natural assets is difficult, and ignores the dynamics of ecological systems
- Theoretical optimal solutions in resource economics may at the same time lead to environmental unsustainable consequences
- It ignores the scale of throughput which disturbs natural systems, and the ecological impacts from the dislocation of natural resources from their natural flows, including their (non-marketable) overburden [Victor, 1991; Hinterberger, Luks, Schmidt-Bleek, 1997].

There has also been confusion about ***total*** and ***marginal*** substitution. According to Pearce [1991], natural capital as a whole is not substitutable – but it is "substitutable at the margin" – for example, allowing some damage to the ozone layer, some degree of climate change. This refers to Pearce's "constant capital" approach where not every environmental asset needs preservation. Pearce [ibid.] further pointed out that even a utilitarian approach (cost benefit analysis) must account for the environmental challenges of uncertainty, irreversibility, and uniqueness. This is termed "critical capital" which is necessary for life support that needs special protection [ibid.]. However, the problem is that then "acceptable levels" for global warming or other forms of natural capital depletion must be defined.

Pearce [ibid.] suggested cost benefit analysis (weighing present costs against future gains) to determine these levels. This implies that the cost of an abatement procedure (such as reducing CO_2 levels) is only worthwhile when exceeding the maximum net benefit[2].

The major problem with this approach is that it is purely based on monetary assessments. Without an ecological bottom line it is questionable that the

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[2] In an example by Nordhaus, in Pearce [1991], this refered to a CO_2 reduction between 6 to 17 per cent by 2050, significantly lower than some existing political commitments in Europe or the Kyoto Protocol.

"substitutable margin" can be determined, especially with regard to already stressed ecosystems.

2.2.4. Natural capital

Natural capital can be divided into three main categories: 1. Renewable (self-producing and self-maintaining, such as living species and ecosystems using solar energy and photosynthesis). 2. Replenishable (for example, the atmosphere or ground water). 3. Non-renewable[3] (such as fossil fuels and minerals) [Costanza, 1992, in Rees, 1996a].

However, rather than the depletion of non-renewable resources it is the disruption and depletion of the non-marketable, renewable and replenishable natural capital – of natural ecosystems - which is the most troublesome [Mooney and Ehrlich, 1997; Rees, 1995; Costanza and Daly, 1992; Myers and Reichert, 1997].

The most important difference between biophysical and monetary analysis is that the former looks at the whole system, recognising absolute limits for substitutability, and the latter only at issues at the margin[4]. While the costs of harvesting non-renewable resources will increase with their further depletion, the use of living natural capital may not become more costly even though harvest or use rates are above sustainable levels, such as deforestation, soil erosion, ozone depletion in the stratosphere [Wackernagel, 1999a].

Moreover, there is the possibility that ecological capacity can be extended beyond sustainable limits –the so-called overshoot [Catton, 1980], which marginal analysis will not detect but may be the most significant sustainability challenge [Wackernagel, 1999a]. An increasing number of people is depleting the planet's natural stock instead of living off its interests. Overshoot can happen without much notice, or a "big bang" because nature reacts with some inertia. Paradoxically, it is "possible that standards of living are waxing, while ecological capacity is waning" [Myers and Simon, 1994, in Wackernagel and Silverstein, 2000].

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[3] On human time scales.

[4] Marginal substitution of natural capital with manufactured capital [Wackernagel et al., 1999].

2.3. Strategies: How to make the use of natural capital sustainable

Due to the interdependence of population, economy, and resource consumption, environmental pressures increase with population and economic growth [GUA, 2000]. To avoid further shrinking of natural capital, the dematerialization of the economy, reduction of throughput[5] and increased resource productivity have been suggested [Hinterberger, Luks, Schmidt-Bleek, 1997; Schmidt-Bleek, 1994; Weizsäcker, Lovins and Lovins, 1997]. Dematerialization is one of the most prominent concepts, aiming to de-couple environmental damage from economic growth. *Factor* X and *eco-efficiency* can be distinguished as the two main strategies for dematerialisation [GUA, 2000].

2.3.1. Factor X

The concept's basic thought is that the high global use of resources will result in excessive stress on the sink-capacity of global ecosystems. The Factor Four Report to the Club of Rome [Weizsäcker and Lovins, 1997] includes examples of quadrupling resource productivity while sustaining global welfare. The achievement of a global factor four would lead to immense macro-economic gains and is technically feasible [Weizsäcker, Lovins & Lovins, 1992, in GUA, 2000]. Since less than 20 per cent of humans consume more than 80 per cent of the natural resources, an absolute reduction in resource use of at least 50 per cent is necessary to make environmental space for poor nations [Schmidt-Bleek, 2000, in GUA 2000]. However, factor four is only a minimum requirement and higher factors of at least ten for rich nations have been suggested for achieving sustainability [Schmidt-Bleek 1994; International Factor 10 Club, 1997]. (For further reading: Wuppertal Institute for Climate, Environment, Energy and its authors; BUND / Misereor, 1996; Schmidt-Bleek, 1997].

Factor X concepts certainly imply deep structural changes in market structures and current policies, like changes in taxation, subsidies, and the evaluation of natural resources, but also of "needs": For example whether a car is needed for

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[5] O'Connor [1994, in Ryan, 1995 p.26] pointed out that it is not necessarily the quantitative throughput of the economy that should be minimised, but the qualitative changes in the flow of throughput.

mobility, or whether one needs to get from here to there: ***Using*** instead of ***owning*** [Schmidt-Bleek 1994; Hinterberger, Luks, Schmidt-Bleek, 1997].

The outlook for factor X reductions is optimistic: Some believe that a factor four in materials intensity over the next 40 years is essential from an economic and ecological aspect, since win-win opportunities would be so large that companies who do not join in would loose competitiveness [Hawken, 1995]. There are several examples for countries and international organisations where factor X concepts have at least been drafted [for example, Günther, 1998; BMU, 1998].

2.3.2. Eco-efficiency

The concept of eco-efficiency is very similar to factor X since it also aims at decoupling the economy from the environment.

Meeting needs with less natural and manufactured resources but with more use of people has become an environmental and economic imperative [WBCSD, 1996, in GUA, 2000]. This means:

- More efficient and equitable resource use by innovation in the use of resources and labour.
- Meeting human needs rather from labour-intensive services than capital-intensive products [GUA, 2000].

However, there are drawbacks associated with the means by which companies promote the reduction of environmental impacts and dematerialization. It is not clear whether service or leasing will automatically yield environmental benefits, and if instead not a more rapid product turnover will be the result of these efficiency gains [Howes, Skea, Whelan, 1997; Pearce, 1998; GUA, 2000; Brezet, Bijma, Sylvester, 2000]. Because efficiency gains can be compensated by the growth of the economic product, technological effects must not be outweighed by growth effects. In the case of energy and material use, the hope for technological improvements is in vain as long as it is not accompanied by a change in behaviour that is potentially resource saving [Hinterberger et al., 1998]:

> The increasing service component in the economy is doubtless one of the reasons why energy consumption per unit of economic output has steadily fallen (..) but this has not stopped total energy use from rising [Brookes, 1991; in ibid., p. 8].

Onisto [1999] brought the dilemma to the point: Although the WBCSD defined eco-efficiency with the aim to reduce impacts to at least in line with the Earth's carrying capacity [WBCSD, 1998; in ibid], the mainstream eco-efficiency movement fails to prioritise what is sustainable, and whether the level of efficiency practiced is sufficient. They completely fail to address sustainability because it is detached from the context of a natural systems level that provides a basis for indicators.

Since the Rio Earth Summit in 1992, a plethora of eco-indicators, policies, conventions, and numerous corporate environmental reports have blossomed. Few, if any business initiatives include a clear measurable baseline for sustainability [Gray, 1994, in Onisto] but measure eco-efficiency gains, cost reduction, pollution control, increased earnings [Onisto, 1999]. The result from Rio +5 review in 1997 was that "the world's largest countries have failed utterly to honour the pledges they made at the 1992 Rio Earth Summit" [James Gustave Speth, former Head of the UN Development program, in ibid., p. 40]. The growing preoccupation by business on indicators containing a variety of environmental measures, which apparently address sustainability, is dangerous since it distracts from the reality [ibid.]. But the greatest danger comes from creating the appearance that the environment has been adequately considered while in reality, promoting efficiency of unsustainable processes only accelerates unsustainable practices [Wackernagel and Rees, 1996]. Sustainability is about accounting for natural capital [Soros, 1997; Adams, 1994; Hall, 1992; Goodland et al., 1993, in Onisto, 1999; Wackernagel and Rees, 1996]. "Knowing the ecological bottom line, that is, how much nature is consumed per unit of production, should become a strategy to differentiate products and services" [Robèrt et al., 1995].

2.3.3. Physical assessment methods for sustainability

Physical assessment methods are based on thermodynamic principles and can be grouped into mass flow analysis and thermodynamic analysis [GUA, 2000].

Details can be found in [ibid.] and also in [Chambers, Simmons and Wackernagel, 2000], illustrated in [Table 1].

Physical assessment methods	
Mass flow analysis	MIPS, Rucksacks
	Life cycle analysis
	Environmental space
	Carrying capacity
	Ecological footprint
Thermodynamic analysis	Entropy
	Exergy
	Net primary productivity

Table 1. Overview of physical assessment methods [based on GUA, 2000]. Not comprehensive.

The ecological footprint method is explained in [section 2.5].

2.4. Gaia: A different view

There is yet no scientific agreement on what controls the complex interactions that form the Earth's atmosphere, but two extreme viewpoints can be distinguished [Nisbeth, 1991]:

1. That there is no control, life happened by chance and utilises what is there. The atmosphere is accidental, only constrained by chemical and physical properties. Today, only a few scientists hold this view.

2. That life controls and manages the functions of the Earth. This is not the view of most scientists, but increasing evidence is confirming this theory.

In his thought-provoking book, *The Ages of Gaia*, James Lovelock [1995] takes a distant view of the Earth as seen from outer space. He developed a theory of the Earth as a living, self-regulating and self-changing super-organism, Gaia. Over aeons, this system has evolved dominated by life: Active feedback processes operate automatically, whilst comfortable conditions for life are maintained by solar energy. The conditions are only constant in the short-term, as they evolve with the changing needs of an evolving biota. Life and its environment are closely interconnected so that evolution is concerned with planet Gaia itself, and not with separate organisms or the environment. Hence, Gaia forces a planetary perspective, and this is where Lovelock's approach is different from the anthropocentric concerns of the Brundtland Report: That it is the health of the planet that matters, not that of a single species. It is the health of the Earth that is most threatened by major changes in natural ecosystems. In Gaia, humans are just another species, neither the owner nor the stewards of this planet. Their future depends on a correct relationship with Gaia, rather than on human self-interest. Lovelock's conclusions, now merging again with many environmentalists, are that the current market philosophy should make the value of Gaia's services more appreciated - yet humans, despite of being aware, continue to destroy ecosystems at overwhelming rates:

> Because we have been busy removing its skin for farmland, taking away the trees that are the means for recovery. We are also adding a vast blanket of greenhouse gases to an already feverish patient. Gaia is more likely to shudder, then move over to a more stable state, fit for a different and more amenable biota. It could be much hotter, but whatever it is, no longer the comfortable world we know. These predictions are (..) uncomfortably close to certainty [op. cit., p. 227].

He concludes that humans must in their own interest accept that the Earth is at least as important as they themselves believe to be. This means avoiding perturbing a seemingly unstable and failing super organism, which may jump into a new but unwanted stable climate. After all, in a Gaian sense, "there is no tenure for anyone on this planet, not even a species" [op. cit., p. 239].

Lovelock's approach is different from the mainstream sustainability agenda (such as the Brundtland Report), which focuses strongly on meeting human's rights and equity. Paradoxically, equity issues may be among the first to suffer in a world with increasingly perturbed ecosystems.

2.5. The ecological footprint: What is it?

EFA is different from most other tools that measure sustainability in that it accounts biophysical resources. It is grounded on the approach by Vitousek et al. [1986], who calculated the net primary productivity (NPP) appropriated by humans. Both approaches have in common that they illustrate biophysical limits by measuring demand and supply of biocapacity. However, intellectual foundations originate from the 1960s and 1970s, such as Borgström's *Ghost Acreage* [1973]. A chronological overview can be found in [Wackernagel, Lewan, Borgström, 1999].

The overarching question in ecological footprint analysis (EFA) is whether nature's productivity is sufficient to satisfy present and future demands of the economy indefinitely. The ecological footprint for a particular population is defined as:

> The total area of productive land and water ecosystems required to produce the resources that the population consumes and assimilate the wastes that the population produces, wherever on Earth that land and water may be located, using prevailing technology [Rees and Wackernagel, 1996, p. 228].

This means that

a) most of people's consumption and much of the waste they produce and
b) the biologically productive areas appropriated for production of this consumption and waste assimilation

can be calculated [Wackernagel, Lewan, Borgström, 1999].

EF assessments account for as many ecological impacts as possible without exaggerating human impact on the Earth. So far, EF accounts have included land for agriculture, pasture, forests, built up land, oceans for fisheries, and land for energy supply. With regard to waste, land for CO_2 absorption, and in some studies, land for denitrification, acidification, and phosphorus retention have been included [see Folke et al., 1997; Wackernagel, Lewan, Borgström, 1999; Krotscheck, 2000, in Chambers, Simmons and Wackernagel, 2000; Narodoslawsky and Krotscheck, 1997].

2.5.1. Two approaches: Compound and component footprinting

Two main approaches in EF calculations can be distinguished, the compound and the component method. Both methods are complementary [Chambers, Simmons and Wackernagel, 2000], the first is a top-down, the latter a bottom-up approach:

The ***compound*** method, originated and refined by Mathis Wackernagel et al., is primarily used for nations and is the more robust and comprehensive method since it is based on international trade analyses [Lewan, pers. comm. 25.10.01; Chambers, Simmons and Wackernagel, 2000]. The first part of a nation's consumption calculation is a consumption analysis based on trade flows and energy data. This is calculated by adding imports to domestic production, and subtracting exports (to gain the "apparent consumption"). The balance is calculated across approximately 60 biotic resource categories, such as timber, pulp, cereals, tubers and animal products. Each category contains primary resources like raw timber or milk, and their derived, manufactured products like paper or cheese, which have to be converted into their round wood or raw milk equivalents. This includes a waste factor between raw material production and final consumption and is calculated to obtain more accurate measurements. Apparent consumption varies from final consumption because it includes resources for producing exports and excludes resources embodied in finished imported goods [Wackernagel, Lewan, Borgström, 1999]. The final consumption is obtained after adjusting all components for their biological productivities.

Using Food and Agriculture Organisation (FAO) estimates for world average yield, the total amount of resources consumed is divided by the corresponding annual (world average) biological yield, resulting in the (world average) land and sea areas required to sustain a nation's annual consumption [ibid., Chambers, Simmons, Wackernagel, 2000].
The total amount of waste generated is divided by the corresponding required (world average) absorption capacity[6]. These areas are part of the total footprint [Wackernagel, 2001].

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[6] On a global level, wastes other than CO_2 have no absorption capacity allocated today.

The per capita footprint (aa) of raw material consumption for each major resource (*i*) in a given year is estimated by dividing average annual consumption of that item (c) in kg/capita by its average productivity (p) in kg/hectare (ha) [GUA, 2000].

$$aa_i = \frac{c_i}{p_i} \quad \text{[ha/capita]} \quad \text{(Equation 1)}$$

Space directly occupied by buildings and other infrastructure is added to the built up area [Wackernagel et al., 1999].

The second part determines the energy balance of both locally generated energy and the embodied energy in traded goods, adjusted by fuel specific carbon content where possible. Several screening steps are included to avoid double accounting [Chambers, Simmons, Wackernagel, 2000].

Calculating the per capita footprint provides useful information for comparisons with other countries. In the final part, the per capita EF for a country is computed by totalling all ecosystem areas appropriated (aa_i) corresponding to the sum of consumed EF components (n). Multiplying the per capita EF by its population size results in a country's EF. Therefore, the total EF expressed in a formula is [Wackernagel and Rees, 1996]:

$$\text{EF} = \sum_{i=1}^{i=n} \text{aa}\, i \quad \text{[ha/capita]} \quad \text{(Equation 2)}$$

Equivalence factors scale the results to obtain world average productive space. This facilitates comparisons with the global available biocapacity. To estimate how much biocapacity exists within a country, yield factors equate local productivity of each land category to the global average, thus scaling national areas proportionally to their global bioproductivity. At least 12 per cent of bioproductive space is usually reserved for biodiversity protection [Chambers, Simmons, Wackernagel, 2000; Wackernagel, 2001; Wackernagel et al., 1999] although the *Living Planet Report* (LPR) only reserved 10 per cent [WWF, 2000].

The ***component*** approach focuses on local activities such as transport, and uses pre-calculated EF-conversion factors for the region under consideration [Simmons, Lewis, Barrett, 2000]. The Environmental Consultants *BFF* have led the development contemporaneously with the compound footprint pioneered by Wackernagel et al. [1997 and 1999, in ibid.]. The component approach uses 24 basic components, aiming to account for most consumption by a series of component analyses, including interviews [Chambers, Simmons, Wackernagel, 2000; Lewan, pers. comm. 25.10.01]. The EF for a certain component is calculated from available collated life cycle data. When comparing overall results of both methods, the authors found that the majority of anthropogenic impacts were captured. The method also includes screening steps, sensitivity analyses and adjustments to avoid double counting [Chambers, Simmons, Wackernagel, 2000].

Advantages of the component approach include easier communication and being more instructive due to the breaking down of impacts. Since the compound method captures all resources that are used in a country (irrespective of their activities), it can capture indirect effects more effectively. At the same time, this makes it less suitable for distinguishing activities that are of particular interest for resource consumption. In the component approach, data can easier be collected where national statistics are not available. Its ***disadvantages*** are in data variability and reliability, making national and international comparisons difficult [ibid., also Lewan, pers. comm. 25.10.01]. Besides the need for careful consideration of life cycle effects for each component, calculating direct and indirect life cycle impacts is very data intensive. However, both methods face varying degrees of data availability and accuracy, and cannot include all uses of nature by resource use and waste absorption. In conclusion, the required level of detail, and the target of the analysis determine the choice of approach [Chambers, Simmons, Wackernagel, 2000].

2.5.2. *The Footprint of Nations study*

National footprints are among the most reliable estimates because most of the data required – such as ecological productivity, resource production and trade figures - are already measured by national statistical institutes [Wackernagel et al., 1999]. The footprint of nations study (FONS), originally commissioned by the Earth Council for the Rio 5+ Forum held in Rio de Janeiro in 1997, examined 52 nations covering 80 per cent of the global population. It has been steadily improved since. It also shows to what extent a nation's consumption matches its available biocapacity [Wackernagel, Callejas and Deumling, 2000].

The accounts document that humanity's consumption already exceeds global capacity by more than a third. The report is updated annually and is based on the latest available UN-statistics [Table 2][7] [ibid.]. The accounts include six mutually exclusive productive land categories, which compete with each other. For national accounts, the bioproductive space required by a country (the EF, or demand side) and the productive space available (the supply side) are then summarised and compared. It has to be remembered that the EF is not only calculated for land space actually consumed but also for the (virtual) space that would be required if a country sequestered its produced CO_2 emissions.

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[7] Full report available at: http://www.redefiningprogress.org/programs/sustainability/ef/deficittable1_nations.html. Last accessed January 2002.

Country	**Ecological Footprint [ha/cap]**	**Existing biological capacity [ha/cap]**	**Ecological deficit (if neg.) incl. biodiversity [ha/cap]**
Column:	***a***	***b***	***c = b-a/88%***
Australia	9.1	9.4	-0.9
Austria	5.5	4.1	-2.1
Bangladesh	0.6	0.1	-0.6
Canada	9.4	11.2	0.5
China	1.8	0.9	-1.2
Denmark	9.4	5.7	-4.9
Germany	6.3	2.5	-4.6
Hong Kong	5.9	0.1	-6.6
India	1.1	0.7	-0.5
Indonesia	1.5	3.2	1.5
Netherlands	6.6	2.4	-5.1
Sweden	7.8	8.0	-0.8
Switzerland	6.1	2.2	-4.7
United Kingdom	6.2	1.8	-5.3
United States of America	12.2	5.6	-8.4
WORLD	**2.8**	**2.2**	**-1.1**

Table 2. EF of 15 selected countries modified from [Wackernagel et al., 2000], for WWF International.

The table documents that many countries have an ecological deficit. This means that the country's area alone cannot sufficiently provide for the current lifestyle of its residents [Wackernagel et al, 1997].

The United States' ecological deficit is more than 50 per cent [Wackernagel et al, 2001] with an EF four times greater than the global average EF and more than five times greater than the globally available supply per capita.

Only few countries have an ecological surplus. However, this is seldom used for biodiversity protection but rather for exporting goods [Chambers, Simmons, Wackernagel, 2000; Wackernagel, et al., 1997]. Canada, for example, has one of the highest footprints yet the table suggests that the country is still below its biological capacity. However, Canada is a net exporter of embodied energy and therefore CO_2 emissions [Wackernagel and Rees, 1996]. In 1995, Canada imported 247.74 tonnes of dairy products while at the same time exporting 247.77 tonnes [Wackernagel et al., 1997, in Barrett, 2000], producing unnecessary overheads of CO_2 from transportation due to exchange of the same goods [Barrett, 2000]. Furthermore, van Vuuren, Smeets & de Kruif [1999] estimated that areas for carbon sequestration range from 20 per cent for non-industrialised countries to above 50 per cent for industrialised nations.

When interpreting the results of a nation it must be remembered that the EF underestimates the true human impact, and that if a nation's population and consumption continue to rise, possible ecological remainders will soon be used up [Wackernagel et al., 1997]. The latest FONS[8] [Wackernagel et al., 2001] showed that only 9 out of 52 nations have an ecological surplus. All European countries apart from Finland run an ecological deficit. This is possible due to importing biocapacity from other countries to support the present levels of consumption [Wackernagel and Silverstein, 2000]. It also means that if all countries adapted the lifestyle of the nations with a deficit, there would not be enough biocapacity to support them sustainably [Wackernagel et al., 1997].

The key difference is the gap between the industrialised and "developing" countries. Both Bangladesh and India, despite their small EF, have ecological deficits due to high population rates and low bioproductivity of their soils [for comparison, see Wackernagel, Callejas and Deumling, 2000]. To make EFA internationally comparable, all results are expressed in ha of world average land with world average productivity, or yield[9]. This makes The Netherlands,

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[8] http://www.rprogress.org/programs/sustainability/ef/ef_projsum.html

[9] The use of global yield factors for all countries is based on Wackernagel et al.'s assumption that everyone on Earth has an equal right to the most productive land, hence no country should be disadvantaged by low local yields. This implies that sustainability must, in the end, be global (local yield factors are only used in regional comparisons within a country). Some have

for example, appear larger than it actually is due to the high productivity of its soils. With a biological capacity of only 2.4 ha per person, The Netherlands have the capability to buy biocapacity from elsewhere and live on 6.6 ha per person. Most poorer countries do not have the financial resources to import biocapacity at the same scale [Wackernagel and Silverstein, 2000].

The EF of nations makes the imbalance and competition for ecosystem services between the poor and the rich worlds strikingly visible, raising the issue of equal rights to global resources. This can be interpreted as the ethical side of the EF. At the same time, it shows that we may have already dangerously overshot nature's regeneration capacity. However, it implies a sustainability variable (use of global yields) assuming globally equal rights to precious resources. This is in line with the Brundtland Report [WBCSD, 1987]. Despite these results, the EF itself is only a calculation procedure and does not make suggestions how to reduce the impact. It reflects the ecological state of the world and questions what can be done to improve it.

2.5.3. *EF and sustainability*

This section explores the Ecological Footprint (EF) concept and discusses its relevance for the ecological sustainability dimension. There is a vast amount of literature on non-monetary sustainability indicators, summaries can be found, for example, in [Munashinghe and Shearer, 1995, in Ryan, 1995]. For methodological and ideological aspects see Aznar, Holmberg and Lindgren [1996].

Holmberg et al. [1999] give a structure of principles that should be fulfilled in a sustainable society. Hence, nature's functions and diversity are not systematically:

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disagreed with this approach [van den Bergh & Verbruggen, 1999; Haberl et al., 2001]. However, increasing yield factors is not necessarily a precondition for decreasing land area or being sustainable since obtaining higher yields requires a higher amount of embedded energy (i.e. fertilisers, machinery, transport). Secondly, using local yield factors asks different questions (i.e. confined to the local level) and does not address global dependence or sustainability.

1. Subject to increasing concentrations of substances extracted from the lithosphere.
2. Subject to increasing concentrations of substances produced by society.
3. Impoverished by over-harvesting or other forms of ecosystem manipulation (for example, decreasing the thickness of productive soils, nutrient contents, ground water, genetic variation).
4. Resources are used fairly and efficiently in order to meet basic human needs worldwide.

At the same time, these principles lead to the strengths and limits of the EF as a sustainability indicator. The following discussion is mainly summarised from [ibid.]:

Principles 1 and **2** address the deterioration of the ecosphere through increased accumulation of substances that are either extracted from the Earth's crust or otherwise produced by society. With regard to fossil fuel use, the EF accounts for the biocapacity required to offset its CO_2 emissions. Principles 1 and 2 are also relevant with regard to fertilisers because their use can increase crop yields on the same area of land. At the same time, however, additional areas to avoid nutrient leakage, and land for absorbing CO_2 have to be added for their production. Compounds that are foreign to nature (like PCB or flame retardants) cannot be accounted for by the EF as no assimilation capacities can be identified [ibid.]. Other tools are better suited to monitor these.

Systematically including waste flows other than CO_2 is problematic since it depends on a) whether the assimilation capacity of the flow is known, b) whether it can be estimated indirectly (for example, through weathering and sedimentation rates), c) if the assimilation capacity can adequately be transformed into an area, and d) if double counting of areas can be avoided [Holmberg et al, 1999]. Some regional assessments have included acidification, denitrification, and copper assimilation. However, including other wastes systematically is difficult because assimilation capacities are only known for a few substances that occur naturally, and these capacities vary between regions. When trying to include other waste flows, double accounting must be avoided as some areas for assimilation of substances will still be available for other purposes (if areas are not destroyed by high concentrations of the flows emitted). There are flows that can be aggregated without risking double accounting (primary or additive aspects) such as food and fibre production, and secondary, non-additive aspects if the same area can be used for more than one purpose (such as fibre production and assimilation). If assimilation capacities do not exceed the corresponding absorption area required, their areas will not be added to the EF. These non-additive aspects may be aggregated as a "shadow" footprint [Figure 3]. If some of the secondary substances emitted do exceed this area, the EF should increase accordingly [ibid.].

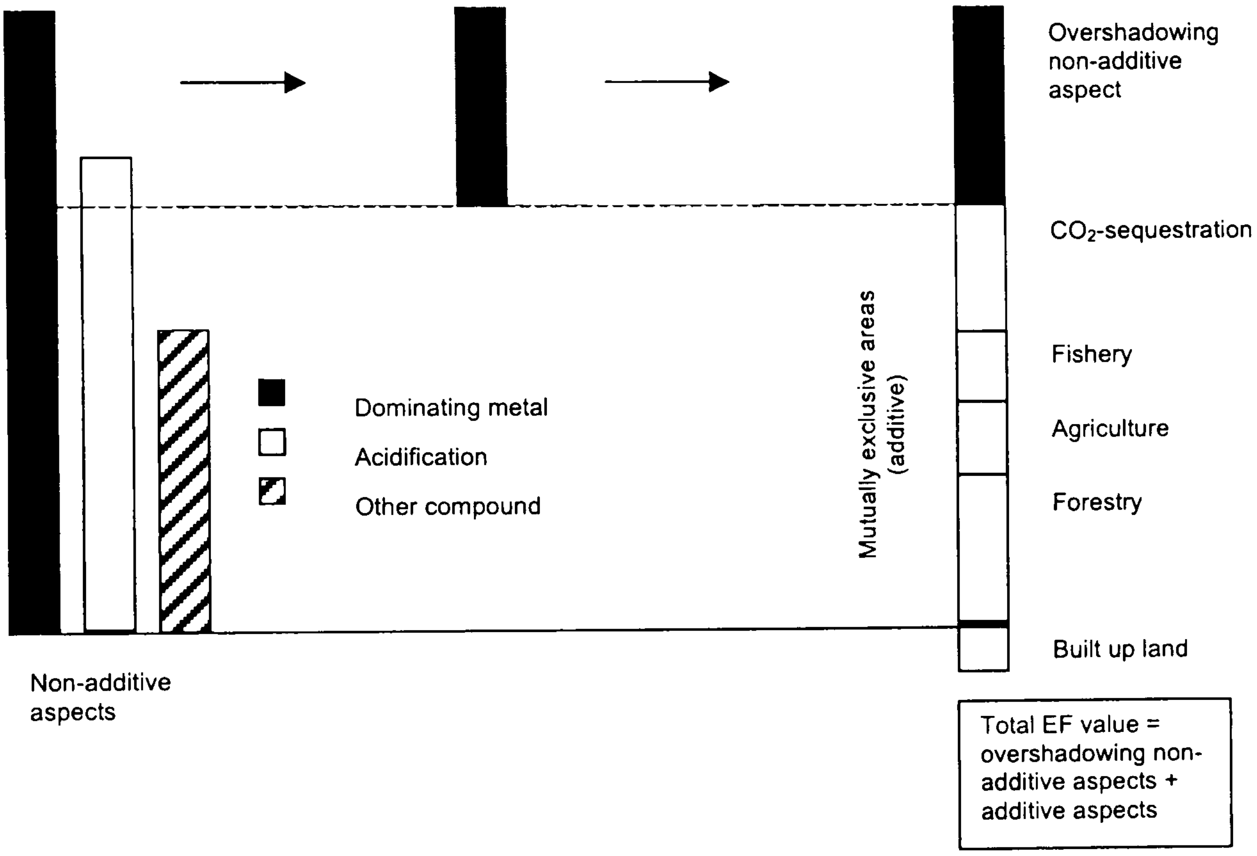

Figure 3. Additive and non-additive aspects of an EF [adapted from Holmberg et al., 1999].

Under *Principle 3*, "harvesting and manipulation of the ecosphere must not deteriorate long-term productivity or threaten biodiversity". If it is to be included in the EF it must be known whether a) the influence on long-term production capacity and biodiversity are known, b) if this can be estimated indirectly, c) if this influence can be transformed into an area and d) if double counting is avoidable. Principle 3 accounts for the following activities [ibid.]:

- Built up or degraded land
- Forestry and agriculture: Accounted for by their current timber and crop yields, optimistically assuming that these can be maintained. This leads to an underestimation of human impact on long-term productivity and biodiversity. Land that has lost its productivity is subtracted from productive areas. To preserve biodiversity, a small and most likely insufficient percentage of bioproductive space is reserved. Natural factors, climate, soil, and human influence affect the biocapacity of cropland and forests. These effects are partly covered by yield factors that compare local to global yield. However, systematic long-term deterioration through bad management or loss of conditions for maintaining biodiversity is not included yet, making EF results conservative [ibid.]. Categories agriculture and forestry could be supplemented by more detailed indicators, for example, ecosystem health [Rapport, 2000].[10]

- Fisheries are included as a food-providing source. The latest EF for fish production is obtained by calculating the area required for protein production [WWF, 2000]. There are several EF studies for specific fisheries [see Folke et al., 1998; Naylor et al., 1998].

- Water has only more recently been included in EF analysis [Callejas, 1998, in Holmberg et al., 1999]. The so-called "green" water present in biomass does not need to be accounted for separately. The so-called "blue" water in aquifers and rivers can be divided into consumptive and throughflow water [Holmberg et al., 1999]. The EF of consumptive water (such as decline from irrigation) can either be represented by the corresponding catchment area [Jansson et al, 1999] or by calculating the recharge area of the aquifer that corresponds to the excess use of the aquifer's renewable yield[11]. Circulating throughflow water is not actually consumed but the EF can be established for the embedded energy for treating, piping, pumping and heating the water [Holmberg et al., 1999; Chambers, Simmons, Wackernagel, 2000]. Qualitative aspects of freshwater that do not need additional areas to offset

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[10] This would add a qualitative aspect to the –so far- purely quantitative nature of the EF [Kevin Lewis, BFF, pers. comm., 22.5.02].

[11] Including both catchment areas and aquifer recharge rates would lead to double counting.

lost bioproductivity (like the presence of man-made compounds) should not be addressed by the EF [Holmberg et. al, 1999].

Principle 4 addresses the ethical dimension of sustainability. The EF as an ecological indicator does not claim to address the fourth principle [Rees and Wackernagel, 1996] although it is indirectly linked to it as it reveals the trans- and dematerialisation of certain material flows [Holmberg et al., 1999]. Using the fair Earth share is certainly ethical [Lewis, pers. comm., 22.05.02].

2.5.4. Carrying capacity and overshoot

Because EFA measures both population and resource use, it relates to Catton's classical definition of human load and human carrying capacity – the "maximum persistently supportable load" [Catton, 1980, in Rees, 2000]. Human load is a function of its population, its consumption per capita and its ecological efficiency in resource use [Wackernagel, 1999b]. The EF also resembles the more familiar representation of human impact (I) as a product of population (P), affluence (A) and technology (T) expressed in the I = PAT formula [Ehrlich and Holdren, 1971]. The EF of a population corresponds to the impact (I) in this formula and is a "function of population size and consumption converted into (bioproductive) land area" [Rees, 2000]. The size of the per capita EF will change with material consumption, or affluence (A) and the technology (T) used by this population [Rees and Wackernagel, 1996].

Discussing carrying capacity (CC) of the Earth for the human species is difficult due to the underlying questions about population numbers, technology, culture, social free will and consumption. Hence, there is no predetermined limit for humans [Cohen, in Allenby, 1999]. However, the debate on whether there are fixed, flexible (as the Brundtland Report [WBCSD, 1987] implies), or no limits for human CC seems to be influenced by the disciplinary background [Mather and Chapman, 1995].

Whilst shrinking carrying capacity is a core issue of the sustainability debate [see for example Daily, 1997; Meadows, Meadows and Randers, 1991; Vitousek et al., 1986; Simon and Kahn, 1984, in ibid.] conventional economists deride concepts of human carrying capacity because the view prevails that carrying capacity is indefinitely expandable and therefore irrelevant [Daly 1986, in Rees and Wackernagel, 1996; Pearce, 2000]. Hence it is the notion of *limits* that can always be overcome in conventional economic views. Since humans can temporarily increase their biocapacity through trade and technology, on a finite planet there cannot be a net import of carrying capacity - at best, the global balance will be zero [for example, Lewan and Simmons, 2001].

From a trophic-dynamic view, the relationship of humans (and their industrial metabolism) to the rest of the ecosphere is not different to other consumer species on Earth [Rees and Wackernagel, 1996]. In thermodynamic terms, "all our toys and tools" (the human made capital of economists) are the "exosomatic equivalent of organs" which likewise require continuous flows of energy and materials to and from the environment [Sterrer, 1993, in ibid., also Soellner, 1997]. In other words, the economy is a subsystem of nature that ultimately depends on its intact services.

2.5.4.1. Examples for shrinking CC and overshoot

There are many physical examples to suggest that the use of renewable resources may indeed have exceeded the rate at which nature can regenerate. Vitousek et al. [1986] estimated that about 40 per cent of the terrestrial net primary productivity (NPP) is already used or lost through human activity. Haberl [1997, in Pearce, 2000] comes to similar results for Austria. Calculations by Pauly and Christensen [1995, in Rees, 1996a] estimated a value of 25 to 30 per cent for the continental shelf. According to the United Nations Food and Agriculture Organisation (FAO), 11 of the world's 15 most important fishing areas and 70 per cent of the major fish species are overexploited. Per capita seafood catch declined in 1989 [Brown and Flavin, 1999]. For biodiversity, the largest decimation of plant and animal life is currently happening for the last 65 million years. The principal cause for plant extinction is habitat destruction, mostly through land clearing for agriculture and ranching [Bright, 1998, in ibid.]. The world's now generally overgrazed rangelands cover about twice the area of croplands, yet increasing demands for meat and human settlements will put even more pressure on these already deteriorating areas [Dregne et al, 1991, in ibid.]. With the expansion of the fossil fuel based economy, the capacity of natural systems to fix CO_2 have been overwhelmed. From a concentration of around 280 ppm at the beginning of the industrial revolution, CO_2 concentrations have accumulated to 363 ppm in 1998. Mining alone strips more of the Earth's surface each year than natural erosion by rivers. Worldwide, emissions of lead exceed natural rates by a factor of 27 [Gardner and Sampat, 1999]. Using natural capital accounting, Wackernagel et al. [1997] estimated that in 1992 the global economy had overshot the Earth's ecological capacity by 25 per cent, increasing to 35 per cent in 1997. According to Rees and Wackernagel, [1994, in Rees, 1996a] it is a fundamental question whether

> the physical outputs of remaining species populations, ecosystems, and biophysical processes, and the waste assimilation capacities of the ecosphere are adequate to sustain the anticipated load of the human economy (..) [p. 2].

Rees [1988, in 1996a] therefore redefined human CC as:

> The maximum rates of resource harvesting and waste generation that can be sustained indefinitely without progressively impairing the productivity and functional integrity of relevant ecosystems wherever the latter may be located [p. 4].

2.5.4.2. *Biophysical limits*

Through globalised trade, people have worldwide access to resources [Wackernagel and Rees, 1996]. While standard carrying capacity asked "how many people can the Earth support" EFA asks how large must an area be to indefinitely sustain a defined population with the current consumption and technology. For this reason, EFA has sometimes been termed the *inverse ratio of CC* [Rees, 1992, in Rees, 1996a]. Because EFA includes a population's consumption and its technology while reflecting interregional trade, the EF implies a fixed limit – the finite globe - but allows for flexible limits on sub global scales (if the fair Earth share is not applied)[12].

Areas inhabitable by green plants capable of photosynthesis are restricted to the Earth's surface [Rees, 1996a]. Therefore, the amount of bioproductive *area*

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[12] This clarifies that the EF is an indicator only, since applying the fair Earth share (global limit) also implies fixed limits on sub global scales.

available to mankind and each country is clearly limited. The EF could therefore be an indicator for ecological limits [Haberl, Erb, Krausmann, 2001][13].

In a first step, EFA assumes that it would be possible to estimate the required areas of land and water by using optimistic yield figures to produce the goods and services for a given population with current technology. The sum of such a calculation for all significant consumption categories would result in a conservative area estimate of natural capital requirements for that population [Rees, 1996a].

In a second step, the EF compares this result with the available supply of resources. This is a measure of strong sustainability because it assesses the use of "natural capital" in physical terms (not the physical economy) but also demonstrates its overshoot [Haberl, Erb, Krausmann, 2001].

The EF of a population can be compared with the available biocapacity on a global or local level: If the EF is greater than the available biocapacity (EF>BC) then this is interpreted as overshoot. Therefore, the challenge is for the EF to stay within the available BC [ibid., and other literature by Rees/ Wackernagel]. However, because EF is a conservative estimate and ecological limits cannot be determined with ultimate precision [Wackernagel, 1999b], an EF < BC is not necessarily sustainable [Haberl, Erb, Krausmann, 2001]. Rather, the EF should be regarded as a minimum requirement for sustainability [Lewan and Simmons, 2001].

This strong sustainability approach has been criticised in the past [for example, van Kooten and Bulte, 2000]. At the same time, it is precisely this that gives the EF an advantage over other socio-economic tools [Haberl, Erb, Krausmann, 2001; Onisto, 2001; Chambers, Simmons, Wackernagel, 2000], while pointing to the precautionary principle:

> Since we are in a situation of true uncertainty about the assumptions on technological progress (..), we should at least

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[13] However, it must be remembered that ecology is about systems, not only plant area. Area only serves as an indicator [Lewis, 2002, pers. comm.].

> provisionally assume that they are not true, since the cost of their being wrong are potentially so high (..). This makes the EF a useful provisional indicator of sustainability on the global scale [Costanza, 2000, p. 342].

So far, humans have not been very successful in planning for their activities based on physical resources [Lewan, 1999]. Yount [1999] pointed out that an awareness of limits may only occur via obvious limits of such resources (such as waste assimilation capacities) where connections between causes and symptoms are obvious. At that point, however, it may be politically impossible, or the delay between corrective action and response too long.

2.5.4.3. Technology and carrying capacity

Contrary to conventional belief, trade and technology often aid the efficient and rapid depletion of natural capital [Wackernagel, 1999b]. In theory, shifting to more resource efficient technologies should support a given population with a higher material standard, or an increasing population with the same material standard, thereby increasing CC. In reality, efficiency gains have in the past been accompanied by increased per capita *and* aggregate consumption [for example, Rees, 1996a; Gardner and Sampat, 1999; Bartelmus, 1999]. One example is mobile phones: Whilst their weight decreased tenfold between 1991 and 1996, subscribers to mobile phone services increased eightfold during the same time period, offsetting gains from reduced phone weight. Additionally, older phones were not simply replaced by newer models but remained part of the household [Jackson and Clift, 1998]. This phenomenon is an essential and inherent part of the modern economy based on behavioural responses, otherwise known as the ***rebound effect*** by economists [Jaccard, 1991; also Saunders, 1992, in Rees 1996a]: If companies save money through more energy and material efficient production processes, it can increase wages, dividends, or lower prices which in turn lead to increased net consumption in stakeholders and consumers. Energy efficiency gains have therefore been working against sustainability goals – they indirectly reduce carrying capacity [Rees, 1996a]. What follows is that to cancel the rebound effect, efficiency gains must be greater than the environmental consequences of overall consumption.

2.5.5. *Thermodynamic principles and the EF*

Solar energy of high quality enters the Earth's surface of which less than one per cent is stored by photosynthesis as biomass. Biomass is re-used by ecosystems including humans, which in turn generate lesser quality of "waste heat" that is re-emitted into space. Although the amount of energy coming in and going out is the same, its quality has decreased, or the order (entropy) has increased [Lovelock, 1995; Lewan, 1999]. Since all processes degrade the quality of energy, thereby producing wastes, their "bills must be paid for by processes run by energy from outside the ecosphere" – in other words, by the "bioproductive areas receiving sunlight" [Holmberg et al., 1999, pp. 28]. These flows and matter entering and leaving a system can be measured, monitored, and assessed through EFA [Rees, 2000].

2.5.6. *The popularity of the EF*

More recently, the EF methodology has received increasing attention as a tool to measure sustainable development, for example [NGS, 2001; Bicknell et al., 1998; Berg et al., 1996; BFF et al., 2000; Ferng, 2001; Barrett, 2001; Haberl, Erb, Krausmann, 2001; van Vuuren, Smeets & de Kruif, 1999]. Since the development of the original concept around 1990 it has been applied to geographical regions, some products and services, for example [Wackernagel, 1998; Simmons, Lewis, Barrett, 2000; Chambers, Simmons, Wackernagel, 2000; Frey et al; 2000b; Naylor et al., 1998]. Conceptual simplicity both in calculation and vision has been pointed out as the EF's major strengths [Rees and Wackernagel, 1996]. Because everyone can relate to *"land"* restricted to the Earth's surface, the EF can communicate human's use of nature. Since the EF of any defined population can be compared with the supply of nature, it can be measured whether the demand exceeds the available supply and how large the ecological deficit, or "sustainability gap", is [ibid.]. According to van Vuuren and Smeets [2000], the popularity of the EF as a potential sustainability indicator is due to six reasons:

2.5.6.1. *Visualisation of consumption*

The EF, in contrast to most environmental tools, highlights the true consequences of consumption by focussing on:

- Squandering of resources
- Composition, size, and impacts of consumption
- Geographical re-allocation of environmental pressures [Van Vuuren, Smeets & de Kruif, 1999]

2.5.6.2. *Focus on renewable resources*

Land use and CO_2 levels are key factors in sustainable development and are key parameters in the EF. Land is becoming an increasingly scarce resource in some countries, aided by soil erosion and other forms of degradation [Brown, 1999]. At the same time, agricultural land, which supports far less biodiversity than natural forests, has expanded at the expense of natural forests. Many of the areas set aside to protect biodiversity are located in or around agricultural land, thus being difficult to protect [WRI, 2000].

2.5.6.3. *Distribution of natural resources*

By calculating the per capita EF for individuals or regions and comparing it to the global average, the EF addresses the current distribution of resources [van Vuuren, Smeets & de Kruif, 1999]. By presenting minimum requirements, which should not be exceeded in a sustainable society, the EF challenges the distribution of bioproductive Earth space between nations and non-human species inhabiting the planet in the face of growing resource consumption [Holmberg et al., 1999; see also Brown, 1999]. Around 20 per cent of the world population occupy about 70 per cent of the global EF [Holmberg et al., 1999].

2.5.6.4. *Environmental consequences of trade*

Trade can have both positive and negative consequences for sustainable development [van Vuuren, Smeets & de Kruif, 1999]. The EF examines trade from an ecological perspective [Wackernagel and Rees, 1996]. It is important to make the connections and consequences of trade visible – human's increasing dependence on other nation's ecosystems world-wide [Deutsch et al., 2000].

2.5.6.5. *Communication tool*

The EF is a visually powerful tool. Since the EF can be calculated on a per capita basis and for an individual, the EF allows for comparisons between countries or with the global level. This flexibility makes it possible that everyone can relate a certain lifestyle to environmental problems, making the EF popular with its proponents [van Vuuren, Smeets & de Kruif, 1999].

2.5.6.6. Aggregation

The EF has been criticised for being too aggregated to be useful [see section 2.5.7.2]. However, at the same time this is an advantage as it facilitates the comparison of environmental impacts from different activities [ibid.]. However, the EF can also be presented in a non-aggregated way [van Vuuren and Smeets, 2000; Ferguson, 2001].

2.5.7. General criticism of the EF

EFA for nations have been discussed very controversially in the past. Some argue in favour of its broad use in policy [see Wackernagel and Silverstein, 2000; Rees and Wackernagel, 1999; Lewan, 1999; Templet, 2000; Yount, 2000; Herendeen, 2000, Holmberg et al., 1999], some see a limited usefulness, sometimes in modified versions [e.g. Deutsch et al., 2000, Folke, 1997, Costanza, 2000; Moffat, 2000, Rapport, 2000]. Others are very critical of the EF [van Kooten and Bulte, 2000; van den Bergh and Verbruggen, 1999; Ayres, 2000; Opschoor, 2000] or of single indicators in general [for example, Lange, 1999]. Within this discussion, it has also been pointed out that without meeting the triangle of ecologic, economic, and social challenges, sustainability cannot be achieved [Lange, 1999; Luks and Stewen, 1999].

The most important and most often raised pro and contra points found in the literature have been listed below.

2.5.7.1. EF analyses are incomplete

A key objection to EF analysis is the aggregating and weighting procedure resulting in ecological impact. Adding up the direct and indirect consumption of a population in terms of land use was criticised for being incomplete, lacking regional or local features of land use [Ayres, 2000; van den Bergh and Verbruggen, 1999; van Kooten and Bulte, 2000].

EF, like other aggregate and complex models, cannot be complete for all human impacts and they do not claim to be [Rees and Wackernagel, 1996]. They underestimate the true human impact by choosing the most conservative figures from official statistics and including only the most important, mutually exclusive areas of consumption. At the same time, it is acknowledged that other impacts exist but that the priority is to focus on the "big picture' [Wackernagel and Silverstein, 2000; Wackernagel, 1998]. Since development of the original concept in 1990 by Rees and Wackernagel, EFA has become more refined, for example, including sea space, global and local yields to express regional differences [see Wackernagel, Lewan, Borgström, 1999]. Other studies include footprints for water use [Chambers, Simmons, Wackernagel, 2000; Barrett, 2000] and waste products other than CO_2 [Folke et al, 1997; Krotscheck and Narodoslawsky, 1996, in Lewan and Simmons, 2001; Jansson et al, 1999; BFF et al., 2000]. Ferng [2001] incorporated economic analysis into EFA. [Haberl, Erb and Krausmann, 2001] calculated variable local yields for an EF study of Austria.

2.5.7.2. EF analyses are too aggregated

This point was raised by Ayres [2000] and Opschoor [2000], which is a criticism of aggregated indicators in general (such as GNP, ISEW, or money) and not of the EF alone. There are both drawbacks and benefits from single indicators: The conversion and aggregation of complex resource pattern into a single number has the substantial benefit as it aides decision making. Even multi-criteria analysis (NB: like LCA) needs different aggregation methods. On the downside, making decisions without being careful and informed about where numbers came from, is problematic [Costanza et al, 2000]. The "beauty of an aggregate indicator" [ibid., p. 342] may result in overlooking the details. However, no single indicator can answer all questions. Multiple indicators will always be required [Opschoor, 2000] as well as the "intelligent and informed use of the ones we have" [Costanza, 2000, p. 342].

2.5.7.3. EF proposes self-sufficiency and has an anti trade bias

This is another point raised by Ayres [2000] and van den Bergh and Verbruggen [2000] relating to whether it is valid to apply EFA to lower than global levels such as nations, regions or cities [Lewan and Simmons, 2001]. The EF measures the net input from outside a region and translates this input into area units. It does not measure the input over time, but the input at a given time in a snapshot [Costanza, 2000]. As such, the EF demonstrates that people depend increasingly on other people's ecological capacities to produce their own goods and services. Many people are not aware of this relationship. Hence, the EF is not against trade but strongly indicates global interdependence. In the end, not all countries can be net importers of biocapacity. It is therefore in the self-interest of all populations to protect increasingly scarce ecosystem capacities [Borgström and Wackernagel, 1999; Deutsch et al., 2000; Lewan and Simmons, 2001]. Although sustainable trade may be possible, the current system of international trade (which ignores environmental externalities and differences in labour conditions) is probably neither sustainable nor fair. The willingness to export biocapacity must also be met with the willingness to import it. But the amount of voluntarily exported biocapacity may exceed long-term sustainability, or the export may not be voluntary [Costanza, 2000]. It also reveals other trade imbalances from an ecological point of view – like the 1:1 exchange of products which could be sourced locally as demonstrated in the Canadian EF [section 2.5.2]. Hence, more sustainable trade practices would result in smaller footprints. Although trade has the potential to be sustainable, current trade practices are often not.

2.5.7.4. *Carrying capacity is irrelevant*

This point was raised because a) yields for renewable resources can be increased and technology can extend resource constraints, and b) through trade, a limited resource can be imported in exchange for exporting another resource [van Kooten and Bulte, 2000, in Lewan and Simmons, 2001].

Several sources, for example in [Worldwatch Institute, 1999] have demonstrated that carrying capacity can be altered: For example, it can decline in eroded areas due to desertification, and likewise, it can be improved through sensible management practices [Lewan and Simmons, 2001].

Because the EF compares the demand and supply for carrying capacity, it would show changes in either the demand or the supply side not in the year of assessment but in subsequent snapshots. For example, if technology led to higher overall energy efficiencies, this would reduce the EF. However, if these technology improvements lead to an increased exploration of a resource the EF would increase simultaneously [ibid.].

With regard to trade, shifting to areas with high biological yields does not necessarily lead to a smaller EF in the importing country because of the inputs and practices involved in gaining high yields. The EF reveals the net importers of ecological services [Folke et al., 1998; Naylor et al., 1998].

2.5.7.5. Highly urbanised areas like Singapore can never be sustainable

Van Kooten and Bulte [2000, in Lewan and Simmons, 2001]. Due to mixed evidence, optimal sizes of human settlements are not known. On the one hand, cities (or other highly urbanised spots) may just have a more dispersed footprint with a transportation overhead [Lewan, and Simmons, 2001]. [Folke et al., 1997] estimated that the cities in the Baltic Sea drainage basin use at least 565 to 1130 times an area of their actual size, with annual carbon emissions alone of 1.84 tonnes per capita (compared to the IPCC goal of 0.9 tonnes per capita by 2050 – Ocean studies board, NRC, USA, in ibid.). As cities need productive ecosystems, it becomes clear that the whole planet cannot consist of cities [ibid.].

According to Rees and Wackernagel [1996], cities with their high concentration of human population and resource consumption have ecological impacts that would not occur in more dispersed settlements. Cities significantly disturb biochemical cycles of nutrients and other chemicals by disintegrating consumption and emissions, and requiring transport over long distances as they rely strongly on imports. They also produce concentrated levels of various pollutants that otherwise may be diluted and dissipated safely over a much larger area. At the same time, cities have the potential to reduce the EF through lower per capita costs for environmental treatment systems, less occupied land per capita, reduced fossil fuel use through public transport, better possibilities for recycling and reuse to name a few. By internalising ecological costs and through ecologically sustainable incentives, cities have at least the potential to contribute to sustainability [ibid.]. Walker [1995; in Rees and Wackernagel, 1996] showed that a structure of high density, high-rise apartments reduces the per capita EF by 40 per cent compared to single-family housing. But although urban structure has a significant impact on individual resource consumption, many consumption related ecological problems are rooted in social behaviour and individual habits rather than the structure of settlements. The EF can compare different urban structures and transport technologies [ibid.].

2.5.7.6. The EF does not distinguish between sustainable and non-sustainable land use

A point raised by van den Berg & Verbruggen [1999], Haberl [2001], and van Vuuren, Smeets & de Kruif [1999].

This is true as the EF does not capture unsustainable land use at the same time it happens, but whether widespread practice is sustainable or not will appear over time: If unsustainable management practices in one year led to increased desertification, the biocapacity (and yields) would decrease in future estimates [Lewan and Simmons, 2001]. Hence, *as a whole,* the EF can account for unsustainable land use [Ferguson, 2001]. Secondly, because EFA assumes sustainable management practices and optimum yields [Holmberg, et al., 1999], excluding areas that simultaneously can provide several services, the severity of the real situation will consistently be underestimated [Wackernagel and Silverstein, 2000].

2.5.7.7. Suggestions for improving the EF

[Rapport, 2000] suggested that indicators for ecosystem health should be included, because human-dominated ecosystems show many signs of ecosystem stress that are irreversible. However, qualitative aspects would rather give additional information [Lewis, pers. comm., 09.05 2002]. Including geographic information systems to measure the temporal and spatial impacts from unsustainable practices was another suggestion [Moffat, 2000], which would be a further investigation into local biocapacity [Lewis, pers. comm., 09.05 2002.]. Although such refinements may not change the overall outcome, they could make the EF more detailed from an analytical point of view.

2.6. Environmental analyses of mobile phones

Many LCA and related publications on mobile phones can be found, for example:

- [Nissen et al., 1997]. Environmental Assessments of Electronics: A new model to bridge the gap between full life cycle evaluations and product design.

  The study explains a model for simplified assessment procedures based on the material content of a mobile phone instead of complete life cycle. The model is based on the toxicity related environmental properties of the product's materials and concentrates on a few possible impacts to ease decision making at the design level.

- [Müller et al., 1999]. Environmental aspects of PCB microintegration.

  This study presents environmental improvement assessment by means of a screening method based on a Toxic Potential Indicator (TPI).

- [Oiva et al., 2000]. Case study of the environmental impacts of a mobile phone.

  This case study deals with the material content estimation, identification of environmentally relevant components, and possible optimisation alternatives with regard to the toxicity and recycling potential of a *Nokia* mobile phone.

- [Nissen et al., 1999]. Environmental Screening of Packaging and Interconnection Technologies.

  Screening parameters for toxicity of materials in electronic products. Six different packaging and interconnection technologies were used as parameters for trend analysis and their evaluation regards reuse/recycling processes.

- [Middendorf and Nissen, 1997]. Simplified assessment for PCB.

  Development of a simplified assessment tool for first and basic valuation of the environmental impacts of a PCB as an alternative to a full LCA [see Nissen et al, 1997].

- [Irasarri et al., 2000]. Specific mobile phone recycling process.

  Development of specific recycling process for the treatment and valorisation of end of life (EoL) mobile phones.

- [Chung and Kim, 2001].
  Development of clean technology in wafer drying processes.
  Investigation of new wafer drying system based on clean technology.

- [Zeininger, 2000]. Factor 4 approach in electronics.
  Demonstration of Factor 4 on a mobile phone with 60 per cent less copper and polymers, further the easy separation of thermoplastics and electronic modules, easy exchange of components, exclusion of harmful substances and use of recyclable polymer compounds.

- [Müller et al., 2000]. Implementation of environmental issues in SME.
  Green electronics handbook for environmental improvement of SMEs, addressing the life cycle of electronic products from product design to EoL.
- [Mead, Donaldson, Snowdon, 2000]. Advancing ecodesign decision-making through eco-supply chain management in the telecommunications industry.
  Development of methodology for improved component selection in eco-design and product life cycle management.

- [Eisenreich et al., 2000]. Arboform – a thermoplastic made of renewable resources.
  Potential application of organic compounds in electronics industry to replace mineral oil based thermoplastics.

- [Petterson, 2000]. Solar cells in electronic consumer products.
  Technical concepts and design of solar powered devices. Industrial trends, possibilities for new product design and environmental benefits.

- [Flipsen et al., 2000]. In search of application fields of fuel cells.
  Miniature fuel cell applications for devices up to 1 kWh.

- [Hahn and Müller, 2000]. Future power supplies for portable electronics and their environmental issues.
  Overview current and future power supplies with focus on microbatteries and fuel cells.

- [Cameron and Lohse, 2000]. WWF-dialogue with industry: Eliminating hazardous substances from electrical and electronic appliances

  Initiatives and steps for phasing out hazardous substances.

- [Brezet, Bijma, Sylvester, 2000]. Innovative electronics as an opportunity for eco-efficient services (ES).

  Examination whether eco-efficient services in electronic technologies are beneficial for the environment. Conclusion: The hypothesis that industry-driven ICT-based services per definition contribute positively toward the development of ES must be rejected. However, at the same time, available new technologies (human powered energy, energy efficient devices etc.) are crucial for a shift from ecodesign of products towards ES.

- [Wright, 1999]. Product end-of –life management.

  LCA of two generations of mobile phones with focus on EoL. Part of this thesis was used as a basis for our studies [Chapter 6].

- [Federico et al., 2001]. Material Input per Unit Service (MIPS) of the Italian mobile phone network.

  Survey on the material requirements for mobile phone service in Italy, resulting in a 75 kg rucksack for a typical T27 *Ericsson* mobile phone that included production, transportation and one year of use. For the network structure (radio base station building phase, its energy consumption and maintenance), hidden flows of around 2.4 million tonnes per year were calculated (183.9 kg per user considering 41.4 million subscribers in Italy). The estimated MIPS value per minute phone was about 0.2 kg per minute, or 0.6 kg per SMS.

- [Doka, 2001]. Yield losses in electronics production are significant to LCA.

  Reject or fail rates in electronic component production are rather high, cumulative losses can have a significant effect on life-cycle inventories. This can lead to an underestimation of environmental impacts. Given examples include the production of silicon microchips and liquid crystal displays. Infrastructure of electronic products may be more relevant than previously thought.

- [Spielmann and Schischke, K., 2001]. Environmental assessment in production of electronic components – possibilities and obstacles of LCA methodology.

  To date, LCA for electronics is only reliable for small systems, such as single components: Variability and uncertainty in available LCA data bases pose serious problems, especially due to data gaps in up- and downstream processes, for example, in semiconductor production (SCP). Very specific emissions assessments, especially for toxicity, are lacking. Focus should be on the evaluation of generic electronics data, modularisation of infrastructure processes in SCP, and up-to-date evaluation of SC processes.

- [Ram et al., 1999]. Environmental performance of mobile products.

  LCA comparison for identification of key elements for reduction of environmental impacts in mobile phones. Digitalisation, miniaturisation and integration will reduce the environmental load per product but increasing numbers will reverse this trend for the overall sector. Examination and environmental assessment needed (eco-indicator and IZM TPI). Key elements for further reduction in environmental loads: Energy systems and PCB (less hazardous substances, further miniaturisation, swift implementation of design for environment).

- [Wright et al., 1998]. Mobile phone takeback and recycling: Analysis of the ECTEL project.

  Snapshot of energy balance associated with mobile phone takeback in different scenarios. Conclusion: Takeback and recycling are beneficial for the environment despite decreasing trend in mobile phone weights. Energy in component manufacture largest contributor to life cycle energy burden (use phase was not included in this study), hence reduction of components and increased resource efficiency (silicon wafers!) important. If sales as predicted, takeback rates must be substantial before there are benefits for total system. Recovering of "bottom drawer stock" advisable.

- [Betz, Schuckert, Herrmann, 1998]. Life cycle engineering as decision making support in the electronics industry

  Model of a PWB as a decision-supporting tool. Materials extraction needs most energy, especially regards precious metals Au, Ag, Pd. Transportation relatively insignificant. Manufacturing: Reduction of energy and waste important. Specific research is needed for production processes of electrical components.

- Ericsson Environmental report [1999].

  This report identified energy use as most significant in business activities. Gasoline-equivalents for average mobile phone subscriber was 16 litres between the years 1991 – 1997, this was reduced to 11 litres between 1996 – 1999 (NB: equivalent to minus 31 per cent).

- [Stutz et al., 2000]. Energy use in the life cycle of a cellular phone: A study of the impacts during manufacturing and use.

  This presentation was very relevant for our contemporaneous study. Key findings were:

  - In one populated PWB, Au, Ag, and Pd use most energy - small amounts of precious metals contribute most to energy aspect (this supports the authors' conclusion from the PC study [Frey et al, 2000a,b] and some results from the mobile phone study presented here.
  - Energy use was highest for 1. PWB (electricity and gas), 2. Materials (gold etc.), 3. IC production (clean rooms and tools).
  - Air conditioning, heating and lighting (overheads) more significant than line contributors (this supports our assumptions with regard to PWB production).
  - User profile: 56 Wh/day (2 hours talk time), of which only 6.5 per cent are used for calls and standby, the rest are losses of power supply
  - For a conservative 2W standby mode, energy ranks over life cycle are 1. 2W standby for one year, 2. PWB production, 3. Raw material extraction,

4. IC production, 5. Air conditioning, 6. to 9.: Heating, lighting/computers, reflow oven, 2W standby for one day.

Conclusions from this report [ibid.]:

- High initial energy in raw materials/purchased components is greater than energy per phone from production.
- Within manufacture, air conditioning dominated over other plant operations.
- Over time, use phase starts to dominate energy content of phone.
- Standby losses significant in large product numbers. US: 45 TWh per year consumed by electronics in standby mode. Germany: 15 million mobile phones (51 Wh/day) equal 280 GWh per year. 30 to 50 per cent (150 GWh) can be saved by unplugging power supply when not in use.
- Use phase contributes up to 50 per cent towards energy use and global warming potential.
- Improvements in charging and stand-by paramount.

This study is different with regard to:

- Three generation of phones were analysed (including time analysis), mainly focussing on CO_2.
- Estimated CO_2 from materials per total component and per mg component (normalisation) and identified respective main CO_2 contributors.
- Raw materials: Statistical analysis for unknown metals and 95 per cent confidence intervals (three scenarios per mobile phone case study); CO_2 analysis for phone parts.
- Inefficiencies in charging and in use were not measured.
- This study is supportive of findings by Stutz et al. [2000], also Betz, Schuckert, Hermann [1998] with regard to the precious metals Au and Pd, further PWB energy pattern, and some pattern in manufacture.

2.7. Summary

Humans are perturbing significantly all grand biochemical cycles and other Earth system processes. Many natural global cycles, such as for most metals and metalloids, are exceeded by human activities. It is yet not known how the

Earth's ecosystems function as a whole, and how they will respond to human interference. In general, ecological sustainability can therefore be defined as avoiding serious perturbations of the natural cycles.

The Brundtland definition of SD may be socially ambiguous but is lacking a scientific and systemic (global) perspective. However, despite these shortcomings, the Brundtland Report is important because it brought SD concepts into mainstream policies. Since its introduction, several concepts have been developed to measure sustainability. Key aspects of sustainability include its weak and strong orientation, natural capital, and possible degrees of substitutability.

There is a lively debate between proponents of monetary and of physical resource assessments, which are based on thermodynamic principles. Since SD is an interdisciplinary challenge, monetary analysis alone is inadequate. Factor X concepts to dematerialise the economy/reduce the throughput of material flows are important to reduce the pressure on ecosystems. However, this will only succeed if efficiency gains are not outweighed by the effects of total resource use. Since mainstream environmental management systems do not include an ecological bottom-line, efforts towards eco-efficiency risk being mere business reviews while actually accelerating resource depletion. To address sustainability, including a natural systems level is necessary: No benchmark, no meaningful results.

In contrast to the conventional sustainability discussion, the Gaia theory looks at Earth from a planetary perspective and reminds us that humans are just another species who in their own interest must live within the means of super organism Earth.

EFA is different from most other tools that assess sustainability because it accounts for biophysical resources. The EF illustrates whether the present consumption can indefinitely be sustained in a finite world.

By aggregating productive areas corresponding to resource and waste flows, the demand for bioproductive space can be compared with its available per capita supply. Shrinking natural resources have to be divided by an increasing population. Two complimentary EF methods and an EF example for nations were presented. The results show that currently, humanity exceeds nature's supply by a third. As a calculation procedure, the EF only reflects the ecological state of the world in a snapshot but does not tell *how* impacts should be reduced.

Subsequently, the EF's relevance regards sustainability, its strengths and limitations, and further implications such as carrying capacity, thermodynamics and technology were discussed: The EF's strengths are in capturing the major environmental impacts for which area values can be established, but is not suitable in accounting for substances foreign to nature. It also must be remembered that the EF is a single, quantitative indicator only, and that for qualitative assessments, other tools are required (of which some may complement the EF in the future).

As a strong sustainability indicator, the EF illustrates biophysical limits. This is contrary to the classical economic view of infinite resources. However, exactly this enables the EF to detect overshoot and communicate people's dependence on intact ecosystems. It also visualises the consequences of trade and technology, both of which have the potential to contribute to SD but often fail to do so.

Advantages and criticism of the EF found in the literature have been discussed and improvement measures have been suggested.

In conclusion, all aggregate indicators have their limitations and the EF is no exception. Despite this, the EF is a vivid indicator of global and regional dependence. This gives the EF the advantage over other tools that measure, for example, toxicity or material flows alone. Like an accountant for natural capital it compares the demand with the supply side based on resource flows. The EF is unique in that it sets a conservative benchmark for sustainability, thus underestimating human impact but at the same time applying the precautionary principle. This is in line with Gaia: Both remind us that the environment, economy, and society are not three equal concepts, but that economy and society are subsystems of the environment.

Environmental assessments of mobile phones are mainly LCA based. Most focus on selected parts of the life cycle or on electrical components and specialise on toxicological aspects. The energy study by [Stutz et al., 2000] gave valuable support for this study, although structure and orientation of this study are different. From the literature searched, and through many conversations with people involved in EF, no studies have been found which calculate the EF of electronic products.

CHAPTER 3: METHODOLOGY EF ANALYSIS (EFA)

For the EF to be a useful tool to measure sustainability, it should be:

a) Responsive to change [Barrett, 2000]. If, for example, carbon emissions from the life cycle of an electronic product are decreasing it must be reflected in the size of the EF.
b) Able to indicate the effects of future trends or policies [ibid.]. For example, which strategies are the most effective to improve the environmental performance of a product.

This chapter explores how the EF concept can be applied to an electronic product. The methodology was split into two sections:

- **A**: The estimation of direct land use data from mining activities and the subsequent development of a database for a range of materials. This included calculating the direct land use using density of materials, size of ore bodies, site specific data and ecological rucksacks.

  Ecological rucksacks are the mass of material moved or transformed by mineral industries to obtain the net tonnage, such as overburden, earth and waste from quarrying [Schmidt-Bleek, 1997]. Each tonne of waste and overburden associated with a traded mineral requires energy and changes the landscape. Even if put back into place, these ecological rucksacks of mining alter the sustainability of the affected area through future erosion and altered slope stability [DL, 1998a].

- **B**: The estimation of indirect land use required from CO_2 sequestration by land and sea, which was caused by the use of an electronic product. In this study, CO_2 absorption by forests based on data from the Intergovernmental Panel on Climate Change (IPCC) on biomass accumulation was used [IPCC, 1997a) and Wackernagel, 1996]. CO_2 absorption rates by oceans were included according to information from the Hadley Centre, UK [C. Jones, pers. comm., 1999].

3.1. Part A: method for direct land use

In life cycle analysis, land use is generally understood as the requirement of land areas for anthropogenic processes. Land use includes inland waters and the continental shelf, but also activities which affect the condition of the respective area including soil structures and animal and plant life. As a result from an environmental aspect, the quality of the affected area may decrease [Müller-Wenk, 2001].

The extraction of abiotic resources (dead matter) is not necessarily linked with land use. However, if the extraction of abiotic resources occurs at the surface, and/or is combined with the deposition of (not usable) material, this process may not only reduce natural resources but also significantly lead to land use (such as in peat, clay, or subterraneous ore extraction with high overburdens) [ibid.].

Effects of land use are mainly:

a) Land competition: Land can be regarded as a natural resource. Unlike oil resources, for example, it does not disappear through its use but it is not available for other uses. Although sometimes uses can overlap (grazing land for cows can also serve as an area of recreation) often uses are mutually exclusive (areas for growing cotton for export cannot be used at the same time to plant beans for local consumption) [ibid.].

b) Biodiversity degradation: Use of land for human purposes generally means a reduction of biodiversity through a decline in species numbers and / or in geographical distribution[14]. The use of a specific area not only reduces biodiversity in that area, but also in other areas of the region (for example, if frogs cannot cross a busy road any more, they will also disappear from the adjacent wetlands). Land use has been identified as the primary cause of biodiversity loss [ibid.].

c) Life support functions: Land use also affects higher system levels such as climate, hydrological cycles, or organic substance cycles. For example,

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[14] At least short term, long term depends since some species (e.g. corn crake) preferably thrive on managed lands [Billett, pers. comm., May 2002].

> transformation of wooded area into roads will reduce CO_2 absorption[15] and increase the albedo of the Earth's surface. The anthropogenic use of land has a significant effect on the functioning of Earth's life support systems [Müller-Wenk, 2001].

Collecting land use inventory data is a time consuming job and an almost impossible one for a single LCA. At the time of this analysis (1998/1999), the only area data available was from [ETHZ, 1996]. However, current research projects on land use impacts are under way at TNO Industrial Technology Delft, who have linked the Dutch and the Swiss ETHZ database [Lindeijer, 2001] but also at ETHZ [Koellner, 2001] who developed at least 20 different land use types, and at SETAC, who currently attempt to standardise best available practices for the complex land use issue [Müller-Wenk, 2001].

ETHZ [1996] used land transformation (such as transformation of wooded land into arable land to prepare it for the intended land use) and land occupation (use of an area for a specific purpose over a period of time) in one terminology which is expressed as metres squared multiplied by years [m^2 yr]. Hence, effects from fragmentation of ecosystems cannot be sufficiently regarded [ibid.]. In contrast, [Lindeijer, 2001] makes a clear distinction between occupation, expressed as [m^2 yr] and transformation, expressed as square metres [m^2].

3.1.1. Development of a database

Since the aggregated results of this study were finally used as a snapshot of a situation at a given time, the aim was to obtain an absolute measure such as m^2 per kg resource extracted. Hence, this study neither distinguished between the type of land use, nor the quality of the affected area, nor the time of land occupation. From [ETHZ, 1996] the author primarily resorted to dividing a given area in [m^2] by the average total output of a mine where possible. This was termed the direct land use (DLU), in [m^2] per [kg] material [Appendix A].

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[15] This is only true if compared to growing, but not mature forest since these are neither a source or sink of carbon. However, mature trees would be in a dynamic steady state for carbon, whereby roads etc. would be static.

To account for ecological rucksacks in land use, in some cases, multipliers were applied to an area where they were not already included. This is a simplification and should only be used until better data is available. However, to account at least to some degree for the areas appropriated beyond the commercially valuable amount of a commodity, this is the most direct measure at present where other data is not available.

Data for land use could not easily be obtained. DLU [m^2] was only included for resource extraction and, where possible, in areas for further processing, such as buildings. For ecological rucksacks or overburden, multipliers to the net production from Douglas and Lawson [DL, 1998a,b; and 1997] and [Schmidt-Bleek, 1997] were used since they were based on a range of estimates. Background information for extraction and other processes were included where considered necessary.

3.1.1.1. Iron ore and pig iron

Pig iron production in the blast furnace requires iron ores enriched to an iron content of 60 to 70 per cent. Main producers for iron ores are the former UDSSR, South Africa, Brazil, Canada and Australia [ETHZ, 1996; WRI, 1998]. Apart from Sweden, most iron ores are mined in open-pit mines. Due to the long transport distances and capital-intensive plants required for smelting, either iron-rich ores are used, or ores are enriched at the extraction site. Assumptions for land use in extraction and processing bear high uncertainties [ETHZ, 1996].

If an iron-ore layer of 30m thick with a specific weight of around 3000 kg/m^3 ore is assumed [ETHZ, 1996], 1.1E-05 m^2 land area per kg ore can be calculated. To this extraction data a multiplier of 5.2 [DL, 1998b] was applied, resulting in **5.77E-05 m^2/kg** for the production of pig iron. For smelting, the only data available in [ETHZ, 1996] was for one plant ["Hochofen-Oxygenstahl"] with an area of 12.5 km^2 and an output of 10 million tonnes of pig iron. This results in **1.25 E-03 m^2** per kg of pig iron, which was added to the extraction data. The total of **1.31E-03 m^2/kg** pig iron was used.

The value of 1.1E-05 m^2 per kg pig iron was also used as an approximation for chromium, since Cr is mined from chrome iron (chromite) ($FeCr_2O_4$) [Lide, 1998].

3.1.1.2. Aluminium

With a concentration of around 8 percent, aluminium is the most ubiquitous mineral found in the earth's crust [ETHZ, 1996; OU, 1974]. The largest mining sites are found in Australia and in Guinea, with Australia as the main producer of aluminium. Together they satisfy half of the global Aluminium demand [ETHZ, 1996; WRI, 1998]. Bauxite consists of around 40 to 55 per cent aluminium oxide or aluminium hydroxide, and is derived from surface mining. In Gove, Australia, the Bauxite layer of about 3 to 4 metres thickness is covered by an approximately 60 cm thick layer of humus, which has to be removed. Bauxite has a density of 2500 kg per m^3 [ibid.]. According to ETHZ [1996], the humus layer is needed to fill the site after mining, and therefore no areas for deposits were allocated [ibid.]. From an estimated average layer of 3.5 m, a land use of 1.14 E-04 m^2/kg bauxite was derived. This, however, does not include overburden for the bauxite ore. [Schmidt-Bleek, 1997] give a multiplier of 5 for bauxite, which results in 5.70E-04 m^2/kg bauxite. For one kg of aluminium, 3.68 kg bauxite per kg of aluminium is required [ETHZ, 1996]. After calculating the direct land use for bauxite and including the ore-commodity ratio for aluminium, **2.10E-03 m^2/kg** aluminium was used.

3.1.1.3. Sand and Gravel, concrete, cement, clays, gypsum (construction materials)

Clay minerals are secondary minerals as they are formed by the weathering of other minerals. They are fine-grained and composed of hydrous aluminium phyllosilicates with small quantities of iron, alkalis, and alkaline earths. Clays can be classified into speciality clays, such as bentonite and montmorillonite, and into kaolinitic clays such as ball clay, stoneware clay and kaolin. Common clay, a mixture of rock flour and clay minerals, is mainly used for construction purposes [Ripley, Redman, Crowder, 1996].

[Olschowy, 1993 and Weibel et al., 1995, in ETHZ, 1996] give values of

1.80E-04 and 2.5E-05 m^2/kg for ***sand and gravel.*** The first value was used as it includes area for infrastructure. Due to lack of data, this value was also used for the other construction materials clay, gypsum, concrete and cement.

Portland ***cement*** consists mainly of calcium carbonate [$CaCO_3$], silicic acid, potter's earth and iron oxide. ***Concrete*** is a compound made from cement, water, gravel, sand and construction chemicals. After hydraulic hardening it fastens into an artificial stone [ETHZ, 1996]. (Energy in cement production was not included, only DLU).

For ***gypsum***, a hydrous calcium sulphate [$CaSO_4 \cdot 2H_2O$] which, when calcined, releases three-quarters of its water to form Plaster of Paris [Ripley, Redman, Crowder, 1996]. [ETHZ, 1996] give an multiplier of 0.5 kg per kg gypsum based on average values from three natural gypsum deposits. Due to lack of further data, the same value as for sand and gravel was used.

3.1.1.4. Bentonite

Bentonite is a clay similar in its properties to fuller's earth. It is formed under water by the decomposition of volcanic glass, and consists mainly of montmorillonite. It is used as a bond for sand and asbestos and in the steel, soap, paper, and pharmaceutical industries [ETHZ, 1996; Larousse, 1997]. The average thickness of the bentonite layer is 3 m with density of 2.5 t per m^3 [ETHZ, 1996]. This results in 1.33E-04 m^2 per kg bentonite. With a multiplier of 4 [DL, 1998a], a value of **5.32E-04 m^2** per kg bentonite was obtained.

3.1.1.5. Limestone

Limestone contains calcite [$CaCO_3$] sometimes with small amounts of dolomite [$CaCO_3 \cdot MgCO_3$]. Limestone, dolostone and sandstone are common types of sedimentary rocks. Limestone is derived from surface mining. First, the humus layer has to be removed and deposited before the underlying limestone can be mined. The limestone is then transported to a mill for crushing, and later burned to lime. Two kg of limestone produces around one kg of lime. In most West European countries the aim is to reconstitute the destroyed landscape as naturally as possible. This however, can take many years [ETHZ, 1996]. [Olschowy, 1993, in ibid.] give an area of 0.05 cm^2 per kg of limestone (5.0E-6 m^2/kg) which does not include areas for calcination. [DL, 1998b] give an multiplier of 1.36 for limestone. This resulted in **6.80E-06 m^2/kg** ***limestone*** or **1.36E-05 m^2 per kg** ***lime.***

3.1.1.6. Manganese

Manganese is mined in surface mining. As manganese dioxide, it is used for binding sulphur and for de-oxidation in steels and cast irons. To produce 1 kg of manganese, 4 to 6 kg of ore are required [ETHZ, 1996; DL, 1997]. From an area of 84.5 km^2, about 200 million tonnes of ore can be mined resulting in 0.423 m^2/t of manganese ore [ETHZ, 1996]. With an ore to metal ratio of 6, this results in an area of **2.54E-03 m^2** per kg of manganese.

3.1.1.7. Copper

Copper is one of the most widely used metals, and is naturally relatively abundant in high concentrations. On average, 55 g of copper per tonne are found in the Earth's crust, about half as much as chromium and twice as much as cobalt [ETHZ, 1996]. 90 per cent of copper is mined from sulphide ores. The sulphide ores have to be processed to obtain ore concentrates. Copper is usually mined in open-pit operations, resulting in amphitheatre-like holes up to 800 metres deep. Depending on the mining site, the ore-layer can be up to 12 m thick. Several ore-bodies may be found on top of each other. The ores can have a concentration of 0.1 to a few per cent of copper [VDI, 1992; NZZ, 1990, 1991 in ETHZ, 1996]. For the land-use calculations, data from a "typical" copper mine, Bingham Canyon in Utah, United States, were used [NZZ, 1991 in ETHZ, 1996]. Bingham Canyon occupies an area of 770 ha. Since its discovery in 1863, 1.7 billion tonnes of ore and around 3.3 billion tonnes of overburden were mined, producing around 12 million tonnes of copper [ETHZ, 1996]. This is equivalent to 6.41E-04 m^2 per kg copper and an overburden factor of 416 kg per kg copper. Here the multiplier of 450 from [DL, 1998a] was used who included a range of sources. A value of **2.88E-01 m^2/kg copper** was calculated. For 60 per cent recycled copper the value was changed accordingly to **1.15E-01 m^2/kg**. Land use data was neither available for subsequent processes, infrastructure in copper production, nor for the deposition of slag.

3.1.1.8. Barites

Barite is a common mineral found in association with lead ores, but it also occurs as nodules in limestone and locally as a cement in sandstone [Larousse 1995]. Pure barite (barium sulphate, $BaSO_4$) contains 58.8 per cent barium and has a specific weight of 4500kg/m^3. China is the main producer of barite, followed by GUS, India, and the US. 85 per cent of the barite produced is used as a rinsing agent in drilling mud for increasing the back pressure during drilling operations [ETHZ, 1996; Larousse, 1997]. The remainder is used as a filler, for example in paints, rubbers and glass. The technical benefits and low prices of barite are the reasons that no alternatives exist to date [ETHZ, 1996]. Barite is derived from surface and underground mining . For washing the ores, about 12600 l of water per m^3 ore are needed. After settling, the barite sediments are transported to be crushed in wet or dry processes. Around 17 kg of ore is needed to produce 1 kg of barite [ibid.]. This source gives a value of **1 m^2/t barite**, considering an output of 90 kg of Barite per m^3 broken ore and an ore layer of 10m [ETHZ, 1996]. As a factor of 17 was already included between the specific density of the ore (2000 kg/m^3) and an output of 90kg barites/m^3, the value of **1.0E-03 m^2/kg** was retained.

3.1.1.9. Coal products

The world wide resources of hard coal and lignite differ widely in their composition and characteristics due to the differences of their original biomass, the age of the resource, and the varying temperatures and pressures in situ at that time [ETHZ, 1996]. Under anaerobic conditions and in the presence of bacteria, the sequence for carbon products is probably as follows: Plant material → peat → lignite → subbituminous coal → bituminous coal → semi-anthracite → anthracite → graphite → diamond [Ripley, Redman, Crowder, 1996].

Resources of lignite are around 50 million years old, and resources of hard coal about 250 million years of age. Lignite (brown coal) has less energy than hard coal. Although Europe is rich in coal resources, in 1990 the European Community (EC) imported 30 per cent of its coal demand from abroad due to the lower costs. At the same time, all coal producing EC countries subsidise their coal industries to a certain degree [ETHZ, 1996]. Base for the following assumptions are the average lignite and hard coal qualities used within UCPTE *(union pour la coordination de la production et du transport de l' électricité)* [ibid.]. For all energy systems used in this study, the space required in power stations was not included as this was based on consumption over time (MWh).

3.1.1.9.1. Extraction of coal

According to [ETHZ, 1996], data about the surface and underground mining is not consistent and varies considerably. [Ibid.] estimate that 28 per cent of hard coal and 94 per cent of lignite consumed in UCPTE countries is mined from open pits. Two-thirds of this lignite comes from Germany. Pits for lignite surface mining can be up to 600 m deep [ibid.]. Surface mining of hard coal is common outside Europe, involving blasting operations. Lignite is hardly mined underground. The development of surface and underground mining operations for coal is relatively high in expenditure and may take years [ibid.]. In Canada, more than 90 per cent of the coal is mined by open-pit or strip mining methods [Konda and Kochar, 1986, in Ripley, Redman, Crowder, 1996].

In ***surface mining***, the specific area for extraction is in direct proportion to the dimensions of ore bodies [ETHZ, 1996]. A direct land-use value of 0.18 m^2/t or **1.80E-04 m^2/kg** for **raw hard coal** and 0.04 m^2/t or **4.00E-05 m^2/kg** for **raw lignite** was found. These values are a weighted average according to the produced volumes of coals in the UCPTE countries [ibid.].

For surface mining in Germany, overburden is usually put back into the pit and following recultivation measures, the restored land is often used for agriculture. In contrast, overburden from underground is used in construction. For one tonne of raw hard coal, about 0.9 tonnes of waste rock have to be extracted of which 80 per cent is piled up to mountains which are recultivated. These mountains lead to changes in temperature and humidity, changing flora and fauna. Around 0.013 m^2/t of usable coal are estimated. For lignite, a value of 7 tonnes of waste rock per tonne of raw, usable coal [ETHZ, 1996] was found.

Other sources cite different multipliers. For global mineral production of 1995, [DL, 1998a] give multipliers of 4.87 for hard coal and 9.9 for lignite and brown coal. [Schmidt-Bleek, 1997] used a factor of 6 for hard coal and 11 for brown coal. Since the coal values in [ETHZ, 1996] may already include overburden values in their area calculations they were not included here to avoid double counting.

Other areas affected by coal mining also have to be considered, such as noise, dusts, and ***lowering of the ground-water level*** [ibid.]. To prevent mining sites from turning into swamps, large volumes of water have to be drained. This means that the ground-water level is lowered substantially, causing problems for surface water, drinking water, and for the lowered areas themselves. Ecosystems in wetlands and marshes are severely affected, especially where ground water used to be available for root systems [Euler, 1984, in ibid.]. It was suggested that only upper ground-water levels should be included in land-use calculations as lower ground-water levels bear no clear direct relevance for ecosystems [ibid.]. Upper subsidence for groundwater levels was given as 0.31 m^2 per tonne for hard coal. For lignite mining in Germany only, values were estimated to be somewhat lower than those for hard coal due to shallower pits [ETHZ, 1996]. As no further direct data was found, the same values were assumed as for lignite.

For ***underground*** mining operations in Germany, plants and equipment above ground occupy about **0.02 m^2** per tonne of raw hard coal, while underground between 0.1 and 1 m^2 per tonne of coal are removed [ibid.]. In the Ruhr region, entire villages and castles can be undermined without detrimental effects to buildings. However, under certain conditions - for example in areas with high groundwater levels - up to 20 m of surface may be lowered as a consequence. Although these do not have direct ecological impacts, the indirect effects can be severe. Due to hard coal mining in this region, an area of about 75000 ha would be flooded if the pumps, which are running day and night, were switched off [Schmidt-Bleek and Bringezu, 1994]. This draining and pumping is high in routine expenditures and leads to a complete destruction of hydrological systems [ETHZ, 1996]. Because other data was not available, only the directly removed areas were included with one m^2 per tonne of coal [ibid.]. This does not account for ecological damage. [Table 3] gives a summary.

Production steps coal	**Surface hard coal mining m^2/t** Europe/UCPTE 70% of area	**Surface lignite / brown coal mining m^2/t** Europe/UCPTE, 30% of area	**Underground hard coal mining m^2/t** Europe/UCPTE 50% of area
Mining	0.18	0.04	0.02
Subsidence	0.31	0.31 (assumed the same as hard coal)	1.00
Processing	0.0126	0.0126	
Sum	**0.50**	**0.36**	**1.02**

Table 3. Direct land use coal extraction, based on [ETHZ, 1996].

For the direct land use the UCPTE coal mix was retained as in [ETHZ, 1996]. In 1993, UCPTE countries (without Luxembourg) consumed 176.648 million tonnes of hard coal, and 316.77 million tonnes of brown coal or lignite [ibid.]. This reflects a ratio of 36 per cent hard coal and 64 per cent brown coal or lignite. 28 per cent of UCPTE hard coal is from surface mining [ibid.], [Figure 4].

For above ground infrastructure, the only data available was 0.0126 m^2/t for surface-mined coals [ibid.].

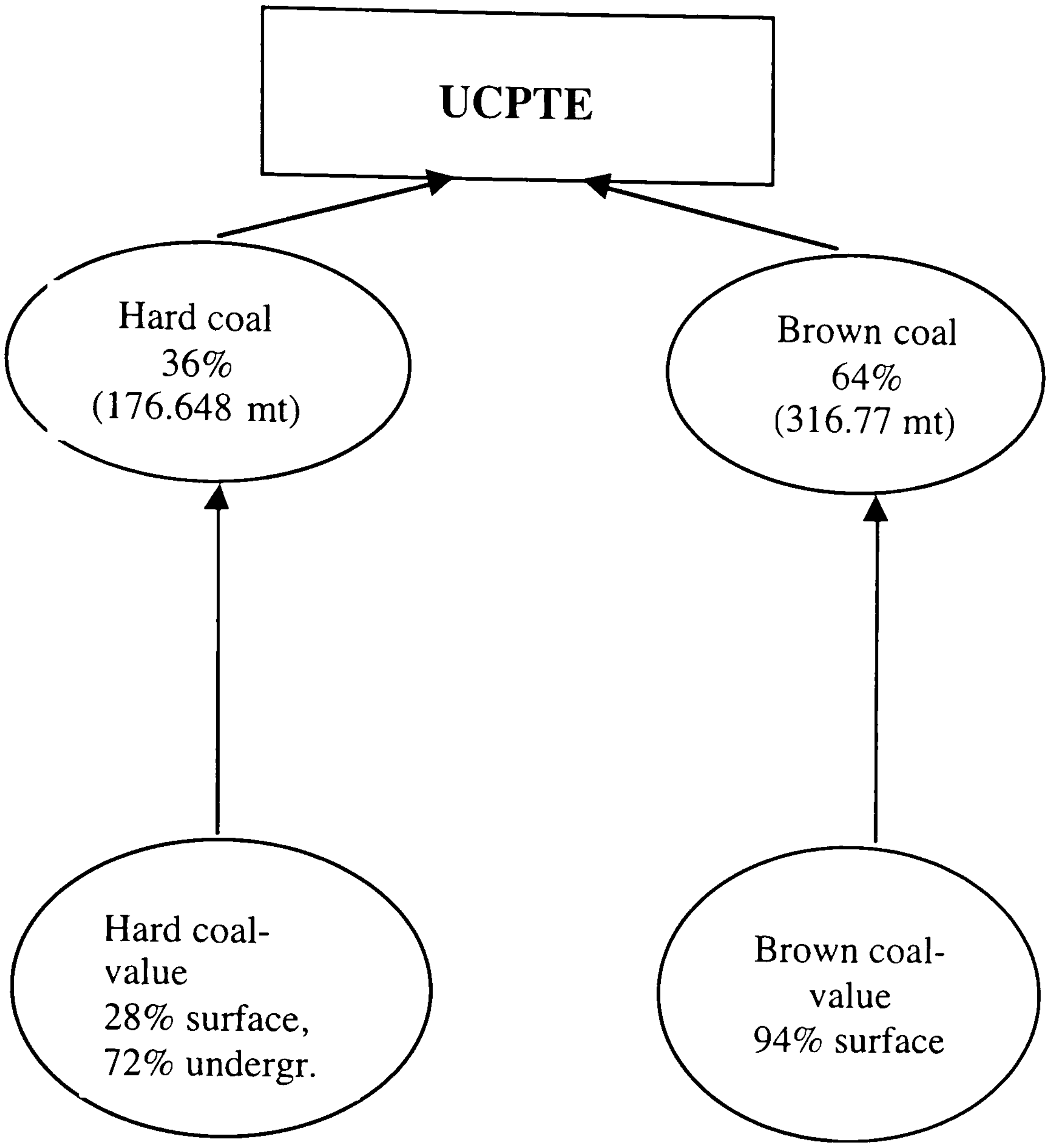

Figure 4. Structure UCPTE mix [data from ETHZ, 1996].

3.1.1.10. *Crude Oil*

Crude oil is a brown - greenish fluorescent liquid once produced by bacteria from animal and plant remains. Chlorophyll and hem-derivatives such as porphyrins prove its biological origin. Due to anaerobic bacterial breakdown and increased pressures, it is estimated that 60 to 70 per cent of sedimentary organic carbon is released as CO_2. Little is known about the chemical transformation from organic material to crude oil, however, the characteristics of exploitable oil resources are determined by the different types of sediment fossils, pressure, temperatures, and other physical parameters during oil formation and migration [ETHZ, 1996].

3.1.1.10.1. *Exploration*

To estimate whether drilling operations have to take environmental considerations into account, the expected volumes of oil to be drilled and the specific rate of success have to be known. World wide, the success of exploration drills is only 10 per cent. The specific volume derived per meter drilled depends very much on the geological situation and varies up to four orders of magnitude depending on the region [ibid.]. While expenditures for exploration and access are almost negligible for oil from the Middle East, they have to be taken into account in European, Russian, and sometimes African crude oil. Europe aims to be self- self-sufficient regarding its oil demand, and crude oil exploration is very energy intensive: Per meter drilled about 300 kg of diesel is needed. According to [ETHZ, 1996], one per cent of the energy content in crude oil is required for its exploration.

Since sufficient data for onshore operations was not available, only the land use for offshore drilling operations was calculated:

95 per cent of West European oil comes from ***offshore*** operations, mainly Great Britain and Norway [ibid.]. For offshore operations, such as in the North Sea, only the impacts on the seafloor were considered. Residues and drilling mud, which are discharged into the sea, severely affect the benthos (animal and plant organisms living on the seafloor) within a radius of one km, or 260 m^2 per metre drilled. This is very high in relation to the remaining stages in the oil process chain [ibid.].

If on average 47000 kg of oil are produced for every metre drilled (md) [ETHZ, 1996], **5.53 E-03 m^2/kg** crude oil can be derived or 1.29 E-04 m^2/MJ. (260m^2/47000 kg= 5.53E-03 m^2/kg; / 42.6 MJ[16] = 1.30E-04 m^2/MJ). A further **1.25E-05 m^2/kg** for crude oil storage was calculated as about 0.2 ha per 3400 md are required according to [ETHZ, 1996]. The result is **5.54E-03 m^2/kg** for the exploration step.

However, discharging the drilling residues and wastes cause the lion's share of land-use (benthos) in offshore-explorations [ibid.].

3.1.1.10.2. Crude oil processing

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[16] Lower heating value crude oil: 42.6 MJ/kg [ETHZ, 1996].

For *offshore* oil mining, [ibid.] estimated 0.005 m^2 per tonne of crude oil for infrastructure on the mainland. The equivalent of **5.0E-06 m^2/kg** was used. Neither land-use for overseas oil transport, nor pipelines or turnover areas were included.

3.1.1.10.3. Refining plants

In refining plants, crude oil is transformed into products such as heating oil, kerosene, diesel and gas. Refining consists of many steps from preparation and cleansing to the improvement or elimination of certain substances [ETHZ, 1996]. A citation of 0.011 to 0.013 m^2 per tonne of crude oil was found [Concawe, in ibid.] of which the average of **1.20E-05 m^2 per kg** was used. For crude oil production, finally an overall figure of **5.56E-03 m^2 per kg oil** was applied [Table 4]. Additional space for the storage of oil products, for space required in oil power stations and waste could not be included due to insufficient data.

Crude oil production	**Area [m^2/kg]**
Extraction crude oil (offshore)	5.53E-03
Storage	1.25E-05
Infrastructure offshore (mainland)	5.00E-06
Refining	1.20E-05
Sum	**5.56E-03**

Table 4. Land use crude oil production

Most of the direct land use is caused by the initial offshore exploration, as more than 90 per cent of damage affects the benthos due to the spread of drilling waste. Exploration and production of crude oil prevail with regard to water emissions [ETHZ, 1996].

3.1.1.11. Natural Gas

Natural gas is a fossil fuel which has been formed over million of years by geo- and biochemical processes alongside coal and crude oil. Under anaerobic conditions, organic matter from animal and plants was transformed into compounds rich in hydrogen. More recent theories suggest that some oil might not be of biological origin, but from the Earth's interior [ETHZ, 1996].

3.1.1.11.1. Exploration

A significant amount of natural gas is produced alongside crude oil (LPG, propane gas). ETHZ data are based on the main countries of production for UCPTE: The Netherlands, Norway, Germany, GUS, and Algeria. 30 per cent of gas from The Netherlands and 100 per cent of Norway's gas is from offshore production [ETHZ, 1996]. Hardly any data was available for the land-use of natural gas production. In offshore operations, pipelines are left in place after the operations have ended. Only offshore plants weighing more than 4000 tons located in waters less than 75m deep have to be removed. All other plants may be abandoned there [ibid.]. From tables in [ETHZ, 1996] the amount of gas was calculated which is produced alongside crude oil for UCPTE. This amounts to around 22 per cent. As other data was not available, the land use from exploration referring to crude oil was calculated which assumes that the same mass [kg] of gas per metre drilled is produced as for oil (which is purely speculative). Taking into account that LPG has a lower weight than crude oil (0.57 kg/l for LPG versus 0.95 kg/l crude oil; UK Petroleum Industry Association (PIA), pers. comm., 9.4.02), the disturbance of benthos would be 5.30E-03 m^2 per litre petroleum gas or 9.22E-03 m^2 per kg (260m^2 disturbance to benthos per metre drilled = 260m^2/47000 kg oil = 5.53E-03 m^2/kg oil; one kg crude oil = 1.05 l, one kg propane gas = 1.74 l). 22 per cent of 9.22E-03 m^2 per kg result in **2.03E-03 m^2 per kg of propane gas** (offshore only) which was used as an approximation for the offshore gas exploration. ETHZ [1996] further used the land use values for infrastructure in oil production also for gas corrected by its heating value.

On a per kg basis, a crude oil figure of 1.25E-05 m^2 per kg for storage amounts to 2.09E-05 m^2 per kg gas. Accounting for only 22 per cent, **4.59E-06 m^2/kg propane** were obtained[Table 5].

Petroleum gas production (22% of UCPTE)	**Area [m^2/kg]**
Extraction crude oil (offshore)	2.03E-03
Storage	4.59E-06
Sum	**2.03E-03**

Table 5. DLU propane gas production

Transport of gas via ship and pipelines, preparation and treatment of crude gas, regional distribution of gas and space in gas power stations were not calculated due to insufficient data. Construction processes for high-pressure pipelines which connect The Netherlands (NL) with Northern Italy, or GUS countries with Germany, cause significant impacts on the landscape, a reason why in most countries there is an obligation to conduct environmental assessments. ETHZ [1996] suggest a land use value of 20000 km^2/ km pipeline. During use, a safety zone of 10m on either side must be allocated. About 15 per cent of the pipelines lead through woodland, with a higher percentage in GUS, and a lower percentage in NL. Because of the high efforts associated with the demolition and removal of old pipelines they remain in the ground [ETHZ, 1996].

3.1.1.12. Uranium

3.1.1.12.1. Mining

Up to 1990, the countries with the highest total volumes of uranium (U) produced were the US, Canada, Germany, South Africa, Czechoslovakia, and Australia [ATW, 1993 in ETHZ, 1996]. Mining begins after a chain of specific and extensive prospection[17] and exploration steps [ibid.]. Older data [Pickert et al., 1981, in ibid.] suggest that about 68 per cent of uranium is mined in surface operations, 27 per cent underground and that 5 per cent may be dissolved chemically from the ore. This ratio is probably not up to date, as major changes

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[17] Prospect: Area which shows sufficient promise of mineral wealth to warrant exploration. Searching methods include, amongst others: Aerial surveys, magnetometry, geophysical and geochemical tests, seismic probe, electroresistivity measurement, pitting, trenching and drilling [Larousse, 1997].

in the uranium market have occurred since. In the US, the number of mines has reduced drastically, from 381 in 1980 to 11 in the year 1991. Average uranium ores have concentrations of 0.1 to 1 per cent of uranium, the Key Lake mine in Saskatchewan, Canada, is exceptional with a concentration of 2.6 per cent [ETHZ, 1996].

For *surface mining*, rock layers which have to be removed should be less than 100 metres thick [ibid.]. For the surface mined uranium (U), the average affected area per kg values from two referenced surface mines were used - the Key Lake mine, Canada, and a mine referenced by the US Department of Energy (DOE) in 1983 [DOE, 1983, in ETHZ, 1996]. For the Key Lake mine, the affected area of 1.1E+07 m^2 includes mines, slopes for mixed ores and waste slopes. The affected area of the DOE mine measures 1.2E+06 m^2. Overall these two mines produced 7.4E+07 kg and 1.6E+07 kg of uranium, respectively [ibid.]. The on average affected area of the two mines was calculated and divided by the total average uranium output of 4.5E+07 kg. Therefore, around **1.36E-01 m^2/ kg** for surface mined uranium can be allocated.

If the thickness of rock on top of the ore bodies is above 100 meters or too hard, uranium must be mined **underground** [ibid.]. For underground mining, an average value of **8.60-03 m^2** uranium was calculated from the affected areas of three mines - a US mine (UMO), the Ambrosia Lake mine in New Mexico, and a US DOE reference mine. The affected mining areas were given as 2.0E+05, 3.0E+05, and 1.6E+04 m^2, which were divided by their overall average uranium output (2.2E+07, 3.9E+07, and 4.8E+06 kg uranium, respectively) [ibid.]. For the UMO mine, ore and waste slopes, buildings, and infrastructure were included. [DL, 1998b] suggest a multiplier of 900 for Uranium. For the same reason as above, including overburden into area would lead to double accounting here. To account for the ratio between surface and underground mined uranium (68:27) a weighted figure of **9.45E-02 m^2** per kg uranium was calculated for the extraction step.

Large differences exist between mines due to the specific soil characteristics and climatic conditions of each mine. Using a typical reference-mine is therefore difficult, and using average values may not always be justified [ETHZ, 1996].

3.1.1.12.2. Preparation of Uranium: Estimating the long-term radioactive emissions from preparation plants

The objective of uranium ore preparation is to separate the uranium from the ore. This results in a highly concentrated uranium salt, or "yellowcake", which contains about 70 per cent uranium. The process requires large volumes of water for crushing, grinding and dilution, plus acidic or alkaline chemicals for leaching processes. Most leaching processes are acidic, depending on the metallurgical properties [Pickert et al., 1981, in ETHZ, 1996]. Long-term radiation from settling ponds contributes to about 80 per cent of the land use. Radon (Rn) emissions continue until thorium (Th)-230 from the ore residues is decayed [ETHZ, 1996].

In general LCA practice, radon emissions are accounted for until emissions from sludge ponds have decreased to original background radiation levels of the mining area [ETHZ, 1996]. This may be different if sludge is deposited elsewhere. In nature, Rn is in balance with its predecessor isotope, U-238, with a half-value-period of 4.51E+09 years [ibid.]. Hence, background radiation does not change over a period of about E+04 to E+06 years provided that geological conditions remain constant. This point is essential for discussing long-term emissions. However, forecasting long-term emissions is difficult due to the uncertainties involved [ibid.].

To further estimate the approximate long-term emissions from sludge ponds [ETHZ, 1996] assumed that most plants in the vicinity of human settlements were closed and stabilised after operation (based on cost-benefit analysis) but with the primary aim to protect citizens from additional radiation. Data was based on three reference plants in three different geographical and climatic zones: Tropical, temperate, and semi-arid [ETHZ, 1996]. Around 10 per cent of the global total uranium is processed in tropical, 30 per cent in temperate, and 60 per cent in semi-arid regions [UI, 1994, and IAEA, 1992, in ETHZ, 1996]. From the average, weighted surface area of sludge ponds in these regions [ETHZ, 1996] give area values of 0.05 m^2/kgU for tropical, 0.007 m^2/kgU for temperate, and 0.07 m^2/kgU for plants in semi-arid regions [EPA, 1983; Young et al., 1982, in ETHZ, 1996). Among other US Environment Protection Agency

(EPA) standards, sludge ponds have to be controlled for at least 200 years but up to 1000 years where necessary [ETHZ, 1996].

Estimates in [ibid.] for long term Rn emissions were based on two main assumptions:

a) The Rn -flux after stabilisation is a factor two above the background radiation in areas rich in uranium.
b) Integration intervals of long term emissions from Rn-222 are then equivalent to the half life period of Th -230, which is 80000 years (at this point, Rn- emissions from sludge ponds are expected to have decreased to the order of magnitude of background emissions in uranium-rich areas).

The temporal flux of Rn depends much on morphological changes in the sludge sediments, and on the geological environment. It was further assumed that surface and structure of sludge ponds remain constant. Hence, the flux of radon decreases proportionally to the decay of Th-230. At the end of this time period, Rn is only produced at half its original rate [ETHZ, 1996].

For ***stabilised ponds*** in tropical climates [ETHZ, 1996] assumed an initial maximum Rn-flux of 0.1 Bq/m^{2}s, this being the highest value they found in the literature and equivalent to US EPA minimum requirements. For temperate and semi-arid climates, EPA limits of 0.74 Bq/m^{2}s were used. Long term Rn-emissions were estimated at 6.0E+07 kBq per kg uranium [ibid.]

Considering the surface areas of sludge ponds and the assumptions made, including a recovery period of 80000 years to reduce radiation levels to initial background levels of the mining area, the area equivalent for uranium is **3900 m^2 kg^{-1} yr** [ibid.]. Here, this figure was used exceptionally in order to account for radiation and the securing of sludge ponds. As this order of magnitude leaves other stages in the nuclear fuel chain (NFC) insignificant, the following process steps were only added for background information and to demonstrate the complexity of the NFC. Land use for power stations was not included.

Overall, the NFC requires about 8 kg natural uranium per TJ electricity (TJe). This means that **0.4 m^2/TJ**[18] will be lost over a very long period of time [ETHZ, 1996]. A nuclear power plant of 1000 Megawatts with an operating performance of 80 per cent and an output of 1 million TJe over 40 years will require about 40 ha of land space for storing ore residues in sludge ponds [ibid.]. Due to lack of data, neither regional nor geographical effects nor effects on soil and groundwater could be considered. Technical data from plants may be outdated, and data on radioactive water emissions are not complete [ibid.].[19].

3.1.1.12.3. *Conversion of* U_3O_8 into UF_6

The conversion into UF_6 is necessary for the subsequent production of fissile U-235, and for increased purity of the product. The input-output-ratio for yellowcake and converted uranium is about 1:1 [Schneider, 1982, Perkins, 1982, in ETHZ, 1996].

DLU values from three conversion plants [ETHZ, 1996] were calculated, using the average affected areas (4E+05, 3E+05 and 2.7E+5 m^2) and dividing by total average output (of 4.8E+08, 3.2E+08 and 1E+08 kg uranium). This resulted in **1.07E-03 m^2/ kg UF_6** output.

3.1.1.12.4. *Enrichment of uranium*

For the worldwide use in light-water reactors, fissile U-235 concentrations have to be raised above the natural 0.7 per cent to around 3 to 4 per cent. This is mainly done in either a gaseous diffusion process or by centrifuge separation [ibid.].

In all plants working with UF_6, the chemo-toxic risks outweigh the risks of radiation by far [ibid.]. Therefore, all systems have to meet extremely high insulation standards to keep emissions at minimum. Air emissions have to be

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[18] 3900 m^2 yr kgU^{-1} times 8 kgU TJ^{-1} = 31200 m^2 yr TJ^{-1}; 31200 m^2 yr TJ^{-1} divided by 80000 yrs =0.4 m^2/TJ.

[19] 0.4 m^2/TJ times 1E-06 = 40ha. Hence, with a land use of 3900 m^2 yr kg^{-1} uranium, 31200 **m^2 yr TJ^{-1}** are required to account for radiation (or, 0.4 m^2/TJ times 80000 yr. = 32000 m^2 yr TJ^{-1}).

checked for radioactivity and hydrogen fluoride (HF). Due to high standards, UF_6 emissions are very low [Pink et al, 1984, in ETHZ, 1996].

For land use, ETHZ [1996] referenced two diffusion and two centrifuge plants and their total output of enriched uranium. From the total average affected area of 1.33E+06 m^2, divided by a total average output of 1.95 E+08 kg of enriched uranium (UTA, Uranium separation process) about **6.80E-03 m^2/kg UTA** can be calculated.

Data quality was reported to be relatively complete [ibid.].

3.1.1.12.5. Fuel rod production

In brief, fuel rod production contains the process steps

- powder production
- tabs production
- fuel rod production
- fabrication of structural parts and assembly of fuel elements [ibid.]

By calculating the average affected areas from two production plants (Columbia Westinghouse, USA, and a DOE reference plant with 2.4E+05 and 3E+04 m^2 respectively) and their average total outputs (3.6E+07 and 1.8E+07 kg uranium, respectively) [ETHZ, 1996] a value of **5.0E-03 m^2/kg U** for fuel rods was derived.

3.1.1.12.6. Recycling of fuel rods

Worldwide, there are not enough capacities to recycle the total output of nuclear fuel. This is either due to lack of economic pressure for building new plants, due to cheaper, direct disposal possibilities of nuclear waste, or due to a "wait and see" approach for deciding on disposal strategies by several countries. In ETHZ [1996], the authors assumed reprocessing of all fuel elements. Reprocessing of fuel elements saves natural uranium and eliminates the uranium separation process [ibid.]. Only the recycling of UO_2 was included and not that of mixed oxide fuels (MOX, which also contain plutonium, and "Magnox" from Sellafield). Before entering the recycling plant (RP), the used fuel elements have to be stored for at least one year at the nuclear power station (NPS) to reduce radiation and emissions from thermal decay. At the RP, they have to be stored again. During the first five years radioactivity decreases by a three-hundred-fold, thermal energy by a thousand-fold. This is necessary to ease further chemical and technical processes. In brief, fuel elements are chopped into pieces of a few centimetres long before being dissolved in hot nitric acid for leaching. What follows is a sequence of extraction steps to cleanse the uranium and plutonium from fission and activation products and unwanted actinides [ibid.].

For the land use of RP, the average fenced area of three RP (Sellafield, UK, a DOE reference plant, and Wackersdorf, Germany) of 9.4E+05 m^2 was divided by the total average throughput of uranium (3.86E+7 kg) as given in [ETHZ, 1996]. This results in **2.50E-02 m^2/ kgU.**

3.1.1.12.7. Intermediate and final storage of nuclear waste

Before and after recycling, nuclear fuel elements require intermediate storage space. A planned intermediate deposit in Switzerland (ZWILAG) consists of a building for highly active waste (HAA) from recycling plants (RP) and non-conditioned fuel elements, a deposit for medium active waste (MAA) from RP and NPS, another deposit for medium to less active waste (SMA) for the same purpose, plus a building including a "hot cell" for inspection and transfer of fuel elements and HAA glass ingot moulds. Two treatment plants were planned for the incineration ("Plasmarc furnace") and conditioning of low active waste (SAA) and also the construction of a transfer station [ETHZ, 1996].

The direct land use for ***intermediate storage*** was calculated from the average affected area (including infrastructure) for intermediate storage of 1.40E+04 m^2 divided by the total average throughput of 1.70E+04 m^3, as in [ibid.]. From this, **8.24E-01 m^2 per m^3** waste was obtained. The density of this waste was not known.

Radioactive waste further has to be concentrated and insulated for ***final storage***. According to Swiss law, a continuous and secure disposal of radioactive waste is mandatory. Two types of deposits were chosen: One deposit "B" for SMA from NPS and for active waste from industry, medicine and research, located in secure rock; another deposit "C" for glassed HAA and MAA from reprocessed fuel elements or for the direct disposal of burnt fuel elements [ibid.]. The Swiss project "Gewähr" [Nagra, 1985a, in ETHZ, 1996] includes the construction of a rock laboratory. For the deposits, complex evaluation procedures and geophysical examinations took place with seven drilling operations up to 1500m deep and several other exploratory drilling operations. After 10 years of evaluation, suggestions for a final deposit B could be made. Evaluation procedures for deposit C, which started in 1981, have not concluded and a decision is not expected until the early 2000s due to the task's complex nature. The total construction process is expected to last 26 years. On arrival at the final storage place, complex deposit and waste specific sorting, handling and further conditioning and sealing procedures must take place [ibid.]. The space needed for final storage as given in [ETHZ, 1996] is 15.3 [m^2yr $m^{3\,(-1)}$] for SMA over 74.5 years (drilling, operation, and storage) and another 25m^2 yr for 50 years of recultivation. For HHA, an area of 356 [m^2yr $m^{3\,(-1)}$] over 83 years (deep drilling and storage in secured rock) plus 376 [m^2 yr $m^{3\,(-1)}$] for another 50 years of recultivation time is required [ibid.]. This is equivalent to **0.2** [m^2 yr $m^{3\,(-1)}$] plus another **0.5** [m^2 yr $m^{3\,(-1)}$] for SMA. For HAA, the equivalent direct land use is **4.2** [m^2 yr $m^{3\,(-1)}$] plus **7.52** [m^2 yr $m^{3\,(-1)}$]. [Table 6] summarises the NFC.

Land use NF chain [adapted from ETHZ, 1996]	**m^2 kg^{-1} U** (unless stated otherwise)
U- mining (surface)	1.36E-01
U-ore preparation	**3.90E+03** m^2 yr
U- conversion	1.07E-03
U- enrichment (UTA)	6.80E-03
Fuel rod production	5.00E-03
Nuclear power plant	1.66E-07 per MJ (specific) – N/A
Recycling of fuel rods	2.50E-02
Intermediate storage	8.24E-01 m^2 yr $m^{3\,(-1)}$
Final storage	1.25E+01 m^2 yr $m^{3\,(-1)}$
	NF chain: 8 kgU/TJ required [ETHZ, 1996]. This equals 31200 m^2 yr per TJ (3.12E-02 m^2 yr MJ^{-1})

Table 6. Land use nuclear fuel chain

Within the NFC, sludge ponds receiving the waste from U-ore preparation (yellowcake production) have the highest land use due to radiation [ETHZ, 1996]. [Table 6] also highlights the complexity of the NFC.

3.1.1.13. Commodities for which no area values could be found

Commodities for which no area values could be found so far are:
Nickel, lead, zinc, antimony, minor sulphide metals arsenic, bismuth, cadmium, cobalt, germanium, gold and silver, indium and molybdenum, also platinum group metals (platinum, palladium, iridium, rhodium, ruthenium, osmium) and rhenium, selenium and tellurium.

3.1.1.14. Wood

To account for wood in the life cycle inventory of products, default values for biomass calculation from the Intergovernmental Panel on Climate Change, (IPCC) were used. The average annual accumulation of dry matter (dm) for temperate forests (plantations) is given as 5 tonnes of dm per hectare [tdm ha^{-1} yr^{-1}] [IPCC, 1997a]. To account for the biomass lost beyond the commercial wood portion, an expansion ratio of 1.90 for logged forest [IPCC, 1997b] was added as well as 15 per cent humidity [Wackernagel, 1996].

0.91 m^2 kg^{-1} yr were obtained (5000kg dm ha^{-1} yr^{-1} multiplied by 1.90 + 15% =10925 kg ha^{-1} yr^{-1}, divided by 1E+04 = 1.09 kg $m^{2\,(-1)}$ yr^{-1}; 1/1.09= 0.91 m^2 kg^{-1} yr).

It should be noted that both uranium (radiation) and wood (renewable) include a time factor [m^2 kg^{-1} yr] as opposed to the remaining resources.

A summary of the different DLU values for non-renewable materials is given in [Figure 5]. Uranium is exceptional due to its high land requirements from yellowcake production and the assumptions made.

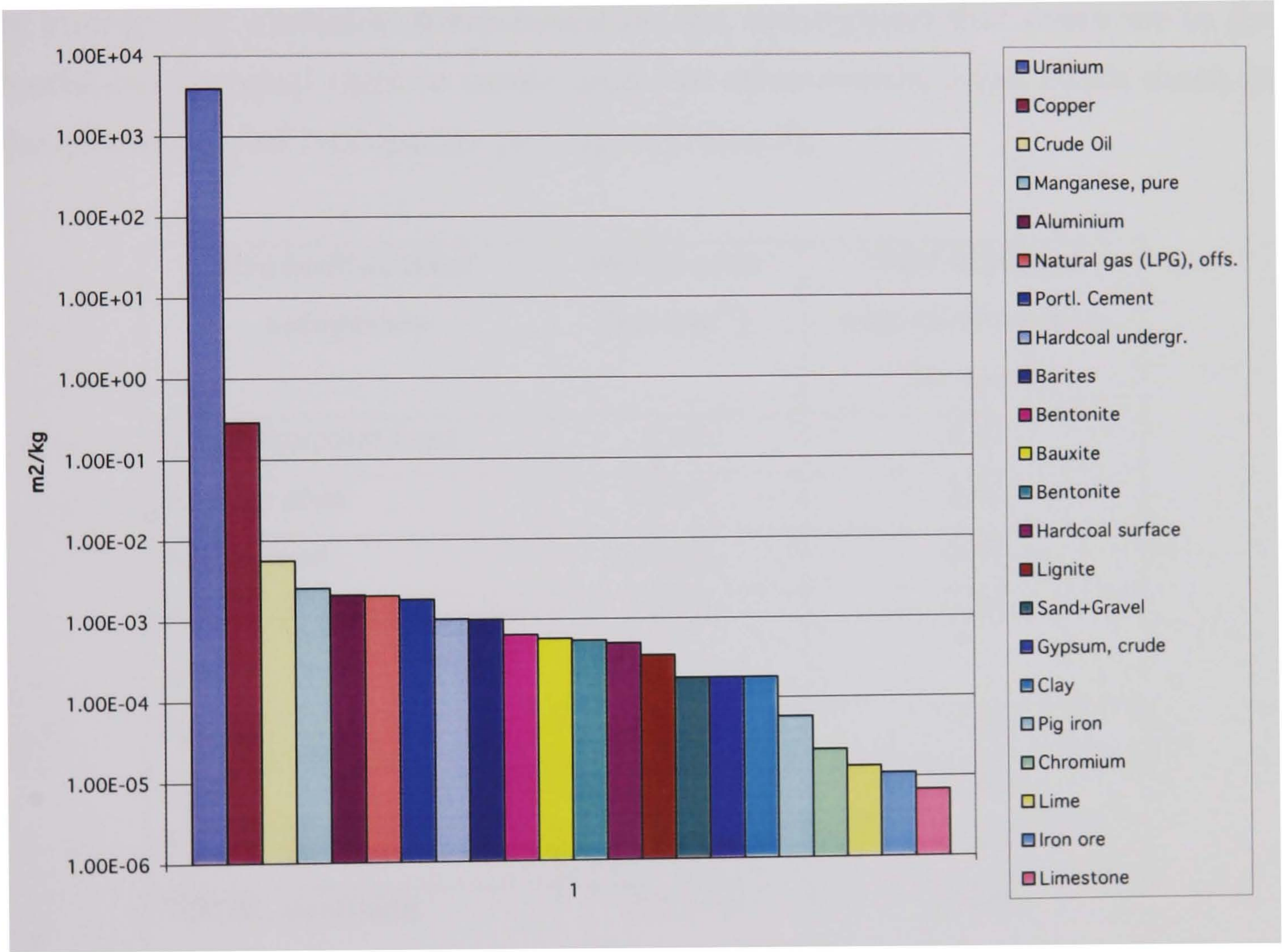

Figure 5. Descending order of DLU for non-renewable resources [m^2 kg^{-1}]. (Note that uranium is in m^2 kg^{-1} yr).

3.2. *Part B: The ecological footprint method*

The world's ecological footprint (EF) changes proportionally with global population size, average consumption per capita, and the resource technology used. Decreasing productive land space must be divided by an increasing population. Because insufficient data are available for some uses of the biosphere, the EF is a conservative estimate of human impact [WWF, 2000]. This chapter explains the basic calculation procedure for the EF, and how it can be applied to electronic products.

3.2.1. The principle of fair Earth shares

The EF, or ***demand*** of a population for bioproductive space, can be compared with the biocapacity, or ***supply*** available in that area. This reveals how much nature a population needs, and how much nature is available. Wackernagel et al. have estimated a minimum condition for sustainability. This is the amount of biologically available space based on the assumption that everyone in the world has an equal right to fertile land - in other words, a fair Earth share, or the existing global biocapacity per capita [Table 7].

Productive land categories	**World area [ha cap^{-1}]**	**Yield adjusted equivalence area [ha cap^{-1}]**
CO_2 absorption land	0.00	0.00
Built-up area	0.04	0.12
Arable land	0.22	0.69
Pasture and wooded area	0.79	0.31
Forest	0.58	1.03
Sea	0.55	0.03
TOTAL existing	2.18	2.18
TOTAL available	-12% for biodiversity	**1.92**
TOTAL available terrestrial	-0.03 [ha cap^{-1}] for sea	**1.89**

Table 7. The benchmark for sustainability, adapted from [Wackernagel et al., 2000]

At the time of writing, the year 1996 was the most recent for which UN statistics were complete for all countries. That year, the Earth had 12.5 billion (bn) hectares (ha) of bioproductive land available, consisting of around 1.3 bn ha arable land, 0.2 bn ha of built up land, 4.6 bn ha of pasture and wooded area, 3.3 bn ha of forest and 3.3 bn ha of fishing grounds. Dividing the global area of bioproductive sea and land space by the population of around 5.7 bn people in 1996 results in a statistical average of around 2.2 ha world-average space per person [Wackernagel et. al., 2000].

However, it is important to protect some land for biodiversity. The World Commission on Sustainable Development [WCSD, 1987] suggested that at least 12 per cent of this space should be preserved for the other 10 to 30 million species on the planet. In this case, the available space shrinks to 1.92 ha per person [Wackernagel, Callejas, Deumling, 2000]. These 12 percent may be politically courageous, but are probably not enough to secure long term biodiversity [Wackernagel, Lewan, Borgström, 1999]. Some conservation biologists estimate that even from an utilitarian viewpoint 25 to 60 per cent are required [Noss and Cooperrider, 1994]. This would shrink the available space to at least 1.63 hectares per person. At present, only 3 per cent are set aside as reservations and parks [Wackernagel, Callejas, Deumling, 2000; WBCSD, 1987]. Deriving one figure for biodiversity protection is probably impossible due to regional differences. While the natural background rate of extinction is estimated at 1 to 10 species a year, this century the rate accelerated to at least 1000 species a year [Tuxill, 1999]. However, high uncertainties are involved in these figures. Dobson [1998] for example, gives a high estimate of between 10000 and 25000 per year.

The *LPR* [WWF, 2000] accounts for biodiversity as a percentage on the demand side (therefore increasing the required space for biodiversity with the EF), but previous assessments subtracted biodiversity space from the supply side.

For the same year, however, the global per capita demand for productive space, the EF, was 2.85 ha versus a supply of 1.92 ha, thus exceeding the biologically productive space by a third [WWF, 2000] or about 48 per cent when 12 per cent space is set aside for other species.

This shows that through the production of goods, services and wastes humans are using more productive space than nature can regenerate – they are depleting nature's stock. This is also in line with another indicator. For example, the Living Planet Index (LPI) used by the World Wide Fund for Nature (WWF) decreased by 33 per cent between 1970 - 1997. The LPI is the average of three other indices that monitor the change in animal populations over time in forest, freshwater, and marine ecosystems [WWF, 2000]. This poses the challenge for a sustainable society: To leave bioproductive space for other nations' consumption and emissions, and pristine habitat for the other species on this planet.

The ecological benchmark of 1.92 ha of bioproductive space per person was also used as the basis in this study. However, since only terrestrial Earth space was used here, the actual benchmark for this study is **1.89 ha per capita** which includes 12 per cent biodiversity production, or **1.60 ha per capita** when 25 per cent are included.

3.2.2. Categories of bioproductive space and equivalence factors

This section explains the calculation method for the different land categories, and how these were integrated into this study.

Generally six major land categories are used in footprint analysis, which represent the biosphere, hydrosphere, and atmosphere. They can be divided into several subcategories for more refined analyses:

- Fossil energy land
- Built up area
- Arable land
- Pasture and wooded area
- Forest
- Sea space [Wackernagel and Rees, 1996]

The various goods, services, and wastes people generate and use can be allocated to these land categories. Because ultimately surface area is restricted to the globe, EF measurements are in area units. These are then transformed into standardised hectares of world average productivity (area-units equivalents) to facilitate international comparisons. In other words, EFA does not compare land surfaces consumed with land surfaces supplied, but bioproductive ***space*** consumed with bioproductive ***space*** supplied.

To avoid double counting, the EF only accounts for functions that mutually exclude each other on the same plot of the earth's surface (for example, standing forest that is felled for timber production cannot be used for CO_2 absorption at the same time). Some regional studies [Folke, et al, 1997; Wackernagel, Lewan, Borgström, 1999; Rockström et al., 1999; Jansson et al., 1999; also Nilarp, 1994; Wirsenius, 1994, in Holmberg et al., 1999] have included overlapping services, such as water catchment areas, areas for denitrification and phosphorus retention, copper assimilation, and acidification. These areas could be integrated as a shadow footprint because they are not additive [Holmberg et al., 1999; Chambers, Simmons and Wackernagel, 2000].

In this study, overlapping services are not included, therefore the footprint area (A) according to [Holmberg et al., 1999] is:

$$A_{\text{EF electronic product}} = A_{\text{additive aspects}} \qquad \text{(Equation 3)}$$

To aggregate the six land categories into footprints and supply of biocapacity, they are adjusted by equivalence factors according to their biomass yield. This accounts for the different biocapacities between land categories: One ha of land with a high biomass yield represents more area-units than one ha with a low biomass yield. Equivalence factors compare the categories' relative yield to world-average land, which has an equivalence factor of 1. A factor of 3.2 means that this land category is 3.2 times more productive than the global average. These factors are the same for each country because they compare global average land categories. Therefore, the physical global areas, and likewise, the areas scaled by their equivalence factors, must add up to the same global total. Without this adjustment, the totals would be distorted as the various land categories reflect large differences in bioproductivity [Wackernagel et al, 1999]. Primary biomass yields are available from United Nations (UN) statistics, such as the Food and Agriculture Organisation (FAO) and the World Resources

Institute (WRI). Arable land, pasture and forest are defined by the FAO's land use statistics [WWF, 2000; Wackernagel, Callejas, Deumling, 2000].

3.2.2.1. Arable land

Arable land refers to the most productive land because it can yield the largest amount of biomass per ha. Nearly all of the best arable land is already cultivated [FAO, in Wackernagel et al., 1999; Brown and Flavin, 1999]. It has been estimated that about 10 million ha of arable land are lost per year [Pimental and Pimental, 1996, in Wackernagel et al., 1999.]. In 1996 there were about 0.22 ha per capita of arable land available. Arable land has an equivalence factor of 3.2 [Wackernagel, Callejas, Deumling, 2000].

3.2.2.2. Built up land

Built-up land is land directly occupied by buildings, waterpower dams, infrastructure, badly eroded land or otherwise degraded land. It is accounted for according to the space occupied by buildings or activities. Built-up land has lost its productivity. Since most human settlements are located in the most fertile regions, built up land has the same equivalence factor as arable land (accounting for the productivity lost). This is a simplification [Wackernagel, Lewan, Borgström, 1999]. With increasing demand for cropland, inferior land may have to be upgraded to compensate for the productivity lost. In this case, restoration expenditures for materials, time and energy etc would have to be charged to that land account [Wackernagel and Rees, 1996]. In 1996 there were about 0.04 ha per capita of built up land [Wackernagel, Callejas, Deumling, 2000].

In this study, built up land was used for degraded land from mining operations and for infrastructure, expressed as direct land use (DLU).

3.2.2.3. Pasture and wooded area

Pasture and wooded area refers to unimproved grazing land for cattle and dairy farming. It generates meat and dairy products as well as other animal products like leather, hides and wool. This land is less productive than arable land, which is mainly due to the plant to animal biomass conversion ratio of ten. About 0.8 ha per capita existed in 1996. Pasture has an equivalence factor of

0.4 [ibid.]. The expansion of pasture has been the main cause of diminishing forest areas [Wackernagel et al., 1999].

3.2.2.4. Sea

Sea space refers to the productive continental shelf which is used for fisheries. These approximately 8 per cent of space provide 95 per cent of the fish harvest. There are about 0.6 ha per capita of sea space in 1996. World average sea has an equivalence factor of 0.06 [Wackernagel, Callejas, Deumling, 2000].

This study only refers to the terrestrial space in our study, as sea space for protein production is irrelevant for electronic products (not to be confused with the ocean's function to absorb CO_2). For this reason, sea space was subtracted in our calculations, thus changing the ecological benchmark to 1.89 ha per capita.

3.2.2.5. Forests

Forest space refers to natural forest and plantations due to their capacity to produce timber and other wood-based goods [Wackernagel, Lewan, Borgström, 1999]. But more importantly, forests provide major ecosystem services such as climate regulation, soil protection, regulation of hydrological cycles and providing biodiversity habitats [Myers and Reichert, 1997]. Globally, there are 3.3 bn ha of forest or 0.6 ha per capita. Forest has an equivalence factor of 1.8. [Wackernagel, Callejas, Deumling, 2000].

3.2.2.6. Fossil energy land

Fossil energy land is assumed to be newly planted forest area and refers to the spatial impact from fossil fuel use. The method was introduced by Wackernagel and Rees [1996] and has been used since. These authors also introduced alternatives to this method which are described later, but they chose CO_2 sequestration as it produces the smallest EF. Fossil energy land is reserved for the bioproductive space needed to sequester fossil carbon emissions. It is assumed that the anthropogenic addition of fossil CO_2 to the biosphere should be removed, which is a strong sustainability assumption. Global absorption rates are used because CO_2 accumulation is a global problem. Unlike the other land types, this land does not necessarily exist but it shows how much forest would be needed for carbon sequestration in order to offset human CO_2 emissions. It also represents the degree to which the Earth must be larger in order to absorb these CO_2 emissions. Earlier studies by Wackernagel et al. have only included carbon sequestration by forests, but since the *Living Planet Report (LPR)* [WWF, 2000], CO_2 absorption by oceans is also accounted for. EF studies by other authors [Folke et al., 1997; Frey, Harrisson, Billett, 2000 a,b] have also included oceans as a carbon sink.

Newly planted forest will serve as a CO_2 sink until the biomass is harvested and decays, or reaches maturity. It can take up carbon from the atmosphere for 40 to 100 years depending on climate and tree species [IPCC, 1997b]. In order not to release the sequestered carbon the mature forest must be left undisturbed and allowed to renew itself spontaneously. Harvesting is only possible with little wastage and if transformed into long-lasting products [IPCC, 1997b]. If fossil fuel use continues, additional areas for carbon absorption would have to be set aside to avoid accumulation in the atmosphere when the first generation of forests have matured. This area has not been included so far [Wackernagel, Lewan, Borgström, 1999]. To calculate the EF for fossil energy land, the average global bioproductivity of different forest types is calculated over a harvest cycle of 40 years to produce annual estimates for each type of forest. Subsequently, the totals of these estimates are used to produce an estimate for annual global biomass production. This estimate is divided by the global area of bioproductive forest in the same year, resulting in a global average rate of forest biomass production per hectare forest per year (t ha^{-1} yr^{-1}) [Lewis, unpublished working paper, 2001]. Based on IPCC data [1997 a, b] and in line with Wackernagel [1996], a 25 per cent "root to shoot ratio" is added to account for carbon absorption by underground biomass. For carbon density, the IPCC [1997a] default value of 0.5 tonnes of carbon per tonne of dry matter (tdm) is assumed. Therefore, the annual accumulation of biomass per ha forest (tdm ha^{-1} yr^{-1}) can be calculated as:

Annual biomass forests = 2.27 tdm ha^{-1} yr^{-1}
= 2.27 times 1.25
= 2.83 times 0.5
= **1.42 tonnes of carbon ha^{-1} yr^{-1}** [Wackernagel, 1996].

The conversion rate between C and CO_2 is 44/12, therefore:

1.42 times 44/12 = 5.2 tonnes of CO_2 per ha per yr.

$1/5.2 = 0.19$ ha years per tonne of CO_2 [ha yr t^{-1}].

CO_2 sequestration land, like forests, has an equivalence factor of 1.78 [Wackernagel, Callejas, Deumling, 2000].

In this study on electronic products, it was first assumed that oceans absorb 25 per cent of the annual fossil CO_2 emissions [Hadley Centre, pers. comm., 2000][20] which is a relatively low figure. IPCC estimates [1996, in Jansson et al., 1999] range between 20 and 57 per cent. Therefore, scenarios with a 35 per cent CO_2 absorption by oceans were also included. [Table 8] lists the different land categories and their equivalence factors.

Land types	**Equivalence factors (1996)**
CO_2 absorption land	1.78
Built-up area	3.16
Arable land	3.16
Pasture and wooded area	0.39
Forest	1.78
Sea	0.06

Table 8. Land types and equivalence factors [Wackernagel, Callejas, Deumling, 2000] used in this study.

One of the key factors in EF analysis is that there are two types of forest, one for forestry and another for storing carbon.

The reasons are a) that this avoids double counting and b) only new forests are needed for sequestration. However, new forests are not as biologically diverse as old forests [Wackernagel et al., 1999]. Two other alternatives worth mentioning to calculate the fossil fuel footprint lead to more or less the same result and with the same underlying assumption: Humanity must not

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[20] The Hadley Centre estimated a range between 25 and 33 per cent [Hadley Centre, C. Jones, pers. comm., 2000].

undermine the functions and biodiversity of the ecosphere [Holmberg et al., 1999]. [Table 9] lists some fuel specific energy–to–land ratios:

Fuel type	**Global average energy to land ratio [GJ ha^{-1} yr^{-1}]**
Coal	56
Crude oil	73
Natural gas (fossil)	96
Hydro electricity	1000

Table 9. Fuel specific energy-to-land ratios, 1996 data [Wackernagel, Callejas, Deumling, 2000]

3.2.2.6.1. Criticism of the sequestration method

The sequestration method as used in the EF has been criticised for several reasons:

3.2.2.6.1.1. Forever forests

The carbon sequestration method only accounts for the annual occupied forest area, whereby in order not to release the fixed carbon, forests will have to remain *forever* to maintain this function – unless the mature wood is converted into long-lasting products. Only young and growing forests sequester significant amounts of carbon, maturing forests only sequester significant amounts for some decades until a peak is reached – after which they remain carbon neutral [Haberl, Erb, Krausmann, 2001; Herendeen, 2000]. Therefore (NB: if using fossil fuels continues), the same fossil energy land cannot be used year after year, but new fossil fuel land would have to be acquired each year [Haberl, Erb, Krausmann, 2001].

Using the net CO_2 absorption potential of immature forests also leads to both an overestimation of the net CO_2 uptake, as it saturates to zero as the peak is reached and then becomes a carbon source (unless wood is prevented from decay, like being transformed into long-lasting products, p. 97), and to an underestimate of net carbon uptake since increased CO_2 may also stimulate increased biomass growth [Herendeen, 2000]. Because the distribution of land use changes, fertilisation, and other terrestrial effects vary, these changes should ideally be included in national accounts. However, it is almost impossible to determine to whom to credit or debit these changes since the distribution over nations varies. For this reason it has been assumed that these effects result in a zero net effect as they cancel each other [Wackernagel, Callejas, Deumling, 2000][21]. [Wackernagel and Silverstein, 2000] pointed out that the strong sustainability approach of maintaining natural capital could also be interpreted as the "need to compensate future generations with an equivalent amount of stored energy". The sequestration approach, however, merely suggests that impacts from fossil fuel use should be reversed – visualised in terms of the ecological capacity required.

A different suggestion is to adjust the available supply of forests that are already regarded as sinks. Such absorption forests, however, would require very large portions of earth surface: With carbon accumulating at approximately 3.5 Gt per year [Hadley Centre, C. Jones, pers. comm.; 1.02.02] and an absorption rate of 1.42 t ha^{-1} yr^{-1}, the world's forests would have to be increased by 2.5 Gha [2.5 E+9 hectares] (assuming that existing forests are already at sink capacity – Lewis, pers. comm., 2001). Existing forest sinks are very difficult to determine at the sub-national level [Wackernagel and Silverstein, 2000]

3.2.2.6.1.2. Forests as carbon sinks questionable

Recent studies have questioned the role of forests as a carbon sink, as forests may sequester less carbon than previously assumed [see New Scientist, 1999], thus questioning the CO_2 sequestration rates applied in EF analyses. Wackernagel, Lewan and Borgström [1999] admit that carbon sequestration through new forests "is the only technology applied today, and an insufficient one" but that it is still the prevailing sequestration technology. At least for their first 30 to 50 years, growing forests are the only ecosystems known that can

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[21] CO_2-abs. spreadsheet

remove significant amounts of CO_2 [Wackernagel and Silverstein, 2000]. Land use changes in forests account for the largest changes in biomass stocks [IPCC, 1997b]. The *LPR* [WWF, 2000] accounts for the role of oceans in CO_2 absorption. However, there is also the possibility that oceans can turn into sources of carbon through rising temperatures and other co-factors [see Princeton model, in Wackernagel, Lewan, Borgström, 1999; Nisbeth, 1991]. The Baltic Sea, for example, seriously eutrophied, is not a net carbon sink [Jansson et al., 1999].

The sink problem, however, also shows that humans cannot plant their way out of trouble. The EF does not suggest that in order to solve the CO_2 problem people merely need to plant more trees, but to strive for a balance in the ecosystem atmosphere – so far, an unaccomplished task. The EF stresses the need to reduce CO_2 emissions, although it does not tell us how to do it.

Sequestration can only be a partial solution since there is not sufficient land on Earth that can be provided for this function [WWF, 2000]. If the world were much bigger, or CO_2 emissions smaller, there would be sufficient ecological capacity available to absorb these emissions. Hence, fossil fuel use is expressed in terms of the ecological capacity required to reverse the impact of its waste, or CO_2 emissions [Wackernagel and Silverstein, 2000]. This does not mean to abandon further efforts for finding more accurate absorption data, but from the data and methods available, this method seems to be the most appropriate at present for the above mentioned reasons.

The carbon sink discussion highlights that the land allocated for CO_2 absorption is significantly underestimated, especially if forests are not the sinks they once were believed to be [Barrett, 2000]. Despite its limitations, calculating the corresponding areas needed to sequester present CO_2 emissions is helpful in monitoring overall trends in energy efficiencies (and their change over time) and in revealing more "space efficient" technologies, such as in some renewable energy systems or in products requiring energy.

3.2.2.6.1.3. *Alternative ways of CO_2 elimination*

It has also been argued that a) there are other ways of absorbing CO_2 such as pumping it into old oil or gas fields or the deep ocean [Ayres, 2000; Ferguson, 2001]; b) that there are other energy sources which do not generate CO_2 that have not been included, and c) other greenhouse gases such as methane and other pollutants are neglected [Ayres, 2000]. Some authors seem to rather welcome increased atmospheric CO_2 emissions, for example, van Kooten & Bulte [2000], van Kooten and Folmer [1997, in ibid.].

One could agree with Ayres with regard to a) as there may be other possibilities. It also points to the definition of the EF which says "..using prevailing technology". If, for example, pumping waste gases such as CO_2 into the deep ocean became a significant technology, methodologically the waste absorption rates could be included in the footprint (although this solution may be counterproductive [Seibel, 2001][22]. This rather underlines the flexibility of the EF: If a widespread technology proves not to be a sustainable practice, the results should show up in subsequent EF assessments. It also underlines that the EF cannot directly distinguish between sustainable or unsustainable practices, but will show the results of good or bad management over time. However, at present, there is no widespread man-made technology to remove CO_2 from the atmosphere.

Point b) refers to the same issue - it has been calculated that some alternative energy sources (some of which still need a significant amount of conventional energy and are hence not zero emitters - for example, nuclear power or photovoltaics) have smaller footprints [Table 10]. Point c) refers to the incompleteness of the EF. This is true, since with some exceptions, no other emissions than CO_2 have been included on a larger scale. EF analyses do not claim to be complete since the current main obstacle for further integrating pollution is lack of reliable research data on interactions between pollutants and bioproductivity [Lewan and Simmons 2001]. Compounds foreign to nature (such as PCBs) cannot be calculated in EFA because assimilation capacities

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[22] According to Seibel [2001], dumping iron into the sea to absorb CO_2 might 1. result in a plankton bloom, thereby reducing oxygen levels in the water which will encourage bacteria to produce methane, nitrous oxide and other greenhouse gases. 2.Liquefying CO_2 and pumping it directly to the ocean floor: The CO_2 from a single power plant treated his way would reduce the pH of the water by 0.1. This increased acidity should be enough to harm local sea life [ibid.].

cannot be identified for such substances [Holmberg et al., 1999]. Because EFA accounts only for the most important impacts, including possible additional impacts would add valuable insights, but will not change the overall result of the analysis. This becomes important when deciding whether the results of a footprint analysis should serve analytical or educational purposes.

Electricity source	**Electricity footprints [ha yr GWh^{-1}]**
Natural gas	45
Fuel oil	59
Fuel wood	93 to 97
LPG	51
Wind	6 to 27
Photovoltaics	24
Biomass woody	27 to 46
Hydroelectricity	10 to 75

Table 10. Footprint comparison between fossil energy sources and some renewable sources [Chambers, Simmons, Wackernagel, 2000].

3.2.2.7. Alternative A: The biomass method

One alternative, which is supported by Ferguson [2001] is to assess the bioproductive area required to produce a plant based substitute for fossil fuel. As ethanol and methanol are potentially renewable sources comparable to liquid fossil fuels, one can calculate the land area required for growing biomass to produce the equivalent amount for fuel including process energy. Early EF papers used an energy to land ratio of 100 gigajoules (GJ) per hectare year [Wackernagel and Rees, 1996], but later EF publications use lower energy to land ratios between 56 to 96 GJ ha^{-1} yr^{-1} depending on the carbon emission factors of different fossil fuels [for example, Wackernagel, Callejas, Deumling, 2000]. An optimistic estimate for ethanol would be a net productivity of 80 GJ ha^{-1} yr^{-1} [Wackernagel and Rees, 1996] whereas a modest estimate is 47 GJ ha^{-1} yr^{-1} [Ferguson, 1999, in Barrett, 2000]. However, the latest sequestration method, in line with using the most conservative estimate [Wackernagel and Silverstein, 2000] still results in the lowest EF by accounting for only 65 per cent forest absorption (35 per cent by oceans) [see WWF, 2000].

A strong argument for using the biomass method is its direct connection to energy use and avoiding the time factor of the sequestration method. Additionally, biomass is "likely to be the major energy source" in the future [Ferguson, in Lewis, 19.01.2001; unpublished working paper]. However, as shown above, this approach would lead to larger footprints. Another criticism is that this approach is detached from the major energy sources used at present, as bio fuels and other renewable energy sources are currently underrepresented. The biomass method would not reflect today's energy consumption behaviour [Lewis, ibid.]. It is also controversial as to which degree bio fuels can substitute for fossil fuels because this involves competition for land areas available for other purposes, such as food production and biodiversity [Nakic'enovic', Grübler, McDonald, 1998; Berndes et al., in Holmberg, 1999]. However, a real transition from fossil fuels to plant-based fuels should lead to a smaller footprint [Holmberg et al., 1999].

3.2.2.8. *Alternative B: Rebuilding natural capital*

This alternative considers rebuilding natural capital at the same rate as fossil fuels are being consumed. "Replace what is consumed" was suggested by World Bank economist El Serafy [1988, in Wackernagel and Rees, 1996] and would also lead to an absorption rate up to 80 GJ ha^{-1} yr^{-1} [Wackernagel and Rees, 1996]. Like alternative A, this would result in a larger EF.

In conclusion, all three methods have their limitations. However, based on IPCC's sequestration rates, the conversion estimates in [Table 9] have been adopted by Wackernagel et al. as the most conservative method. It was chosen because it avoids overestimating the anthropogenic impact from fossil fuel use [ibid.]. However, the accumulation of CO_2 in the atmosphere is only one of many impacts from the use of fossil fuels. Additionally, no land has been reserved to allow for continued fossil fuel use once the forests have matured. Therefore, the method still significantly underestimates the true ecological impact from fossil fuels. Additionally, this method also has the advantage that it accounts for other CO_2 sources than fossil fuels, such as from cement production [Holmberg et al., 1999].

3.2.2.9. The issue of nuclear power

Since the EF cannot incorporate risk directly, assumptions have to be made for certain activities. At present, Wackernagel, Lewan and Borgström [1999] assume as a first approximation that nuclear energy has the same footprint as fossil energy: Rough calculations suggest that the lost ecological bio-production caused by the Chernobyl accident compared to the total nuclear power produced since the 1970s leads to nuclear per [MJ] footprints larger than those of fossil fuel [ibid.]. Since nuclear energy is not even economically competitive with fossil fuel [Fischedick et al., 1996; World Bank, 1994, in ibid.], it will most likely be replaced in the short run with fossil fuel based energy [Wackernagel, Lewan, Borgström, 1999].

However, the above approach may potentially open the EF to the criticism of value judgements as there are more accurate indicators to assess risks from nuclear power [Barrett, 2000].

Although nuclear power appears to have a very small footprint if only accounted for the power station, the nuclear fuel chain is highly complex and high maintenance for safety reasons. This study adopts ETHZ [1996] data to account for the time until radiation levels from sludge ponds are reduced to background radiation levels of the area mined [p. 84]. This involved the use of a different time unit [m^2 yr kg^{-1}] compared to the other non-renewable materials, but at the time it was felt that this approach was suitable to incorporate long term deterioration from a point source.

3.2.3. The EF approach and electronic products

In this study, the aim is to establish the EF for a product. Because sustainability is determined by many factors, the criteria for assessing the sustainability of a product could nevertheless be deduced from the sustainability principles outlined in Chapter 2: *Principles 1 and 2* [pp. 42] address the deterioration of the ecosphere through accumulation of substances that are either extracted from the Earth's crust or otherwise produced by society, and emissions of a product can be measured. Subsequently, the corresponding land space required - provided the assimilation capacities can adequately be transformed into an area – can be calculated. This excludes compounds foreign to nature (such as PCB or flame-retardants); other tools are better suited to assess these. Since the global EF method for emissions is currently limited to CO_2, the question is how much bioproductive space is required to offset the carbon emissions of an electronic product.

Principle 3 [pp. 42] addresses harvesting and manipulation of the ecosphere, which, in a sustainable society, must not deteriorate long-term productivity or threaten biodiversity. When applied to products, the degree to which a product contributes to the deterioration of bioproductive land can be calculated. Because electronic products contain a plethora of mined materials, the direct land use from mining the required materials can be estimated. Although the *fourth principle,* the ethical dimension, cannot directly be addressed on a product level the fair Earth share can show how much of this benchmark is consumed by one or several products.

[Barrett, 2000] pointed out that the EF should be a) responsive to change and b) able to indicate the effects of future trends or policies in order to be a useful tool for measuring sustainable development.
These criteria must also be valid on a product level: For example, if CO_2 emissions from a product have decreased through energy efficiency measures this must be reflected in the size of the EF. Likewise, a product's EF should be able to estimate and monitor progress in product development, such as through the choice of different materials or technologies.

However, problems arise when attempting to combine areas from non-renewable materials contained in electronic products with areas resulting from the sequestration method, a renewable process. This is further complicated as electronic products require energy for as long as they are in use.

In a first approach, all burdens from the life cycle of an electronic product were aggregated and presented as the total EF and subsequently compared with the fair Earth share. This implied that

- Areas from non-renewable and renewable materials were allocated to every year of use.
- The EF becomes smaller the longer a product lasts (which may not be the case in electronic products)[23].
- No distinction was made between renewable and non-renewable resource consumption.
- Areas from transport were distributed over the life time of a product.
- Areas corresponding to the life time burdens of an electronic product were compared with the available fair Earth share [ha cap^{-1}].

Therefore, in a next step, the life cycle phases materials extraction, manufacture, and, for simplicity, benefits from recycling were allocated to the year of purchase whereas only the use phase was divided over the product's life time. For every other year of use, only resources from the use phase were accounted for. This revealed the instantaneous rate of consumption in a given year (EF) of the life cycle, expressed as [m^2]. The advantage of this approach was that areas corresponding to non-renewable and renewable materials could be allocated to the time when their actual consumption occurred, thereby obtaining a truer picture of electronic product use and avoiding different time units. This approach also allowed the modelling of EF-time series for electronic products.

3.2.3.1. *Calculation procedure for electronic products*

Since electronic products require a range of certain materials that are different from a complete household or nation, the principle of calculation is the same but not all land categories may directly be affected by one product. At present, the only land categories that were identified for electronic products were built up land, forest land and fossil energy land. However, it is nevertheless important to keep the different land categories for comparison with the ecological benchmark and because subsequently, other products, or products with wider system boundaries, may be added or a deeper analysis is required. Hence, the general EF formula for electronic products can be expressed as:

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[23] For example, over 40 years and a sequestration rate of 5.2 tonnes of CO_2 ha^{-1} yr^{-1}, one hectare can absorb 208 tonnes of CO_2.

$$\text{EF}\, product = \sum_{i=1}^{i=n} D_i + A_i \qquad \text{(Equation 4)}$$

Where D_i are the appropriated direct land use areas (based on the life cycle inventory of an electronic product) and A_i are the appropriated additional land areas (for example, from waste absorption).

3.3. Summary and discussion

This EF methodology consists of part A (estimating direct land use data) and part B (the actual footprint method including CO_2 sequestration). Both approaches only account for mutually exclusive land areas (additive aspects). For direct land use (DLU), no distinction was made with regard to different land use types, the quality of the areas affected, or between land transformation and occupation. With more and better data available, some of these parameters may enrich EFA.

Usually only DLU data from mining activities could be included as sufficient data for infrastructure (pipelines, buildings, roads) and further process steps were often not available. Additionally, most of the data found was site specific, making generalisations difficult.

To estimate the DLU for several commodities, many assumptions had to be made: In the cases of bentonite, iron ore and aluminium, theoretical approximations were obtained from the thickness of ore layers, density, and specific overburden values. Where DLU was calculated from total area and outputs, ecological rucksacks or overburden were not included to avoid double counting. For offshore mined natural gas, direct damage to the benthos was extrapolated from offshore oil production, assuming the same yields per metre drilled but accounting for the different densities. In the case of coals, lowering of the ground water table was accounted for as indirect ecosystem loss, which is an approximation. For uranium, accounting for radiation meant including a time factor. This was limited to the sludge ponds from yellowcake production, which caused the lion's share of land use in the nuclear fuel chain and made the other process steps insignificant in comparison. Since only mutually exclusive areas were accounted for, this method may be more accurate than estimating areas lost from nuclear accidents. However, overall DLU values except for uranium are very small, serving rather an indicative purpose for the collateral damage from mining.

Inherent to the EF method used in this study is the principle of fair Earth shares, pointing to an ecological benchmark: The world's EF changes with global population size, global average consumption, and technology. Shrinking land space must be divided by an increasing population. Comparing the demand for biocapacity (EF) by a population or product with the available supply shows a snapshot of a situation at a given time: At present, with a 12 per cent rate of biodiversity protection, the available supply of biocapacity is 1.92 ha per person, or 1.63 ha with a rate of 25 per cent. Here, only the terrestrial fair Earth share was used, 1.89 ha with 12 per cent biodiversity protection, and 1.60 ha with 25 per cent. This study contains six categories of bioproductive space, including equivalence factors, which scale land categories according to their global biomass yield. At present, the only emissions accounted for in most EFA is CO_2. For sequestering CO_2 emissions from fossil fuel use, ocean absorption rates of 25 and 35 per cent were included in line with other sources. Despite its limitations, this study adopts the carbon sequestration method because it is still the prevailing technology, directly reflects the current pattern of energy use, and is the most conservative estimate. It also has the advantage that it can reflect "space-saving" technologies. Nevertheless, it is mainly a calculation procedure since carbon sequestration can only be a partial solution to curb anthropogenic CO_2 emissions.

In line with the first three sustainability principles outlined in Chapter 2 [p. 42], this EF methodology can be applied to electronic products if:

- The product's (CO_2) emissions can be measured and can adequately be transformed into a corresponding area. This is linked to *principles 1* and 2 (deterioration of the ecosphere through the accumulation of substances)
- The degree to which an electronic product contributes to the deterioration of long-term productivity or threatens biodiversity (*principle* 3) can be

measured and impacts can adequately be transformed into land space (for example, through mining activities).

- A product's demand for biocapacity (its EF) can be compared with the available per capita supply, the ecological benchmark.
- Technological change can be measured, the methodology thus being responsive to change and potentially indicating trends of future product developments.
- Although the ethical sustainability dimension, *principle four*, cannot directly be addressed on a product level, applying the fair Earth share is inherently ethical by demonstrating how much of this share is used by a product.

In a first approach, the total areas corresponding to the life cycle burdens of an electronic product were aggregated into an EF, virtually ignoring time units. This, however, bears difficulties with regard to non-renewable and renewable processes and does not reflect the use of electronic products accurately. In a second step, the instantaneous rate of consumption is measured by dividing the areas from the product life cycle as they would rather occur, thus avoiding different units of measurement for non-renewable resources and allowing the modelling of time series.

CHAPTER 4: EXPLORATORY STUDY – THE ECOLOGICAL FOOTPRINT OF A PERSONAL COMPUTER

To test whether ecological footprint analysis (EFA) can be applied to an electronic product, data was used from an existing life cycle analysis (LCA) of a generic personal computer (PC) for the 1995 market [Table 11], conducted by [Atlantic Consulting & IPU, 1998] on behalf of the European Commission. The goal of that study was to identify the most significant environmental burdens of a PC, and areas for improvement. The functional unit consisted of the control unit, monitor, and keyboard. Mouse and CD ROM drive had not been included in the LCA due to data paucity. The lifetime of the PC was three years [ibid.].

Definition of generic PC for 1995 market	
200MHz CPU and cooler	Power supply
16MB EDO RAM	Mini tower cabinet
4 MB RAM PCI graphics adapter	CD-ROM drive
3 GB IDE hard disk	15" SVGA colour monitor
3.5" floppy drive	Keyboard and mouse
Power consumption Monitor and Control Unit (incl. Keyboard)	100 and 60 Watts
Lifetime	3 years (230 days or 5520 hours)
Transport distance truck / van	525 km
Disposal routes Europe	63% landfilled, 22% incineration with 75% heat recovery, 15% recycling
Recovery rates metals	Steel 97%, Al 95%, other 100%

Table 11. Generic PC data [Atlantic Consulting & IPU, 1998].

In this exploratory EF study [Frey, Harrison, Billett, 2000 a, b] a bottom-up approach was used to estimate the land space needed to appropriate the resources and emissions of a PC. Area was also used as a single indicator to make the results comparable to the current (1996) terrestrial biocapacity per capita, the ecological benchmark.

4.1. Direct land use of resource consumption

The database for direct land use (DLU) at the time of the PC study was similar to the one described in Chapter 3. However, because the methodology has been refined since, area [m^2] per mass [kg] values differed for some resources. Updated values for pig iron are higher (E-03 versus E-05) since a different data source was used and some infrastructure, such as buildings, was included. For the same reason, new values for sand and gravel, cement and clay are about one order of magnitude higher (E-04 versus E-05). For limestone, updated values include overburden and the ratio between limestone and lime (E-05 versus E-06). Updated values for hard coal are slightly lower because for reasons of uncertainty, some areas for coal processing were excluded but lowering of the groundwater table has been included. For crude petroleum, new values are also slightly lower but of the same order of magnitude (E-05). For the PC study, area values for MJ were also calculated according to benthos damage from crude oil extraction (but were not needed in the mobile phone study). Unspecified fuel was assumed to be oil, unspecified biomass was treated as wood. Former DLU values for uranium only included the directly occupied space for infrastructure and mining, hence values were lower. For natural gas, updated values are higher (E-03 versus E-06) since assumptions about damage to the benthos for gas of offshore origin have been included (the former value only contained some infrastructure). However, since all DLU values are very small, the differences do not affect the outcome significantly. Packaging for the PC was not included in this study.

4.1.1. Direct land use PC system

For non-renewable resources, ranking orders for values in [kg] were different from their corresponding values expressed as [m^2]. The majority of the first four ranks are fossil fuels since these were the highest by mass [Table 12]. In contrast to the table shown in [Frey, Harrisson, Billett, 2000b], area for biomass has not been included here. Copper is ranked highly due to its high ecological rucksack of 450 kg per kg metal [DL, 1998b], indicating a high land use for a small amount of material extracted [Frey, Harrisson, Billett, 2000a,b]. For the keyboard, the high rank of oil as a raw material in both kg and m^2 is due to the high ratio of oil (12 per cent) compared to the other PC systems (0.6 per cent for the monitor and 0.25 per cent for the control unit). This is because of the keyboard's relatively high plastic content.

PC system	Resource consumption [kg]	Direct land use [m^2]
Control Unit	1. Hard coal (fuel) 2. Lignite (fuel) 3. Crude oil (fuel) 4. Natural gas (fuel)	1. Crude oil (fuel) 2. Copper 3. Hard coal (fuel) 4. Lignite (fuel)
Monitor	1. Hard coal (fuel) 2. Lignite (fuel) 3. Natural gas (fuel) 4. Crude oil (fuel)	1. Crude oil (fuel) 2. Copper 3. Hard coal (fuel) 4. Lignite (fuel)
Keyboard	1. Hard coal (fuel) 2. Crude oil (fuel) 3. Crude oil (raw mat.) 4. Natural gas (fuel)	1. Copper 2. Crude oil (fuel) 3. Crude oil (raw mat.) 4. Hard coal (fuel)

Table 12. Ranks for non-renewable materials by mass and area

4.1.2. Direct land use distribution over life cycle

According to Atlantic Consulting & IPU [1998], resource consumption for the PC system [kg] for control unit and monitor over the life cycle is highest for the use phase, followed by manufacture and material production. For the keyboard, the sequence is in reverse order since its process energy for the use phase was allocated to the control unit [ibid.]. The keyboard also contains fewer materials than the other two PC parts [Figure 6].

In contrast, DLU from materials for control unit and monitor is highest for material extraction, followed by use phase and manufacture. Fuels of fossil and biomass origin, and also copper mainly represented these stages. For the keyboard, manufacture is second to material production and included mainly biomass fuel, crude oil for ABS production, copper and fossil fuels [Figure 7] and [Appendix B,]. If biomass (assumed as wood) is excluded, this sequence is the same but less pronounced, especially for the control unit since it contained most of the biomass (mainly fuel) in the PC system.

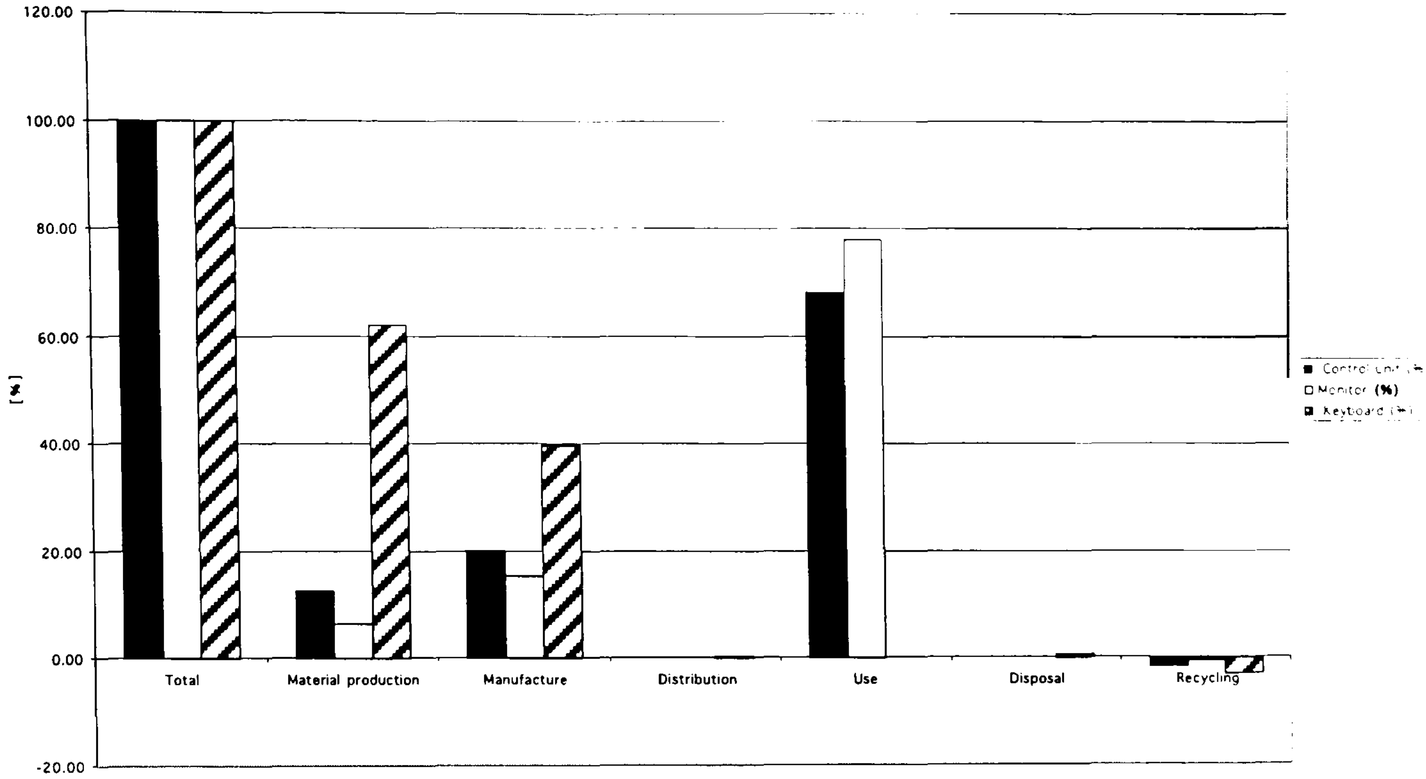

Figure 6. Life cycle of resource consumption by mass for PC system [%]

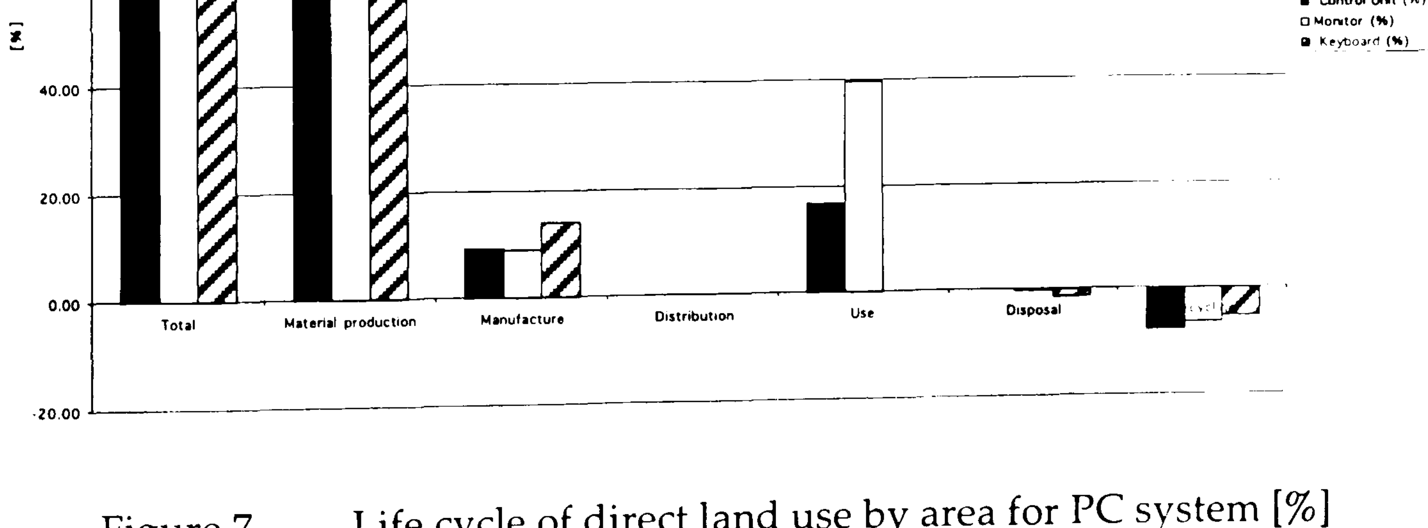

Figure 7. Life cycle of direct land use by area for PC system [%]

Total DLU for the PC system was 1.60 m^2. This is slightly higher than in [Frey, Harrisson, Billett, 2000] because area values for wood did not include humidity and an expansion ratio. DLU was highest for the control unit, followed by monitor and keyboard. For the PC system, 72 per cent of the DLU was caused by material extraction, more than 25 per cent by the use phase, and 9 per cent by manufacture. The remainder was negligible [Table 13].

PC life cycle	Control Unit [m²]	Monitor [m²]	Keyboard [m²]	Sum [m²]	PC system: [%]
Total	**0.92**	**0.64**	**0.04**	**1.60**	**100.00**
Material production	0.75	0.37	0.04	1.16	72.14
Manufacture	0.09	0.06	0.01	0.15	9.39
Distribution	0.00	0.00	0.00	0.00	0.12
Use	0.15	0.26	0.00	0.41	25.54
Disposal	0.00	0.00	0.00	0.00	-0.06
Recycling	-0.07	-0.04	0.00	-0.11	-7.12

Table 13. Total DLU over life cycle PC

4.2. Fossil energy land from carbon sequestration PC system

Since CO_2 emissions were only available for the total PC system, primary energy values had to be used to calculate the *fossil energy land* required to absorb carbon emissions [Appendix B]. In line with Wackernagel, Lewan, Borgström [1999], hydropower was calculated as 1000 GJ per hectare year (100 MJ $m^{2\ (-1)}\ yr^{-1}$). The EF component for hydropower was based on the space occupied by hydropower dams and corridors for voltage cables [ibid.]. For the mobile phone EF study [Chapter 7], CO_2 emissions were used directly to calculate the energy footprint.

4.2.1. Fossil energy land from materials energy

For the PC system, land space from materials energy amounts to around 26 m^2 of which the monitor uses 64 per cent, the control unit 17 per cent and the keyboard around 20 per cent. By area, CO_2 emissions from the material production phase account for almost 100 per cent of the life cycle. This reflects the relatively high energy costs in the extraction of non-renewable materials. However, in comparison, fossil energy land from materials energy is only 1.5 per cent of the amount required for process energy [Frey, Harrisson, Billett, 2000b], [Table 14] and [Figure 8].

Life cycle PC	**Control unit** [%]	**Monitor** [%]	**Keyboard** [%]
Total	100	100	100
Material production	99.28	99.73	99.99
Manufacture	0.19	0.04	0.01
Distribution	0.04	0.02	0.00
Use	0.48	0.21	0.00
Disposal	0.01	0.00	0.00
Recycling	0.00	0.00	0.00

Table 14. Distribution of fossil energy land [%] from materials within PC system

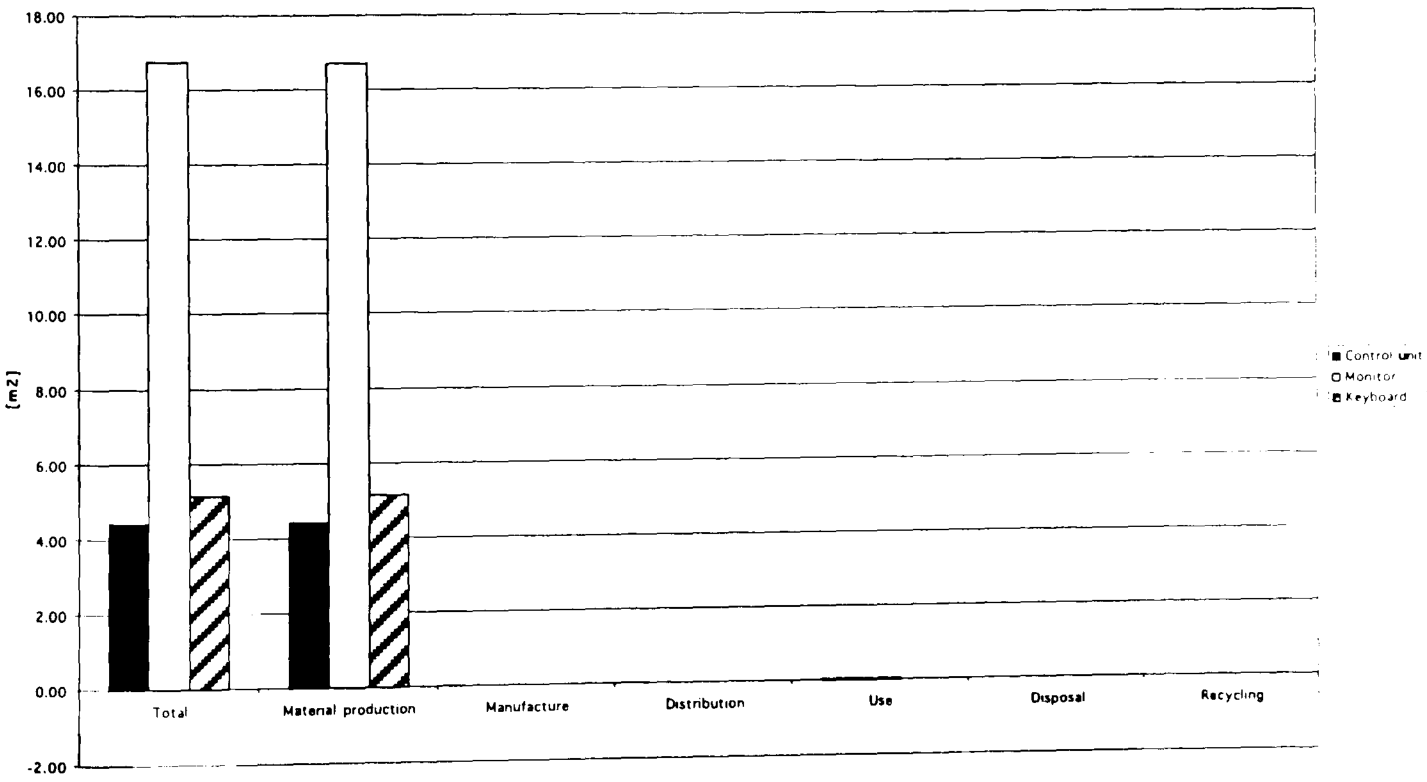

Figure 8. Fossil energy land [m^2 PC^{-1} yr] for PC from materials energy

4.2.2. Fossil energy land from process energy

Fossil energy land from process energy equates to 1757 m^2. Around 60 per cent were required by the monitor and 40 per cent by the control unit (keyboard less than 1 per cent). The use phase of monitor and control unit accounted for 80 and 72 per cent, respectively, followed by manufacture. In the keyboard, material production and manufacture required most space [Frey, Harrisson, Billett, 2000b], [Table 15] and Figure 9].

Life cycle PC	**Control unit [%]**	**Monitor [%]**	**Keyboard [%]**
Total	100.00	100.00	100.00
Material production	7.41	2.92	58.62
Manufacture	21.32	17.81	48.61
Distribution	0.08	0.08	0.79
Use	71.87	79.53	0.00
Disposal	0.19	-0.13	-5.46
Recycling	-0.88	-0.21	-2.55

Table 15. Distribution of fossil energy land [%] from processes for PC system

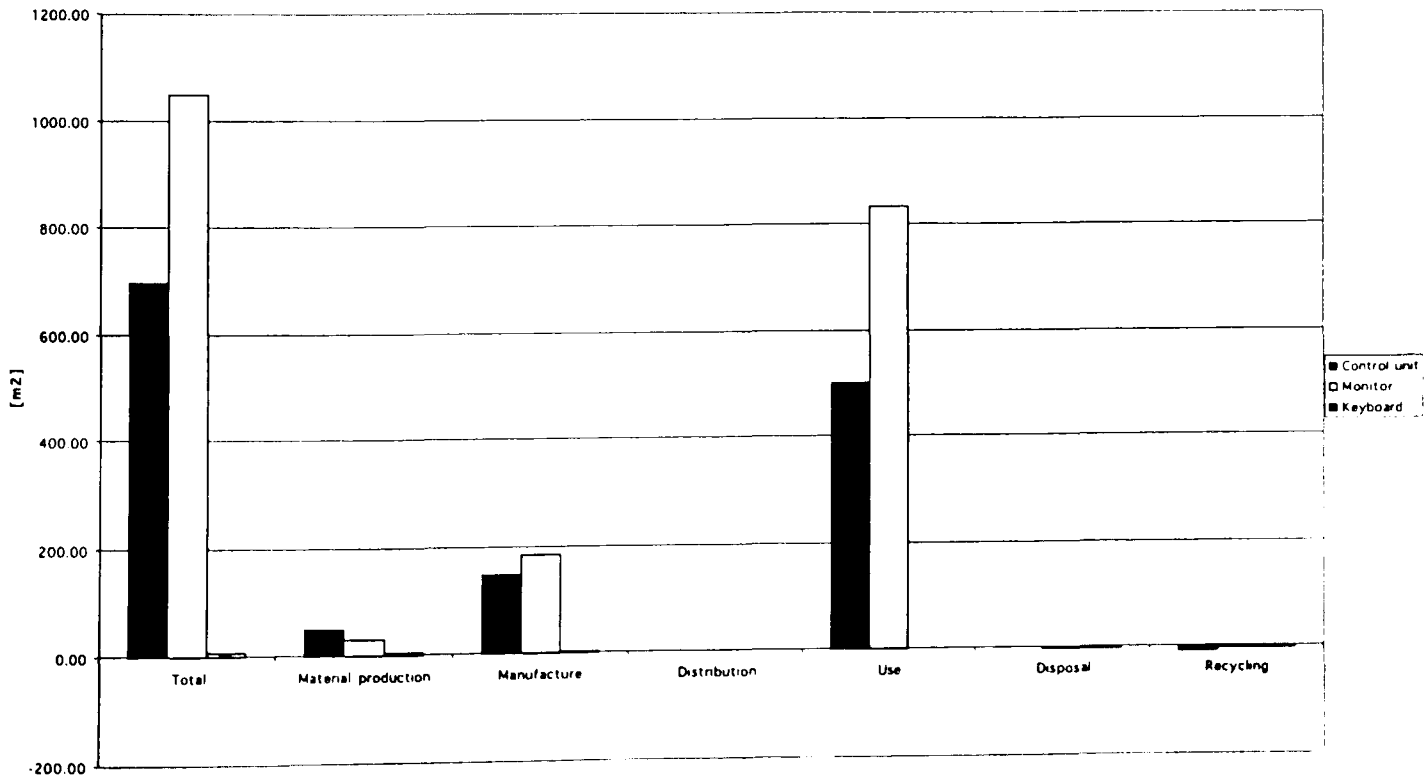

Figure 9. Fossil energy land [m^2 PC^{-1} yr] for PC from process energy

4.2.3. Fossil fuel land for total primary energy (TPE) of PC system

Overall, the use phase requires the lion's share of fossil energy land to absorb the carbon emissions of a PC, manufacture and material production only require a fraction of the use phase. Some small benefits were gained from recycling [Frey, Harrisson, Billett, 2000b], [Table 16].

Life cycle PC	**Sum** [m^2 PC^{-1} yr]	**[%]**
Total	**1783.03**	**100.00**
Material production	114.43	6.42
Manufacture	340.41	19.09
Distribution	1.42	0.08
Use	1335.89	74.92
Disposal	-0.59	-0.03
Recycling	-8.54	-0.48

Table 16. PC system: Distribution of fossil energy land for PC by area (materials and processes)

4.3. The EF of a PC

By aggregating DLU and fossil energy land to absorb carbon emissions, the total sum of land area consumed by a PC was obtained [Table 17]. This area amounts to 1785 m^2 or around 0.18 hectares (ha) during the PC's lifetime. Overall, the monitor required the largest area due to its use phase, followed by the control unit for the same reason. Direct land use consumption was highest in the control unit due to its high content of biomass. Overall, the keyboard required the least land area, which consisted mainly from expenditures for material extraction and manufacture.

Total PC system	**DLU** **[m^2 PC^{-1}]**	**Fossil energy land** **[m^2 PC^{-1} yr]**	**Total used life cycle** **[m^2 PC^{-1}]**	**PC system** **[%]**
Control Unit	0.92	702.11	703.03	39.39
Monitor	0.64	1065.91	1066.56	59.76
Keyboard	0.04	15.00	15.05	0.84
Total PC	**1.60**	**1783.03**	**1784.63** (0.18 ha)	**100.00**

Table 17. Total land area [m^2] used by a PC

After including 25 per cent carbon absorption by oceans, the total area used is reduced to around 1339 m^2 or 0.13 ha over the PC's life cycle of three years. When comparing this figure to the globally available biocapacity per capita of 1.89 ha (assuming a 12 per cent rate for biodiversity protection), a PC requires about 7 per cent of this share. Due to updated land use figures and updated global biocapacity per capita [WWF spreadsheets, 2000], this share is slightly lower than in [Frey, Harrison, Billett, 2000b].

At the time of the PC study, neither equivalence factors nor time series were included. However, equivalence factors [Table 8] should be used when comparing the EF with the globally available biocapacity. Including equivalence factors based on [WWF, 2000] and a 25 per cent carbon absorption rate by oceans, the PC's EF is 2383 m^2, or 13 to 15 per cent of the fair Earth share during it's life cycle depending on the rate for biodiversity protection (12 or 25 per cent). With a 35 per cent ocean absorption rate (used in most other EFA), the PC's share of the fair Earth share is between 11 and 13 per cent [Figure 10].

However, aggregating non-renewable DLU values and renewable processes over the life time of an electronic product is problematic [see pp. 106], although both could be presented in a disaggregated way. Taking a snapshot - the annual EF [m^2] - of this PC with a 25 per cent carbon absorption rate by oceans resulted in around 1198 m^2 for the first year and around 592 m^2 for every other year of use [for details see Chapter 7, p. 182]. This was equivalent to 6 per cent of the fair Earth share for the first year and about 3 per cent for every other year of use (7 and 4 per cent with 25 per cent biodiversity protection). With a 35 per cent ocean absorption rate, figures were around 1040 m^2 for the first year and roughly 513 m^2 for every other year (equivalent to around 6 and 3 per cent of the fair Earth share for both biodiversity protection ratios), [Appendix B][24].

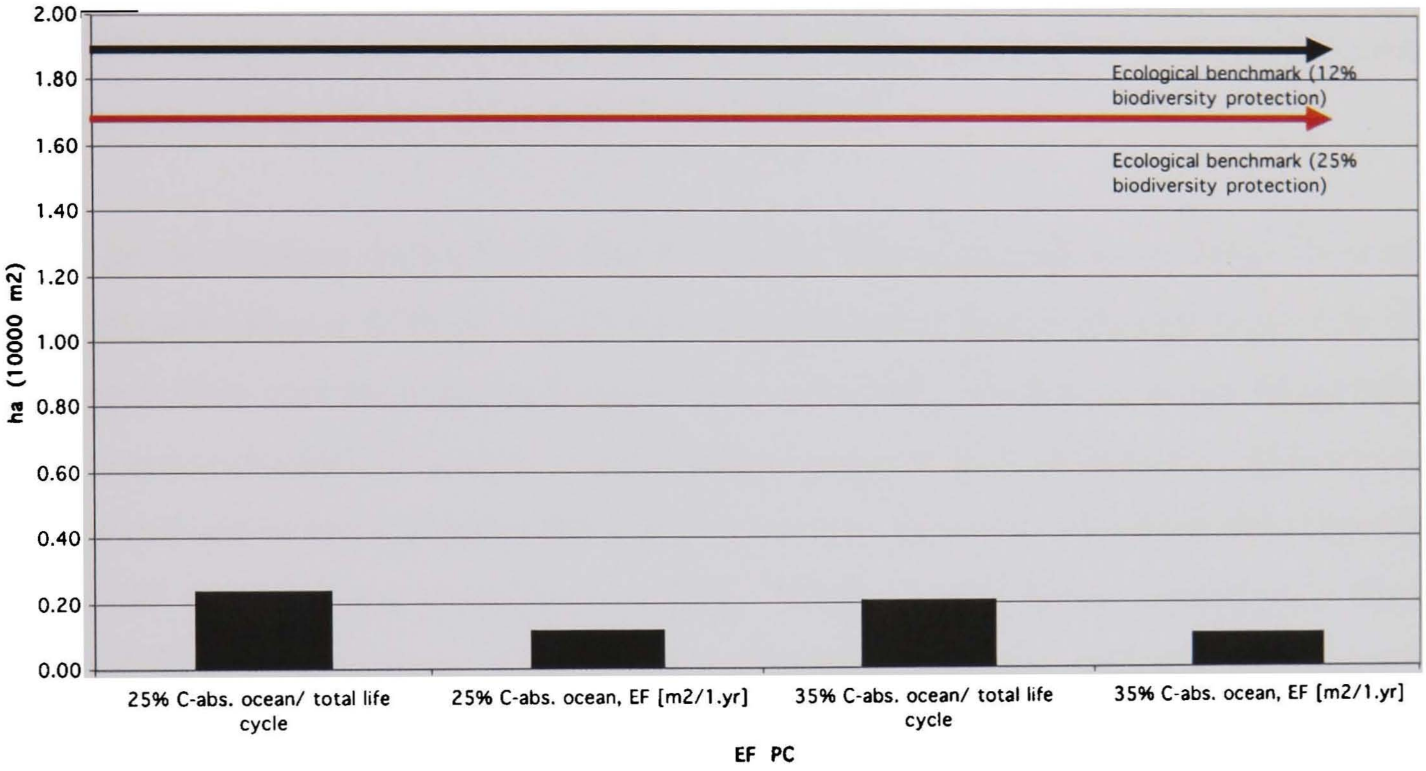

Figure 10. EF comparison PC life cycle and ecological benchmark (fair Earth share, (1996).

4.4. *Summary and discussion*

The PC under consideration required an area of 1785 m^2 or 0.18 ha during its lifetime of three years – this is much larger than its actual size and is equivalent to 7 per cent of the global per capita supply of biocapacity once 25 per cent carbon absorption by oceans have been subtracted. The PC's land use was mainly determined by its fossil fuel use, for which monitor and control unit

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[24] Another alternative is presenting the energy EF in time units related to the fair Earth share, as it has been done for a newspaper [see Wackernagel and Rees, 1996]. With an Earth share of 1.89 ha cap^{-1} and 8760 hours (hr) per year, EF PC = 594 m^2 for the year of purchase = ((8760 hr yr^{-1}) 594m^2)/18900 m^2 yr^{-1} = 275 hr = 11 days of the fair Earth share are used by the PC in the first year of use. However, it was felt that comparing areas can be easier visualised.

were the main culprits. These results are probably underestimated since land use data availability was poor (especially for some minerals with large ecological rucksacks) and not all impacts could be considered. 7 per cent is thought to be a very high share for a single electronic product, considering that people also need energy for heating, lighting, transport, and so on [Frey, Harrison, Billett, 2000a]. However, this figure did not include equivalence factors.

Small amounts of resources extracted can lead to high values in DLU and materials energy. However, materials energy only accounted for 1.5 per cent of the process energy [Frey, Harrison, Billett, 2000b].

Based on the factors included in the PC study, the required areas from DLU are insignificant (about 0.09 per cent) in comparison to fossil energy land. On the one hand, this can be expected since only mutually exclusive areas (degraded land) were included. However, calculations suggest that at least 57 E+09 tonnes of material are removed from the Earth's surface per year of which the majority (37.5E+09 tonnes) are overburden [DL, 1998]. Apart from emissions, these material flows also cause significant environmental site and off-site impacts [DL, 1999a]. Secondly, DLU figures were not available for all materials (especially precious metals) and do not contain entailing effects from mining, such as acidification, erosion, or other impacts. As such, these DLU results are only rough approximations for impacts on an area scale, and most likely underestimated [Frey, Harrison, Billett, 2000b].

After including equivalence factors, the total EF of the PC was 0.24 ha (0.2 per cent from DLU, or 4 m^2) requiring 13 to 15 per cent of the fair Earth share, depending on the biodiversity protection ratio. (11 to 13 per cent of the fair Earth share with a 35 per cent carbon absorption rate by oceans). However, this aggregation procedure does not represent the EF of a PC very accurately.

In a snapshot, however, the PC's EF was around 0.12 ha (1200 m^2) in the first year (equivalent to 6 per cent of the fair Earth share) and 0.06 ha (592 m^2) for every subsequent year of use (3 per cent of the fair Earth share). With a 35 per cent ocean absorption rate, figures were around 0.10 and 0.05 ha, equivalent to 6 and 3 per cent of the fair Earth share.

Although only an exploratory study and far from comprehensive, the results gave a first approximation of the demand for bioproductive space by a single product.

CHAPTER 5: STATISTICAL ANALYSIS

5.1. *Method*

To estimate energy requirements for certain chemical elements in a mobile phone for which no data was available (Beryllium, Be; Gallium, Ga; Indium, In; Neodymium, Nd; Samarium, Sm; Lanthanum, La), the literature was searched for a relationship between general abundance and ecological rucksack/overburden values. The underlying general assumption was that the scarcer an element, the higher the rucksack or overburden value must be and hence, its energy expenditures for mining. Abundance values for the Earth crust were taken from [Lide, 1998], rucksack or overburden values from [DL, 1998a,b] and for silver and platinum, values were taken from [Schmidt-Bleek, 1997]. (Since these multipliers to the net commodity can be either overburden or ecological rucksacks, in the following "rucksacks" will be used). Since no relation could be found by forming clusters [Appendix C] and the collected raw data was not homogenous, the logarithms of the data values were plotted, thereby obtaining a linear relationship. As a result, Antimony (Sb) was considered as an outlier because its rucksack differed by a factor E–03 to E-05 compared to the other elements in the same abundance group of <1 parts per million (ppm) per kg. Subsequently, the available pairs of abundance and rucksack values were correlated to estimate the degree of statistical association between the two variables. Since there was a strong negative correlation between abundance and rucksack data, simple linear regression analysis in *SPSS* (version 10) was used to estimate and predict multipliers for the above-mentioned "unknown" materials.

For the regression analysis it was assumed that for each rucksack individual measurements had been carried out, that they all came at random from the sampled population, and are independent from each other (that is, each material has its own population of rucksack values)[25]. In reality, however, these

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[25] According to [Zar, 1999], for each abundance value there exists a population with the same standard deviation, and for each abundance value there exists a rucksack value with a normally distributed population.

values are rough estimates only but it would have been impossible to find the real values (only by digging up these materials and measuring their rucksacks) [Figure 11].

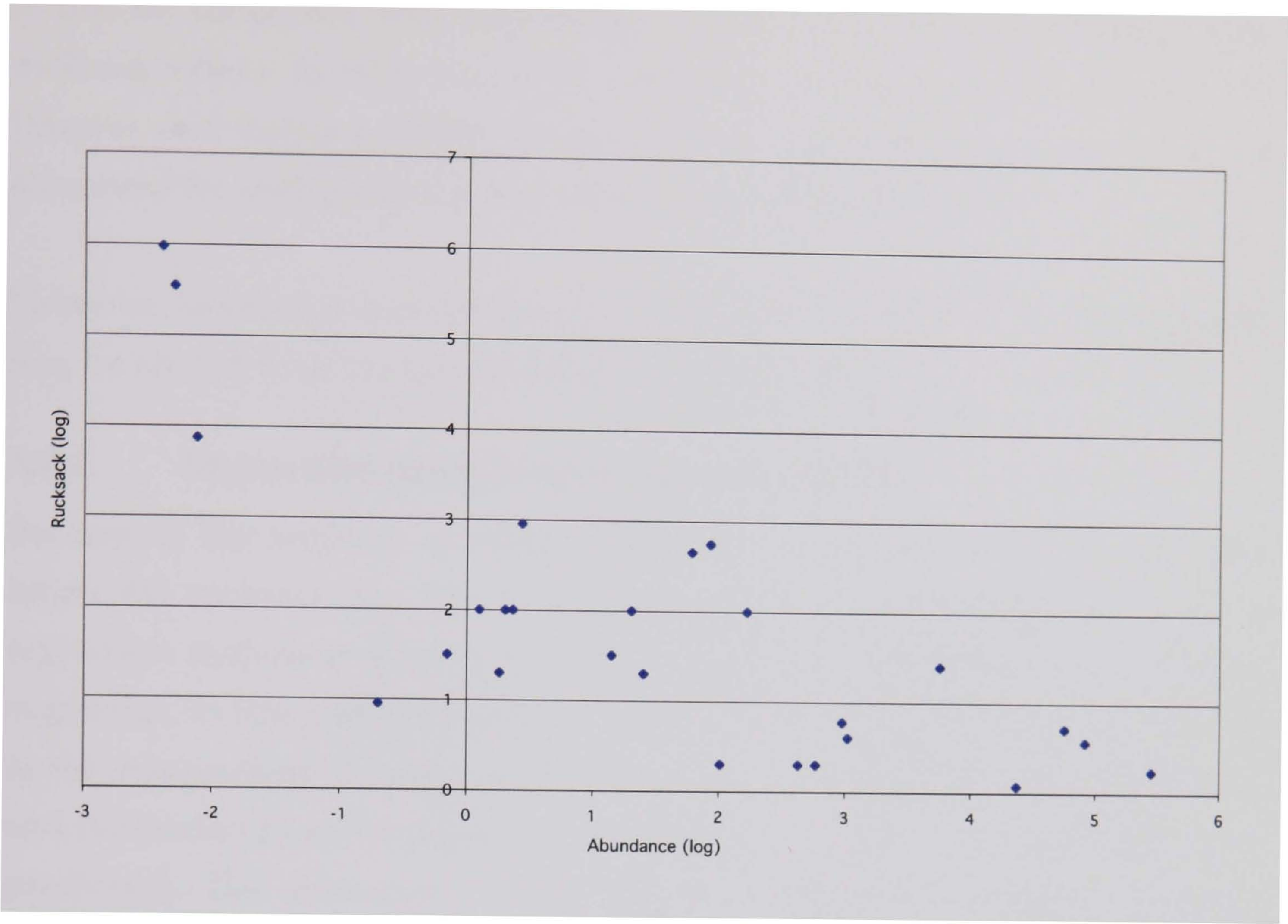

Figure 11. Scatter plot of abundance and rucksacks for minerals

5.2. *Results statistical analysis*

SPSS was used for calculating correlation coefficients and building the regression model for the known pairs of abundance and rucksack values ("non-blanks"). From this model, rucksacks were predicted for the elements Be, Ga, In, Nd, Sm, and La, including their individual 95 per cent upper and lower confidence limits (UCL/LCL). The model with the rucksacks to be predicted ("blanks") including their individual 95% UCL and LCL, was calculated in *Excel* since the available SPSS version did not have the function to calculate the individual statistics for the predicted regression values. The details from the SPSS and *Excel* calculations can be found in [Appendix C].

5.2.1. *Correlation coefficients*

For a sample size of 25 pairs, the Pearson correlation coefficient between the variables "abundance" and "rucksacks" was **r = –0.8** which is statistically significant ($p<0.005$); so was Spearman's rho for a two-tailed test[26] with $r_s = -0.7$ ($p<0.005$). Hence, the probability that there is no real underlying effect (here: no association between abundance and rucksacks) is less than one in two hundred. It can be concluded that abundance values are strongly correlated with rucksack values. In other words, by using the coefficient of determination (r^2) [Martin and Bateson, 2000], 64 per cent of the variation in rucksacks is accounted for statistically by the variation of abundance values.

However, correlation does not imply that there is causation since both variables may be related to an independent third variable [ibid.].

5.2.2. *Regression model for non-blanks in SPSS*

Because of the negative correlation between abundance and rucksacks (the larger the rucksack, the less the abundance), it was possible to carry out a regression analysis to predict rucksack values from abundance values. For the regression, in line with [Howitt and Cramer, 2000], abundance (X) was defined as the independent variable (since this is where the predictions are made from) and rucksacks (Y) as the dependent variable (since these are the rucksacks to be predicted). The abundance values (X_i) from which the required rucksack predictions (Y_i *(hat)*) were to be made were within the range of the given, observed X_i values[27].

The slope of the regression of rucksacks on abundance was **−0.58** and the intercept was **2.74**.

To test whether the regression is significant, the F-value in the analysis of variance (ANOVA table in SPSS output, Appendix C) examines whether there is really a linear relationship between the two variables by forming an F-ratio of the mean square for regression to the residual mean square [Kinnear and Gray, 2000; Zar, 1999]. Since the F-value in the ANOVA table was highly significant ($p<0.0005$) it is very unlikely that there is no linear regression relationship

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[26] Two-tailed test: No direction is specified, the prediction is simply that the scores are different [Martin and Bateson, 2000].

[27] It is generally unsafe to predict Y_i *(hat)* values for X_i values outside the observed range of X_i [Zar, 1999].

[Kinnear and Gray, 2000]. In other words, there is only a chance of one in two thousand that the relationship is not linear.

The percentage of the total variation in Y that is explained by the fitted regression can be obtained by dividing the regression sum of squares over the total sum of squares, measuring the strength of the relationship[28] [Zar, 1999]. In this example, 31 per cent of the total variation in rucksacks (Y) is explained by the fitted regression.

The t- statistic tests the probability that the population slope is zero. This means the probability of obtaining a sample slope of at least as large in absolute value as the one observed must be calculated if the null hypothesis is true. If this probability is small, it can be rejected [Norusis, 1995]. In the SPSS-coefficients table [Appendix C], the value for the t-statistic is –6.80, meaning that the sample slope is minus 6.8 standard error units below the hypothesized value of zero, according to [ibid.]. Since its significance was also very small ($p<0.0005$), there is only a very unlikely chance (one in two-thousand) that the population slope is zero – there appears to be a linear relationship between abundance and rucksacks.

Therefore, the regression equation is:

$$Y(hat)_i = (b \times X_i) + c \quad \text{(Equation 5)} \qquad \text{[Zar, 1999].}$$

Where $Y\,(hat)_i$ is the rucksack to be predicted, b is the slope, X_i is the observed abundance value, and c is the intercept.

Plotting the standardised residuals against the predicted rucksack scores[29] showed no obvious pattern. According to [Kinnear and Gray, 2000], this means that the regression assumptions of linearity and homogeneity of variance have been met.

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[28] The so-called coefficient of determination, r^2 [ibid.].

[29] Ideally, standardised residuals should be distributed normally [Kinnear and Gray, 2000].

The Kolmogorov-Smirnov statistic measures the greatest difference in cumulative probabilities across the entire range of values. A high significance value means that there is no evidence against the null hypothesis that the sample has a normal distribution [Kinnear and Gray, 2000]. The same is valid for the Shapiro Wilk statistic [Norusis, 1995]. Both significance levels for the Kolmogorov-Smirnov and Shapiro-Wilk tests (in SPSS) were not significant for the standardised residuals ($p>0.05$). Assuming normality is therefore acceptable.

5.2.3. Regression model for predicted values

Using the data from the regression model [equation 5], rucksack values were predicted for the remaining elements (the calculated statistics in *Excel* were the same as in SPSS). The general formula for 95 per cent confidence limits is [Zar, 1999]:

$$\text{confidence limit} = \text{statistic} \pm (t)\,(\text{SE of statistic}) \quad \text{(Equation 6)}$$

Where the statistic is the predicted value, *SE* is the standard error, and $t_{0.05(2),\,n-2}$ is 2.069.

The formula for calculating confidence limits for a predicted (rucksack) value Y_i for a specified (abundance) value X_i is given in [Equation 7] [ibid.].

$$(S\overline{Y}i)_1 = \sqrt{S2_{Y} \cdot X\left[1 + \frac{1}{n} + \frac{(Xi - \overline{X})2}{\sum x2}\right]} \quad \text{(Equation 7)}$$

Where $(SY_{(hat)}i)_1$ is the confidence limit for a predicted rucksack

$S^2\,Y{\cdot}X$ is the squared standard error of the estimate[30]

$\overline{X}$ is the average of the observed abundance sample

Since confidence limits were calculated for individual scores and not for the

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[30] Also called residual mean square [Zar, 1999].

mean scores, wider margins from the regression line were obtained [Figure 12].

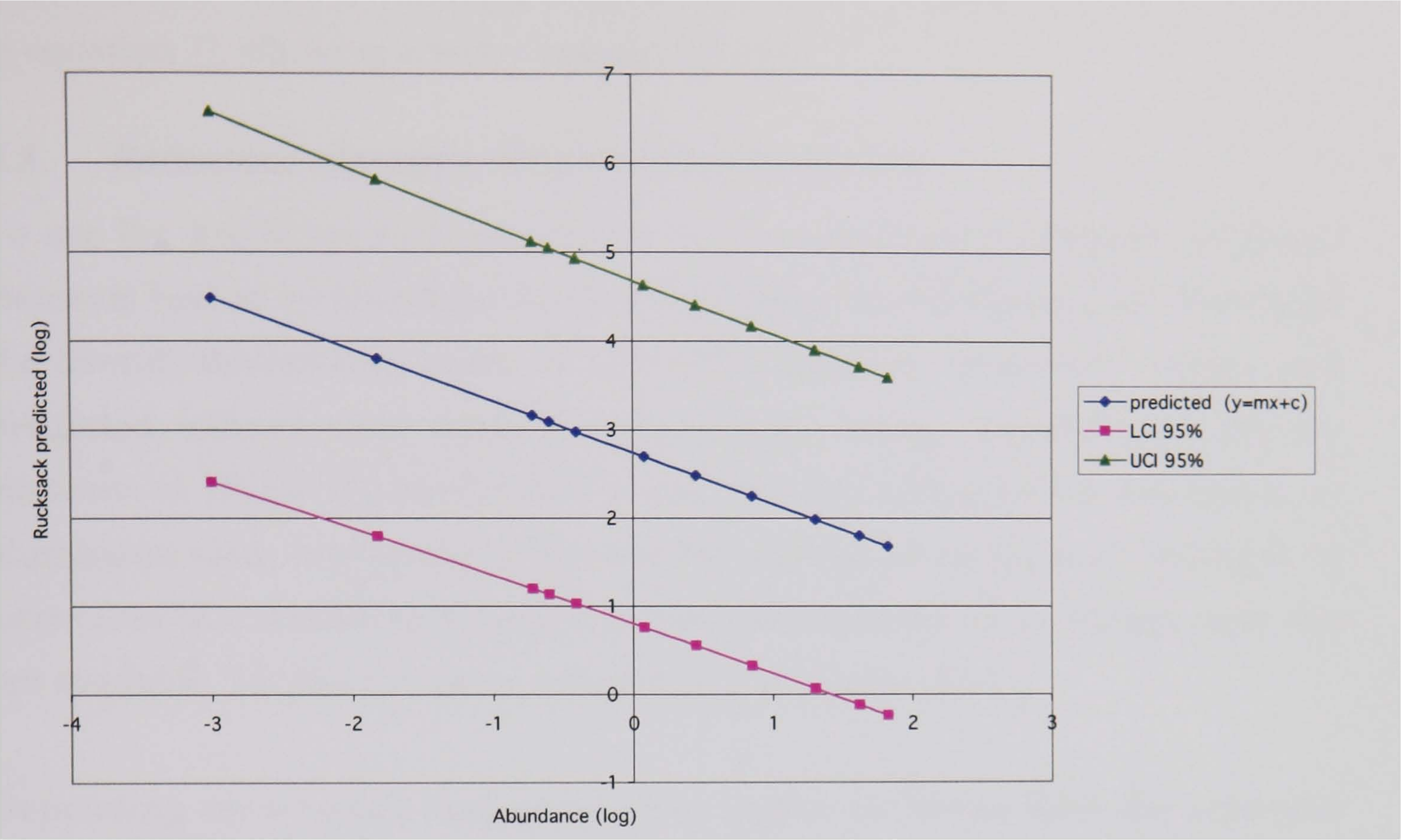
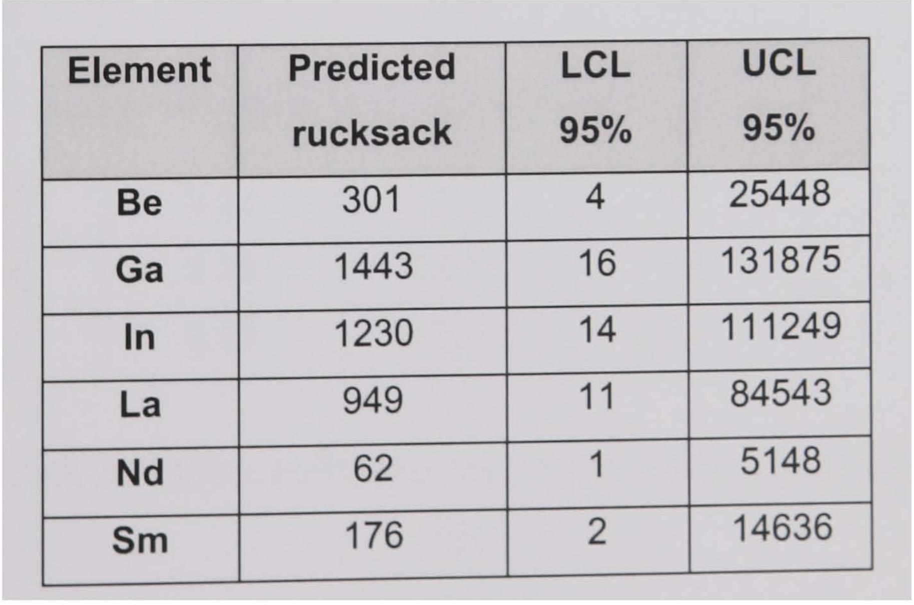


Figure 12. Predicted values (log) including their UCL and LCL

5.2.3.1. *Predicted rucksacks and their UCL / LCL*

The predicted rucksack values including their UCL and LCL were re-transformed into normal data [Table 18].



Element	Predicted rucksack	LCL 95%	UCL 95%
Be	301	4	25448
Ga	1443	16	131875
In	1230	14	111249
La	949	11	84543
Nd	62	1	5148
Sm	176	2	14636

Table 18. Predicted rucksacks for selected elements including their UCL/LCL (normal data)

The wide range between the LCL and UCL values is explained by the additional variation in an actual value rather than a mean value (denoted by 1+ in equation 7), allowing a wider margin for error.

5.3. *Reference elements for predicted rucksacks*

To use the predicted rucksack values for the subsequent analyses, reference elements had to be found for further modelling. In the absence of other data, the overall descending order of rucksacks (known "observed" values and predicted values) were used to approximate energy expenditures for the elements in [Table 18] except for Ga and Nd. Modelling of Ga was based on aluminium since it is found in bauxite, Nd was based on tin since basing it on zirconium (Zr) would have meant further assumptions as Zr energy data was not available. Tin has the same rucksack as Nd [Appendix C].

Depending on whether rucksacks were higher or lower than the reference element, the respective ore per kg ratios were calculated and used as inputs in the LCA software [Table 19]. These ratios were used as an aid to approximate energy requirements in raw material extraction.

Element [reference]	Predicted multiplier-ratio	95% LCL multiplier-ratio	95% UCL multiplier-ratio
Be [Cu]	0.67	0.008	57
Ga [Al]	392	4	3.58E+4
In [Zn]	38	0.42	3477
Nd [Sn]	0.62	0.008	51
Sm [Cu]	0.39	0.005	33
La [Ag]	0.13	0.0014	11

Table 19. Elements and their reference multiplier ratios including 95% LCL and UCL[31]

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[31] Table reads: Beryllium requires 0.67 times the amount of ore than copper as predicted, or 0.008 times more with a LCL ratio.

5.4. Summary and conclusion

In order to estimate energy requirements for certain elements present in mobile phones, a correlation between abundance and rucksack values was established. For the available sample size of 25 data pairs, a significant, strong correlation was found, suggesting that 64 per cent of the variation in rucksacks is statistically explained by the variation of abundance values (the higher the rucksack, the lower the abundance).

Simple linear regression analysis was used to estimate and predict rucksacks for six "unknown" materials. With regard to the "observed" rucksack values found in the literature, it was assumed that each material has its own population of rucksack values, and that these values come at random from the sampled population. However, in reality it would have been impossible to obtain and measure all these rucksack values. Additionally, the sample size of 25 pairs is not very large, but it was the only data available.

Further assumptions had to be made with regard to the allocation of reference elements to the previously estimated regression results. Hence, for now, these results should only be used as an aid for a first approximation and be updated once better data becomes available. However, choosing individual instead of mean confidence limits gave a wider error margin, thus covering more extreme assumptions about rucksacks. It would be interesting to compare values from the "real world", once available, with the obtained statistical estimates, and to test other variables whether closer overall relationships can be found.

CHAPTER 6: MOBILE PHONE ENERGY ANALYSIS

To calculate an ecological Footprint (EF) of a mobile phone a life cycle approach was used to obtain and structure relevant data. The study focused on total primary energy (TPE) requirements and especially CO_2 emissions during the life cycle; the latter were used as a first order approximation for waste flows in the subsequent EF analysis (EFA). As a basis, a former life cycle analysis (LCA) on a mobile phone by [Wright, 1999] was used but major changes in raw material extraction and manufacturing energy were included.

6.1. Assumptions

Due to data paucity, several assumptions about the phone's materials had to be made. Since mobile phones contain a wide range of elements, including some rare ones, extraction and production data were not easily available. To find out how much energy is required to extract an "unknown" element, the relationship between abundance and ecological rucksack values was used as described in Chapter 5. Furthermore, assumptions had to be made for the chemical composition of certain materials used in the phone and also for materials not available in the databases.

6.1.1. Statistical analysis elements

Based on the regression analysis in Chapter 5, a sensitivity analysis was conducted for six elements:

- Beryllium
- Gallium
- Indium
- Neodymium
- Samarium
- Lanthanum

The predicted rucksack values for these elements and their upper and lower confidence limits were used in the base case and the corresponding scenarios.

6.2. The life cycle energy analysis approach

To assess the ecological footprint (EF) of a mobile phone, a formal base structure was designed similar to LCA.

6.2.1.1. Goal and scope definition

To define the goal and scope of the system under study, this study followed the guidelines issued by the European Commission [EC, 1997] and SETAC Europe [1997].

The purpose of this chapter is to describe a simplified life cycle energy approach for a mobile phone to provide a basis for the subsequent EF analysis. Environmental impacts such as acidification, eutrophication or toxicity were not included as they cannot be sufficiently accounted for in EFA.

6.2.1.1.1. Functional unit

The functional unit for this analysis is the use of one mobile phone handset during its life cycle with an average consumer lifetime and an average amount of daily talk time use. This study accounts for the charger's energy consumption in standby mode, but does not account for environmental impacts associated with the main phone battery, the charger itself, any other accessories or the telecommunication network infrastructure required for using the phone. Ideally, these should have been included since they may have a significant influence on the final result. However, data availability and time constraints of this study did not allow for this.

6.2.1.1.2. System boundaries

The system boundary includes four life cycle stages of a mobile phone (cradle to grave):

- Raw materials production (including extraction data where possible)
- Parts and phone manufacture
- Use phase,
- End of life (EoL) (assuming 95 per cent of precious metals are recycled, the remainder is landfilled. No evaluation was made of the waste deposited).

The life cycle begins with the ***raw materials extraction and production*** phase. Data describing the materials and substances contained in a phone were based on information from *Nokia Mobile Phones,* including a study commissioned by *Nokia* and conducted by the *Fraunhofer Institute for Reliability and Microintegration (IZM),* Germany. The IZM study focuses on a state of the art mobile phone in 1998 (the *Nokia 6110* model) and contained a good estimation of the phone's material content. The summary list of the product content served as a basis for modelling the components of the phone using the *TEAM*-software tool. No cut-off rules were applied. The material content data used in this study described all the components in the phone. However, raw materials for the charger and battery were not included due to data paucity.

Parts and phone manufacturing includes estimates for the energy required to produce the components for the phone, and the final phone assembly. Data were used from [McLaren and Wright, 1997], a limited amount from more recently collected suppliers' data as well as the author's own investigations. These included dismantling of the phone and identification and measuring of phone parts, such as estimating the size of silicon wafer contained in integrated circuits (ICs).

Due to the limited data available from component manufacturers, the energy required to manufacture each component could not be calculated accurately. Instead, overall energy for phone manufacture was estimated by using a limited amount of data previously collected by *Nokia* for various components [in McLaren and Wright, 1997] and by scaling this data according to the quantity and size of similar component types found in the *Nokia 6110.* This study only accounts for materials remaining within the phone and estimates energy requirements in component manufacture and phone assembly. No account was taken for the process materials and substances used in component manufacture or in final product assembly.

For the phone ***use phase,*** the study used data from on an internal *Nokia* report [Ahonen, 1997, in Wright, 1999]. Energy from the use phase included the energy consumed by the phone battery and by the phone charger in stand by mode. This is an extension of the system boundary, as raw materials for these two items were not included. The study assumes an average product lifetime of 2.5 years with the phone switched on 24 hours using average daily call time. An average EU energy mix was assumed for all cases and scenarios. Energy required for the telecommunications-network was not included.

For the purpose of this study, the ***EoL phase*** was simplified by modelling only one possible option - granulation, smelting, and precious metal recovery. Average energy data from an UK pilot project and a Swedish project was used based on [Wright, 1999]. This included a 95 per cent recovery rate for the metals aluminium (Al), copper (Cu), silver (Ag), gold (Au), palladium (Pd), iron (Fe) and steel.

Transport was not included at this stage, but some available data from [ibid.] was used for the transport from first component supplier - to phone assembly - to-retail sales points, and incorporated directly into the EF-analysis. [Figure 13] shows the system diagram:

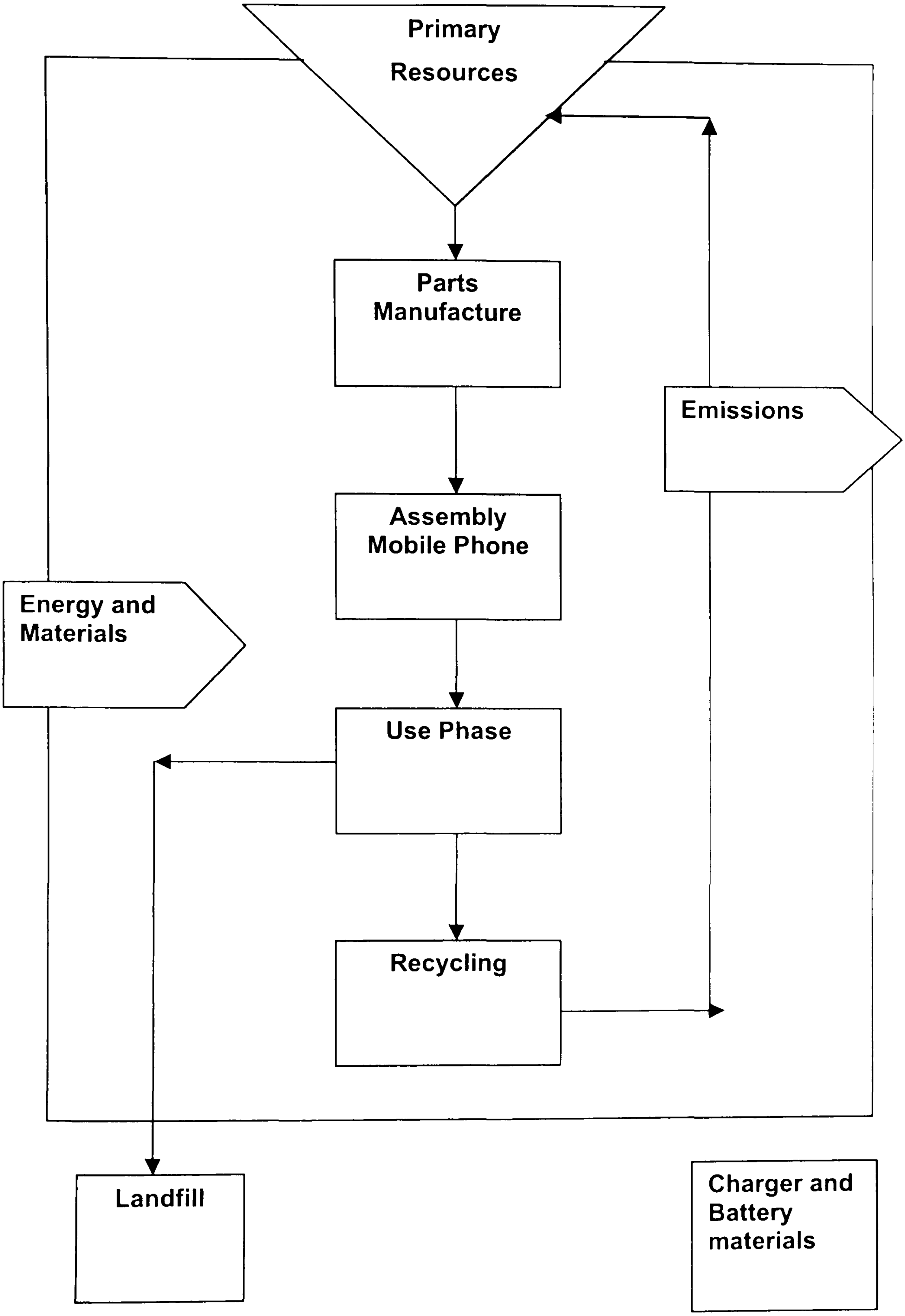


Figure 13. System diagram

6.2.1.2. Level of detail and robustness of study

In this study, the bigger picture of a mobile phone scenario was considered more relevant than a detailed environmental impact assessment. For this reason, this study focused on energy and CO_2, using the latter as a first order approximation for environmental impacts. With regard to emissions, EF analysis to date is mainly limited to CO_2 sequestration although some small regional studies have included other impacts, such as acidification or eutrophication (see Chapter 3). Unfortunately, time and scope of this study did not allow expanding further on these problems, but this is surely an area for future exploration.

Due to the data available and repeated comparison and verification of our own data with previous studies, for example McLaren and Wright [1997]; Wright, 1999] the data provided in this study can be regarded as reliable and sufficiently robust for the intended purpose.

6.2.1.3. Data sources energy analysis

The following data sources were used in this study [Table 20].

Life Cycle Stage	Data source:
Raw material extraction and production	DEAM database [Ecobilan, 1999]. Lithium: ESU, 2001
Parts and phone manufacture	IZM confidential data, Nokia confidential data, McLaren and Wright [1997]; Wright, 1999; Oiva et al., 2000; IKP Stuttgart, C. Herrmann, pers. comm. 02.07.01.
Use	Wright [1999]
End of Life	Wright [1999], Nokia confidential data.

Table 20. Data sources for energy analysis

6.2.2. Methodology energy analysis

Electronic products such as mobile phones contain a large number of different and complex components. An evaluation of electronic products may include a destructive examination or chemical analysis, depending on the product size. Both methods are not very accurate [Oiva et al., 2000], using supplier data is often the more reliable method for gathering data [McLaren, pers. comm., 11.06.02]. This study used a summarised *6110* parts list developed by IZM [Appendix D], who reduced the original full product component list (over 250 parts) to 90 different parts. IZM did this by grouping similar types of components and materials [Oiva et al., 2000]. Supply chain data was used for most of the 90 parts in the list, sourced from *Nokia* suppliers [McLaren, pers. comm., 11.06.02]. For the minority of components for which no manufacturer's information had been available, IZM had estimated package type and material contents based on previous knowledge of similar components [Oiva et al., 2000]. The weight of the mobile phone handset was 90 grams [g], containing more than 100 different materials. This reduced component list and the data sources listed in [Table 20] served as a blue print for our life cycle inventory (LCI) from which two main screening studies were developed: One with older manufacturing energy data (case A) and the other with newly updated manufacturing energy data (case B), supported by supplier's information. Both cases were also calculated with upper and lower confidence limits (UCL, LCL) from the regression analysis.

6.2.2.1. Modelling of components in LCA software

The first meeting between *Nokia* and *Brunel* University took place in August 2000 to make assumptions about how the different materials and chemicals could be incorporated into a life cycle inventory, and about weight ratios of different material compounds. [Appendix D] contains the details about the first assumptions made.

Attempts were made to build models for each of the 90 different components in the phone using *TEAM 3.0* software. Data were not available for all materials. [Table 21] shows approximations for the materials to be used in the component models. The assumptions made in this section are not too critical since the final result appears to be relatively insensitive to these values.

Material:	**Approximation in *TEAM* software** (st.a. = Statistical analysis, RS = rucksack)
Beryllium	Derived from copper (st.a.), treated as 69% of Cu production.
Ag-epoxy	From silver and epoxy resin production (78/22%)
$AgPd_{44}$	From silver and palladium (56 / 44%)
Barium Titanate	Assumed that made from $BaO+TiO_2$.
Cobaltosic Oxide (Co_3O_4):	O_2 production not included, treated as Co.
Chromium	Treated as Fe since mined from chrome-iron $FeCr_2O_4$ [Lide, 1998]. Also used for Cr_2O_3.
Cu and CuO	CuO as Cu
Gallium Arsenide (GaAs):	As derived from Cobalt (same RS as arsenic trioxide) and was treated as such. Ga found in bauxite, hence treated as aluminium. Composition GaAs was 48/52% based on molecular weight.
GaP	As above, but with phosphoric acid as proxy for P. Chemical composition assumed 54/43% based on molecular weight.
Magnesium Oxide (MgO)	As Mg
Indium (In) Tin (Sn) Oxide (ITO)	In treated as alloy of Zn (In commercially obtained from Zn materials) and Sn was used for tin oxide (Sn 35%). Zn was multiplied with factor 38 based on regression analysis.
Manganese oxide, Manganese Dioxide (MnO, MnO_2)	Treated as Mn.

Niobium, Tantalum, and Neodymium	Nb and Ta treated as Sn due to same RS values [100, from D&L, 1998]. Nd was based on 60% of Sn ore based on st.a.
Lithium	700 MJ/kg. ETHZ, Int. J. LCA 6 (1) 2001.
$LiNbO_3$	8.5% Li_2O (as Li) and 91.5% NbO_3 (as Sn)
$LiTaO_3$	1/2 Li_2O_3 + 1/2 Ta_2O_3. Li / Ta 10.3 / 89.7%.
PZT	$ZrTiO_4$ (Zirconium Titanate). As Zr was not available in DEAM, Si (as SiO_2) was used since both are present in zircon ($SiZrO_4$) and sand. SiO_2+TiO_2 (for ZrO_2, baddeleyite) → $SiTiO_4$ (for $ZrTiO_4$).
Ruthenium Dioxide (RuO_2)	Platinum group metal (PGM), treated as Platinum. Mining step not included in DEAM.
Sodium (Na)	Treated as NaCl (Na not available)
Antimony Trioxide (Sb_2O_3)	Treated as Lead (mined with lead ores).
Si production	Treated as SiO_2
Tin bronze	Treated as Sn
Epoxy FR (+GF)	40% glass fibre, 60% epoxy (supplier's information)
Polybutylene (PB)	Treated as PP.
Acrylic resin	As Methyl Methacrylate, since acrylic resins (AR) are formed by polymerisation of monomers / derivatives (esters / amides) of acrylic acids / alpha-methacrylic acids. AR include polymethylacrylate and acrylic rubbers [Larousse, 1995].
Bismaleimid Triazin (BT)	Plastic. Treated as Nylon.

PVAL (Polyvinyl alcohol)	PVAL: polymer prepared from polyvinyl acetates [Merck, 1960]. Treated as Polypropylene.
Polymer	Treated as PP.
E-glass and glass	As glass fibres.
Ferrites	Treated as Fe.
Ceramics ($LaTiO_4$)	La was based on Ag (13%) based on st.a. $2AgO+TiO_2 \rightarrow Ag_2TiO_4$ (only Ag available in database). 75.6% AgO / 24.4% TiO_2.
Diethylene Glycol	Propylene glycol
PAI	Polyamide / -imide. Treated as PA
Polymer, Al-coated	Assumed to have 1% Al coating

Table 21. Approximations materials for energy analysis

6.2.2.2. Raw materials production

For raw materials production, all 90 different component types from the IZM list were incorporated into separate modules using *TEAM* software. All chemical compounds that the parts consist of were included according to their mass and the assumptions made. Unfortunately, the mining step for some raw materials was not available in the software, such as for nickel and the platinum group metals (PGM) platinum and palladium. Although the mass of these materials amount to only 0.5 per cent of the total phone weight of 90 g, the mining step may be significant for the PGM with large rucksacks. Hence, energy requirements for components containing these materials will be underestimated. Also, raw materials for the battery and charger were not included, which leads to some underestimation [details Appendix D, TEAM system description].

6.2.2.3. Parts and phone manufacture

Since energy values were not available for most components, an overall approximation had to be made. The internal parts and components of the phone were manufactured in many different countries. This was accounted for by assuming an average energy mix of these countries (US, Europe, Hong-

Kong, Japan, Chinese Taipei, and Korea) according to some of the component labels. From new supplier's information on chip manufacture, this study also accounts for 21 per cent natural gas. This mix was applied to both case A and B (Wright assumed that all manufacturing energy was electricity due to limited data availability at that time - Wright, 2001, pers. comm.), because it was assumed that gas was also used at the time of Wright's study. These 21 percent may be an overestimate, as it refers mainly to Gallium Arsenide (GaAs) and Silicon (Si) chip and to printed wiring board (PWB) production. However, as these parts are very energy intensive to produce and accounted for most of the energy used in this stage, it was felt that this approach is justified until further data are available.

For case B, an overall manufacturing energy value of 104.9 MJ was calculated. After several unsuccessful attempts to count and identify the different components mounted on the boards and comparing these with the previous data, the current figure was calculated from supplier's information for PWB, information on Si and GaAs chips, and [McLaren and Wright, 1997]. Interestingly, if the energy for all the processes in the PWB (about 20 to 30 different stages, including chemical baths, heating, lighting etc. is included [Nokia, pers. comm., 27.06.01), the energy value to produce one PWB is raised to an order of magnitude of 1000. Ideally, this data should be included, however, since data quality was not very reliable it was left out. The net energy values for PWB were verified with IKP Stuttgart [details Appendix D]. For phone assembly, cases A and B included 9 MJ electricity [industrial average; Wright, 1999] with a European mix.

6.2.2.4. Use phase

For the use phase, energy values in Wright [1999, based on internal Nokia report by Ahonen, 1997] were retained, using an average European electricity mix. The use phase was based on an average product lifetime of 2.5 years (from purchase of product until its disposal). Energy consumption of the phone was based on the energy storage capacity of the battery, and the energy consumption per charge was based on minimum efficiency of fast chargers in 1997. Charging time for a typical battery was given as one hour, standby time between 30 and 100 hours, and talking time between one and three hours.

Based on a Finnish network operator, a typical user in 1996 used the phone 400 times a year for 850 minutes, therefore each call lasting just above 2 minutes. Assuming that the user received the same amount of calls, the use time amounted to 1700 minutes per year. The typical phone in 1997 was charged for 305 hours during its lifetime, resulting in 14.75 MJ per phone-life [Wright, 1999]. Because of its significance, stand-by energy consumption of the charger (1.3 W) was also included with 40.4 MJ per year (101 MJ per life time) based on the assumption that the device is used for 122 hours per year and left on stand-by for the remaining time. This results in a total energy consumption during use of **115.75 MJ** per phone life with the charger plugged in 24 hours a day [Wright, 1999].

This value might be overestimated to date due to better energy efficiencies in mobile phones. Rough data from the *Ericsson* environmental report [Ericsson, 1999] suggests that the decrease in energy consumption (expressed in litres of gasoline) during use for an "average mobile phone subscriber" per year between the time blocks 1991 to 1997 and 1996 to 1999 was approximately 31%. After finishing this analysis, newer charger consumption data became available for chargers sold from 2000 – 2001. These have a stand-by energy consumption of only 0.4 W [McLaren, pers. comm., Nov. 01]. Assuming the same communication patterns, some "back of the envelope" calculations were included at the end of this analysis.

6.2.2.5. End of life

For the end of life (EoL) scenario, an avoided energy approach was used. This means that the avoided energy by recycling a metal is equal to the energy that would have been required to mine and produce the same quantity of a metal. The result shows the overall benefit or loss for this step, which is calculated by subtracting the direct burdens from the avoided burdens.

For outlining the EoL step, an average energy consumption was used for the recycling of phones in Sweden and the UK, based on [Wright, 1999] (data for granulation, smelting, (precious) metal processing). For the UK, this included recovery and granulation of phones in the UK, followed by bulking and despatching to a smelter/refinery in Canada where the granulate was further processed. 95 per cent of Cu, Au, Ag and 85 per cent of Pd was recovered. The total burden of the UK scenario amounted to 15.1 MJ per phone (collection and recycling including transport) before subtracting the avoided burdens. This figure was very high due to an inefficient collection system during the ECTEL UK industry pilot scheme [Wright, 1999]. In contrast to the UK pilot project, the granulation, smelting and metal recovery for the Swedish scenario took place within the country. After granulation with steel and recovery of aluminium, the smelter process was similar to the UK [ibid.]. [Wright, 1999] further assumed the same metal recovery yields for Au, Ag, and Cu. The total burden for the Swedish scenario was given as 0.4 MJ per phone. Although taking the average energy burdens is hypothetical, this approach was regarded fit for the purpose of outlining a possible EoL step. The average total energy costs from recycling in the UK and in Sweden were equally divided over the metals to be recycled (Al, Au, Ag, Pd, Cu, Fe, steel). Fuel for recycling was assumed to be natural gas and lignite, based on [Ecobilan, 1999].

6.3. Energy analysis of phone

Both old and new data series, including their upper (UCL) and lower confidence limits (LCL), were analysed by their life cycle total primary energy (TPE) requirements and CO_2 emissions [Appendix D].

[Table 22] lists the differences between the new cases A and B in comparison to Wright [1999]. Case A and B have both been updated with regard to raw material extraction and production, and phone manufacture/assembly. The EoL stage was simplified for the purpose of this study. For technical reasons, transport data were only included in the footprint calculations. Case B contains the updated manufacturing energy.

The respective UCL and LCL scenarios, which only affect the raw material phases of case A and B, are discussed as of section [6.3.1.2.2].

Life cycle	Wright [1999] Energy/MJ	**Case A** **Energy/MJ**	**Case B** **Energy/MJ**
Raw material extraction	24.77	New calc.: BC 18.21, LCL 18.08, UCL 29.68	As in A
Phone manufacture and assembly	125.52 10.5	125.52 9.00 Update also uses energy mix Asia /US/ Europe and 21% natural gas in manufacture.	104.90 9.00 Updated manufacturing energy with same energy mix as in A.
Use	115.75 (charger and battery), no raw material extraction	Retained	As in A
End of life (EoL)	UK and Sweden EoL scenario (15.1+0.4 w/o avoided burdens)	Average UK and Sweden	As in A
Transport	30.47	(only included in EF)	As in A

Table 22. Overview differences between cases A and B

6.3.1.1. Energy life cycle analysis and carbon emissions CASE A

For base case (BC) A, total primary energy (TPE) requirements were 682.4 MJ for the whole life cycle of a mobile phone, 18.2 MJ for raw material extraction, 331.5MJ for parts and phone manufacture, 340.4 MJ for the use phase, and a net benefit of -7.7 MJ from recycling of metals.

The TPE diagram shows that the production of raw materials has the lowest impact in terms of energy (3 per cent) and there is a net benefit from the recycling of metals (-1 per cent). However, energy needed for raw material extraction may be underestimated due to limited data and because battery and charger where not included. Use of the phone and manufacture of its components require most of the total primary energy (50 and 49 per cent) [Figure 14].

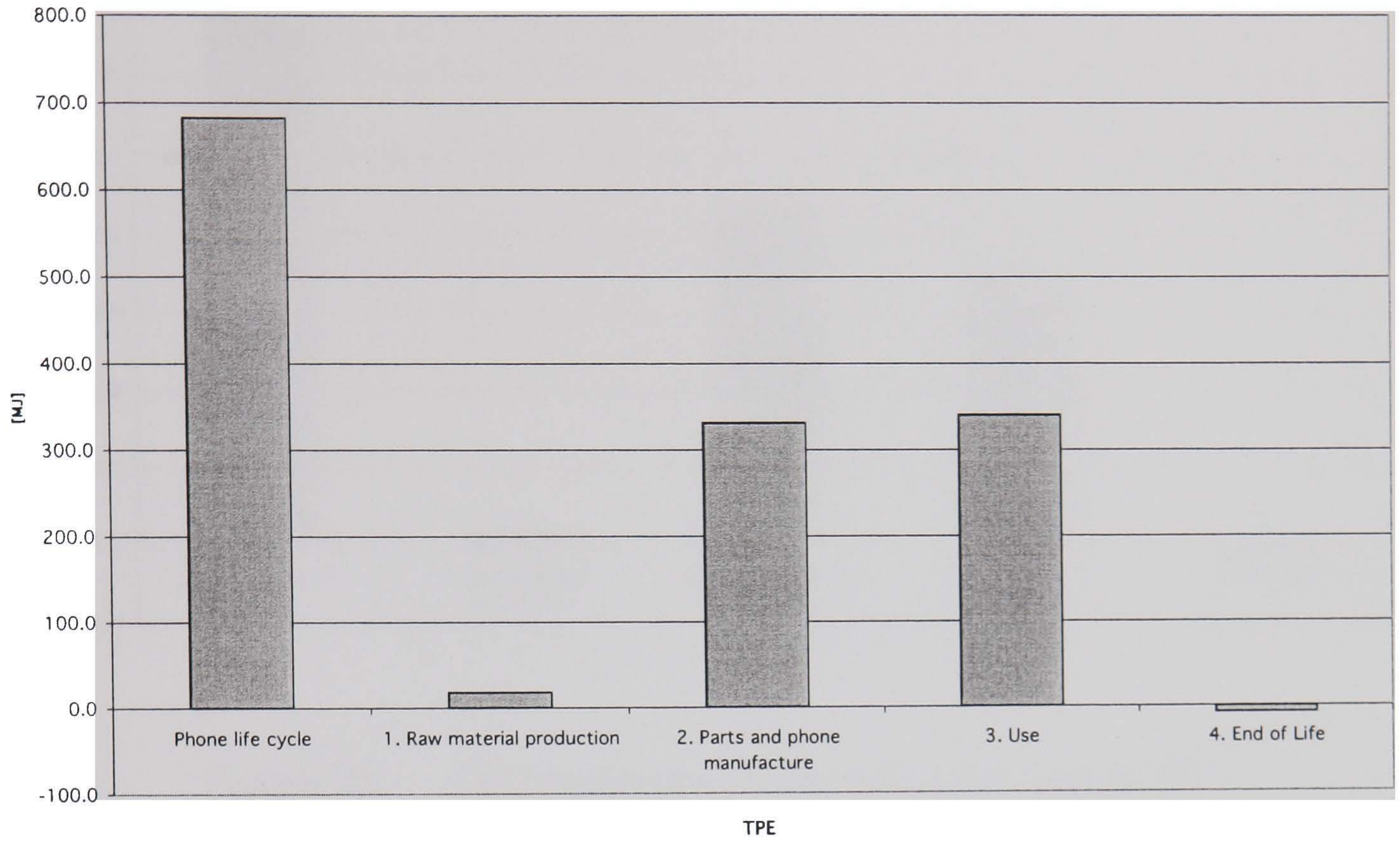


Figure 14. TPE phone life cycle case A (BC)

With regard to CO_2 emissions, values for the overall phone life cycle are 39218.4 grams [g] of CO_2, where 988.2 g are from raw material extraction, 21715.0 g from manufacture, 16954.2 g from the use phase, and -438.9 g were gained from EoL [Figure 15].

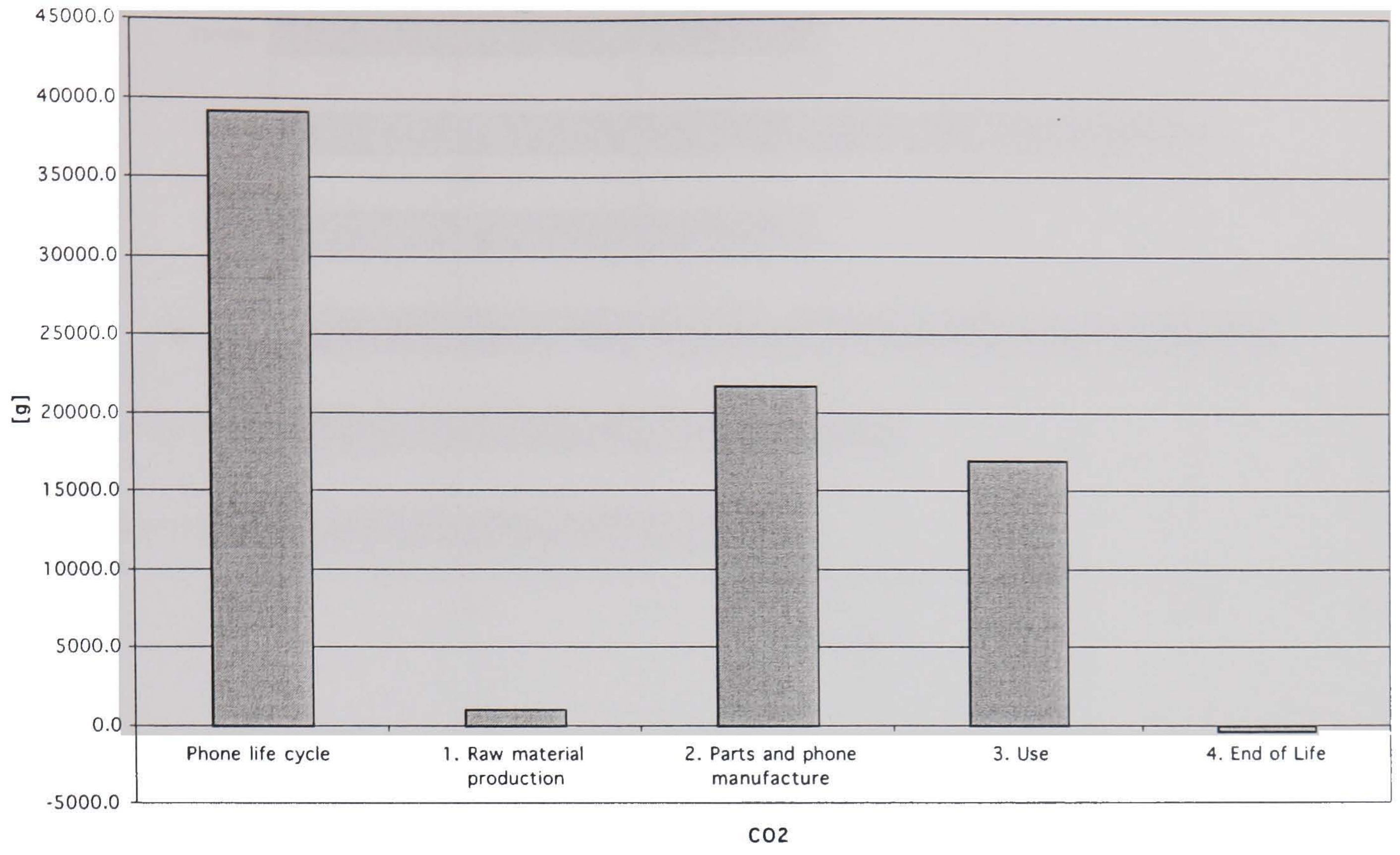


Figure 15. CO_2 emissions phone life cycle case A, BC

Raw material production contributes the least amount of CO_2 (3 per cent) but phone manufacture (55 per cent) outweighs the use phase (43 per cent) by 12 per cent. This reflects the different energy mixes as component manufacture takes place in different parts of the world, mainly Asia and the US. Hong-Kong, for example, uses more than 98 per cent coal, Europe only around 22 per cent [Figure 16], calculated from the *DEAM* database [Ecobilan 1999]. In the model it was assumed that the required energy for phone and parts manufacture is shared equally between the different energy systems. EoL emissions reflected –1 per cent.

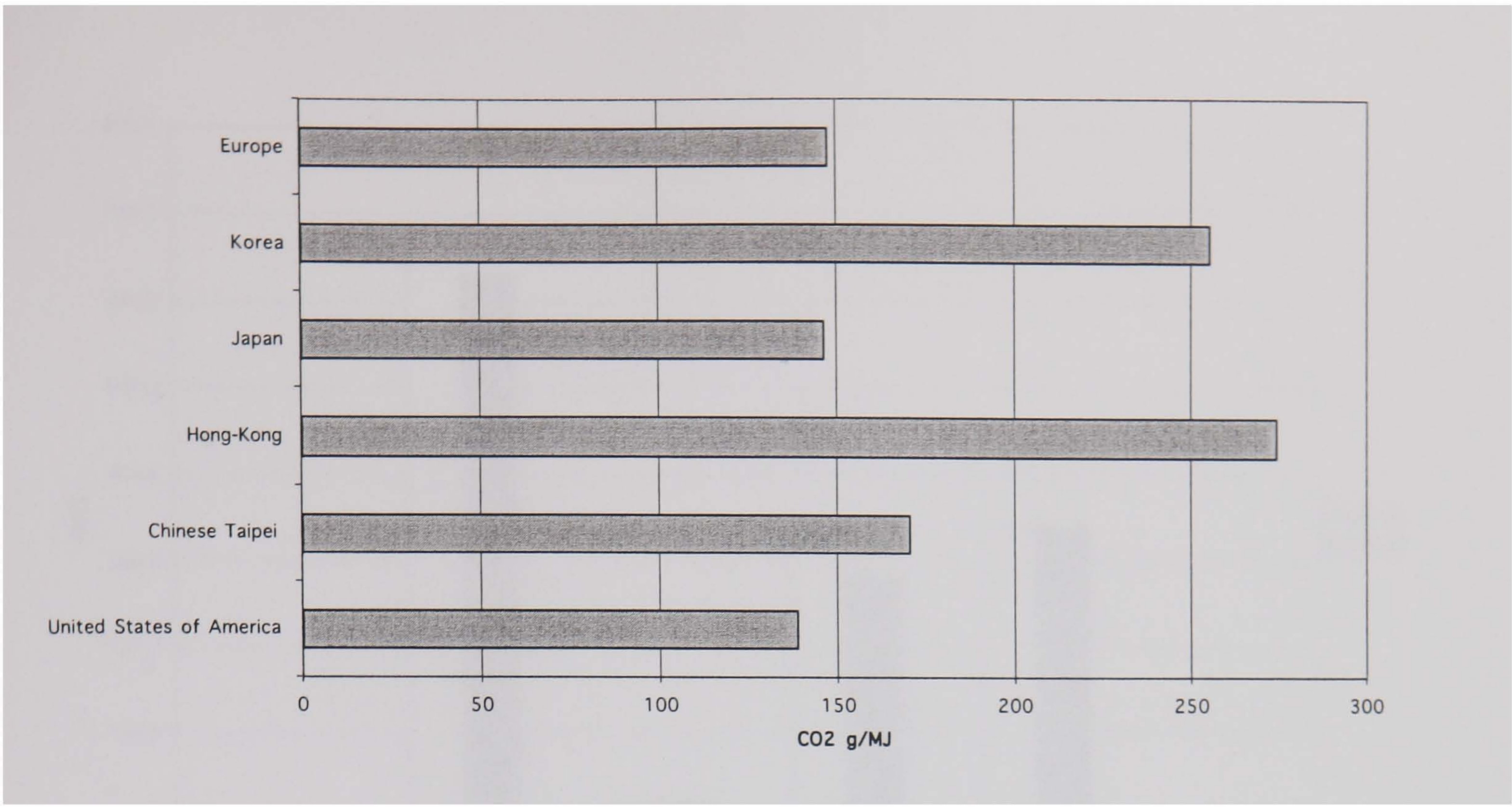


Figure 16. CO_2 emissions [g] for different countries per MJ electricity produced, based on [Ecobilan, 1999]

6.3.1.2. *Energy life cycle analysis and carbon emissions CASE B*

Case B is only different from case A through the updated manufacturing stage, resulting in 632.3 MJ TPE for the overall phone life cycle, of which 18.2 MJ are from raw material extraction, 281.4 MJ from parts and phone manufacture, 340.4 from use, and -7.7 MJ savings from EoL. This equals 3 per cent for raw material extraction, parts and phone manufacture 45 per cent, use phase 54 per cent, and a net benefit from metals recycling of -1 per cent. The total reductions in TPE from case A resulted in 50.1 MJ (632.3 MJ versus 682.4 MJ) due to the updated manufacture stage. Amounts of CO_2 were 35868.3 g in total, with 988.2 g for extraction, 18364.1g for manufacture, 16954.2 for use, and - 438.9 from EoL. This reflects 3 per cent, 51 per cent, 47 per cent, and -1 per cent. [Figure 17] and [Figure 18] compare TPE and CO_2 emissions for base cases A and B. [Table 23] summarises the results.

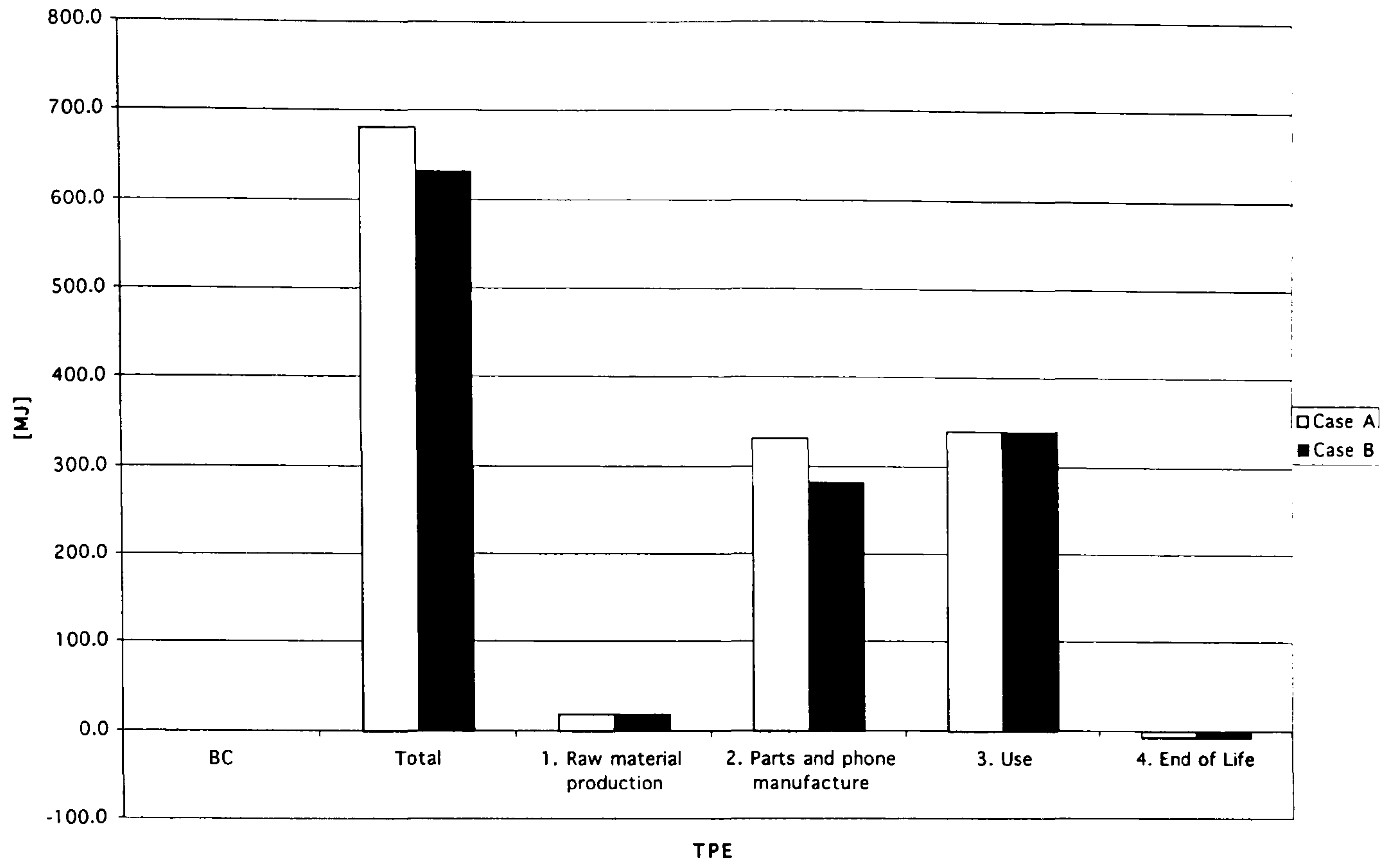


Figure 17. Diagram TPE for base cases A and B

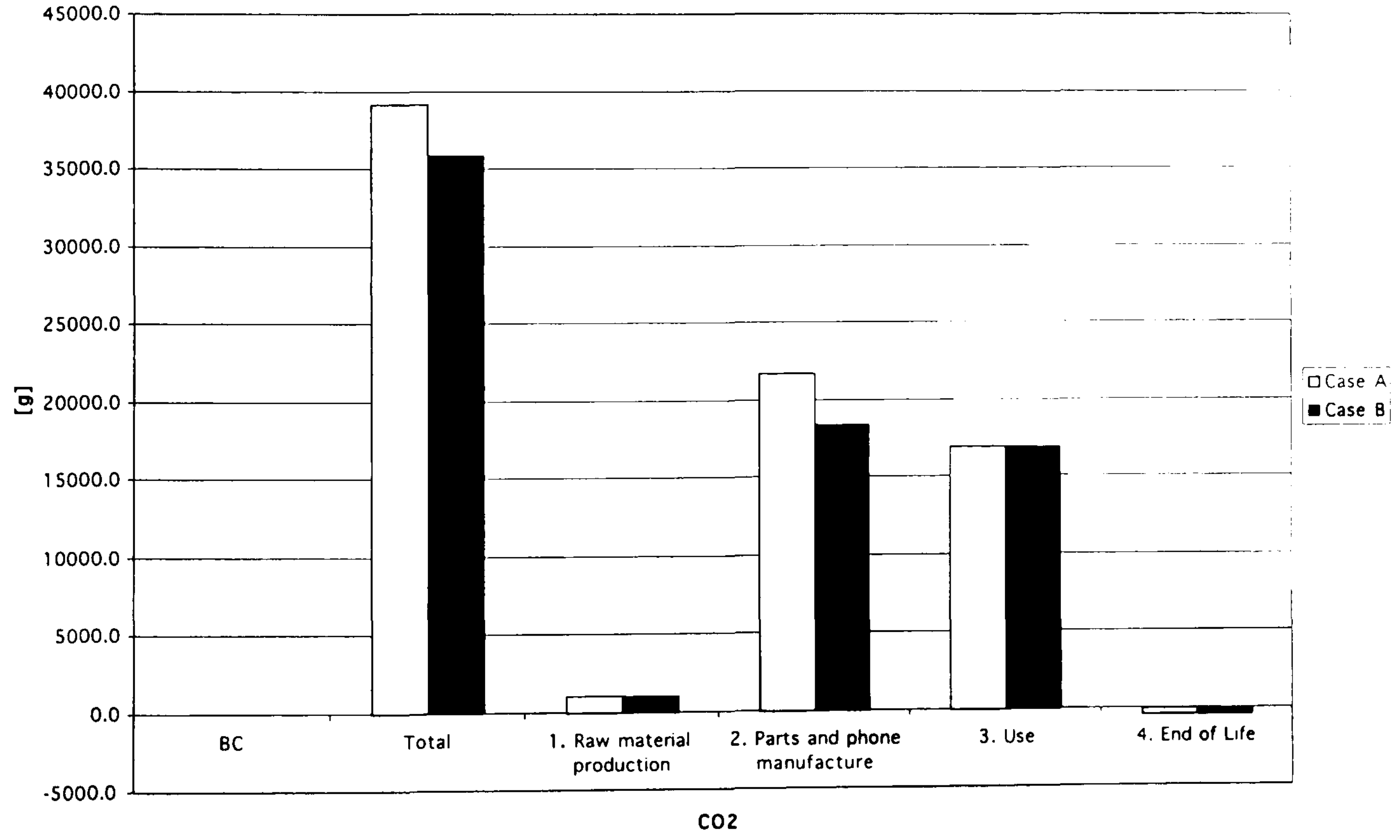


Figure 18. Diagram CO_2 for base cases A and B

Life cycle phases	Case A TPE/MJ	Case B TPE/MJ	Case A CO_2/g	Case B CO_2/g
Total	682.4	632.3	39218.4	35868.3
Raw mat.	18.2	18.2	988.2	988.2
Manufact.	331.5	281.4	21715.0	18364.9
Use	340.4	340.4	16954.2	16954.2
EoL	-7.7	-7.7	-438.9	-438.9

Table 23. Comparison TPE and CO_2 emissions base cases A and B

6.3.1.2.1. Phone components and their CO_2 emissions from raw material extraction

Because raw material extraction was designed in the same way for both cases, the different phone components were only assessed for case B. This had to be accomplished manually in *Excel* spreadsheets. [Figure 19] shows the general CO_2 emissions in [g] from materials in the phone for the BC scenario. Au, Pd, RuO_2, ABS, $AgPd_{44}$, Cu and Ag are the main CO_2 emitters in the phone.

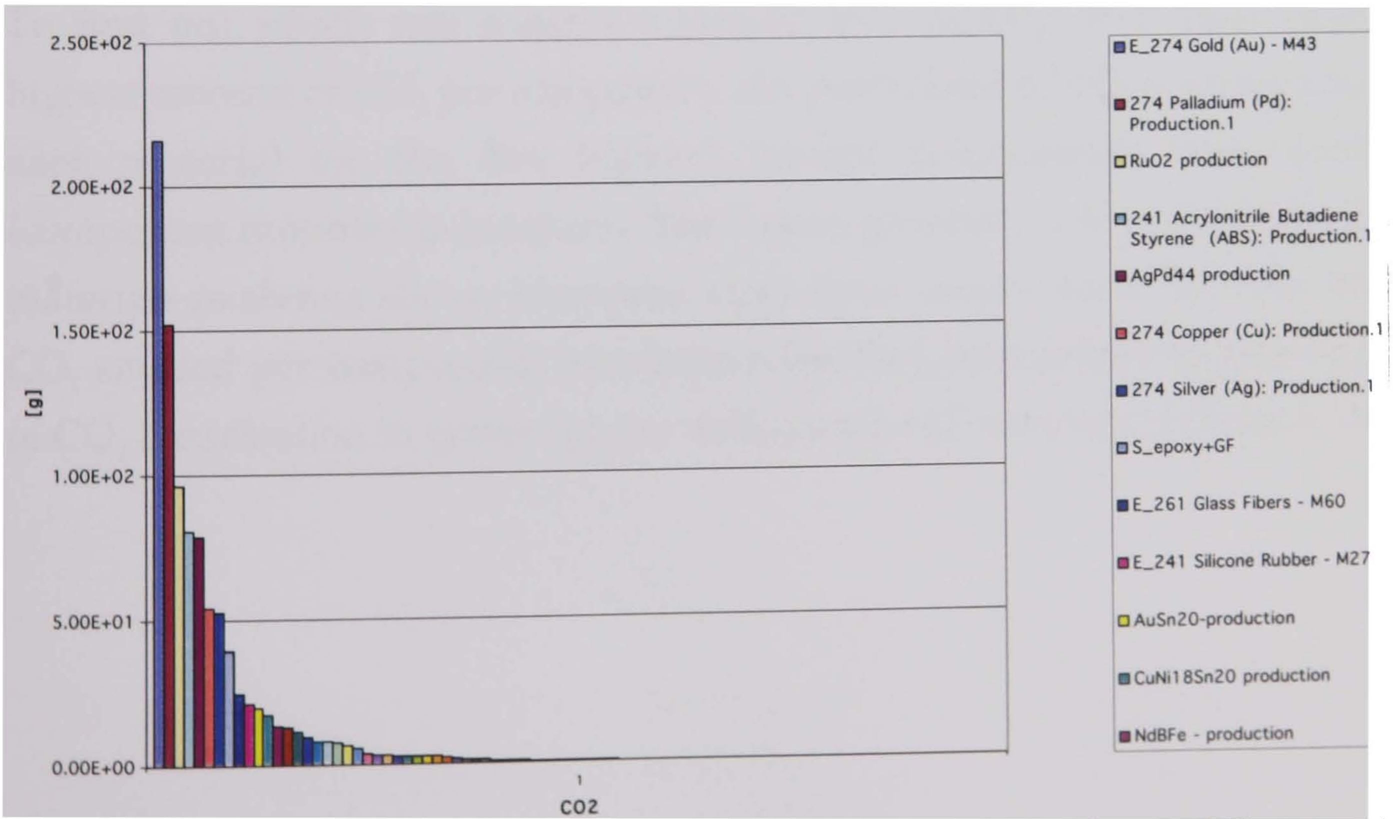


Figure 19. CO_2 [g] from raw materials extraction in phone, BC scenario

From the 90 different components that were assessed in this study [details in Appendix D] the components with the highest overall CO_2 emissions were ranked in descending order [Figure 20].

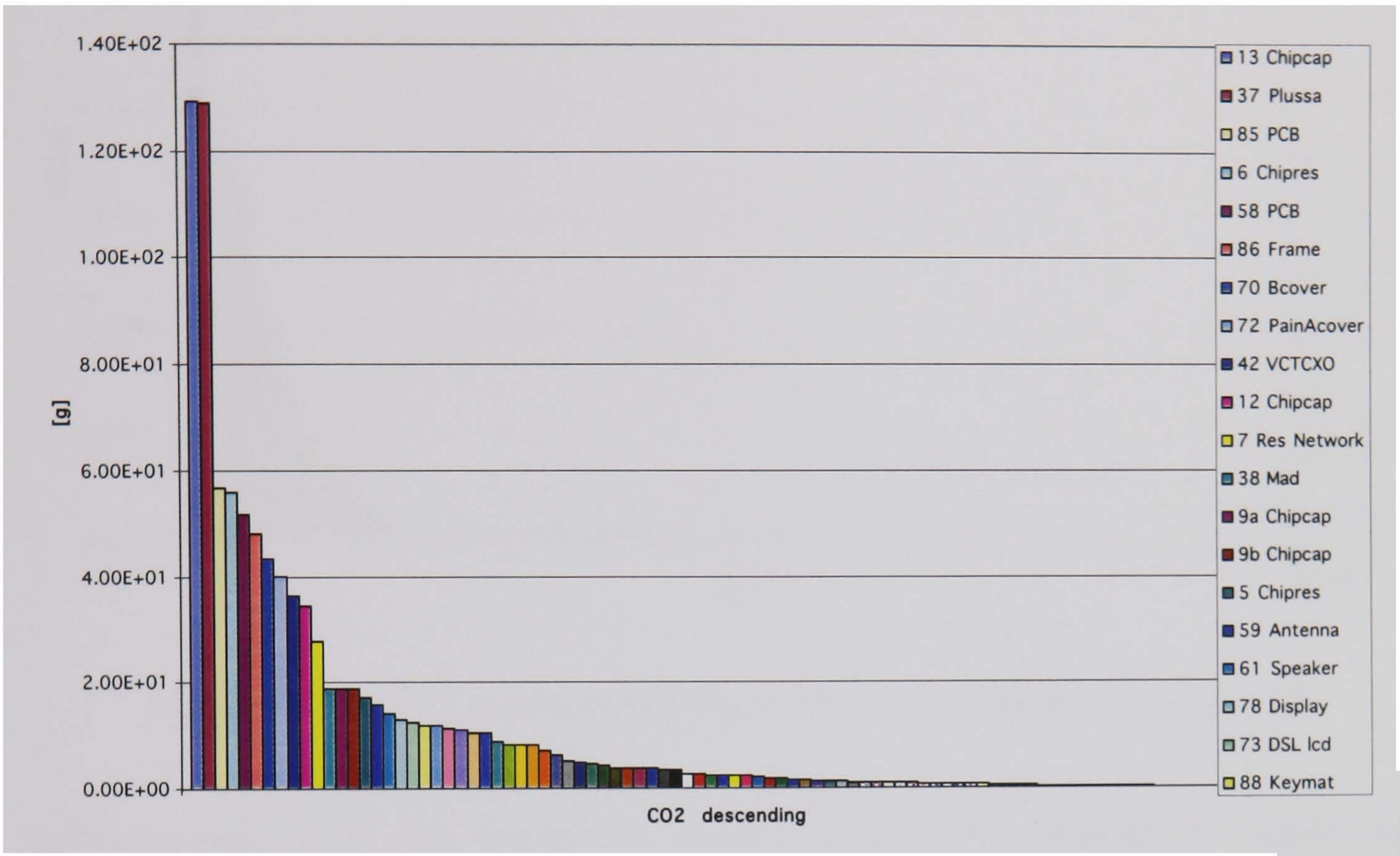


Figure 20. CO_2 emissions [g] from phone parts, BC scenario

To find out which raw materials caused this ranking and contributed the highest amount of CO_2 per component, the percentage of CO_2 contribution from each material for the five highest ranked components was calculated (component numbers in brackets). The results generally reflect the high energy-materials as shown above. However, since these results show the total mass of CO_2 emitted per component, emissions were then normalised to give an order of CO_2 contribution in grams [g] per milligram [mg] component [Figure 21].

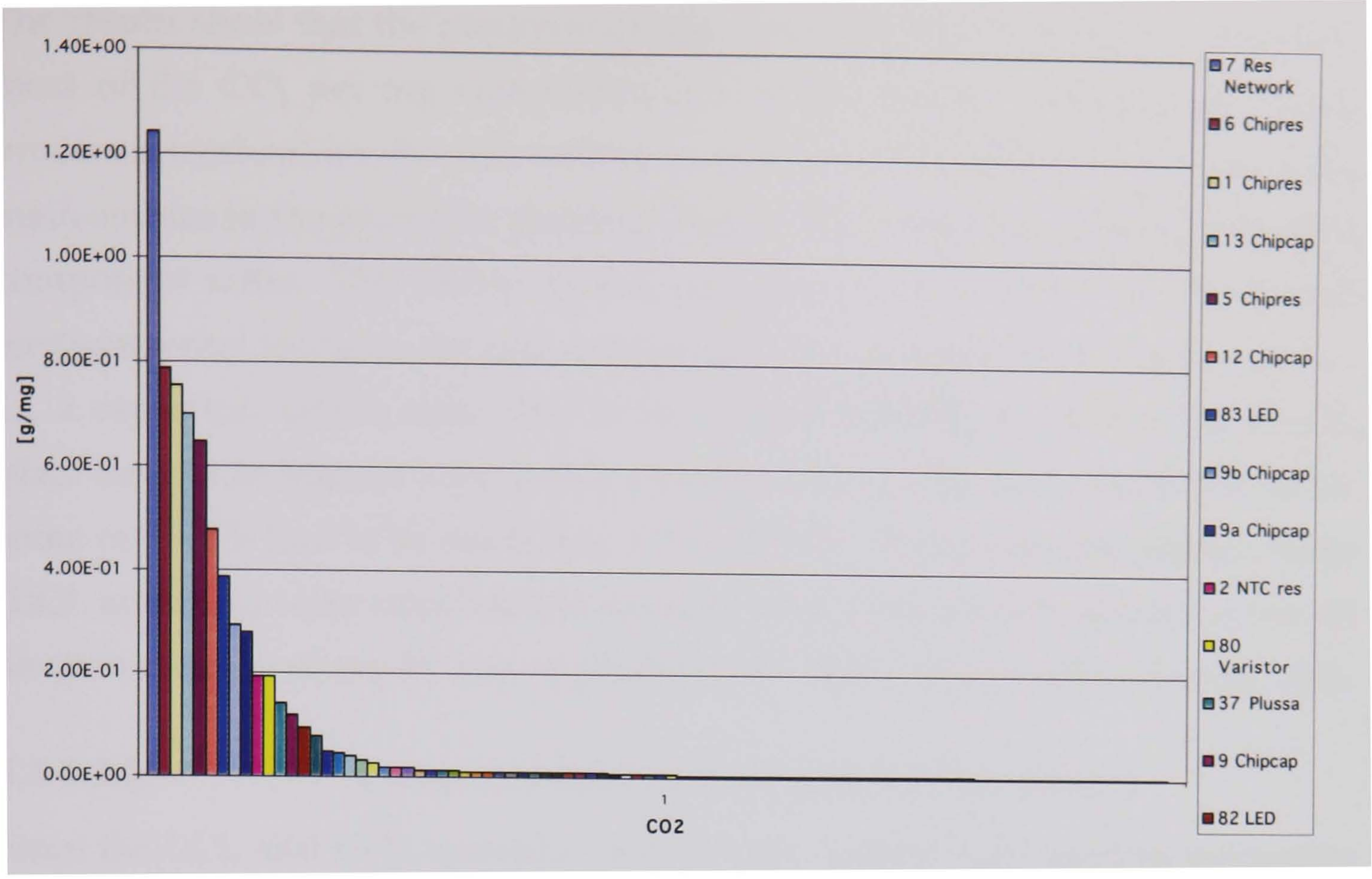
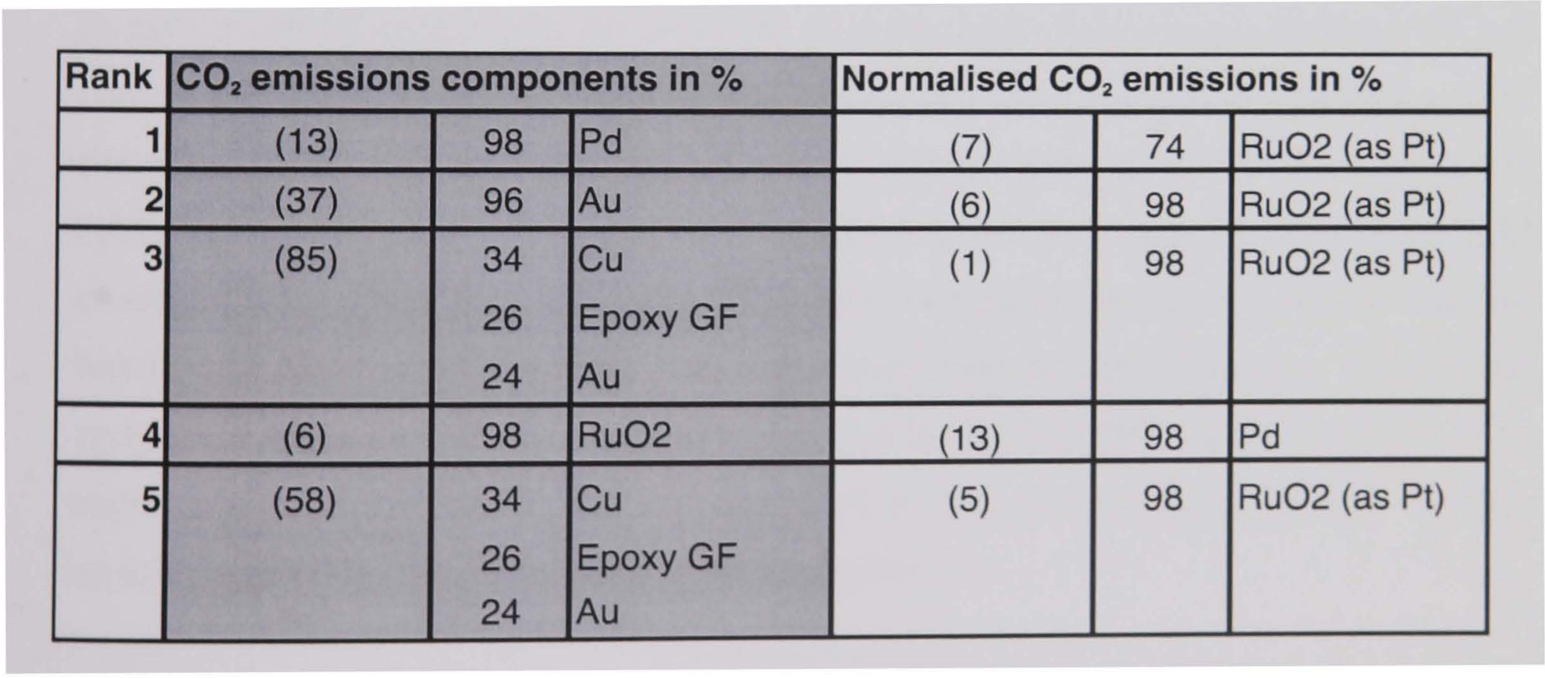


Figure 21. CO_2 emissions [g] per [mg] component (normalised)

Subsequently, the raw materials which caused this change in ranks and contributed to the highest amount of CO_2 per mg component for the BC were calculated [Table 24], [Appendix D].



Rank	CO_2 emissions components in %			Normalised CO_2 emissions in %		
1	(13)	98	Pd	(7)	74	RuO2 (as Pt)
2	(37)	96	Au	(6)	98	RuO2 (as Pt)
3	(85)	34	Cu	(1)	98	RuO2 (as Pt)
		26	Epoxy GF			
		24	Au			
4	(6)	98	RuO2	(13)	98	Pd
5	(58)	34	Cu	(5)	98	RuO2 (as Pt)
		26	Epoxy GF			
		24	Au			

Table 24. Comparison CO_2 emissions components [g/component] and in [g/mg component], BC scenario (values are rounded).[32]

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[32] Table reads: For component number 13 in the first rank, 98% of the CO_2 emissions were caused by Palladium.

The results show that the platinum group metals (PGM) Ru and Pd contributed most of the CO_2 per mg component due to the energy intensive extraction processes (ruthenium, Ru was treated as platinum, Pt). Although gold was the main emitter in the phone by material [Figure 19], it does not appear in the first component ranks. This shows that small amounts of material can have high environmental impacts per unit component. For example, component number 13, a capacitor, which came first in the overall ranking, is now in the fourth place despite its highest overall CO_2 emissions. However, since assumptions for some materials had to be made [pp. 124 and 130], 95 per cent confidence limits (UCL and LCL) were calculated to examine which impact both scenarios would have on the overall result, and on phone parts. This will be explored on [p. 160].

6.3.1.2.2. *Lower confidence limit scenario for case A*

Since the LCL and UCL scenarios would only change raw material extraction and hence, overall results, only these two life cycle phases were mentioned in the following sections followed by the percentage distribution over the total life cycle. A summary of all values is shown in [Table 29] and [Table 30].

TPE values for LCL were 682.3MJ for the phone life cycle in total and 18.1 MJ for raw material extraction. For the total life cycle this is equivalent to 3 per cent in raw material extraction, 49 per cent in parts and phone manufacture, 50 per cent in the use phase and -1 per cent for EoL. For CO_2, values are 39210.3 g over the whole life cycle and 980.1 g for raw material extraction. For the whole life cycle the distribution is 2, 55, 43 and -1 per cent, respectively. Due to only slight changes in raw material extraction, the distribution of energy requirements has hardly changed from the base case. In comparison to the base case, the overall reduction over the phone life cycle was just 0.1MJ for TPE and 8.1 g CO_2. This represents a decrease of just 0.7 per cent in TPE and of 0.8 per cent in CO_2 emissions between raw material phases [Table 25].

Case A	**BC** **TPE/MJ**	**LCL** **TPE/MJ**	**BC** **CO_2/g**	**LCL** **CO_2/g**
Total	682.4	682.3	39218.4	39210.3
Raw materials	**18.2**	**18.1**	**988.2**	**980.1**

Table 25. Case A: Comparison TPE and CO_2 between LCL and BC

6.3.1.2.3. Upper confidence limit scenario for case A

TPE values for the upper confidence intervals (UCL) were 693.9 MJ for the overall phone life cycle and 29.7 MJ for raw material production. This reflects 4, 48, 49 and –1 percent for the total life cycle. For CO_2 the values are 39915.5g for the whole life cycle and1685.2 g for raw material extraction, reflecting 4, 54. 42, and –1 percent. In comparison with the base case, overall TPE has increased by 11.5 MJ, or 697.1 g CO_2, equivalent to 1.7 and 1.8 percent [Table 26].

Case A	**BC** **TPE/MJ**	**UCL** **TPE/MJ**	**BC** **CO_2/g**	**UCL** **CO_2/g**
Total	682.4	693.9	39218.4	39915.5
Raw materials	**18.2**	**29.7**	**988.2**	**1685.2**

Table 26. Case A: Comparison TPE and CO_2 between BC and UCL

However, the differences between the ***raw material*** stages are much more pronounced. Whereas TPE and CO_2 savings in the LCL scenario are only 0.7 per cent compared to the BC, the UCL scenario requires 63 per cent more TPE than the BC and even 70.5 per cent more for CO_2 [Figure 22] and [Figure 23]. This shows that if the UCL in raw materials are true, they could influence the energy requirements significantly and probably also reflect costs (which were not available).

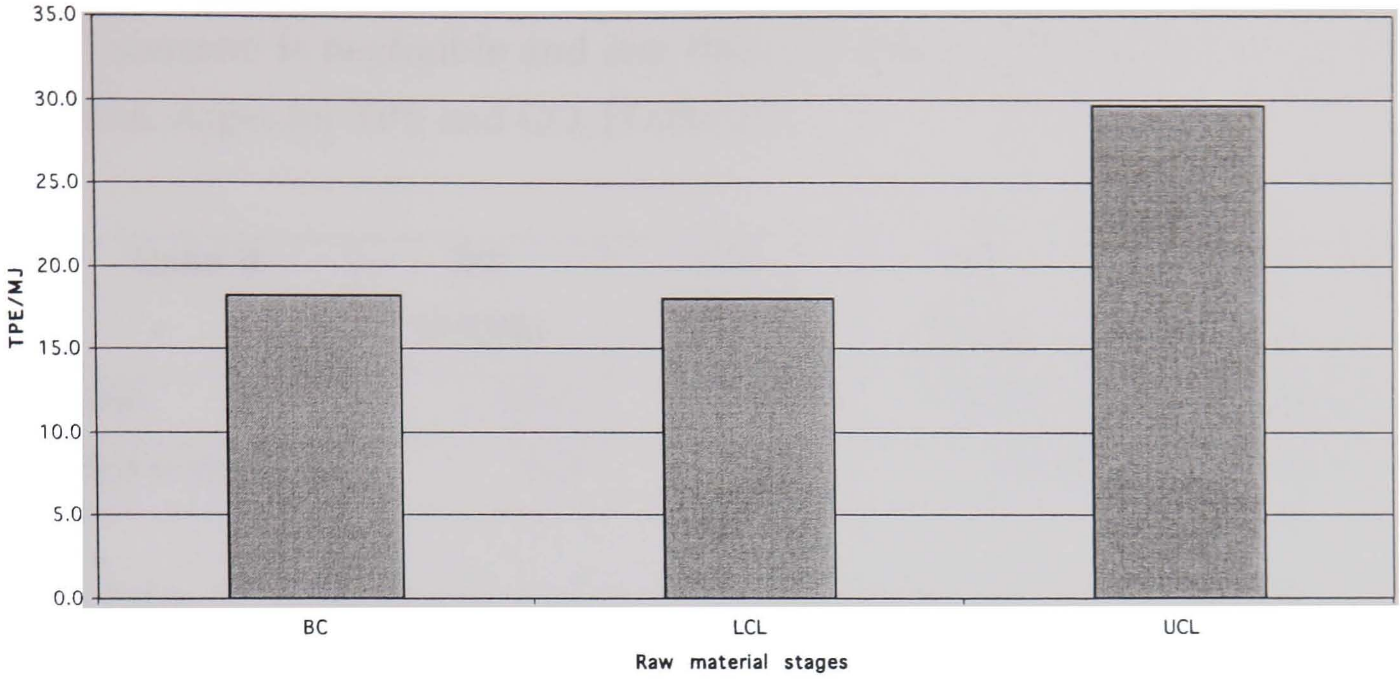


Figure 22. TPE in raw material production case A, BC, LCL and UCL.

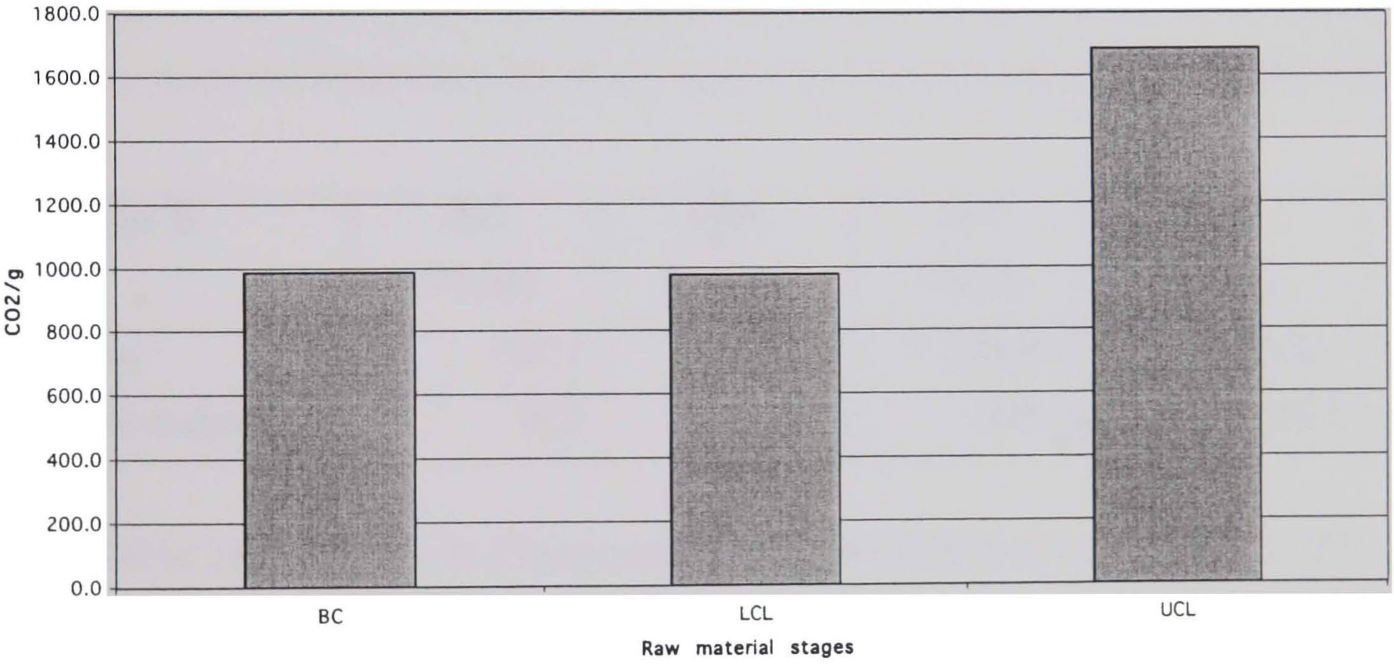


Figure 23. CO_2 in raw material extraction case A, BC, LCL, and UCL.

6.3.1.2.4. *Lower confidence limit scenario for case B*

For case B, TPE values in LCL are 632.2 MJ for the total life cycle and 18.1 MJ for raw material production. Overall, this reflects 3 per cent for raw material production, 45 per cent for manufacture, 54 for the use phase, and –1 per cent from EoL. For CO_2, emissions are 35860.2g in total, with 980.1g from raw materials extraction. This is equivalent to 3, 51, 47 and –1 per cent for the respective life cycle stages. Again, overall, the difference between the LCL and the BC scenario is negligible and less than one per cent between raw material extraction stages for TPE and CO_2 [Table 27].

Case B	**BC** **TPE/MJ**	**LCL** **TPE/MJ**	**BC** **CO_2/g**	**LCL** **CO_2/g**
Total	632.3	632.2	35868.3	35860.2
Raw materials	**18.2**	**18.1**	**988.2**	**980.1**

Table 27. Case B: Comparison TPE and CO_2 between LCL and BC.

6.3.1.2.5. Upper confidence limit scenario for case B

TPE values for upper confidence intervals resulted in 643.8 MJ for the total life cycle, with 29.7 MJ for raw material production (5, 44, 53, -1 per cent distribution over life cycle). CO_2 values were 36565.4 g in total, with 1685.2 g from raw material extraction (5, 50,46, and -1 per cent respectively) [Table 28].

Case B	**BC** **TPE/MJ**	**UCL** **TPE/MJ**	**BC** **CO_2/g**	**UCL** **CO_2/g**
Total	632.3	643.8	35868.3	36565.4
Raw materials	**18.2**	**29.7**	**988.2**	**1685.2**

Table 28. Case B: Comparison TPE and CO_2 between BC and UCL

Overall, there is a difference of 1.8 and 1.9 per cent between BC and UCL scenario for TPE and CO_2 (11.5 MJ and 697.1 g CO_2). For the respective ***raw material*** stages, the differences are the same as for case A (63 per cent more for TPE and 70.5 per cent for CO_2). Like in case A, the difference between the raw material stages between the BC and UCL is very significant, although there is not much difference between the overall results. [Table 29] summarises all cases and scenarios.

Life cycle	Case A TPE/MJ	Case B TPE/MJ	Case A	Case B	Case A	Case B
BC				**Diff. from A [%]**		
Total	682.4	632.3		-7.3		
Raw mat.	18.2	18.2				
Manufact.	331.5	281.4		-15.1		
Use	340.4	340.4				
EoL	-7.7	-7.7				
LCL			**Diff. from BC [%]**	**Diff. from BC [%]**	**Diff. from BC [MJ]**	**Diff. from BC [MJ]**
Total	682.3	632.2	0.0	0.0	-0.1	-0.1
Raw mat.	18.1	18.1	-0.7	-0.7		
Manufact.	331.5	281.4				
Use	340.4	340.4				
EoL	-7.7	-7.7				
UCL			**Diff. from BC [%]**	**Diff. from BC [%]**	**Diff. from BC [MJ]**	**Diff. from BC [MJ]**
Total	693.9	643.8	1.7	1.8	11.5	11.5
Raw mat.	29.7	29.7	63.0	63.0		
Manufact.	331.5	281.4				
Use	340.4	340.4				
EoL	-7.7	-7.7				

Continued overleaf

Life cycle	**Case A CO_2/g**	**Case B CO_2/g**	**Case A**	**Case B**	**Case A**	**Case B**
BC				**Diff. from A [%]**		
Total	39218.4	35868.3		-8.5		
Raw mat.	988.2	988.2				
Manufact.	21715.0	18364.9		-15.4		
Use	16954.2	16954.2				
EoL	-438.9	-43 8.9				
LCL			**Diff. from BC [%]**	**Diff. from BC [%]**	**Diff. from BC [g]**	**Diff. from BC [g]**
Total	39210.3	35860.2	0.0	0.0	-8.1	-8.1
Raw mat.	980.1	980.1	-0.8	-0.8		
Manufact.	21715.0	18364.9				
Use	16954.2	16954.2				
EoL	-438.9	-438.9				
UCL			**Diff. from BC [%]**	**Diff. from BC [%]**	**Diff. from BC [g]**	**Diff. from BC [g]**
Total	39915.5	36565.4	1.8	1.9	697.1	697.1
Raw mat.	1685.2	1685.2	70.5	70.5		
Manufact.	21715.0	18364.9				
Use	16954.2	16954.2				
EoL	-438.9	-438.9				

Table 29. Summary cases A and B: TPE and CO_2 for phone life cycle

6.3.1.3. TPE and CO_2 distribution over life cycle for all cases

With regard to life cycle distribution in per cent, TPE requirements are highest for use, followed by the manufacture, raw material extraction, and EoL. The use phase outweighs the manufacturing phase by about one per cent in case A for all scenarios. This is more pronounced in case B (9 per cent in all scenarios) due to the lower manufacturing energy ratio. The UCL scenarios contributed to a shift in life cycle TPE ratios by one per cent in case A, and two per cent in case B by claiming increased energy in raw material extraction.

Because Asian, US, and European energy mixes were taken into account to model phone manufacture, there is a change in ratios between manufacture and use phase when comparing TPE and CO_2. As the phone was assumed to be used in Europe, but manufactured in many other countries, CO_2 emissions in manufacture exceeded the use phase. As shown earlier, the country of manufacture can be significant with regard to CO_2 emissions. CO_2 from phone manufacture outweighs the use phase by 12 per cent in all scenarios for case A, and by 4 per cent for all scenarios in case B. This difference reflects the higher energy requirements for manufacture in case A [Table 30].

Distribution %	**Case A TPE [%]**	**Case B TPE [%]**	**Case A CO_2 [%]**	**Case B CO_2 [%]**
BC				
Total	100	100	100	100
Raw mat.	3	3	3	3
Manufact.	49	45	55	51
Use	50	54	43	47
EoL	-1	-1	-1	-1
LCL				
Total	100	100	100	100
Raw mat.	3	3	2	3
Manufact.	49	45	55	51
Use	50	54	43	47
EoL	-1	-1	-1	-1
UCL				
Total	100	100	100	100
Raw mat.	4	5	4	5
Manufact.	48	44	54	50
Use	49	53	42	46
EoL	-1	-1	-1	-1

Table 30. Summary TPE and CO_2 distribution over life cycle in per cent.

6.3.1.4. Confidence limits and consequences for phone parts

This section explores how the different scenarios have affected CO_2 emissions for phone components. As for the base cases, the specific CO_2 emissions for all phone components were calculated for the LCL and UCL scenario [details Appendix D]. This was only necessary for case B since the raw material stages are the same in both cases.

6.3.1.4.1. LCL scenario and phone components

For the LCL scenario, there was no difference in the general component ranking from the BC scenario [section 6.3.1.2.1] which had only slightly more (0.8 per cent) CO_2 emissions in raw material extraction. The normalised ranks for the

LCL scenario are almost identical to the BC scenario, revealing differences only in the lower ranks (component number 83, a LED in the seventh position for the BC, was in the ninth position for the LCL. This was due to Au, from which 95 per cent of the CO_2 emissions occurred). As in the BC scenario, Ru and Pd had the strongest influence on the normalised ranking.

6.3.1.4.2. *UCL scenario and phone components*

Here, the ranking of the phone's materials with regard to raw materials extraction is different to the two previous scenarios as shown in [Figure 19]. For raw material extraction, there was a 70.5 per cent difference in CO_2 emissions between the UCL and the BC scenario. Apart from Au and PGM, the highest emitters [Figure 24] represent mostly materials for which UCL have been developed: Nd with an UCL rucksack of 5.15E+03, Ga with 1.32E+05, and La in ceramics ($LaTiO_4$) with 8.45E+04. Therefore, Nd, Ga and La were responsible for the overall differences (1 and 2 per cent) in the UCL scenarios compared to the BC. For Au and Pd, energy values were available in *TEAM* but they are known to have very high rucksack values (9.50E+05 for Au and 3.5E+05 for Pt [DL, 1998a,b; Schmidt-Bleek, 1997]. PGM metal Ru was treated as Pt since both are mined together.

The components with the highest CO_2-emissions are ranked in [Figure 25], the normalised CO_2-emissions per mg component in [Figure 26]. [Table 31] shows the normalised values for the phone parts.

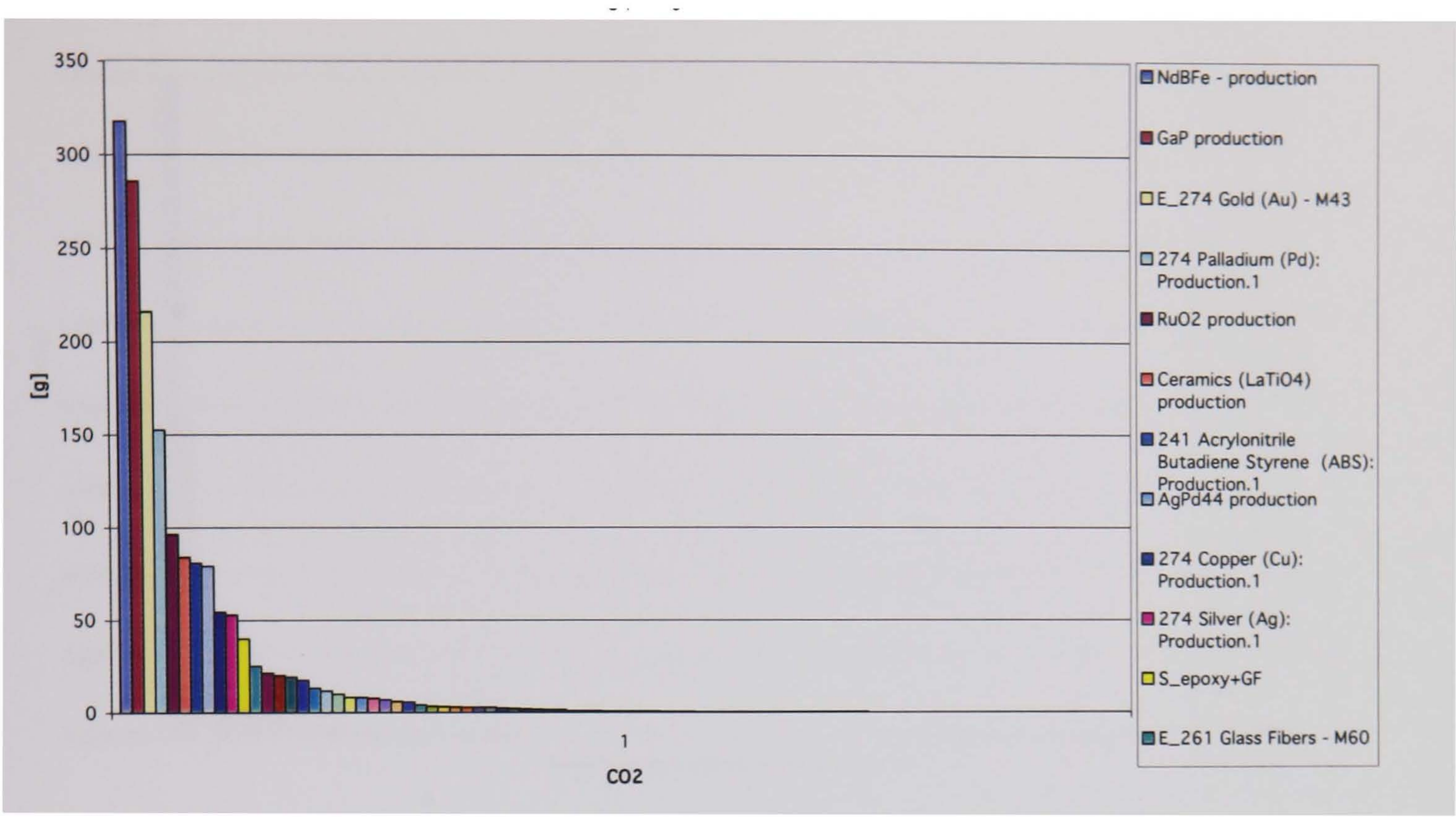


Figure 24. CO_2 [g] from raw materials in phone, UCL scenario

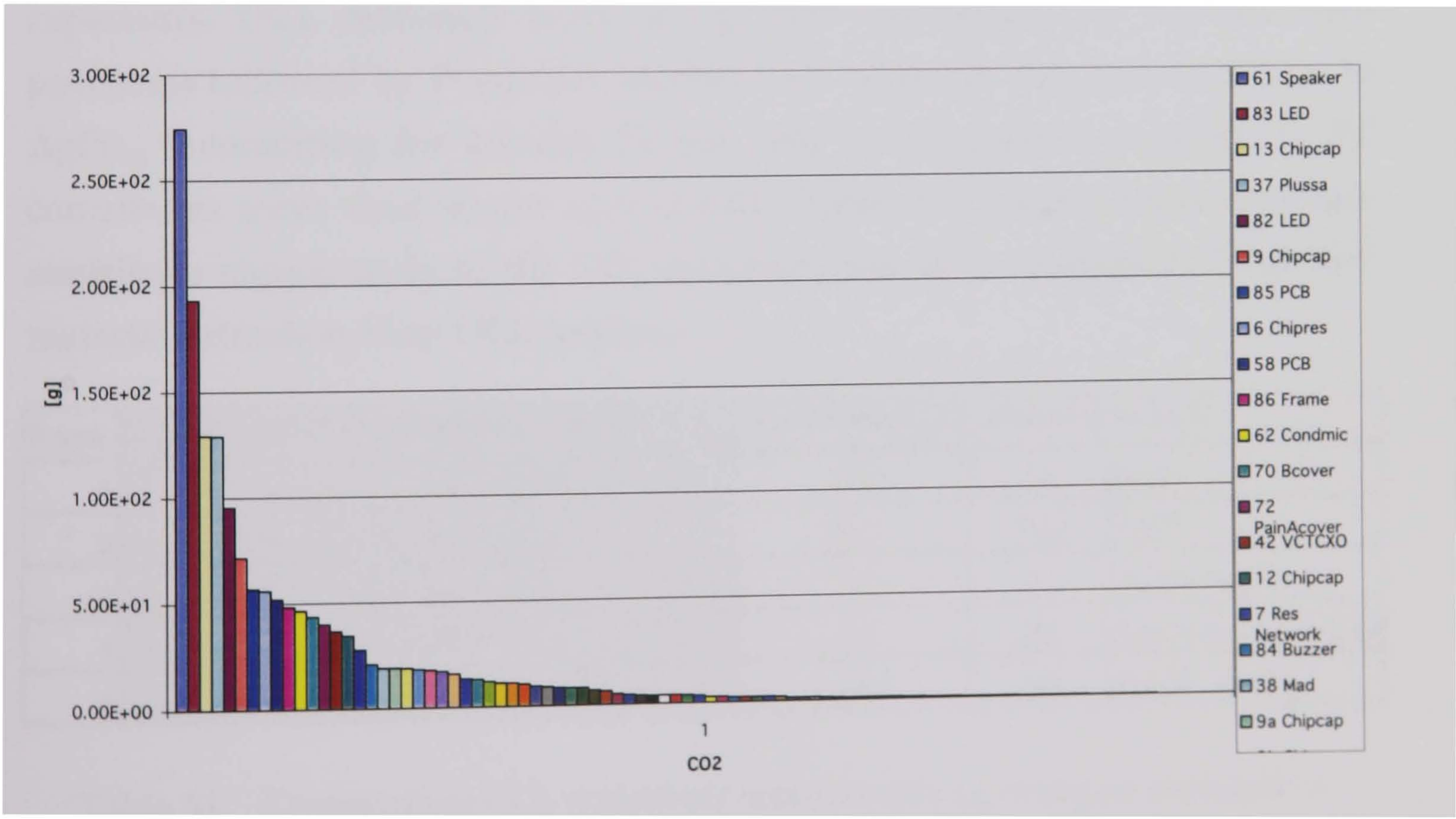


Figure 25. CO_2 from components, UCL scenario

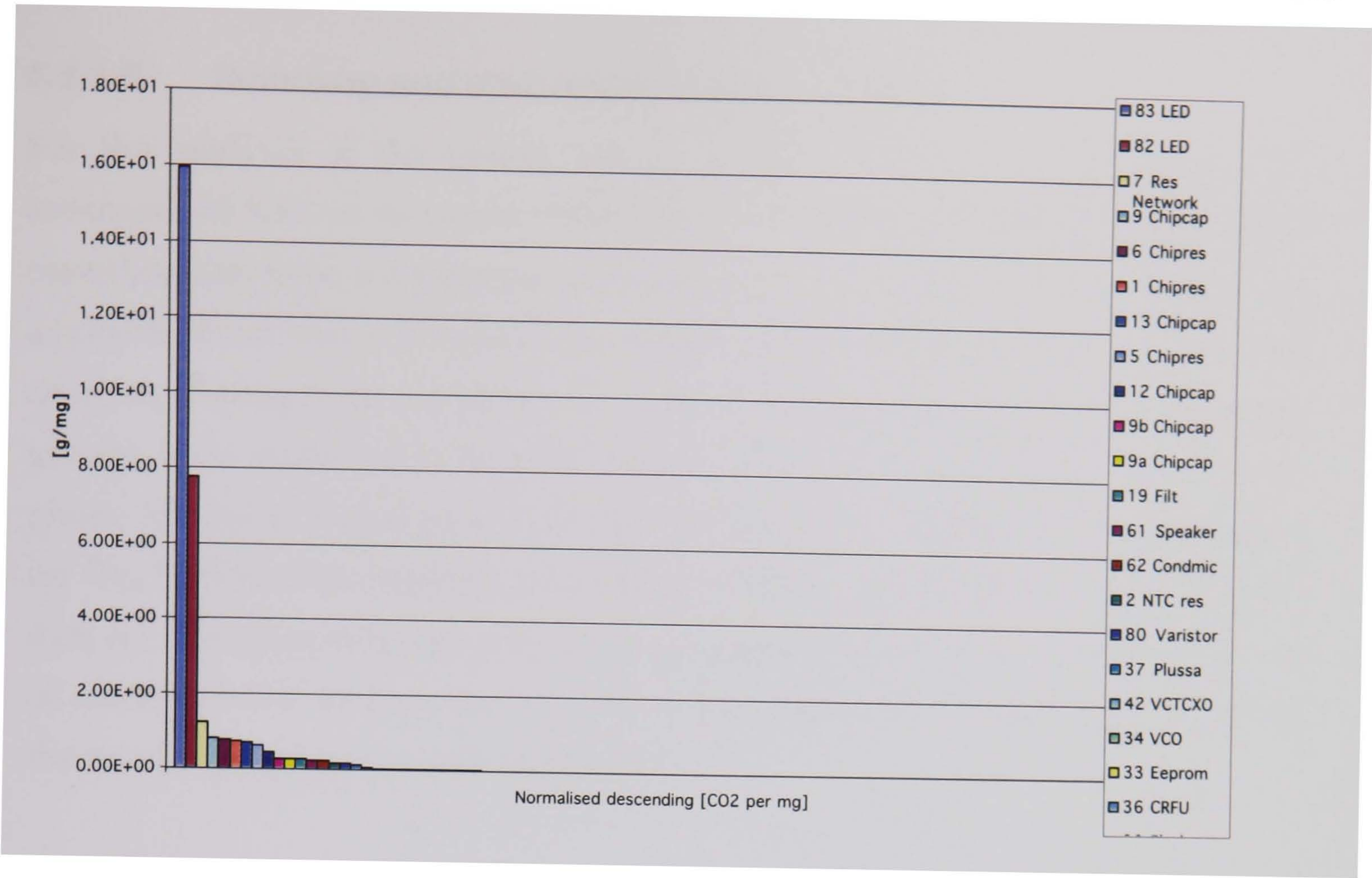
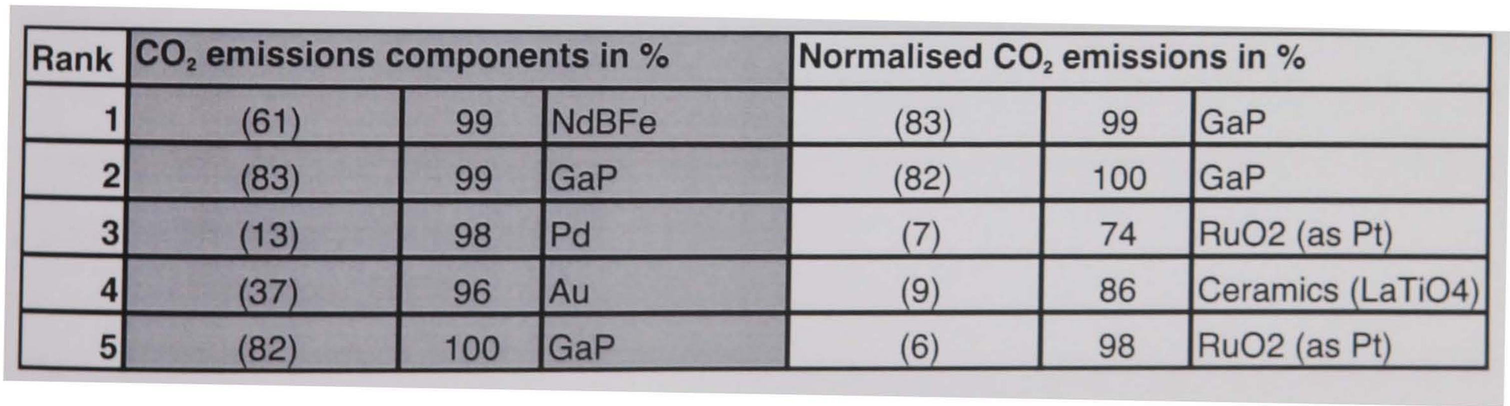


Figure 26. Normalised CO_2 values for components, UCL

The normalised UCL ranks are very different from the BC and LCL ranks. Responsible for the first two positions are LEDs, followed by resistors and capacitors. UCL materials such as GaP are responsible for the first two positions, followed by PGM and another UCL material, ceramics ($LaTiO_4$). In $AgPd_{44}$ (accounting for around 25 per cent in component number 7), Pd contributes more than 96 per cent of CO_2 [Table 31]. Hence, these materials contribute significantly to the CO_2 emissions per unit component from raw material extraction in an UCL scenario.



Rank	CO_2 emissions components in %			Normalised CO_2 emissions in %		
1	(61)	99	NdBFe	(83)	99	GaP
2	(83)	99	GaP	(82)	100	GaP
3	(13)	98	Pd	(7)	74	RuO2 (as Pt)
4	(37)	96	Au	(9)	86	Ceramics (LaTiO4)
5	(82)	100	GaP	(6)	98	RuO2 (as Pt)

Table 31. Comparison CO_2 emissions components [g/component] and in [g/mg component], BC scenario (values are rounded).[33]

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[33] Table reads: For component number 61 in the first rank, 99% of the CO_2 emissions were caused by NDBFe.

6.3.1.5. Summary and discussion energy analysis

For the analysis of the phone, which focused on TPE and CO_2 emissions, assumptions had to be made with regard to "unknown" Earth metals. Some materials had to be substituted on an assumption basis, as data were often not available. From these assumptions, which were partly based on mathematical analysis, mining data, suppliers data and chemical ratios, 90 phone component groups were modelled to be used for the raw material extraction phase of the phone life cycle. Based on a previous mobile phone study of a product group for the 1995 to 1996 markets, two separate cases were modelled with updated data for raw materials and phone manufacture. However, due to the exclusion of certain phone accessories, manufacturing data, and mining steps for PGM, the results are probably underestimated.

6.3.1.5.1. Case A versus B

As expected, cases A and B differed in their overall amount of TPE and CO_2, determined by the different levels of manufacturing energy.

The comparison of results for TPE between base case A (with older manufacturing data) and B (updated) suggest that in case B there has been a decrease of 7.3 per cent of overall TPE, and a decrease of 15.1 per cent between the manufacturing stages. This is a slightly greater reduction than that between product groups launched between 1992 and 1994 (6 per cent) and 1994 and 1996 (4 per cent) – calculated from [McLaren and Wright, 1997]. However, because of mixed available data, a precise time allocation was not possible. Data availability is still very poor and manufacturing energy could only partly be calculated. For CO_2, there was an overall decrease of 8.5 per cent and of 15.5 per cent in phone manufacture.

If a charger with 0.4 W is taken into account (in comparison to the 1.3 W charger, everything else being equal), this would reduce the use phase from 115.75 MJ during a 2.5 years life cycle to 45.75 MJ (12.4 MJ per year electricity charger plus 5.9 MJ electricity standby time). Extrapolated to the TPE equivalent, between use phases this reflects about 60.5 per cent of energy savings (205.8 MJ) or 12 per cent per year (1996 to 2001). When comparing the total life cycle with case B, the results would be equivalent to around 426 MJ (TPE) for BC and LCL, and 438 MJ for the UCL scenario, reflecting overall energy reductions of up to 33 per cent[34]. Over a three-year span (1998-2001), this would be equivalent to 11 per cent energy savings per year if these phones reflected step-changes in mobile phone design.

The worldwide increase in mobile phone subscriptions (rebound effect) and the increasing functionality of electronic products, however, may outweigh these energy and carbon savings.

6.3.1.5.2. Distribution ratios life cycle

The TPE distribution in per cent showed that requirements are highest for use, followed by the manufacture, and raw material extraction. The use phase outweighs the manufacturing phase in both cases whereby case B was more pronounced than case A due to the lower manufacturing energy ratio. The UCL scenarios shifted the TPE and CO_2 distribution by 1 to 2 per cent towards raw material extraction due to high rucksacks and thus, increased energy requirements.

Since Asian, US, and European energy mixes were taken into account to model phone manufacture, a change in ratios between manufacture and use phase occurred when comparing TPE and CO_2. The country of manufacture can be significant with regard to CO_2 emissions. For example, producing one MJ of electricity in Hong-Kong costs 86 per cent more CO_2 than in Europe, and 73 per cent more in Korea. CO_2 from phone manufacture outweighs the use phase by 12 per cent in all scenarios for case A, and by 4 per cent for all scenarios in case B. This reflects the higher overall energy requirements for manufacture in case A.

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[34]

TPE case B (BC, LCL, UCL)	Result TPE with 0.4 W charger	%
632.3	426.5	-32.6
632.2	426.4	-32.6
643.8	438.0	-32.0

6.3.1.5.3. LCL and UCL Scenarios

The UCL and LCL scenarios determined raw material extraction and therefore the overall result in each case. With regard to TPE, overall reductions in the LCL scenarios were negligible and the differences between the two raw material extraction phases were only 0.7 per cent in both cases. However, the overall UCL scenarios were 1.7 to 1.8 per cent higher than the BC and a striking 63 per cent higher when only comparing the extraction stages.

For CO_2, overall results for LCL were negligible, and only 0.8 per cent lower when comparing raw material extraction. The overall UCL scenarios were about 2 per cent higher in cases A and B, and for raw material extraction 70.5 per cent higher than the BC. For the UCL scenarios, the elements in the phone responsible for the higher CO_2 emissions were those for which statistical rucksacks had been estimated: Neodymium (Nd), gallium (Ga) and lanthanum (La).

Although the overall differences between the scenarios are very small (< -1 per cent to 2 per cent) they vary significantly (63 –70.5 per cent) between the raw material stages for the upper scenarios due to larger rucksack and hence, energy values.

6.3.1.5.4. Parts and materials

To determine how the different scenarios affected different phone parts, CO_2 emissions were calculated and ranked per component and per mg component (normalisation). By normalising CO_2 emissions per mg component, the main CO_2 emitters in a certain phone part were obtained, regardless of its weight in the phone. The normalised (CO_2 per mg component) ranking order differed from the general ranking order (CO_2 emissions per component): BC and LCL scenarios gave similar results in the highest ranks, with platinum group metals (PGM) (mainly ruthenium, Ru and palladium, Pd) accounting for up to 98 per cent of CO_2 emissions. CO_2 emissions from PGM are somewhat underestimated, since the mining step for these metals was not included in the DEAM database. The components containing these metals were *resistors* and *capacitors*. Ru was treated as platinum (Pt), which has a larger rucksack (about one order of magnitude) than the predicted Ru value. Therefore, Ru may be overestimated.

However, since the estimated UCL rucksack value for Ru (which was not used) is about one order of magnitude higher than Pt, Ru may well be underestimated.

In contrast, the normalised UCL scenario was dominated by GaP, followed by Ru, ceramics, and partly, $AgPd_{44}$. The culprits here were mainly ***LEDs***. UCL elements Ga and La had a significant influence in this scenario, whereas the LCL scenarios were not significantly different from the BC. These results have to be interpreted with the underlying assumptions in mind, since Ga and La values were based on a theoretical approach. Further research into the extraction of these metals is needed to verify this. Of interest are also the costs of further processing these metals for electronic grades, and to compare these costs with the costs of extraction. Our results suggested, given the high energy costs in the manufacture of Ga chips plus possibly high energy expenditures in extraction, that this may be an element of environmental concern – especially with regard to increasing mobile phone sales, or other products containing LEDs. The high impacts from small amounts of material also support the recycling of components in electronics. To conclude, in the phone Au and PGM are the highest CO_2 emitters in the BC and LCL scenarios, whereas Nd and Ga are more evident in an UCL scenario. On a normalised component level, PGM, Ga and La are among the main culprits in raw material extraction in terms of energy requirements and CO_2 emissions, but phone manufacture and use of the mobile phone contribute the lion's share during the energy life cycle.

CHAPTER 7: THE ECOLOGICAL FOOTPRINT OF A MOBILE PHONE

This chapter presents the results from the footprint analysis (EFA) of the mobile phone, cases A and B, including their upper and lower confidence scenarios (UCL, LCL). The different scenarios only affect the requirements for primary energy materials in raw material extraction, since direct land use values for the predicted elements were not known. This EF study was based on the results obtained from the energy analysis, using CO_2 emissions as a first order approximation for other environmental impacts. Details of cases A and B can be found in Chapter 6 [p. 145]. As for the PC, the EF for the total mobile phone cycle and its comparison with the fair Earth share [ha/cap] is presented first, followed by the phone's EF in a snapshot [m^2].

7.1. Direct land use

Raw material flows from the phone life cycle were multiplied by their respective direct land use values, DLU [$m^2\ kg^{-1}$], according to Chapter 3. Due to data paucity, not all resource flows could be included, and some had to be summarised and simplified to allocate a DLU figure. For many raw materials, such as gold, silver, lead, nickel, zinc, magnesium and cobalt, and uncommon commodities in particular, no DLU values could be found. Hence, for 36 out of 68 materials flows (53 per cent), no DLU data was available, although by weight, around 97 per cent of the resource flows were included for the phone. Nonetheless, this lack of data is significant since it was known from the PC study that small amounts extracted can have a high land use [Frey, Harrison, Billett, 2000 a, b], especially with regard to some precious metals. Therefore, DLU results may be significantly underestimated. The detailed *Excel* spreadsheets (land use data and life cycle data calculated by the *TEAM* software) are included in Appendix E.

7.1.1. Direct land use of non-renewable resources

With the exception of copper, the ranking of non-renewable materials reflects the high land use by energy materials - notably uranium with its high land use from radiation. This ranking was the same in all scenarios for cases A and B. From 32 non-renewable resource flows, coals, despite their relatively low area [m^2] per mass [kg] values, established themselves within the top five ranks due to high consumption rates [Table 32].

Rank	Total [m^2 phone^{-1}]	Extraction [m^2 phone^{-1}]	Manu-facture [m^2 phone^{-1}]	Use [m^2 phone^{-1}]	End of life [m^2 phone^{-1}]
1.	(r) Uranium (U, ore)	(r) Uranium (U, ore)	(r) Uranium (U, ore)	(r) Uranium (U, ore)	(r) Uranium (U, ore)
2.	(r) Oil (in ground)	(r) Copper (Cu, ore)	(r) Oil (in ground)	(r) Oil (in ground)	(r) Copper (Cu, ore)
3.	(r) Natural Gas (in ground)	(r) Oil (in ground)	(r) Coal (in ground)	(r) Natural Gas (in ground)	(r) Oil (in ground)
4.	(r) Coal (in ground)	(r) Natural Gas (in ground)	(r) Natural Gas (in ground)	(r) Coal (in ground)	(r) Natural Gas (in ground)
5.	(r) Lignite (in ground)	(r) Coal (in ground)	(r) Lignite (in ground)	(r) Lignite (in ground)	(r) Coal (in ground)

Table 32. Ranked distribution of DLU [m^2] over phone life cycle for non-renewable raw materials.

7.1.2. Direct land use of renewable resources

There was only a small amount (0.06 kg) of wood used in the mobile phone (0.3 per cent of the overall resource inputs without water) resulting in 0.05 to 0.06 m^2. Most of this was used in manufacture, probably as a filler (59 to 55 per cent, cases A and B) followed by use phase (probably fuel wood, 38 to 42 per cent, cases A, B), and a very small amount in raw material extraction (4 to 5 per cent, respectively). Total water used in the phones was between 89 to 96 litres, but was not included in this study [Appendix E].

7.2. Direct land use results case A (BC, LCL and UCL scenarios)

Case A contained older manufacturing data (higher energy values). Total DLU for this case amounted to between 2.23 for the BC to 2.25 m^2 for UCL. As expected, in all three scenarios the use phase had the highest requirements for land space (54 per cent or about 1.21 m^2), followed by manufacture (45 per cent or 0.9 m^2) and raw material extraction (2 per cent or 0.1 m^2) and some benefits from recycling (-1 per cent, less than 0.1 m^2) - following the life cycle distribution of total primary energy. For the LCL scenario, the overall reduction in DLU compared to the BC was not discernible. The UCL scenario, as expected, has an overall higher land use (less than one per cent) than the BC but between raw material stages, DLU is around 33 per cent higher than the BC due to higher rucksacks in raw materials extraction. The area difference, however, is negligible (0.02 m^2) [Figure 27].

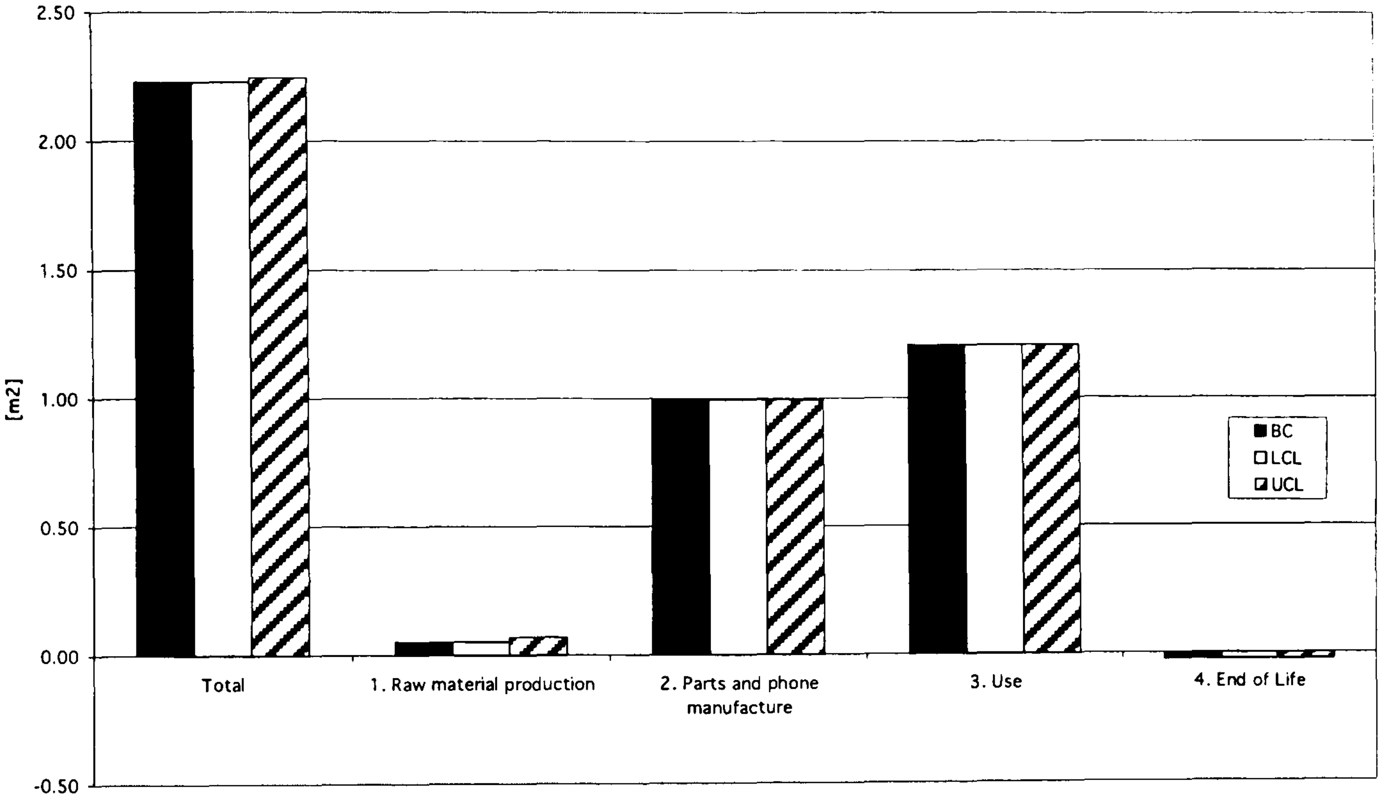

Figure 27. Case A: DLU [m^2] over life cycle for BC, LCL, and UCL scenario

7.3. *Direct land use results case B (BC, LCL and UCL scenarios)*

Since energy in phone manufacture for case B was reduced by around 15 per cent compared to case A, this has effected the resource flows for energy materials and hence, corresponding DLU areas and their life cycle distribution. Total DLU amounted from 2.08 m^2 (BC) to 2.10 m^2 (UCL) which was insignificantly less (0.15 m^2) than case A but reflects an overall difference of -7 percent and -15 per cent between manufacture stages in line with the energy reductions in Chapter 6.

As in case A, raw material extraction for LCL requires slightly less land space than in the BC due to lower rucksack ratios. For UCL, the differences within the life cycle were similar to case A (32 per cent above BC levels), [Figure 28]. Values of cases A and B have been summarised in [Table 33].

However, these area differences between the BC and UCL scenarios are less pronounced than the differences in TPE and CO_2 (63 and 70.5 per cent respectively, between BC and UCL) [details Appendix E].

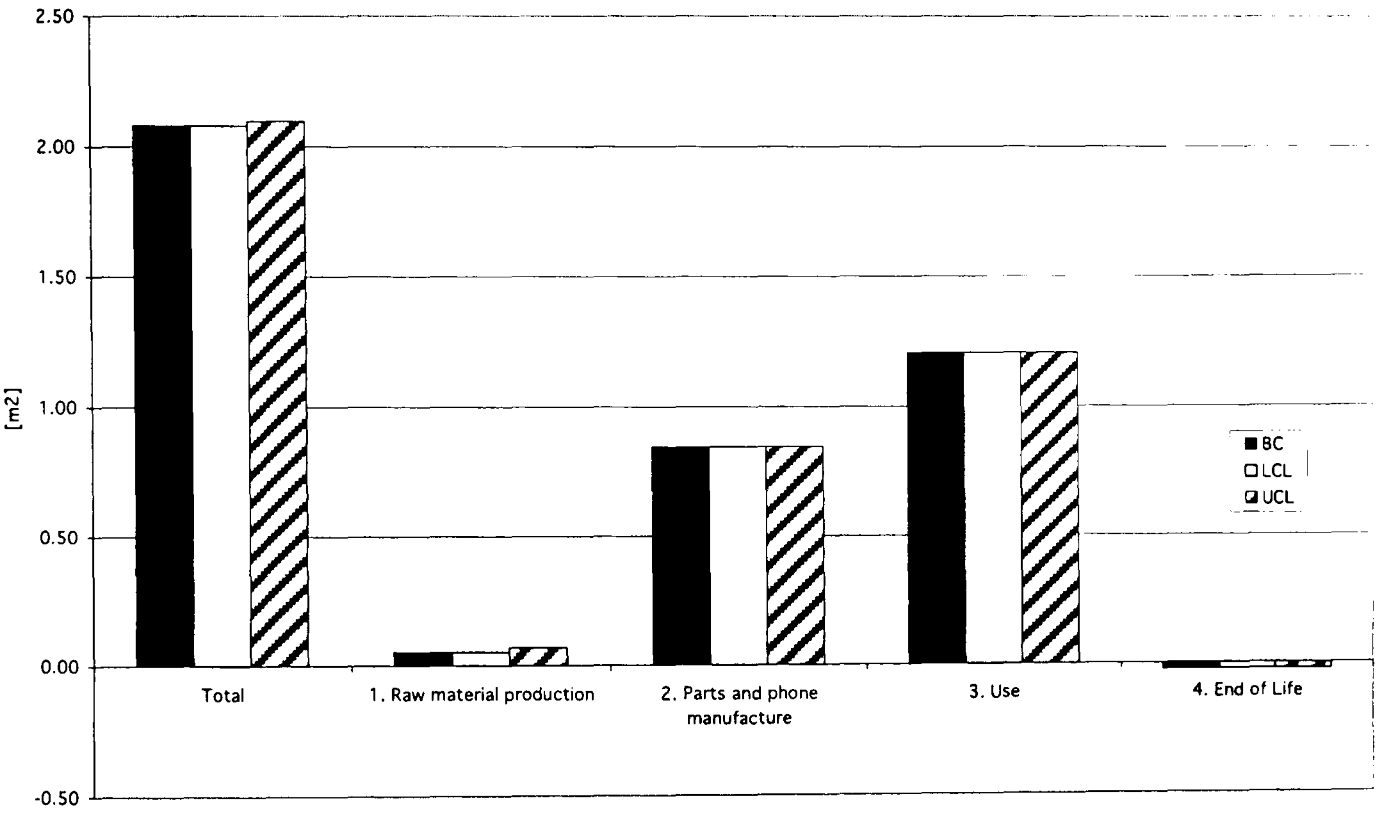

Figure 28. Case B: DLU [m^2] over life cycle for BC, LCL, and UCL scenario

Life cycle	**Case A DLU [m^2 phone^{-1}]**	**Case B DLU [m^2 phone^{-1}]**	**Case A N/S = not significant**	**Case B**	**Case A**	**Case B**
BC				**Diff. from A [%]**	**Diff. from A [m^2]**	
Total	**2.23**	**2.08**		-7	-0.15	
Raw mat.	0.05	0.05				
Manufact.	0.99	0.85		-15		
Use	1.21	1.21				
EoL	-0.02	-0.02				
LCL			**Diff. from BC [%]**	**Diff. from BC [%]**	**Diff. from BC [m^2]**	**Diff. from BC [m^2]**
Total	**2.23**	**2.08**	N/S	N/S	N/S	N/S
Raw mat.	0.05	0.05	N/S	N/S	N/S	N/S
Manufact.	0.99	0.85				
Use	1.21	1.21				
EoL	-0.02	-0.02				
UCL			**Diff. from BC [%]**	**Diff. from BC [%]**	**Diff. from BC [m^2]**	**Diff. from BC [m^2]**
Total	**2.25**	**2.10**	1	1	0.02	0.02
Raw mat.	0.07	0.07	33	32	0.02	0.02
Manufact.	0.99	0.85				
Use	1.21	1.21				
EoL	-0.02	-0.02				

Table 33. Summary DLU values between case A and B (all scenarios).

7.4. *Carbon sequestration for transport emissions*

For both cases, the only transport included in this study was 30.47 MJ (16.13 MJ from first supplier to assembly plant, and 14.34 MJ from assembly plant to customer), [Wright, 1999]. 75 per cent of transport was assumed to be by air, the remainder by truck and ship [Wright, 2001, pers. comm.]. All other transport, especially between raw material extraction and manufacture, could not be included due to lack of data. Hence, transport emissions (and therefore, the final EF) will be underestimated.

Based on IPCC's carbon emission factors (CEF) [IPCC, 1997a] and a carbon sequestration rate of 142 gC m$^{2\ (-1)}$ yr^{-1} [see Chapter 3], fuel specific energy to land ratios were calculated [Table 34].

Fuel types transport	**Carbon emission factor, CEF** [g/MJ]	**Fuel specific fossil-energy-land** [MJ m$^{2\ (-1)}$ yr^{-1}]
Jet kerosene	19.5	7.3
Diesel oil	20.2	7.0
	[IPCC, 1997a]	

Table 34. Fuel specific fossil-energy land used in this study

By multiplying the transport figure [MJ] with the respective CEF, subtracting 25 per cent for ocean absorption and dividing by the carbon sequestration rate, the fossil energy land for transport was obtained [Table 35], which was the same for both cases.

Transport	**C/g**	**Transport demand phone** [m^2 phone^{-1} yr]
Air (75%)	445.62	2.35
Truck / ship (25%)	153.87	0.81
Total used:	599.50	**3.17**

Table 35. Fossil fuel land transport for mobile phone

7.5. Carbon sequestration phone life cycle, cases A and B

Based on the energy analysis results in Chapter 6, fossil CO$_2$ emissions from the phone life cycle were transformed into ***fossil energy land*** according to Chapter 3. This also means that energy efficiencies were translated into the EF. The following values for cases A and B include 25 per cent ocean absorption [Table 36] and [Table 37].

Phone life cycle, CASE A	**BC [m^2 phone^{-1} yr]**	**LCL m^2 phone^{-1} yr]**	**UCL m^2 phone^{-1} yr]**
Raw material production	1.42	1.41	2.41
Parts and phone manufacture	31.28	31.28	31.28
Use	24.42	24.42	24.42
End of Life	-0.63	-0.63	-0.63
Total used	**56.49**	**56.48**	**57.50**
Total used transport	**3.17**	**3.17**	**3.17**
Fossil energy land	**59.66**	**59.65**	**60.66**

Table 36. Case A: Fossil energy land required for BC, LCL, UCL

Phone life cycle, CASE B	**BC [m^2 phone^{-1} yr]**	**LCL m^2 phone^{-1} yr]**	**UCL m^2 phone^{-1} yr]**
Raw material production	1.42	1.41	2.43
Parts and phone manufacture	26.45	26.45	26.45
Use	24.42	24.42	24.42
End of Life	-0.63	-0.63	-0.63
Total used	**51.67**	**51.66**	**52.67**
Total used transport	**3.17**	**3.17**	**3.17**
Fossil energy land	**54.83**	**54.82**	**55.84**

Table 37. Case B: Fossil energy land required for BC, LCL, UCL

7.6. Calculating the final EF

For cases A and B, DLU areas and fossil energy land were scaled with equivalent factors to obtain global areas of bioproductive space. Subsequently, the respective areas were aggregated into the EF and compared to the latest (1996) available supply of biocapacity of 1.89 hectares (ha) per capita (1.60 ha with 25 per cent biodiversity protection), our ecological benchmark. Here, corresponding consumption and waste flows were also listed [Table 38] to [Table 39]. EF shares were summarised in per cent from the available per capita supply [Table 44], details [Appendix E].

Consumption/waste category (CASE A, BC)	**Kg/phone**	**Equivalent total [m^2 phone $^{-1}$ yr]**	**Land category**
Non-renewable materials	23.89	6.88	Built-up land
Renewable materials (wood)	0.06	0.10	Forest land
Carbon [C] emissions (life cycle and transport)	11.30	106.11	CO_2-absorption land
TOTAL DEMAND MOBILE PHONE (EF)		**113.09**	**Share mobile phone [%]**
EXISTING GLOBAL BIO-CAPACITY (-12%) [ha/cap.]		**1.89 ha**	**0.60**
EXISTING GLOBAL BIO-CAPACITY (-25%) [ha/cap.]		**1.60 ha**	**0.71**

Table 38. The EF of mobile phone case A, BC with ecological benchmark of 1.89 and 1.60 ha

Consumption/waste category (CASE A, LCL)	**Kg/phone**	**Equivalent total [m^2 phone $^{-1}$ yr]**	**Land category**
Non-renewable materials	23.89	6.88	Built-up land
Renewable materials (wood)	0.06	0.10	Forest land
Carbon [C] emissions (life cycle and transport)	11.29	106.09	CO_2-absorption land
TOTAL DEMAND MOBILE PHONE (EF)		**113.07**	**Share mobile phone [%]**
EXISTING GLOBAL BIO-CAPACITY (-12%) [ha/cap.]		**1.89 ha**	**0.60**
EXISTING GLOBAL BIO-CAPACITY (-25%) [ha/cap.]		**1.60 ha**	**0.71**

Table 39. The EF of mobile phone case A, LCL

Consumption/waste category (CASE A, UCL)	**Kg/phone**	**Equivalent total [m^2 phone $^{-1}$ yr]**	**Land category**
Non-renewable materials	24.17	6.93	Built-up land
Renewable materials (wood)	0.06	0.10	Forest land
Carbon [C] emissions (life cycle and transport)	11.49	107.90	CO_2-absorption land
TOTAL DEMAND MOBILE PHONE (EF)		**114.93**	**Share mobile phone [%]**
EXISTING GLOBAL BIO-CAPACITY (-12%) [ha/cap.]		**1.89 ha**	**0.61**
EXISTING GLOBAL BIO-CAPACITY (-25%) [ha/cap.]		**1.60 ha**	**0.73**

Table 40. The EF of mobile phone case A, UCL

Consumption/waste category (CASE B, BC)	Kg/phone	Equivalent total [m^2 phone $^{-1}$ yr]	Land category
Non-renewable materials	21.99	6.42	Built-up land
Renewable materials (wood)	0.06	0.09	Forest land
Carbon [C] emissions (life cycle and transport)	10.38	97.53	CO_2-absorption land
TOTAL DEMAND MOBILE PHONE (EF)		**104.05**	**Share mobile phone [%]**
EXISTING GLOBAL BIO-CAPACITY (-12%) [ha/cap.]		**1.89 ha**	**0.55**
EXISTING GLOBAL BIO-CAPACITY (-25%) [ha/cap.]		**1.60 ha**	**0.65**

Table 41. The EF of mobile phone case B, BC

Consumption/waste category (CASE B, LCL)	Kg/phone	Equivalent total [m^2 phone $^{-1}$ yr]	Land category
Non-renewable materials	21.99	6.42	Built-up land
Renewable materials (wood)	0.06	0.09	Forest land
Carbon [C] emissions (life cycle and transport)	10.38	97.51	CO_2-absorption land
TOTAL DEMAND MOBILE PHONE (EF)		**104.02**	**Share mobile phone [%]**
EXISTING GLOBAL BIO-CAPACITY (-12%) [ha/cap.]		**1.89 ha**	**0.55**
EXISTING GLOBAL BIO-CAPACITY (-25%) [ha/cap.]		**1.60 ha**	**0.65**

Table 42. The EF of mobile phone case B, LCL

Consumption/waste category (CASE B, UCL)	**Kg/phone**	**Equivalent total [m^2 phone $^{-1}$ yr]**	**Land category**
Non-renewable materials	22.26	6.48	Built-up land
Renewable materials (wood)	0.06	0.09	Forest land
Carbon [C] emissions (life cycle and transport)	10.57	99.31	CO_2-absorption land
TOTAL DEMAND MOBILE PHONE (EF)		**105.88**	**Share mobile phone [%]**
EXISTING GLOBAL BIO-CAPACITY (-12%) [ha/cap.]		**1.89 ha**	**0.56**
EXISTING GLOBAL BIO-CAPACITY (-25%) [ha/cap.]		**1.60 ha**	**0.66**

Table 43. The EF of mobile phone case B, UCL

The EF results suggest that the EF of a mobile phone is at least 7000 to 8000 times bigger than the actual size of the phone (about 141 cm^2), but the EF becomes smaller with decreasing resource use in either in material extraction (scenarios) or manufacturing energy (case B versus A). While older models require around 113 to 115 m^2 of bioproductive space, the newer models need only between 104 and 106 m^2.

94 per cent of the EF (between 106 to 108 m^2 for case A, and 98 to 99 m^2 for case B) is caused by carbon emissions, of which 5 to 6 per cent are from transport. The remaining 6 per cent (around 7 m^2 for both cases) were caused by direct land use, mainly through mining operations (which in turn was mainly due to uranium) [Figure 29].

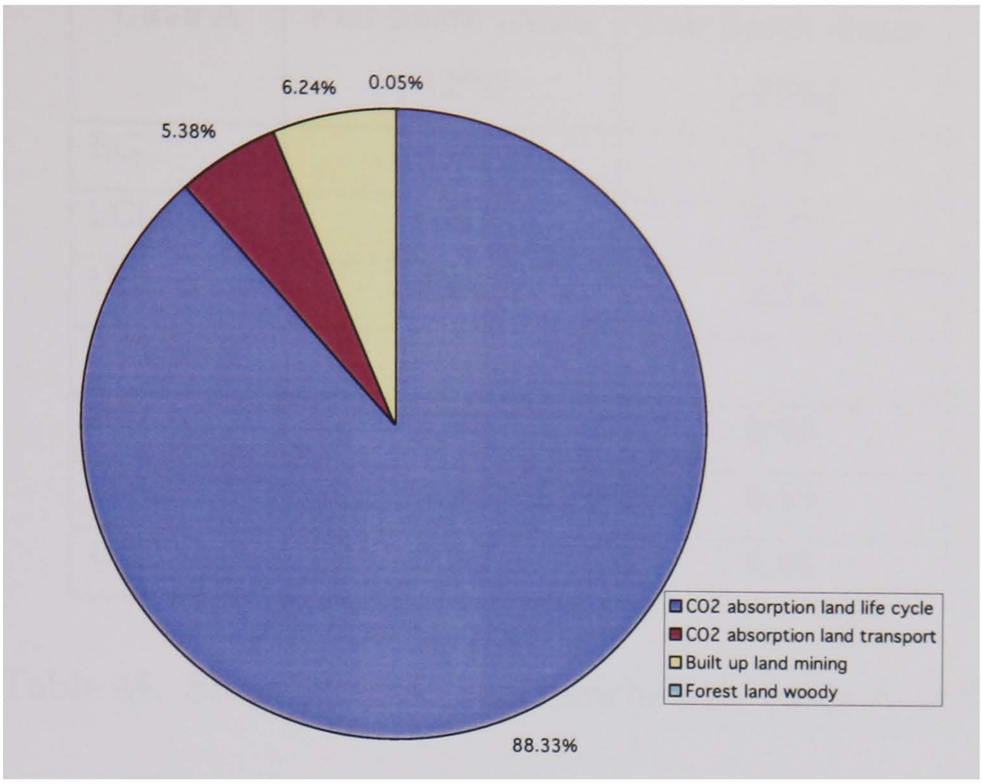

Figure 29. EF components of average mobile phone in per cent

During the total life cycle of a mobile phone, both cases require less than one per cent of the available biocapacity per capita - case A 0.60 to 0.72 per cent, and case B slightly less, 0.55 to 0.66 per cent, depending on scenario and rate of biodiversity protection. With regard to the "fair Earth share", the UCL scenarios were only 0.01 per cent higher than the other scenarios [Table 44]. Although the differences between cases and scenarios were not that distinct for the overall share of existing per capita supply, the results show that EF analysis is sensitive enough to detect differences on very small scales – such as in a small electronic product.

The phone results are likely to be underestimated, since all resources have not been accounted for (for example, wastes other than CO_2, certain transport sections and unaccounted degraded land from mining activities). Furthermore, the ecological benchmark is expected to decrease with every year (the available space in 1998 should be less than in 1996).

Case A	**Fair Earth share [-12%]**	**Fair Earth share [-25%]**
BC	**0.60**	**0.71**
LCL	**0.60**	**0.71**
UCL	**0.61**	**0.72**
Case B		
BC	**0.55**	**0.65**
LCL	**0.55**	**0.65**
UCL	**0.56**	**0.66**

Table 44. Share of ecological benchmark, cases A and B

Because of the focus on carbon in this study, which caused most of the resource use, the differences between per cent are similar to the CO_2 analysis (manufacture outweighs use phase and overall UCL results outweigh the BC by around 2 per cent). The UCL scenarios require about 1.80 m^2 more bioproductive space than their base cases, but when comparing case B with case A, 9 m^2 (8 per cent) were saved through energy reductions in phone manufacture [Table 45].

		EF [m^2 phone $^{-1}$ yr]	**Diff. within case [m^2 phone $^{-1}$ yr]**	**Diff. within case [%]** N/S = not significant	**Diff. A vs. B [m^2 phone $^{-1}$ yr]**	**Diff. A vs. B [%]**
Case A	BC	**113.09**				
	LCL	**113.07**	-0.02	N/S		
	UCL	**114.93**	1.80	2		
Case B	BC	**104.05**			-9.07	-8
	LCL	**104.02**	-0.02	N/S	-9.07	-8
	UCL	**105.88**	1.80	2	-9.02	-8

Table 45. Comparison of mobile phone footprints

7.6.1. *Scenario with 0.4 Watts for charger*

If a 1.3 W charger emits 16954.2 g of CO_2 during a use phase of 2.5 years (stand-by), CO_2 emissions in the use phase for a charger with only 0.4 W electricity consumption would be reduced by about 10253.1 g to 6701.1 g CO_2[35]. Subtracting this amount from all case B scenarios (everything else being equal), the total EF for BC, LCL and UCL scenarios would be between 78 and 80 m^2, reflecting savings of 25 per cent compared to case B. Spread over the time span 1998 – 2001, this results in annual space-savings of around 8 per cent [details Appendix E]. Hence, the EF clearly indicates a trend of declining resource use by a single product over time [Figure 30]. The share of the available per capita supply would be between 0.4 and 0.5 per cent, depending on the rate for biodiversity protection [Table 46].

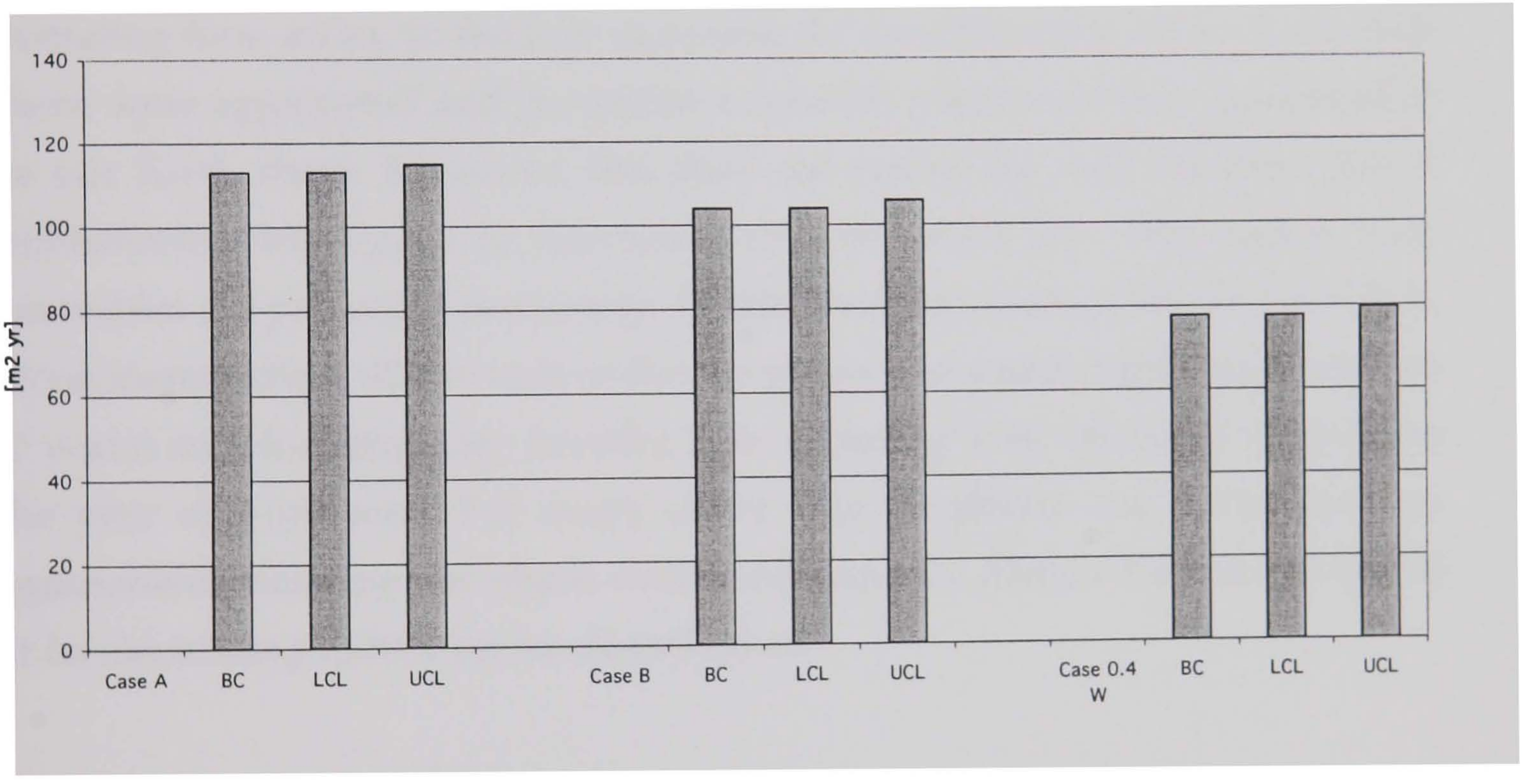

Figure 30. EF comparison: All cases and scenarios

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[35] 1.3 W charger used in analysis consumed in total 115.75 MJ electricity over 2.5 years (40.4 MJ/yr) [Wright, 1999], equivalent to 16954 g CO_2. A 0.4 W charger would therefore use 45.75 MJ/2.5 years:
(12.40 MJ of electricity consumed by a 0.4W charger per year plus 5.9 MJ from phone [Wright, 1999] = 18.3 MJ per year, x 2.5 years = 45.75).

0.4 W scenario	Fair Earth share (-12%)	Fair Earth share (-25%)
BC	0.41	0.49
LCL	0.41	0.49
UCL	0.42	0.50

Table 46. Share of ecological benchmark with 0.4 W scenario

7.7. *Time series for EF*

Since EFA traditionally measures the instantaneous demand and supply of biocapacity (snapshot) but the life cycle of the mobile phone was 2.5 years, the EF of the phone can be accounted for on a yearly basis. This is also useful for estimating time series. In the first approach the total life cycle areas of a mobile phone were aggregated and presented as one EF which was then compared to the fair Earth share. However, this does not reflect the real situation and is problematic with regard to non-renewable materials [pp. 106] unless non-renewables are presented separately. In this time series raw material extraction, phone manufacture, 40 per cent of the use phase (use phase burdens divided by 2.5 years) and, for simplicity, benefits from recycling were allocated to year one (the year of purchase). For every other year of phone use, only resource requirements from the use phase were accounted for. Hence, the time series EF for an electronic product can be described as:

$$EF = B_1 + \sum_{i=2}^{i=n} B_n \qquad \text{(Equation 8)}$$

Where B_1 are the total burdens from year one and B_n only the burdens from each subsequent year of use.

7.7.1. *Time series EF cases A and B*

When calculating the EF as a snapshot, burdens from the use phase are split over the life cycle duration of 2.5 years. Hence, for the first year, the EF for case A and its scenarios are around 85 to 87 m^2, while the EF for case B is between 76 and 78 m^2 (both reflecting between 0.4 to 0.5 per cent of the available per capita supply). For every additional year of product use, the EF is around 19 m^2 [Table 47] and [Table 48].

Case A	**Total EF year 1 [m²]**	**[%] of fair Earth share -12% biodiversity**	**[%] of fair Earth share -25% biodiversity**	**EF of additional year of use [m²]**
BC	**84.75**	**0.45**	**0.53**	**18.89**
LCL	**84.73**	**0.45**	**0.53**	**18.89**
UCL	**86.55**	**0.46**	**0.54**	**18.89**

Table 47. Case A: EF for year one, its share of per capita biocapacity supply, and additional EF

Case B	**Total EF year 1 [m²]**	**[%] of fair Earth share -12% biodiversity**	**[%] of fair Earth share -25% biodiversity**	**EF of additional year of use [m²]**
BC	**75.71**	**0.40**	**0.47**	**18.89**
LCL	**75.69**	**0.40**	**0.47**	**18.89**
UCL	**77.55**	**0.41**	**0.48**	**18.89**

Table 48. Case B: EF for year one, its share of per capita biocapacity supply, and additional EF

7.7.1.1. Time series scenario with 0.4 W charger

With a 0.4 W charger scenario, the total EF for year one is between 65 to 67 m^2 (BC to UCL scenario, assuming everything else being equal to case B), thus requiring 0.3 to 0.4 per cent of the fair Earth share. However, this EF scenario is purely speculative since it represents a newer product and the ecological benchmark is based on year 1996. The available biocapacity for 2001 is most likely lower than for 1996.

For every other year of use the EF is around 8 m^2 [Table 49]. In the year of purchase, the 0.4 W scenario is around 14 per cent more space efficient than case B and also indicates a trend towards space efficient technology [Figure 31].

0.4 W scenario	Total EF year 1 [m^2]	[%] of fair Earth share -12% biodiversity	[%] of fair Earth share -25% biodiversity	EF of additional year of use [m^2]
BC	**65.20**	**0.35**	**0.41**	**8.38**
LCL	**65.18**	**0.35**	**0.41**	**8.38**
UCL	**67.04**	**0.36**	**0.42**	**8.38**

Table 49. 0.4 W scenario: EF for year one, its share of per capita biocapacity supply, and additional EF

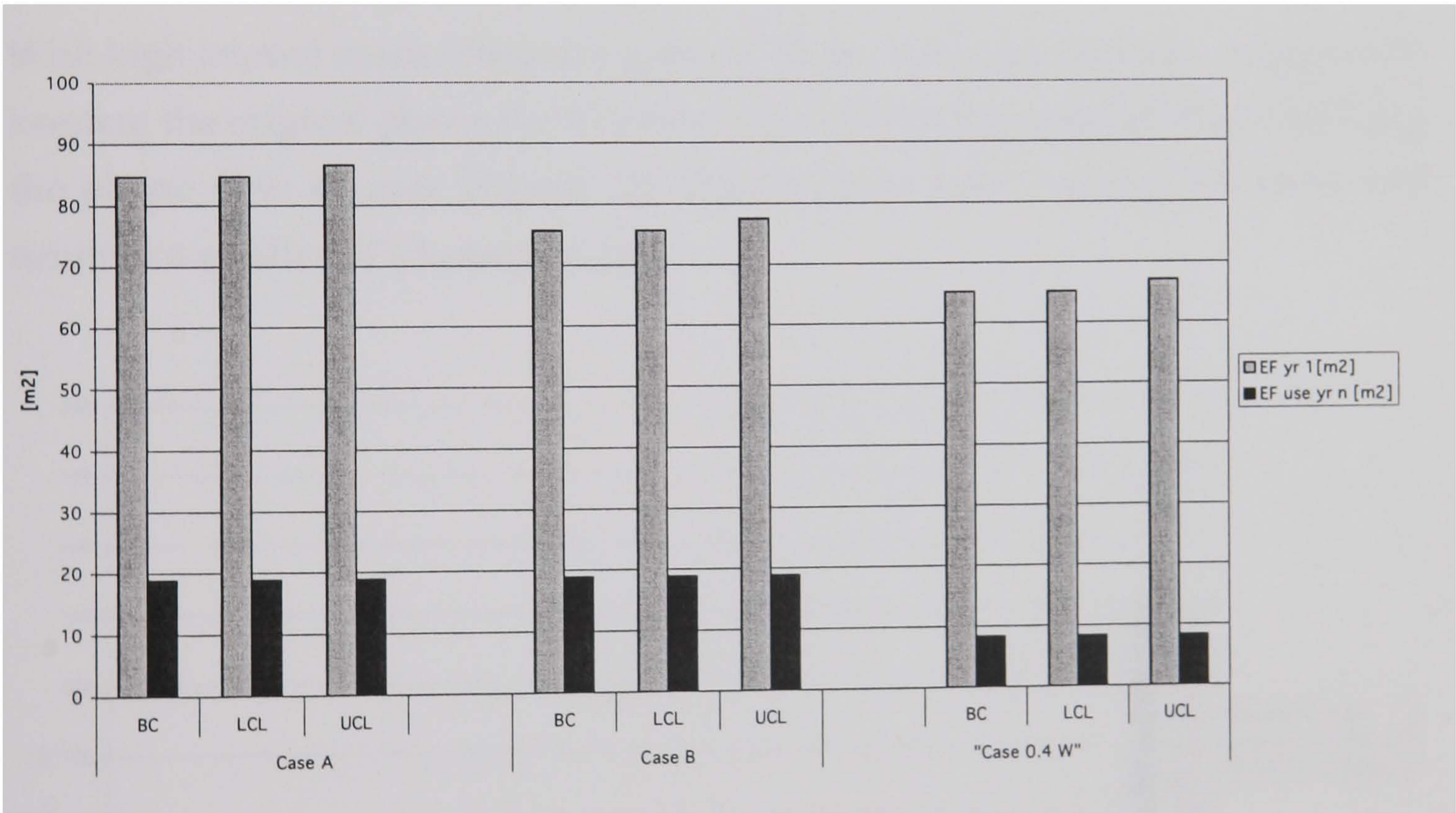

Figure 31. EF time series cases A, B and 0.4 Watt scenario

These results seem to suggest that with improved energy efficiencies, more carbon can be saved if products with lower energy consumption replace older products. However, this is only true as far as the use phase is considered, since each new phone replacement would add new embedded energy through raw material extraction, transport, and especially, manufacture. The following example of the 0.4W phone (with an average EF of 66 m^2 in the first year and 8

m^2 for subsequent years of use) over 10 years illustrates this, where a) the phone is kept, b) the phone is replaced every four years, assuming annual efficiency rates in phone design of 10 per cent, and c) of 20 per cent per year. These reductions refer to upstream burdens and burdens from the use phase.

Assuming annual efficiency gains of only one per cent and varying scenarios for phone replacement (4, 7 and 10 years), even after 40 years it is still more resource saving to keep the phone. At this efficiency rate, a break-even point can be expected after keeping the phone for 37 years before purchasing a new one.

With 10 per cent space savings per year, replacing the phone after 10 years costs less space than keeping the phone for 15 years (meaning the break even point is somewhere between 10 and 12 years at this rate).

With high annual space efficiency gains of 20 per cent, our findings suggest that keeping the original phone for 10 years will result in the same EF than replacing the phone after 4 years [Figure 32]. Replacement after 7 years, however, will result in a smaller EF [Appendix E].

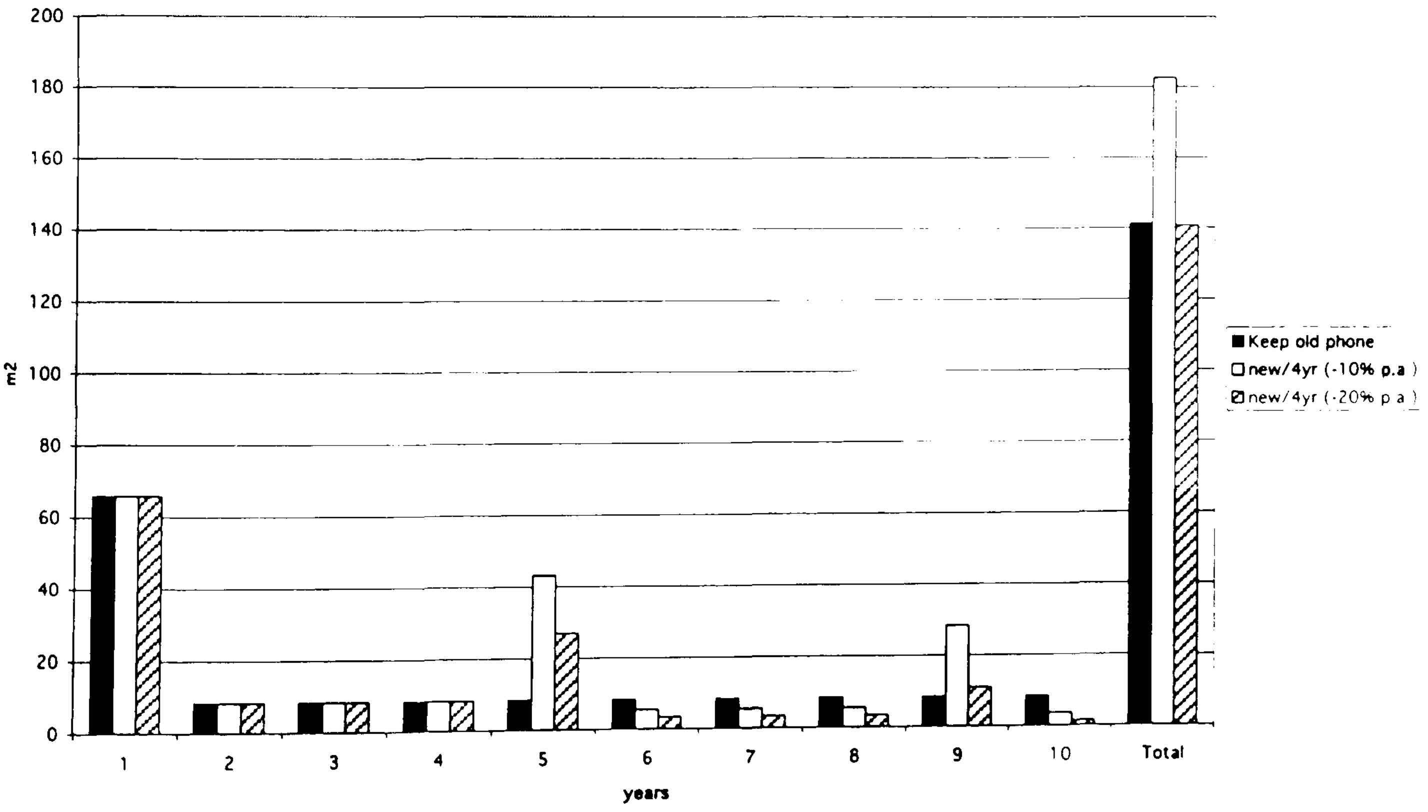

Figure 32. Scenario keeping old phone/replacing it every four years at different efficiency rates

In other words, annual efficiency rates have to be quite high to justify phone replacements for environmental reasons.

Based on these results, maintaining and upgrading an existing phone for quite some time will generally lead to a smaller EF, but break even points will vary depending on annual efficiency gains, modus of phone replacement, and the ratio between upstream burdens and burdens from the use phase. High embedded upstream burdens from extraction, manufacture and transport in comparison to the use phase support the case for keeping an "old phone" for quite some time.

7.7.1.2. Carbon sequestration rate of 35 per cent

If a 35 per cent carbon absorption rate was applied, the total EF for all mobile phone cases considered would be between 2 to 3 per cent smaller and the share of available biocapacity per capita would generally be about 0.1 per cent lower [Appendix E].

7.8. Summary and discussion

7.8.1. Direct land use results

When ranking the materials used during the life cycle of a mobile phone, long-term radiation from uranium caused the highest land use, followed by fossil energy materials despite their relatively small DLU values. The older mobile phone case A required up to 2.25 m^2 of DLU. Case B, updated by manufacturing energy, occupied up to 2.10 m^2 of direct land space, reflecting manufacturing energy savings. Between 54 and 58 per cent of land use resulted from the use phase, or around 1.20 m^2. This distribution is similar to that of total primary energy, since the energy resources required gave rise to certain land requirements. The effect of upper and lower confidence limits (UCL and LCL) for the rucksack estimates of certain commodities were also visible on an area basis. Overall, the UCL scenarios affected raw material extraction by less than one per cent, but by 32 to 33 per cent (0.02 m^2) when comparing BC and UCL manufacturing stages alone. However, this difference in UCL scenarios was not strong enough to change the ranking order for raw materials from the life cycle in total since use phase and phone manufacture outweigh the energy requirements in resource extraction. However, with the exception of uranium, DLU does not account for indirect effects from resource extraction. DLU estimates were crude approximations only, and have to be interpreted with their underlying assumptions and uncertainties. The observed differences between BC and UCL scenarios were smaller in terms of DLU than in terms of energy or CO_2. However, DLU results were sensitive enough to reflect changes throughout the life cycle, in line with the results from the energy analysis.

7.8.2. Total EF results

In summary, with an EF between 104 and 115 [m^2 $phone^{-1}$ yr], a mobile phone's EF is 7000 to 8000 times greater than its actual size. Since fossil energy use translates into carbon emissions and subsequently into carbon absorption land, it has to be remembered that the fossil fuel footprints are dependent on the energy mix - for example, whether based on fossil fuels or others such as hydropower.

Despite their large EF in comparison to their actual size, mobile phones occupy only a small amount - less than one per cent - of the fair Earth share. At the same time, the phone's EF was underestimated because:

- With regard to DLU, only half of the resource flows were included (despite covering 94 per cent by weight). The influence of missing input flows and hence, DLU values may be significant, but since DLU values were very small, most likely not significant enough to outweigh the influence from energy materials. At the same time, DLU values as used here only indicate the collateral damage from mining.
- Waste flows other than CO_2 were omitted (although these would have been a shadow footprint, some may have exceeded the non-additive EF areas).
- Water consumption was not included.
- Reduced bioproductivity from the emission of toxic substances was not included.
- Apart from a small transport section, other transport impacts, especially from global raw material extraction, were not included.
- Raw materials for charger and other accessories, and telecommunications network infrastructure were not included.

- Land space for raw materials extraction (fossil energy land) is also underestimated due to missing mining data for some precious metals.
- The landfill option was not investigated (for example, DLU requirements, emissions, or leaching associated with landfill).

In this study, 94 per cent of the EF is from CO_2 emissions, the remainder is from directly occupied or degraded land from mining operations. On average, the UCL scenarios required 1.80 m^2 more space than their base cases but improvements in manufacture saved around 9 m^2 or 8 per cent. Overall, a mobile phone needs less than one per cent (0.6 to 0.7 per cent for case A and B) of the available biocapacity per capita. Reductions in charger electricity consumption to 0.4 W resulted in a further EF reduction of 25 per cent compared to case B, reflecting 0.4 to 0.5 per cent of the fair Earth share.

This EFA suggests that for the three phone case studies examined, the EF size for the total life cycle has declined by about 8 per cent or around 9 m^2 between cases A and B over a time span of approximately two years (1996 -1998) and by a further 25 per cent (29 m^2) in the 0.4 W scenario from 1998 to 2001. This represents space savings of about 8 per cent per year. However, the differences between cases A and B were due to increased energy efficiencies in phone manufacture, whereas in the 0.4 W scenario, energy requirements were reduced by the use phase. It is likely that charger energy requirements between case A and B had changed, too. Due to this, these cases do not strictly represent three phone generations, but are rather approximations based on the data available at the time.

In 1996, 158 to 189 m^2 reflected 1 per cent of the fair Earth share. Hence, the fair Earth share of 1.89/1.60 ha per person is a high benchmark for a small product. However, despite this small scale, the EF was sensitive enough to detect differences between cases and scenarios.

However, using a snapshot approach made the EF of an electronic product more realistic. The EF for the first year of purchase and use was 85 to 87 m^2 for case A, 76 to 78 m^2 for case B, and 65 to 67 m^2 with a 0.4 W charger, depending on scenario and rate of biodiversity protection. Subsequent years of use only account for burdens from electricity consumption (around 19 m^2 for case A and B, and 8 m^2 for the 0.4 W scenario).

With regard to replacing older phones with new energy efficient ones must take into account the modus of phone replacement, the ratio between upstream burdens and use (the higher this ratio, the more difficult it is to justify a new phone) and the annual efficiency gains in phone generations. This EF study suggests that with annual space savings of 10 to 20 per cent, it is ecologically better to keep and maintain the phone for at least four years or longer if annual space savings are above 20 per cent, and for 10 to 12 years at 10 per cent rates, assuming reductions in both upstream processes and use phase. Since 8 per cent annual efficiency gains were suggested in the latest (0.4W) scenario, reflecting the 2001 market, current phones should be kept for at least 10 years.

The results also suggest that instead of replacing the phone completely, replacing just the charger (if a model with a lower power consumption became available) would be an environmentally better option since it would avoid upstream burdens of a new phone. However, charger manufacture and raw materials were not included in this study, although they can be expected to be significantly less than for the phone.

It would also be interesting how disposable cardboard phones would compare to the above findings, since upstream energy requirements may be lower.

If a 35 per cent CO_2 ocean absorption rate is assumed, overall EF decrease by 3 per cent, but this does not significantly affect the percentage of the fair Earth share. It only reflects changes in the existing biocapacity to absorb emissions, not in the EF.

CHAPTER 8: FINAL CONCLUSIONS AND FURTHER WORK

The focus of this thesis has been to apply EFA on electronic products, using new methods that allow associating the fair Earth share with a complex product such as a PC or mobile phone. Although there are other component EF studies that have included several categories associated with household consumption, as far as the author is aware, no EF study exists that has addressed EFA for electronic products. The methodology discussed in this thesis can be used as a screening tool for electronic products in order to compare their EF with the latest available fair Earth share, and is complementary to other assessment tools, for example, LCA.

8.1. Purpose of the analysis

The need to apply EFA to an electronic products level arose because environmental assessment tools for electronic products are mainly LCA based and focus on toxicity. The EF, in contrast, uses a wider lens, thus capturing the bigger picture of the life cycle consequences of electronic products. Whereas LCA provides information about a product or service through several environmental impact categories (and that is where it ends), EFA translates these impacts (as far as presently possible) into the corresponding bioproductive areas required, further aggregating these into a single indicator and comparing it to the ecological bottom line. As such, the EF goes one step further than LCA, revealing a wider, but still underestimated, picture of resource consumption by adding meaning to material, energy, and waste flows. This sets the EF apart from other environmental assessment tools.

8.2. The EF and the sustainability debate

Chapter 3 discussed main features of the sustainability debate, including weak and strong sustainability. The EF is a strong sustainability indicator because it accounts for biophysical resources and sets a benchmark. However, unlike models that measure marketable, non-renewable resources, the EF is an indicator for renewable resources (that are, so far, not marketable and may not become more costly with further depletion) which are critical for functioning ecosystems and generally not substitutable. Moreover, the EF has the potential to detect overshoot, which most other models cannot reveal. This becomes clear when discussing several strategies aimed at dematerialization and eco-efficiency: Despite important and many successful efforts towards improved energy efficiencies, overall energy consumption has risen. This may be enhanced by unsuitable environmental indicators that focus rather on compliance with environmental standards than on how much natural capital is available and consumed. An important conclusion from this discussion was that although factor X reductions are important, having an ecological benchmark is crucial in order to assess how far humans are off the mark and, subsequently, to challenge environmental decisions.

Advantages and limitations of the EF have been discussed. Most limitations of the EF are those of aggregate indicators in general. However, present hurdles to further add depth to the EF area (for example, pollutant accounting other than CO_2) are due to a lack of reliable research data on how these pollutants interact with, or affect bioproductivity. Improvement suggestions included accounting for ecosystem stress. This would mean adding qualitative criteria, whereas the EF is only a quantitative indicator. Furthermore, one must remember that since bioproductive areas have multiple functions, they cannot entirely be used for anthropogenic purposes. The overall conclusion of this discussion was that despite its limitations, the EF is a vivid indicator of global and regional dependence on functioning ecosystems. This gives the EF an advantage over other tools that measure specific environmental flows. The EF makes a suitable headline indicator for biophysical facts. It deliberately sets a minimum requirement for sustainability by applying a generous precautionary principle, illustrating the reality of living on a finite planet. For other questions, such as *how* CO_2 emissions can be stabilised, different tools are needed. Finally, ecosystems consist of *systems* and not only *areas*. The EF is only an aggregate area indicator, and thus, like any other aggregate indicators, should not be used alone.

8.3. EF methodology and data quality

The EF methodology used in this study partly relied on gathering and calculating direct land use (DLU) data, which was not easily available and often of poor quality. Therefore, many assumptions had to be made and it is important to consider the high uncertainty of these values. However, it was the only data that could be obtained at the time, and only valid until better data becomes available. With regard to the CO_2 sequestration method, it was concluded that despite its limitations, it is the best method at present since a) it is directly linked to current energy consumption practices, b) it is still the prevailing sequestration technology, c) it underestimates the true impact of fossil fuel use (thereby increasing its acceptance), and d) it can reflect space-saving technologies. This nevertheless illustrates that trees will not save us, since absorbing carbon can only be a partial and temporary solution to curb human CO_2 emissions.

First, the total EF over an electronic product's life cycle was calculated and compared to the fair Earth share. The main problems with this approach were that the use phase of electronic products requires dealing with different units of measurement for non-renewable and renewable materials and processes. One solution to this problem would be to present the area requirements for non-renewable materials separately from renewable processes. However, since the EF compares resource consumption and supply of resources at a given time, the product's life cycle had to be broken down into resource requirements at a given time. Subsequently, the life cycle EF was calculated for the first year of product use, containing the embedded upstream lifecycle burdens plus the burdens from the use phase for that year . Only the use phase was divided by the product's lifetime. The resulting EF (snapshot) for electronic products reflects instantaneous resource use, facilitates the aggregation of areas from different processes and the modelling of time series.

8.4. Applying EF analysis to electronic products

8.4.1. The PC exploratory study

A PC's total land area consumed amounted to around 0.13 ha, equivalent to a fair Earth share of 7 per cent, including ocean absorption for carbon. Updating this exploratory study by applying equivalence factors resulted in around 0.24 ha for the PC, or 13 to 15 per cent of the fair Earth share depending on the biodiversity protection ratio (between 12 and 25 per cent). This is a very high share for a single product (competing with the lower rate for biodiversity protection!) and maybe somewhat higher to date since today's (2002) fair Earth share is likely to be smaller. DLU values were insignificant in the PC (0.2 per cent) compared to fossil energy land, which was partly due to poor data availability.

8.4.2. Statistical analysis

A significant statistical correlation between abundance and rucksack values for "unknown" chemical elements was established. Based on regression analysis, for these elements rucksack values were predicted including their upper and lower 95 per cent confidence limits. From these predictions, assumptions were made regarding their energy requirements in raw materials extraction.

8.4.3. Mobile phone energy analysis

Energy analysis results for the mobile phones are underestimated, since data for raw material requirements (charger and battery) and for some precious metals (mining step) were not available. Transport and the landfill option were not considered in this study. Conclusions from the energy analysis were:

- Even on a small scale such as a mobile phone, it became visible that the country of manufacture can have a significant influence on the carbon emissions due to different energy mixes, making manufacture the highest phase in the life cycle for CO_2.
- A declining trend in energy requirements, and therefore carbon emissions due to reduced manufacturing energy and energy in use. Overall, these savings represented between 4 and 8 per cent per year if we assume that the mobile phones represent three different generations within the time span 1996-2001. However, savings in manufacture and use phase may have occurred simultaneously. Because only mixed and sometimes insufficient data was available, a precise time allocation is difficult.
- Within the life cycle, for both TPE and CO_2 the UCL scenarios caused a shift towards raw material extraction between 1 and 2 per cent. This was more pronounced in case B due to its lower manufacturing phase. The significance of the UCL scenarios was most striking between the raw material stages. Because of high rucksack values, UCL scenarios were 63 to 71 per cent above the BC and LCL scenarios.

- Estimated high rucksack values in the UCL scenarios also affected CO_2 ranking orders on the component level: Ranking the CO_2 emissions of components showed the highest overall carbon emitters by mass in the phone. Ranking CO_2 per mg component (normalised) reveals the carbon emissions regardless of the component weight. In the phone, gold and platinum group metals (PGM) had the highest CO_2 scores in the BC and LCL scenarios, while neodymium (Nd) and gallium (Ga) prevailed in the UCL scenarios. In the normalised ranking, only PGM prevailed in BC and LCL scenarios, but Ga, ruthenium (Ru) and lanthanum (La) were highest in the UCL scenarios. This means that in the BC and LCL scenarios, Ru and palladium (Pd) caused up to 98 per cent of the CO_2 contributions contained in resistors and capacitors. In the UCL scenarios, the first two highest ranks were LEDs (GaP causing almost 100 per cent of fossil CO_2 in these components).
- Although PGM, Nd and Ga in the phone were responsible for higher energy and emission values in the UCL scenarios, phone manufacture and use of the phone contributed the lion's share of CO_2 emissions.
- High normalised CO_2 emissions in raw materials extraction for PGM (BC and LCL scenarios) and for Ga and La in the UCL scenarios support the case for recycling and remanufacturing components containing these metals. In addition, since general databases do not include all specific burdens for producing electronic material grades [Spielmann and Schischke, 2001], results may be underestimated.
- Because manufacturing data was mainly based on supplier's information of only a few items such as PWB, GaAs- and Si-chips, overall manufacture is underestimated. This is supported by the study by [Stutz et al., 2000] for overheads and materials. Hence, LEDs, followed by resistors and capacitors, are likely to be of environmental concern, especially with high turnover rates for mobile phones.
- The findings that small amounts of materials extracted can have high emissions, and thus, a high land use, supported our previous results from the PC study [Frey, Harrison, Billett, 2000 a,b]. This is further supported by [Stutz et al., 2000] with regard to energy requirements for Au, Ag and Pd.
- Due to insufficient data, overheads such as heating, lighting, or air conditioning in component manufacture were not included in this study.

However, from the information available this may be a hidden iceberg, which could alter results significantly. [Stutz et al., 2000] support this.

8.4.4. The EF study on mobile phones

- Despite being up to 8000 times greater than its actual size, mobile phones occupy only a small amount of the fair Earth share (less than 1 per cent) with declining footprints over time. However, their EF is underestimated due to data paucity (missing resource flows and transport sections) or for methodological reasons (exclusion of non-additive aspects and of substances foreign to nature), [pp. 42].
- The DLU proportion was higher in the mobile phone than in the PC (6 versus 0.2 per cent). This was due to the inclusion of radiation (securing of sludge ponds in yellowcake production over a long time), [p. 84]. If this time factor is not included, the DLU proportions for PC and mobile phone are the same.
- An important conclusion about the use of EFA in electronic products was that although the fair Earth share (1.60 to 1.89 ha per capita in 1996) is a very high benchmark for a small product such as a mobile phone, EFA was still a sufficiently sensitive method for detecting small differences on a component level, making it possible to monitor technological changes.
- Despite its limitations, the EF gave a useful approximation for the bioproductive space required by a product.
- Mobile phones have become more resource - and hence, bioproductive space-efficient and this trend seems to continue. However, increasing turnover rates for mobile phones may outweigh these efficiency gains.
- Modus of phone replacement, the ratio between upstream burdens and use (the higher this ratio, the more difficult it is to ecologically justify a new phone) and the annual efficiency gains in phone generations determine the break-even points between keeping and replacing a mobile phone. Based on the factors included in this study, it is ecologically better to keep and maintain the phone for at least four years or longer if annual space savings are above 20 per cent, and for about ten to twelve years at 10 per cent rates, assuming reductions in both embedded energy and use phase. However, increased functionality of products (subject to further research) and consumer behaviour may act against this.

- Rather than purchase a new phone, it may be better to exchange for a more energy efficient charger (since embedded energy in the charger will probably be lower than in the mobile phone). A more comprehensive time analysis may be required for this. Materials for the charger were not included in this study due to lack of data.
- Because of a PC's high burdens in the use phase, time series and break even points will most likely differ from the mobile phone results. This was not tested in this study. The high ratio between energy in the use phase and embedded upstream energy may support a faster replacement rate than in a phone, depending on the criteria outlined above.
- Since fossil energy requirements translate into carbon emissions that translate into fossil fuel footprints, the EF results in this study depend on the energy mix used. Using non-fossil energy, for example renewables, will give different outcomes.
- The EF was suitable to detect differences in environmental impact between very different electronic products.
- The results suggest that measuring the amount of nature consumed per unit of production should become a strategy for differentiating products and services.

Finally, the sustainability criteria outlined in Chapter 3 [p. 106] demand that the presented EF methodology can be applied to an electronic product if a) a product's (CO_2)-emissions can be measured and adequately be transformed into a corresponding area, b) the degree to which it contributes to the deterioration of long-term productivity or threatens bioproductivity can be measured and its impacts can adequately be transformed into land space, c) its EF can be compared with the available per capita supply, and d) technological change can be measured, making the EF responsive to change and potentially indicating trends of future product developments. It was concluded that the methodology was suitable for assessing the environmental impacts of electronic products.

8.5. Future work

Further work to extend the study presented could include:

- Multiple regression analysis to regress rucksack values against other potential predictors than abundance in order to find closer overall relationships. For example, in a quick correlation estimate between rucksack and density values for 17 pairs of data, a significant positive Spearman's correlation coefficient of $\mathbf{r}_s = 0.7$ ($p < 0.001$ for a two-tailed test) and a Pearson correlation of $\mathbf{r} = 0.5$ ($p < 0.05$, two-tailed test) was found.
- More detailed and in-depth time series analysis for mobile phone footprints, including the determination of break-even points (BEP) for product replacement. Chalkley, Harrison and Billett [2002] have calculated BEP for electronic products. Applying their BEP- formula[36] to the EF outcomes [p. 183] results in BEPs of the same order of magnitude with small efficiency rates, but larger gaps with higher rates (38 versus 37 years for annual 1 per cent efficiency improvements, 12 years versus 10 to 12 years at 10 per cent annual efficiency gains, and just above 8 years versus our 4 years at 20 per cent. This is explained by assuming efficiency gains in both upstream burdens *and* use for the EF time series, whereas in the formula, upstream burdens are constant.
- Establish the EF of other common electronic products and electrical appliances and compare these with each other, or with different products and services.
- To estimate the EF of electronic products or their components on larger scales, for example, Europe or the world. This might be of specific interest with regard to extrapolating very small differences in a single product (such as changes in raw materials) to a global or European level. A quick "back of the envelope" calculation [Appendix F] suggests that, given the estimated 340 million (m) mobile phones sold world-wide in 2001 [Zogbi, 2001], altogether these phones require more than 2.2 m hectares (ha) of bioproductive space – or as much as was available (in 1996) for 1.17 m world-average citizens at a fair Earth share.
- To include shadow EFs for acidification based on critical loads of sulphur and nitrogen.

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[36] $t^2 = \sqrt{\frac{2B}{M}}$, where t^2 is the BEP, B are the upstream burdens, and M the annual efficiency rate [Chalkley, Harrisson, Billett, 2002].

CHAPTER 9: BIBLIOGRAPHY

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CHAPTER 10: APPENDICES

Appendix A

10.1. Land use database

DLU Land use database

		Iron ore	**Pig iron**	**Bauxite**	**Aluminium**	**Aggregates, Sand+Gravel**	**Gypsum, crude**	**Bentonite**	**Magnesite**	**Limestone**
Direct land use [calc. From ETHZ, 1996]	m2/kg	**1.11E-05**		**1.14E-04**	**5.70E-04**	**1.80E-04**	**1.80E-04**	**1.33E-04**		**5.00E-06**
Overburden-Multiplier										
Douglas and Lawson, 1998			5.2	3		1.38 and 1.75		4	1.2	1.36
ETHZ, 1996					3.68		0.5			
Schmidt-Bleek, 1997				5		0.65				1.2
Direct land use*overburden:	m2/kg	**1.11E-05**	**5.77E-05**	**5.70E-04**	**2.10E-03**	**1.80E-04**	**1.80E-04**	**5.32E-04**		**6.80E-06**
Area for process steps after exploration:	m2/kg		**1.25E-03**							
Sum mining data plus process data:	m2/kg		**1.31E-03**							

		Lime	**Portl. Cement**	**Clay**	**Chromium**	**Manganese Ore**	**Manganese, pure**	**Copper**	**Cu 60% rec.**	**Barites (BaSO4)**
Direct land use [calc. From ETHZ, 1996]	m2 / kg		**1.80E-04**	**1.80E-04**	**1.11E-05**	**4.23E-04**		**6.41E-04**	**2.56E-04**	**1.00E-03**
Overburden-Multiplier										
Douglas and Lawson, 1998			1.38		2		6	450		2
ETHZ, 1996		2:1 L'stone:Lime		1.5			4 (4 kg ore/kg pure Mn)	416		17
Schmidt-Bleek, 1997			10					420		
Direct land use*overburden:	m2/kg	**1.36E-05**	**1.80E-04**	**1.80E-04**	**2.22E-05**		**2.54E-03**	**2.88E-01**	**1.15E-01**	**1.00E-03**

		surface mining 70%	surface mining 3(	underground 50%				All processes included
		land cat II	cat II	cat II				except for MJ
		Hardcoal S	**Lignite**	**Hardcoal U**	**Wood, standing**	**Crude Oil**	**Natural gas (LPG)**	**Uranium (U)**
Direct land use: m2/kg	m2 / kg	**1.80E-04**	**4.00E-05**	**2.00E-05**	temperate plant.reg.	**5.53E-03**	**2.03E-03**	9.45E-02
[calc. from ETHZ, 1996]					IPCC default: 1m3 wood = 0.5 tdm [wb. p. 5.6]			
						95% in W. Europe offshore	22% offshore, UCPTE	weighted surface/undergr.
					5000 kg of dm/yr (average acc. of dm plantation)			
					*15% humidity (Wackernagel et al. spreadsheets)			
					=5750 kg wood/ha/yr			
Subsidence coal m2 / kg [ETHZ, 1996]	m2 / kg	**3.10E-04**	**3.10E-04**	**1.00E-03**	* 1.9 expansion-r. in plantation (IPPC rf. 5.21)			
					= 10925 kg/ha/yr	1.25E-05m2/kg for infra		
					/10'000 m2			
					=1.09 kg wood/ m2/yr			
Overburden-Multiplier:					1/x= 0.9 m2/kg wood/yr			
Douglas and Lawson, 1998		4.87	9.9	4.87		(*1.016)		900
ETHZ, 1996		1.43	1	0.9		1.18t crude oil/t fuel; 1.1 t for diesel		(not calc. due to total area
Schmidt-Bleek, 1997		6	11	6				used)
Direct land use*overburden(+subsidence):	m2 / kg	4.90E-04	3.50E-04	1.02E-03	**9.10E-01**	**5.53E-03**	**2.03E-03**	
Area for process steps after exploration:		1.26E-05	1.20E-06			**2.95E-05**	**4.59E-06**	
Sum mining data plus process data:		**5.03E-04**	**3.51E-04**			**5.56E-03**	2.03E-03	**3.90E+03**
								m2a/kg to account for
								radiation

Appendix B

10.2. PC Study

DLU Control Unit

Resource consumption: Control Unit w/o packaging				[m2/PC unit]		[m2/PC unit]		[m2/PC unit]		[m2/PC unit]		[m2/PC unit]		[m2/PC unit]	x-check m2:		x-check kg:
															9.16E-01		1.62E+02
Resource			Quantity	**M-prod.**	Quantity	**Mfct.**	Quantity	**Distrib.**	Quantity	**Use**	Quantity	**Disp.**	Quantity	**Cred.Rec.**	**Total m2/unit**	**Water (g)**	Total kg
Aluminium	kg		5.08E-01		1.75E-04		7.13E-06		6.54E-05		1.46E-05		-6.88E-02				4.39E-01
		Direct land use m2/qty.		1.07E-03		3.67E-07		1.50E-08		1.37E-07		3.06E-08		-1.44E-04	**9.22E-04**		
CaCO3 (as for limestone)	kg		1.18E+00		2.33E-03		2.03E-02		1.15E-04		1.46E-05		-1.55E-01				1.05E+00
		Direct land use m2/qty.		8.02E-06		1.58E-08		1.38E-07		7.82E-10		9.93E-11		-1.05E-06	**7.12E-06**		
Chromium	kg		3.71E-04														3.71E-04
Clay (as for sand)			1.84E-01		6.01E-05		2.68E-03		2.45E-05		1.03E-06		-6.51E-06				1.87E-01
		Direct land use m2/qty.		6.35E-06		2.07E-09		9.25E-08		8.45E-10		3.55E-11		-2.25E-10	**6.44E-06**		
Cu	kg		4.56E-01		3.37E-02								-6.52E-02				4.25E-01
		Direct land use m2/qty.		1.32E-01		9.72E-03		0.00E+00		0.00E+00		0.00E+00		-1.88E-02	**1.22E-01**		
Crude oil, fuel	kg		2.33E+00		4.37E+00		9.16E-02		9.42E+00		5.33E-02		-2.29E-01				1.60E+01
		Direct land use m2/qty.		1.84E-02		3.46E-02		7.24E-04		7.45E-02		4.22E-04		-1.81E-03	**1.27E-01**		
Crude oil,raw mat.	kg		4.06E-01		5.02E-04		3.15E-04		5.44E-06		4.16E-05		-2.59E-08				4.07E-01
		Direct land use m2/qty.		3.21E-03		3.97E-06		2.49E-06		4.30E-08		3.29E-07		-2.05E-10	**3.22E-03**		
Ground water	kg															**1.87E+03**	
Hard coal, fuel	kg		5.77E+00		1.50E+01		4.45E-04		5.26E+01		1.14E-01		-8.02E-01				7.26E+01
		Direct land use m2/qty.		5.36E-03		1.39E-02		4.14E-07		4.89E-02		1.05E-04		-7.45E-04	**6.75E-02**		
Fe	kg		5.66E+00		1.22E-02		7.49E-06		6.79E-05		1.45E-04		-8.46E-01				4.83E+00
		Direct land use m2/qty.		4.86E-04		1.05E-06		6.43E-10		5.83E-09		1.24E-08		-7.26E-05	**4.14E-04**		
Pb	kg		9.60E-03		1.90E-02								-3.17E-03				*2.54E-02*
Lignite, fuel	kg		1.18E+00		1.12E+01		1.39E-08		4.18E+01		7.36E-02		-1.49E-01				5.41E+01
		Direct land use m2/qty.		5.91E-04		5.61E-03		6.97E-12		2.10E-02		3.69E-05		-7.47E-05	**2.71E-02**		
Mn	kg		3.62E-02		7.84E-05		4.46E-08		3.80E-07		1.76E-08		-5.47E-03				3.08E-02
		Direct land use m2/qty.		9.19E-05		1.99E-07		1.13E-10		9.64E-10		4.47E-11		-1.39E-05	**7.82E-05**		
Nat. gas, fuel	kg		1.37E+00		1.98E+00		5.50E-03		6.68E+00		7.69E-02		-1.40E-01				9.97E+00
		Direct land use m2/qty.		9.70E-06		1.40E-05		3.89E-08		4.73E-05		5.44E-07		-9.91E-07	**7.06E-05**		
Nat. gas,raw mat.	kg		3.35E-01														3.35E-01
		Direct land use m2/qty.		2.37E-06		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00	**2.37E-06**		
Ni	kg		1.02E-02														1.02E-02
Quartz (as for sand)	kg		1.82E-01		2.05E-05						2.63E-09		-1.45E-03				1.81E-01
		Direct land use m2/qty.		6.28E-06		7.07E-10						9.07E-14		-5.00E-08	**6.23E-06**		
Reservoir water	kg															**3.04E+04**	
NaCl	kg		3.20E-01		1.06E-01		1.25E-05		1.14E-04		5.22E-03		-9.30E-03				*4.22E-01*
Surface water	kg															**4.11E+01**	
Sn	kg				3.36E-02												*3.36E-02*
Unspec. biomass, dm, fuel	kg		4.01E-01		2.01E-02		1.79E-08		3.09E-10		3.12E-04		-5.48E-02				3.67E-01
				3.65E-01		1.83E-02		1.63E-08		2.81E-10		2.84E-04		-4.99E-02	**3.34E-01**		
Unspec. biomass, dm, raw mat.	kg		2.77E-05		2.41E-03				8.98E-03		1.58E-05		-1.54E-08				1.14E-02
				2.52E-05		2.19E-03		0.00E+00		8.17E-03		1.44E-05		-1.40E-08	**1.04E-02**		
Unspec. fuel	MJ																
(1.23E-04 m2/MJ) for benthos		**Direct land use m2/qty.**		1.27E-03		7.88E-05		-1.17E-06		7.91E-08		-2.12E-04		-1.78E-04	**9.55E-04**		
Unspec. minerals	kg										1.22E-02						1.22E-02
Unspec. resources	kg																0.00E+00
[illegible]	kg															**6.60E+06**	
Uranium	kg		7.18E-05		1.04E-03		2.32E-09		3.84E-03		6.85E-06		-7.42E-06				4.95E-03
		Direct land use m2/qty.		1.66E-05		2.41E-04		5.37E-10		8.88E-04		1.58E-06		-1.72E-06	**1.15E-03**		
Wood, soft, dm, fuel	kg		2.41E-01		2.02E-03												2.43E-01
				2.19E-01		1.84E-03		0.00E+00		0.00E+00		0.00E+00		0.00E+00	**2.21E-01**		
Zn	kg		3.72E-03		1.71E-01								-5.25E-04				1.74E-01
Sum [m2]				**7.46E-01**		**8.65E-02**		**7.26E-04**		**1.53E-01**		**6.53E-04**		**-7.17E-02**	**9.16E-01**		
Sum [kg] w/o water and MJ			2.06E+01		3.29E+01		1.21E-01		1.11E+02		3.35E-01		-2.53E+00		1.62E+02	**6.63E+06**	
sum m2 w/o woody:				1.62E-01		6.41E-02		7.26E-04		1.45E-01		3.55E-04		-2.19E-02	**3.51E-01**		
sum kg w/o woody:			1.99E+01		3.29E+01		1.21E-01		1.11E+02		3.35E-01		-2.47E+00		1.61E+02		

DLU Monitor

Resource consumption: Monitor w/o packaging				[m2/PC unit]		[m2/PC unit]		[m2/PC unit]		[m2/PC unit]		[m2/PC unit]		[m2/PC unit]	x-check m2:		x-check kg:
															6.44E-01		2.36E+02
Resource	**Unit**		Quantity	**M-prod.**	Quantity	**Mfct.**	Quantity	**Distrib.**	Quantity	**Use**	Quantity	**Disp.**	Quantity	**Cred.Rec.**	**Total m2/unit**	**Water (g)**	Total kg
Aluminium	kg		6.61E-02		2.69E-03		1.03E-05		1.09E-04		5.62E-06		-6.92E-03				6.20E-02
		Direct land use m2/qty.		1.39E-04		5.64E-06		2.16E-08		2.29E-07		1.18E-08		-1.45E-05	**1.30E-04**		
CaCO3 (as for limestone)	kg		4.34E-01		4.69E-04		2.93E-05		1.19E-04		7.36E-02		-3.21E-02				4.76E-01
		Direct land use m2/qty.		2.95E-06		3.19E-09		1.99E-10		8.09E-10		5.00E-07		-2.18E-07	**3.24E-06**		
Chromium	kg		4.21E-02														4.21E-02
Clay (as for sand)			5.17E-01		5.46E-05		3.87E-06		4.09E-05		9.61E-07		-2.66E-06				5.17E-01
		Direct land use m2/qty.		1.78E-05		1.88E-09		1.34E-10		1.41E-09		3.32E-11		-9.18E-11	**1.78E-05**		
Cu	kg		6.62E-01		9.04E-03								-9.84E-02				5.73E-01
		Direct land use m2/qty.		1.91E-01		2.61E-03		0.00E+00		0.00E+00		0.00E+00		-2.84E-02	**1.65E-01**		
Crude oil, fuel	kg		1.81E+00		3.85E+00		1.33E-01		1.57E+01		3.68E-02		-9.29E-02				2.14E+01
		Direct land use m2/qty.		1.43E-02		3.04E-02		1.05E-03		1.24E-01		2.91E-04		-7.35E-04	**1.70E-01**		
Crude oil,raw mat.	kg		1.47E+00		5.85E-04		4.55E-04		9.07E-06		5.23E-05		-1.65E-08				1.47E+00
		Direct land use m2/qty.		1.16E-02		4.63E-06		3.60E-06		7.17E-08		4.14E-07		-1.30E-10	**1.16E-02**		
Ground water	kg															**6.24E+02**	
Hard coal, fuel	kg		2.02E+00		1.09E+01		6.44E-04		8.77E+01		3.07E-02		-2.61E-01				1.00E+02
		Direct land use m2/qty.		1.88E-03		1.01E-02		5.98E-07		8.15E-02		2.85E-05		-2.43E-04	**9.33E-02**		
Fe	kg		9.67E-01		1.33E-03		1.08E-05		1.13E-04		3.14E-05		-1.82E-01				7.86E-01
		Direct land use m2/qty.		8.30E-05		1.14E-07		9.27E-10		9.70E-09		2.69E-09		-1.56E-05	**6.75E-05**		
Pb	kg		5.02E-01		5.11E-03								-1.97E-03				*5.05E-01*
Lignite, fuel	kg		1.90E-01		6.82E+00		2.01E-08		6.97E+01		1.49E-02		-2.31E-02				7.67E+01
		Direct land use m2/qty.		9.52E-05		3.42E-03		1.01E-11		3.49E-02		7.47E-06		-1.16E-05	**3.84E-02**		
Mn	kg		9.54E-03		8.48E-06		6.45E-08		6.33E-07		1.16E-08		-1.17E-03				8.38E-03
		Direct land use m2/qty.		2.42E-05		2.15E-08		1.64E-10		1.61E-09		2.94E-11		-2.97E-06	**2.13E-05**		
Nat. gas, fuel	kg		1.39E+00		1.47E+01		7.96E-03		1.11E+01		2.06E-02		-4.94E-02				2.72E+01
		Direct land use m2/qty.		9.84E-06		1.04E-04		5.63E-08		7.86E-05		1.46E-07		-3.50E-07	**1.92E-04**		
Nat. gas,raw mat.	kg		1.33E+00														1.33E+00
		Direct land use m2/qty.		9.41E-06		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00	**9.41E-06**		
Ni	kg		2.46E-02														2.46E-02
Quartz (as for sand)	kg		3.66E+00		2.01E-06						5.35E-10		-3.11E-04				3.66E+00
		Direct land use m2/qty.		1.26E-04		6.93E-11		0.00E+00		0.00E+00		1.85E-14		-1.07E-08	**1.26E-04**		
Reservoir water	kg															**4.07E+04**	
NaCl	kg		2.80E-01		4.08E-03		1.81E-05		1.91E-04		5.31E-04		-9.53E-04				*2.84E-01*
Surface water	kg															**1.27E+01**	
Sn	kg				9.02E-03												*9.02E-03*
Titanium dioxide	kg	**Direct land use m2/qty.**	1.90E-02														1.90E-02
				6.56E-07		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00	**6.56E-07**		
Unspec. biomass, dm, fuel	kg		1.00E-01		6.94E-03		2.58E-08		5.16E-10		4.07E-04		-1.13E-02				9.60E-02
				9.10E-02		6.32E-03		2.35E-08		4.70E-10		3.70E-04		-1.03E-02	**8.74E-02**		
Unspec. biomass, dm, raw mat.	kg		7.77E-06		1.47E-03				1.50E-02		3.19E-06		-9.57E-09				1.65E-02
		Direct land use m2/qty.		7.07E-06		1.34E-03		0.00E+00		1.37E-02		2.90E-06		-8.71E-09	**1.50E-02**		
Unspec. fuel	MJ	**Direct land use m2/qty.**															
				1.44E-03		1.86E-05		-1.70E-06		1.32E-07		-1.81E-03		-2.16E-04	**-5.68E-04**		
Unspec. minerals	kg										2.47E-03						2.47E-03
Unspec. resources	kg		1.07E-02		6.56E-06						1.74E-09		-1.02E-03				9.69E-03
Unspec. water	kg															9.48E+06	
Uranium	kg	**Direct land use m2/qty.**	5.07E-05		6.27E-04		3.36E-09		6.40E-03		1.49E-06		-3.75E-06				7.08E-03
				1.17E-05		1.45E-04		7.77E-10		1.48E-03		3.45E-07		-8.67E-07	**1.64E-03**		
Wood, soft, dm, fuel	kg	**Direct land use m2/qty.**	6.48E-02		3.80E-03								-3.75E-04				6.82E-02
				5.90E-02		3.46E-03		0.00E+00		0.00E+00		0.00E+00		-3.41E-04	**6.21E-02**		
Zn	kg		2.22E-02														2.22E-02
Sum [m2]				**3.71E-01**		**5.80E-02**		**1.05E-03**		**2.56E-01**		**-1.11E-03**		**-4.02E-02**	**6.44E-01**		
Sum [kg] w/o water and MJ			1.56E+01		3.63E+01		1.42E-01		1.84E+02		1.80E-01		-7.63E-01		2.36E+02	**9.52E+06**	
sum m2 w/o woody:				2.21E-01		4.69E-02		1.05E-03		2.42E-01		-1.48E-03		-2.96E-02	**4.80E-01**		
sum kg w/o woody:			1.54E+01		3.63E+01		1.42E-01		1.84E+02		1.80E-01		-7.52E-01		**2.36E+02**		

DLU Keyboard

Resource consumption: Keyboard w/o packaging				[m2/PC unit]		[m2/PC unit]		[m2/PC unit]		[m2/PC unit]		[m2/PC unit]		[m2/PC unit]	x-check [m2]		x-check kg:
															4.26E-02		3.76E+00
Resource	**Unit**		Quantity	**M-prod.**	Quantity	**Mfct.**	Quantity	**Distrib.**	Quantity	**Use**	Quantity	**Disp.**	Quantity	**Cred.Rec.**	**Total m2/unit**	**Water (g)**	Total kg
Aluminium	kg		1.62E-04		1.51E-05		1.01E-06				8.14E-07		-1.86E-06				1.77E-04
		Direct land use m2/qty.		3.40E-07		3.17E-08		2.12E-09		0.00E+00		1.71E-09		-3.90E-09	**3.71E-07**		
CaCO3 (as for limestone)	kg		5.66E-02		2.36E-05		2.86E-06				8.92E-03		-6.89E-03				5.87E-02
		Direct land use m2/qty.		3.85E-07		1.60E-10		1.94E-11		0.00E+00		6.07E-08		-4.69E-08	**3.99E-07**		
Clay (as for sand)	kg		1.37E-02		4.75E-06		3.78E-07				7.62E-08		-2.58E-07				1.37E-02
		Direct land use m2/qty.		4.73E-07		1.64E-10		1.30E-11		0.00E+00		2.63E-12		-8.90E-12	**4.73E-07**		
Cu	kg		4.36E-02		2.50E-03								-5.57E-03				4.05E-02
		Direct land use m2/qty.		1.26E-02		7.21E-04		0.00E+00		0.00E+00		0.00E+00		-1.61E-03	**1.17E-02**		
Crude oil, fuel	kg		3.55E-01		1.85E-01		1.29E-02				3.48E-03		-9.13E-03				5.47E-01
		Direct land use m2/qty.		2.81E-03		1.46E-03		1.02E-04		0.00E+00		2.75E-05		-7.22E-05	**4.33E-03**		
Crude oil,raw mat.	kg		4.48E-01		5.74E-05		4.45E-05				5.13E-06		-1.23E-09				4.48E-01
		Direct land use m2/qty.		3.54E-03		4.54E-07		3.52E-07		0.00E+00		4.06E-08		-9.73E-12	**3.54E-03**		
Ground water	kg															**6.73E-02**	
Hard coal, fuel	kg		2.84E-01		1.14E+00		6.29E-05				5.57E-03		-3.37E-02				1.40E+00
		Direct land use m2/qty.		2.64E-04		1.06E-03		5.84E-08		0.00E+00		5.18E-06		-3.13E-05	**1.30E-03**		
Fe	kg		2.73E-01		1.32E-05		1.06E-06				7.07E-06		-4.05E-02				2.33E-01
		Direct land use m2/qty.		2.34E-05		1.13E-09		9.09E-11		0.00E+00		6.07E-10		-3.47E-06	**2.00E-05**		
Pb	kg				5.05E-04								-3.90E-05				4.66E-04
Lignite, fuel	kg		3.31E-02		1.07E-01		1.96E-09				3.49E-03		-3.50E-03				1.40E-01
		Direct land use m2/qty.		1.66E-05		5.36E-05		9.82E-13		0.00E+00		1.75E-06		-1.75E-06	**7.02E-05**		
Mn	kg		1.76E-03		7.72E-08		6.29E-09				9.37E-10		-2.62E-04				1.50E-03
		Direct land use m2/qty.		4.47E-06		1.96E-10		1.60E-11		0.00E+00		2.38E-12		-6.65E-07	**3.80E-06**		
Nat. gas, fuel	kg		3.42E-01		3.97E-02		7.77E-04				3.95E-03		-6.73E-03				3.80E-01
		Direct land use m2/qty.		2.42E-06		2.81E-07		5.50E-09		0.00E+00		2.80E-08		-4.76E-08	**2.69E-06**		
Nat. gas,raw mat.	kg		4.13E-01														4.13E-01
		Direct land use m2/qty.		2.92E-06		0.00E+00		0.00E+00		0.00E+00		0.00E+00		0.00E+00	**2.92E-06**		
Quartz (as for sand)	kg		1.33E-02										-6.94E-05				1.32E-02
		Direct land use m2/qty.		4.59E-07		0.00E+00		0.00E+00		0.00E+00		0.00E+00		-2.39E-09	**4.56E-07**		
Reservoir water	kg															**1.64E+02**	
NaCl	kg		3.24E-02		9.87E-03		1.76E-06				1.27E-06		-2.96E-06				4.23E-02
Surface water	kg															**1.37E-03**	
Sn	kg				9.50E-04												9.50E-04
Unspec. biomass, dm, fuel	kg		3.82E-03		2.77E-03		2.53E-09				2.83E-05		-5.19E-04				6.10E-03
		Direct land use m2/qty.		3.48E-03		2.52E-03		2.30E-09		0.00E+00		2.58E-05		-4.72E-04	**5.55E-03**		
Unspec. biomass, dm, raw mat.	kg		2.06E-06		2.26E-05						7.51E-07		-1.90E-10				2.54E-05
		Direct land use m2/qty.		1.87E-06		2.06E-05		0.00E+00		0.00E+00		6.83E-07		-1.73E-10	**2.31E-05**		
Unspec. fuel	MJ																0.00E+00
		Direct land use m2/qty.		1.07E-04		5.29E-06		-1.66E-07		0.00E+00		-5.79E-04		-1.37E-05	**-4.81E-04**		
Unspec. minerals	kg										5.88E-04						5.88E-04
Unspec. resources	kg		1.53E-03										-2.26E-04				1.30E-03
Unspec. water	kg																
Uranium	kg		6.86E-06		1.02E-05		3.28E-10				3.27E-07		-3.71E-07				1.70E-05
		Direct land use m2/qty.		1.59E-06		2.36E-06		7.59E-11		0.00E+00		7.56E-08		-8.58E-08	**3.94E-06**		
Wood, soft, dm, fuel	kg		1.79E-02		2.24E-04												1.81E-02
		Direct land use m2/qty.		1.63E-02		2.04E-04		0.00E+00		0.00E+00		0.00E+00		0.00E+00	**1.65E-02**		
Zn	kg				3.84E-03												3.84E-03
Sum [m2]				**3.91E-02**		**6.05E-03**		**1.02E-04**		**0.00E+00**		**-5.18E-04**		**-2.20E-03**	**4.26E-02**		
Sum [kg] w/o water and MJ			2.33E+00		1.49E+00		1.38E-02		0.00E+00		2.60E-02		-1.07E-01	3.76E+00		**3.76E+00**	
sum m2 w/o woody:				1.94E-02		3.31E-03		1.02E-04		0.00E+00		-5.45E-04		-1.73E-03	**2.05E-02**		
sum kg w/o woody:			2.31E+00		1.49E+00		1.38E-02		0.00E+00		2.60E-02		-1.07E-01		**3.74E+00**		

Ranks in kg and m2 PC system

Resource consumption: Control Unit w/o packaging		Resource consumption: Monitor w/o packaging		Resource consumption: Keyboard w/o packaging	
Resource	**Total kg**	**Resource**	**Total kg**	**Resource**	**Total kg**
Hard coal, fuel	7.26E+01	Hard coal, fuel	1.00E+02	Hard coal, fuel	1.40E+00
Lignite, fuel	5.41E+01	Lignite, fuel	7.67E+01	Crude oil, fuel	5.47E-01
Crude oil, fuel	1.60E+01	Nat. gas, fuel	2.72E+01	Crude oil,raw mat.	4.48E-01
Nat. gas, fuel	9.97E+00	Crude oil, fuel	2.14E+01	Nat. gas,raw mat.	4.13E-01
Fe	4.83E+00	Quartz (as for sand)	3.66E+00	Nat. gas, fuel	3.80E-01
CaCO3 (as for limestone)	1.05E+00	Crude oil,raw mat.	1.47E+00	Fe	2.33E-01
Aluminium	4.39E-01	Nat. gas,raw mat.	1.33E+00	Lignite, fuel	1.40E-01
Cu	4.25E-01	Fe	7.86E-01	CaCO3 (as for limestone)	5.87E-02
NaCl	4.22E-01	Cu	5.73E-01	NaCl	4.23E-02
Crude oil,raw mat.	4.07E-01	Clay (as for sand)	5.17E-01	Cu	4.05E-02
Unspec. biomass, dm, fuel	3.67E-01	Pb	5.05E-01	Wood, soft, dm, fuel	1.81E-02
Nat. gas,raw mat.	3.35E-01	CaCO3 (as for limestone)	4.76E-01	Clay (as for sand)	1.37E-02
Wood, soft, dm, fuel	2.43E-01	NaCl	2.84E-01	Quartz (as for sand)	1.32E-02
Clay (as for sand)	1.87E-01	Unspec. biomass, dm, fuel	9.60E-02	Unspec. biomass, dm, fuel	6.10E-03
Quartz (as for sand)	1.81E-01	Wood, soft, dm, fuel	6.82E-02	Zn	3.84E-03
Zn	1.74E-01	Aluminium	6.20E-02	Mn	1.50E-03
Sn	3.36E-02	Chromium	4.21E-02	Unspec. resources	1.30E-03
Mn	3.08E-02	Ni	2.46E-02	Sn	9.50E-04
Pb	2.54E-02	Zn	2.22E-02	Unspec. minerals	5.88E-04
Unspec. minerals	1.22E-02	Titanium dioxide	1.90E-02	Pb	4.66E-04
Unspec. biomass, dm, raw mat.	1.14E-02	Unspec. biomass, dm, raw mat.	1.65E-02	Aluminium	1.77E-04
Ni	1.02E-02	Unspec. resources	9.69E-03	Unspec. biomass, dm, raw mat.	2.54E-05
Uranium	4.95E-03	Sn	9.02E-03	Uranium	1.70E-05
Chromium	3.71E-04	Mn	8.38E-03	Unspec. fuel	0.00E+00
Unspec. resources	0.00E+00	Uranium	7.08E-03		
		Unspec. minerals	2.47E-03		

Resource	Total m2	Resource	Total m2	Resource	Total m2
Unspec. biomass, dm, fuel	3.34E-01	Crude oil, fuel	1.70E-01	Wood, soft, dm, fuel	1.65E-02
Wood, soft, dm, fuel	2.21E-01	Cu	1.65E-01	Cu	1.17E-02
Crude oil, fuel	1.27E-01	Hard coal, fuel	9.33E-02	Unspec. biomass, dm, fuel	5.55E-03
Cu	1.22E-01	Unspec. biomass, dm, fuel	8.74E-02	Crude oil, fuel	4.33E-03
Hard coal, fuel	6.75E-02	Wood, soft, dm, fuel	6.21E-02	Crude oil,raw mat.	3.54E-03
Lignite, fuel	2.71E-02	Lignite, fuel	3.84E-02	Hard coal, fuel	1.30E-03
Unspec. biomass, dm, raw mat.	1.04E-02	Unspec. biomass, dm, raw mat.	1.50E-02	Lignite, fuel	7.02E-05
Crude oil,raw mat.	3.22E-03	Crude oil,raw mat.	1.16E-02	Unspec. biomass, dm, raw mat.	2.31E-05
Uranium	1.15E-03	Uranium	1.64E-03	Fe	2.00E-05
Unspec. fuel	9.55E-04	Nat. gas, fuel	1.92E-04	Uranium	3.94E-06
Aluminium	9.22E-04	Aluminium	1.30E-04	Mn	3.80E-06
Fe	4.14E-04	Quartz (as for sand)	1.26E-04	Nat. gas,raw mat.	2.92E-06
Mn	7.82E-05	Fe	6.75E-05	Nat. gas, fuel	2.69E-06
Nat. gas, fuel	7.06E-05	Mn	2.13E-05	Clay (as for sand)	4.73E-07
CaCO3 (as for limestone)	7.12E-06	Clay (as for sand)	1.78E-05	Quartz (as for sand)	4.56E-07
Clay (as for sand)	6.44E-06	Nat. gas,raw mat.	9.41E-06	CaCO3 (as for limestone)	3.99E-07
Quartz (as for sand)	6.23E-06	CaCO3 (as for limestone)	3.24E-06	Aluminium	3.71E-07
Nat. gas,raw mat.	2.37E-06	Titanium dioxide	6.56E-07	Unspec. fuel	-4.81E-04
		Unspec. fuel	-5.68E-04		
Total woody:	5.65E-01	Total woody:	1.64E-01	Total woody:	2.21E-02

PC Energy calculations

Carbon absorption by forests:
1.42 tonnes of carbon [t ha^{-1} yr^{-1}] including roots

Europe:		CEF [t C/TJ]	[GJ ha^{-1} yr-1]	[MJ $m2^{-1}$ yr-1]
46%	crude oil	20	71	7.10
22%	Coal	26	55	5.50
18%	Nat.gas dry	15.3	93	9.30
	Lignite	27.6	53	5.30
2%	Hydro		1000	100.00
12%	Nuclear	N/A	N/A	N/A
100%			Net cal.val.=	[MJ $m2^{-1}$ yr-1]
	crude oil		67	6.75
	Coal		52	5.23
	Nat.gas dry		84	8.37
	Lignite		50	5.04
	Nuclear	N/A		N/A

Example: 20t of C per TJ emitted by crude oil vs. 1.42 t of C absorbed=
(20tC/TJ)/1.42tC ha^{-1} yr^{-1} = (20tC/TJ) ha $1.42t^{-1}$ yr^{-1} =1/x =(0.071 TJ yr^{-1} ha^{-1}) 1000 = 71 GJ ha^{-1} yr^{-1}.

Control unit

Energy		Mat. prod.	**m2/PC**	Mfct.	**m2/PC**	Distrib.	**m2/PC**	Use	**m2/PC**	Dispo	**m2/PC**	Cred. Rec.	**m2/PC**	**Total MJ**	**Total m2/PC:**
Primary energy, materials	MJ	**3.35E+01**	4.41E+00	**6.47E-02**	8.52E-03	**1.34E-02**	1.76E-03	**1.62E-01**	2.13E-02	**2.05E-03**	2.70E-04	**-1.38E-06**	-1.82E-07	**3.37E+01**	4.44E+00
Primary energy, processes	MJ	**3.93E+02**	5.17E+01	**1.13E+03**	1.49E+02	**4.17E+00**	5.49E-01	**3.81E+03**	5.01E+02	**1.03E+01**	1.36E+00	**-4.64E+01**	-6.11E+00	**5.30E+03**	6.98E+02
Sum [m2]:			**5.61E+01**		**1.49E+02**		**5.51E-01**		**5.01E+02**		**1.36E+00**		**-6.11E+00**		**7.02E+02**

Monitor

Energy		Mat. prod.	**m2/PC**	Mfct.	**m2/PC**	Distrib.	**m2/PC**	Use	**m2/PC**	Dispo	**m2/PC**	Cred. Rec.	**m2/PC**	**Total MJ**	**Total m2/PC:**
Primary energy, materials	MJ	**1.27E+02**	1.67E+01	**5.12E-02**	6.74E-03	**1.93E-02**	2.54E-03	**2.70E-01**	3.55E-02	**2.28E-03**	3.00E-04	**-8.75E-07**	-1.15E-07	**1.27E+02**	1.68E+01
Primary energy, processes	MJ	**2.33E+02**	3.07E+01	**1.42E+03**	1.87E+02	**6.02E+00**	7.92E-01	**6.34E+03**	8.34E+02	**-1.07E+01**	-1.41E+00	**-1.66E+01**	-2.18E+00	**7.97E+03**	1.05E+03
Sum [m2]:			**4.74E+01**		**1.87E+02**		**7.95E-01**		**8.34E+02**		**-1.41E+00**		**-2.18E+00**		**1.07E+03**

Keyboard

Energy		Mat. prod.	**m2/PC**	Mfct.	**m2/PC**	Distrib.	**m2/PC**	Use	**m2/PC**	Dispo	**m2/PC**	Cred. Rec.	**m2/PC**	**Total MJ**	**Total m2/PC:**
Primary energy, materials	MJ	**3.91E+01**	5.15E+00	**2.85E-03**	3.75E-04	**1.89E-03**	2.49E-04	**0.00E+00**	0.00E+00	**2.31E-04**	3.04E-05	**-5.55E-08**	-7.30E-09	**3.91E+01**	5.15E+00
Primary energy, processes	MJ	**4.39E+01**	5.78E+00	**3.64E+01**	4.79E+00	**5.88E-01**	7.74E-02	**0.00E+00**	0.00E+00	**-4.09E+00**	-5.38E-01	**-1.91E+00**	-2.51E-01	**7.49E+01**	9.86E+00
Sum [m2]:			**1.09E+01**		**4.79E+00**		**7.76E-02**		**0.00E+00**		**-5.38E-01**		**-2.51E-01**		**1.50E+01**

			1.14E+02		3.40E+02		1.42E+00		1.34E+03		-5.90E-01		-8.54E+00		

[m2] total PC system
1.78E+03

Fossil energy land materials (m2/PC)	Control unit	Monitor	Keyboard	Sum m2	
Total	**4.44**	**16.76**	**5.15**	**26.35**	1.50
Material production	4.41	16.71	5.15	26.27	% of process energy
Manufacture	0.01	0.01	0.00	0.02	
Distribution	0.00	0.00	0.00	0.00	
Use	0.02	0.04	0.00	0.06	
Disposal	0.00	0.00	0.00	0.00	
Recycling	0.00	0.00	0.00	0.00	
	17	64	20	% of total m2	

Fossil energy land processes (m2/PC)	Control unit	Monitor	Keyboard	Sum m2
Total	**697.67**	**1049.15**	**9.86**	**1756.68**
Material production	51.72	30.66	5.78	88.17
Manufacture	148.72	186.89	4.79	340.39
Distribution	0.55	0.79	0.08	1.42
Use	501.43	834.40	0.00	1335.83
Disposal	1.36	-1.41	-0.54	-0.59
Recycling	-6.11	-2.18	-0.25	-8.54
	39.7	59.7	0.6	% of total m2

Fossil energy land total (m2/PC)	Control unit	Monitor	Keyboard	Sum m2	**Area PC system (%)**
Total	**702.11**	**1065.91**	**15.00**	**1783.03**	% by LC stage PC
Material production	56.13	47.38	10.92	114.43	6.4
Manufacture	148.73	186.89	4.79	340.41	19.1
Distribution	0.55	0.79	0.08	1.42	0.1
Use	501.45	834.44	0.00	1335.89	74.9
Disposal	1.36	-1.41	-0.54	-0.59	0.0
Recycling	-6.11	-2.18	-0.25	-8.54	-0.5
	39	60	1	% of total m2	

EF Results PC

PC system	DLU [m2/PC]	Fossil energy land [m2 yr]	Total	[ha]	%					
Control Unit	0.92	702.11	703.03		39.39					
Monitor	0.64	1065.91	1066.56		59.76					
Keyboard	0.04	15.00	15.05		0.84					
Total PC	**1.60**	**1783.03**	**1.78E+03**	**0.18**	9.46					
Of which woody:	0.75			0.13	-25% ocean		7	%		

DEMAND BIOPRODUCTIVE SPACE PC with 25% ocean abs.				SUPPLY OF BIOCAPACITY (modified from WWF,1996)				BALANCE [%]
FOOTPRINT PC life cycle				EXISTING GLOBAL BIO-CAPACITY (per capita)				
Category	total	equivalence factor	equivalent total	Category	yield factor	world area	yield adjusted equiv. area	Share PC of per capita global existing bio-capacity
	[m2/ PC]	[-]	[m2/PC]			[ha/cap]	[ha/cap]	
fossil energy land	1337.27	1.78	2378.52	CO2 absorption land		0.00	0.00	
built-up area	0.85	3.17	2.69	built-up area	1.0	0.04	0.12	
arable land	0.00	3.17	0.00	arable land	1.0	0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area	1.0	0.79	0.31	
forest	0.75	1.78	1.34	forest	1.0	0.58	1.03	
sea	0.00	0.06	0.00	sea	1.0	0.55	0.03	
				TOTAL existing		2.18	2.18	
				(minus sea = terrestrial supply)			2.15	
TOTAL used [m2]	1338.87		2382.55	**TOTAL terrestrial available**	(-12% for biodiversity - Brundtland)		**1.89**	13
in [ha]			0.24		(-25% for biodiversity, Noss&Cooperider,1994)		**1.60**	15
			DLU %					
			0.2					

DEMAND BIOPRODUCTIVE SPACE PC with 35% ocean abs.				SUPPLY OF BIOCAPACITY (modified from WWF,1996)				BALANCE [%]
FOOTPRINT PC life cycle				EXISTING GLOBAL BIO-CAPACITY (per capita)				
Category	total	equivalence factor	equivalent total	Category	yield factor	world area	yield adjusted equiv. area	Share PC of per capita global existing bio-capacity
	[m2/ PC]	[-]	[m2/ PC]			[ha/cap]	[ha/cap]	
fossil energy land	1158.97	1.78	2061.38	CO2 absorption land		0.00	0.00	
built-up area	0.85	3.17	2.69	built-up area	1.0	0.04	0.12	
arable land	0.00	3.17	0.00	arable land	1.0	0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area	1.0	0.79	0.31	
forest	0.75	1.78	1.34	forest	1.0	0.58	1.03	
sea	0.00	0.06	0.00	sea	1.0	0.55	0.03	
				TOTAL existing		2.18	2.18	
				(minus sea = terrestrial supply)			2.15	
TOTAL used [m2]	1160.57		2065.42	**TOTAL terrestrial available**	(-12% for biodiversity - Brundtland)		**1.89**	11
in [ha]			0.21		(-25% for biodiversity, Noss&Cooperider,1994)		**1.60**	13

EF Results PC

use phase TPE acc. to p. 37 PA study		13665								
1.02E+04		total life cycle (p. 37)								
4.32E-01		use phase/LC of 3 yrs:		m2 use phase	m2/yr	equiv.total per yr:				
1.02E+04		74.6	%	864.59	288.2	512.6				
Snapshot with 35% (estimate)										
DEMAND BIOPRODUCTIVE SPACE PC [m2] with 35% ocean abs.						SUPPLY OF BIOCAPACITY (modified from WWF,1996)				BALANCE [%]
FOOTPRINT PC [m2]				EXISTING GLOBAL BIO-CAPACITY (per capita)						
Category	total [m2]	equivalence factor [-]	equivalent total [m2]	Category		yield factor		world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share PC of per capita global existing bio-capacity
fossil energy land	582.57	1.78	1036.19	CO2 absorption land				0.00	0.00	
built-up area	0.85	3.17	2.69	built-up area		1.0		0.04	0.12	
arable land	0.00	3.17	0.00	arable land		1.0		0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area		1.0		0.79	0.31	
forest	0.75	1.78	1.34	forest		1.0		0.58	1.03	
sea	0.00	0.06	0.00	sea		1.0		0.55	0.03	
				TOTAL existing				2.18	2.18	
				(minus sea = terrestrial supply)					2.15	
TOTAL used [m2]	584.18		1040.22	**TOTAL terrestrial available**		(-12% for biodiversity - Brundtland)			**1.89**	6
in [ha]			0.10			(-25% for biodiversity, Noss&Cooperider,1994)			**1.60**	6
			plus							3
			512.6	m2 for every other year of use!						3
			0.05							

Appendix C

10.3. Statistical analysis

Note: The terms "overburden" and "rucksack" were used synonymously.

10.3.1. SPSS output (sav)

	Element	abundance	overburden	logab	logob	pre_1	res_1	zre_1	lici_1	uici_1
1	Ag	0.01	7500	-2.12	3.88	3.9774	-0.10234	-0.11271	1.94913	6.00568
2	Al	82300	3.68	4.92	0.57	-0.12607	0.69192	0.76202	-2.12801	1.87587
3	As	1.8	20	0.26	1.3	2.59009	-1.28906	-1.41968	0.659	4.52119
4	Au	0	950000	-2.4	5.98	4.13652	1.8412	2.02776	2.09182	6.18122
5	Ba	425	2	2.63	0.3	1.20692	-0.90589	-0.99768	-0.7167	3.13054
6	Co	25	20	1.4	1.3	1.92409	-0.62306	-0.68619	0.00809	3.84008
7	Cr	102	2	2.01	0.3	1.56816	-1.26713	-1.39552	-0.34852	3.48484
8	Cu	60	450	1.78	2.65	1.70248	0.95073	1.04706	-0.21322	3.61818
9	F	585	2	2.77	0.3	1.12604	-0.82501	-0.9086	-0.79999	3.05207
10	Fe	56300	5.2	4.75	0.72	-0.02996	0.74596	0.82155	-2.0236	1.96368
11	Mg	23300	1.2	4.37	0.08	0.19336	-0.11418	-0.12575	-1.78253	2.16925
12	Mn	950	6	2.98	0.78	1.00331	-0.22516	-0.24797	-0.92698	2.93359
13	Nb	20	100	1.3	2	1.98057	0.01943	0.0214	0.06412	3.89702
14	Ni	84	560	1.92	2.75	1.61731	1.13088	1.24546	-0.29891	3.53353
15	P	1050	4	3.02	0.6	0.97797	-0.37591	-0.414	-0.95328	2.90922
16	Pb	14	32	1.15	1.51	2.07086	-0.56571	-0.62303	0.15336	3.98835
17	Pt	0.01	350000	-2.3	5.54	4.08004	1.46403	1.61237	2.04128	6.11879
18	Si	282000	1.75	5.45	0.24	-0.43781	0.68084	0.74983	-2.46934	1.59373
19	Sn	2.3	100	0.36	2	2.52804	-0.52804	-0.58155	0.59925	4.45684
20	Ta	2	100	0.3	2	2.56342	-0.56342	-0.62051	0.63334	4.49351
21	Ti	5650	25	3.75	1.4	0.55199	0.84595	0.93166	-1.4	2.50398
22	U	2.7	900	0.43	2.95	2.48746	0.46679	0.51408	0.56007	4.41485
23	W	1.25	100	0.1	2	2.68239	-0.68239	-0.75154	0.74754	4.61725
24	Zn	0.7	32	-0.15	1.51	2.82916	-1.32401	-1.45817	0.88751	4.77082
25	Zr	165	100	2.22	2	1.44641	0.55359	0.60968	-0.4719	3.36473

10.3.2. SPSS output (spo)

One-Sample Kolmogorov-Smirnov Test

		Log10 abund	Log10 overb
N		25	25
Normal Parameters [a,b]	Mean	1.6348	1.7860
	Std. Deviation	2.1619	1.5420
Most Extreme Differences	Absolute	.084	.205
	Positive	.079	.205
	Negative	-.084	-.134
Kolmogorov-Smirnov Z		.419	1.024
Asymp. Sig. (2-tailed)		.995	.245

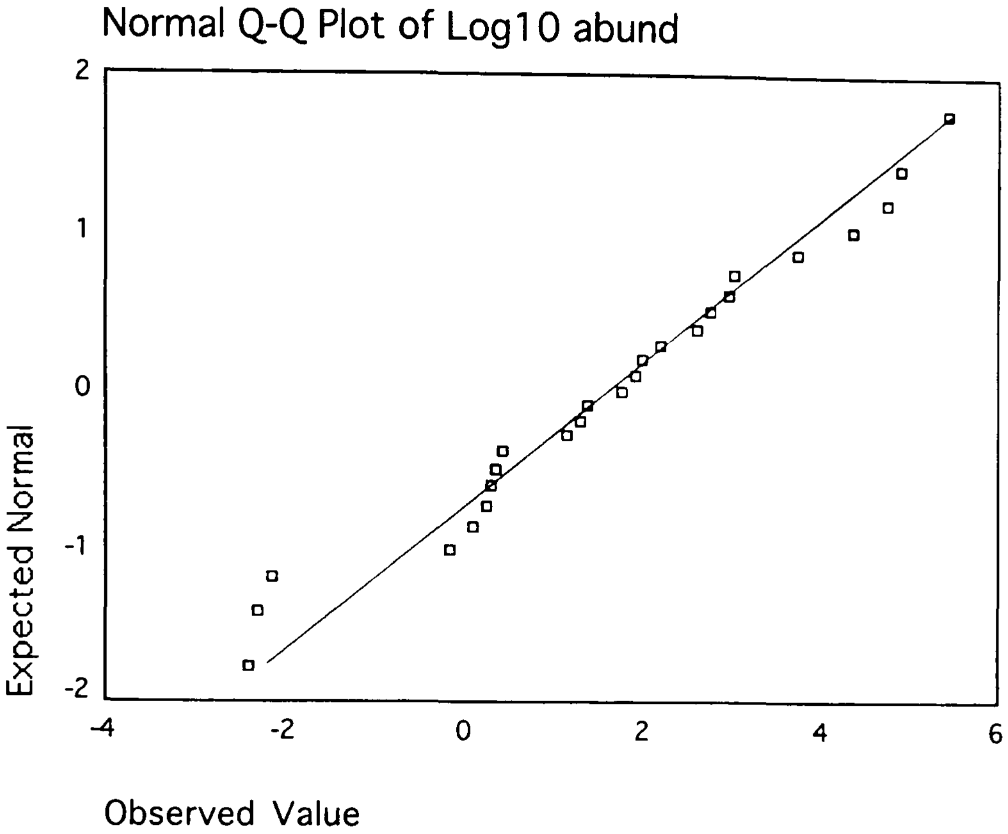
a. Test distribution is Normal.

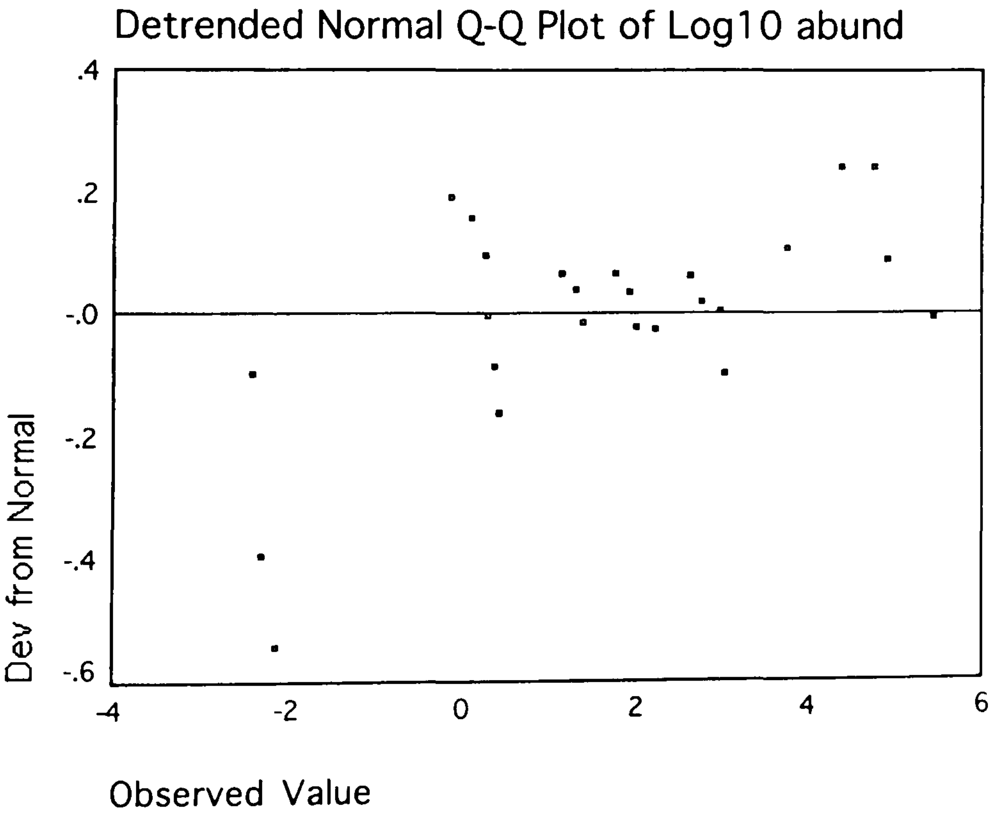
b. Calculated from data.

Case Processing Summary

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
Log10 abund	25	100.0%	0	.0%	25	100.0%

Log 10 abundance





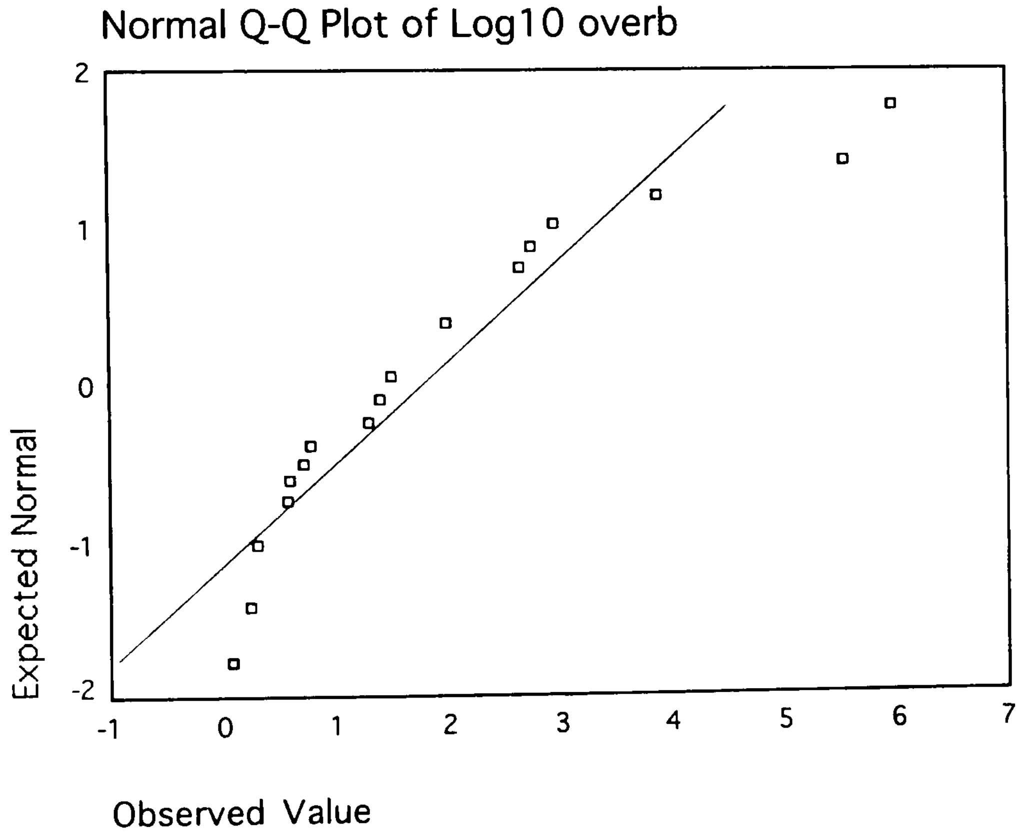
Log 10 overburden

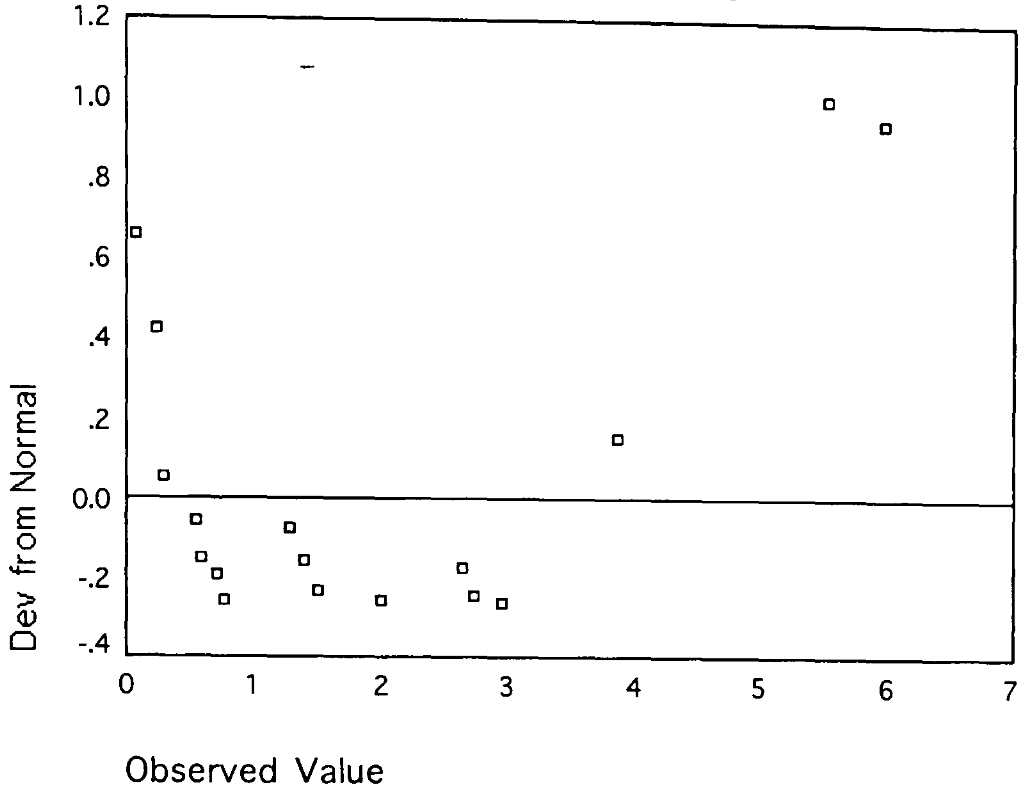
Tests of Normality

	Kolmogorov-Smirnov [a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Log10 overb	.205	25	.008	.855	25	.010*

**. This is an upper bound of the true significance.

a. Lilliefors Significance Correction





Detrended Normal Q-Q Plot of Log10 overb

Correlations

Correlations

		Log10 abund	Log10 overb
Log10 abund	Pearson Correlation	1.000	-.817*
	Sig. (2-tailed)	.	.000
	N	25	25
Log10 overb	Pearson Correlation	-.817*	1.000
	Sig. (2-tailed)	.000	.
	N	25	25

**. Correlation is significant at the 0.01 level (2-tailed).

Nonparametric correlations

Correlations

			Log10 abund	Log10 overb
Spearman's rho	Log10 abund	Correlation Coefficient	1.000	-.766**
		Sig. (2-tailed)	.	.000
		N	25	25
	Log10 overb	Correlation Coefficient	-.766*	1.000
		Sig. (2-tailed)	.000	.
		N	25	25

**. Correlation is significant at the .01 level (2-tailed).

Regression

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	Log10 abund[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: Log10 overb

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	38.106	1	38.106	46.219	.000[a]
	Residual	18.963	23	.824		
	Total	57.069	24			

a. Predictors: (Constant), Log10 abund

b. Dependent Variable: Log10 overb

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	2.739	.229		11.939	.000	2.264	3.213
	Log10 abund	-.583	.086	-.817	-6.798	.000	-.760	-.406

a. Dependent Variable: Log10 overb

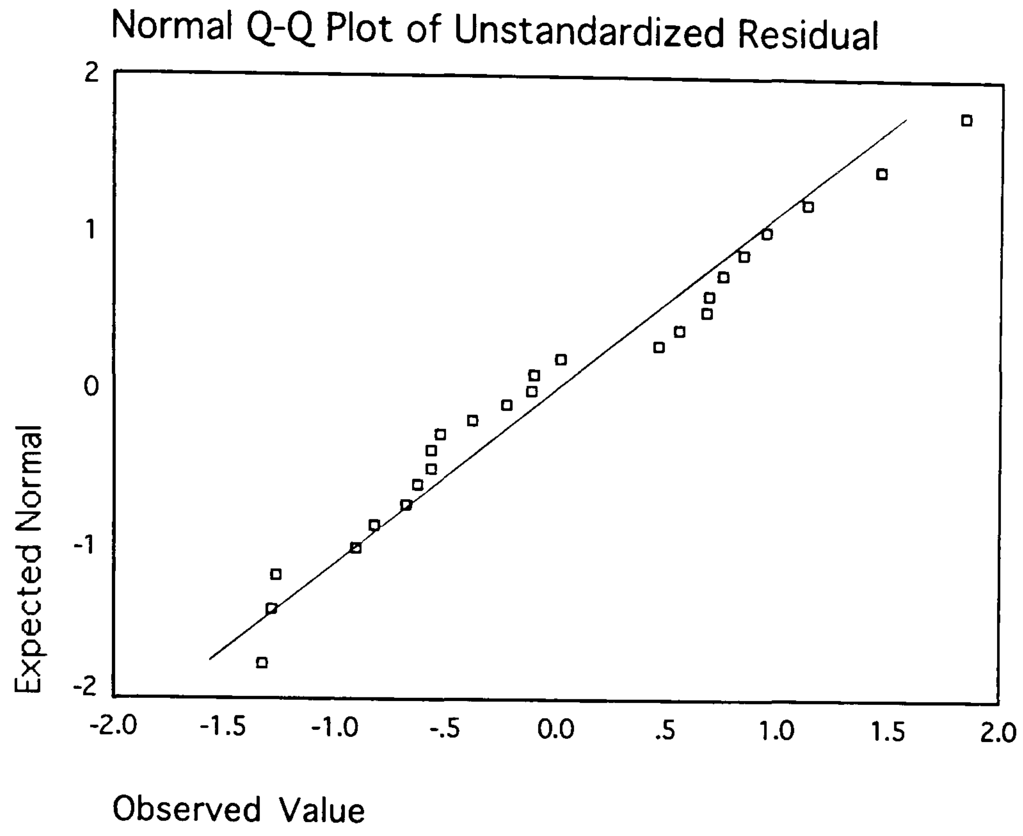
Unstandardized Residual

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Unstandardized Residual	.124	25	.200*	.956	25	.401

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction



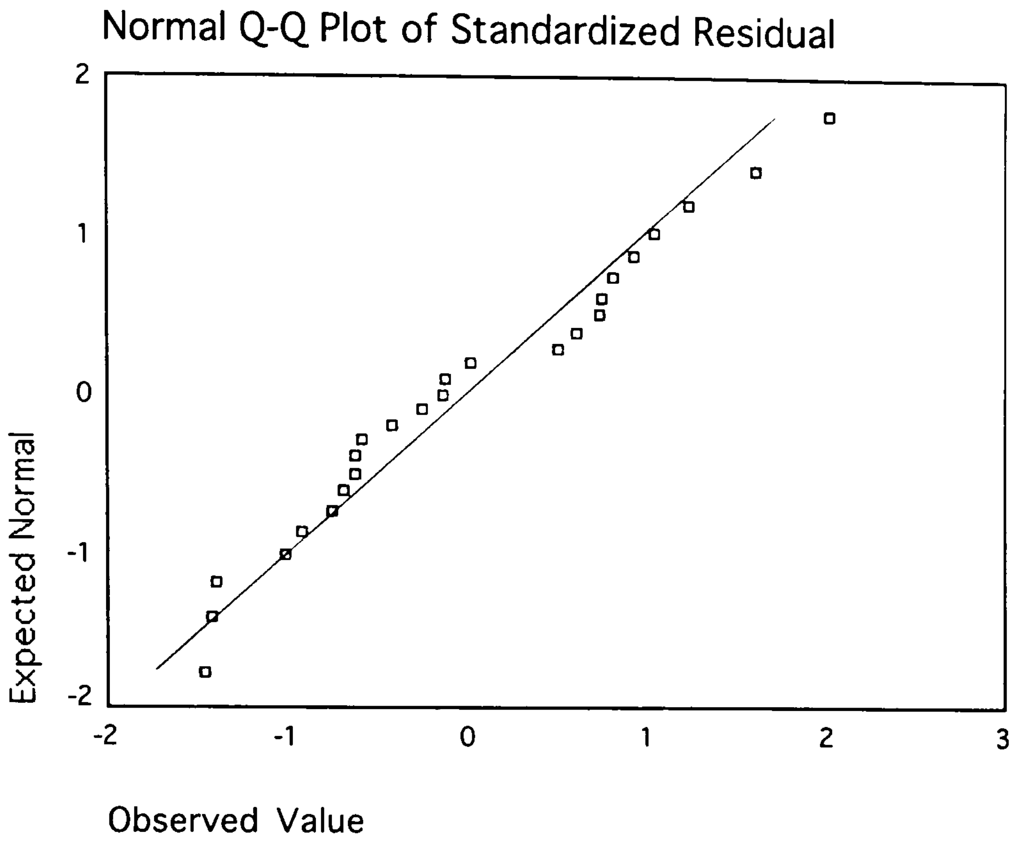
Standardized Residual

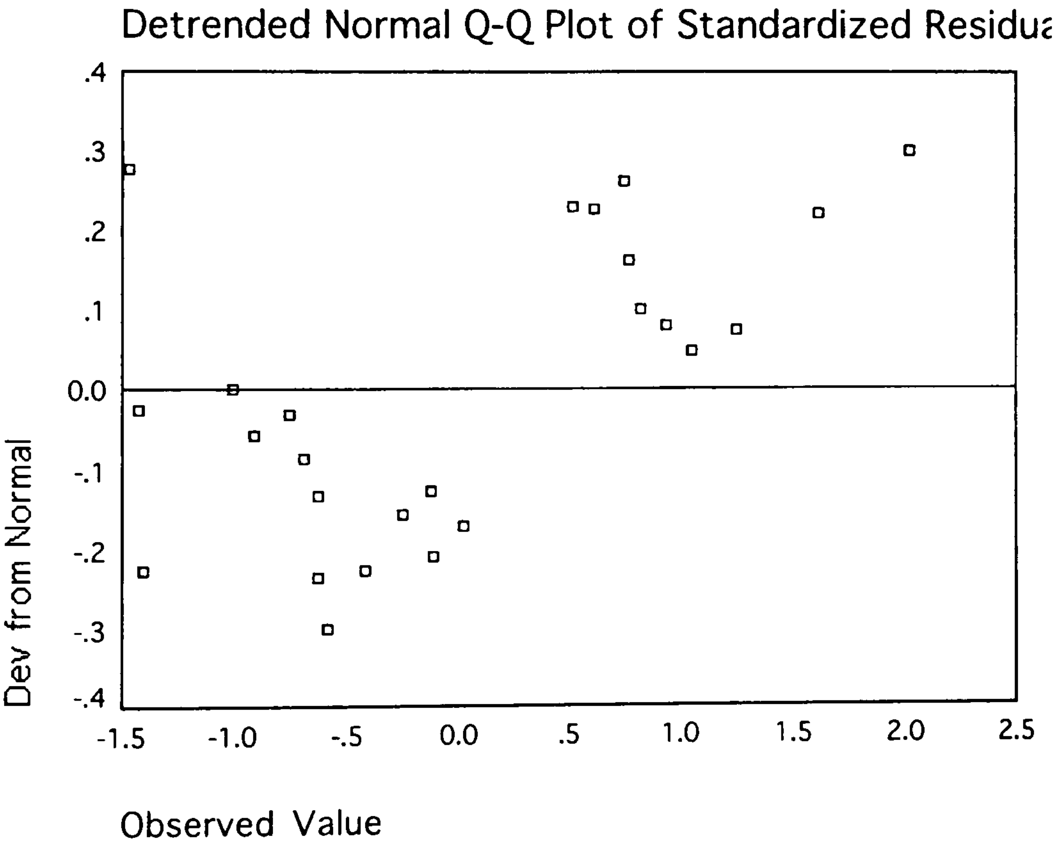
Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Standardized Residual	.124	25	.200*	.956	25	.401

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction


Normal Q-Q Plot of Standardized Residual
Expected Normal
2
1
0
-1
-2
-2
-1
0
1
2
3
Observed Value


Detrended Normal Q-Q Plot of Standardized Residuε
Dev from Normal
.4
.3
.2
.1
0.0
-.1
-.2
-.3
-.4
-1.5
-1.0
-.5
0.0
.5
1.0
1.5
2.0
2.5
Observed Value

10.3.3. Excel spreadsheets statistical analysis

First approximations

First approximation of overburden/rucksacks by abundance in Earth crust (OB/rucksacks in brackets, usually after DL, 1997, 1998). Classification in line with Graedel and Allenby, 1995.

Ti
Al (3.68
Fe (5.2)
K
Na

Group > 0.1%
abundant

Cr
F
Mn (6)
Zr (100)

Group >100 ppm
common

B
Ce
Co
Cu (450)
Ga
La
Li
Nb (100)
Nd
Ni (560)
Pb (32)
Rb
Sc
Y
Zn

Group 10-99 ppm
relatively common
Abundance between 1.4 E+01 and 3.3 E+01 ppm (average 2.4 E+01 ppm or mg/kg).

As
Be
Br
Eu
Ge
Ho
Mo
Sm
Sn (100)
Ta (100)
Tb
U (900)
W (100)

Group 1 - 9 ppm
uncommon

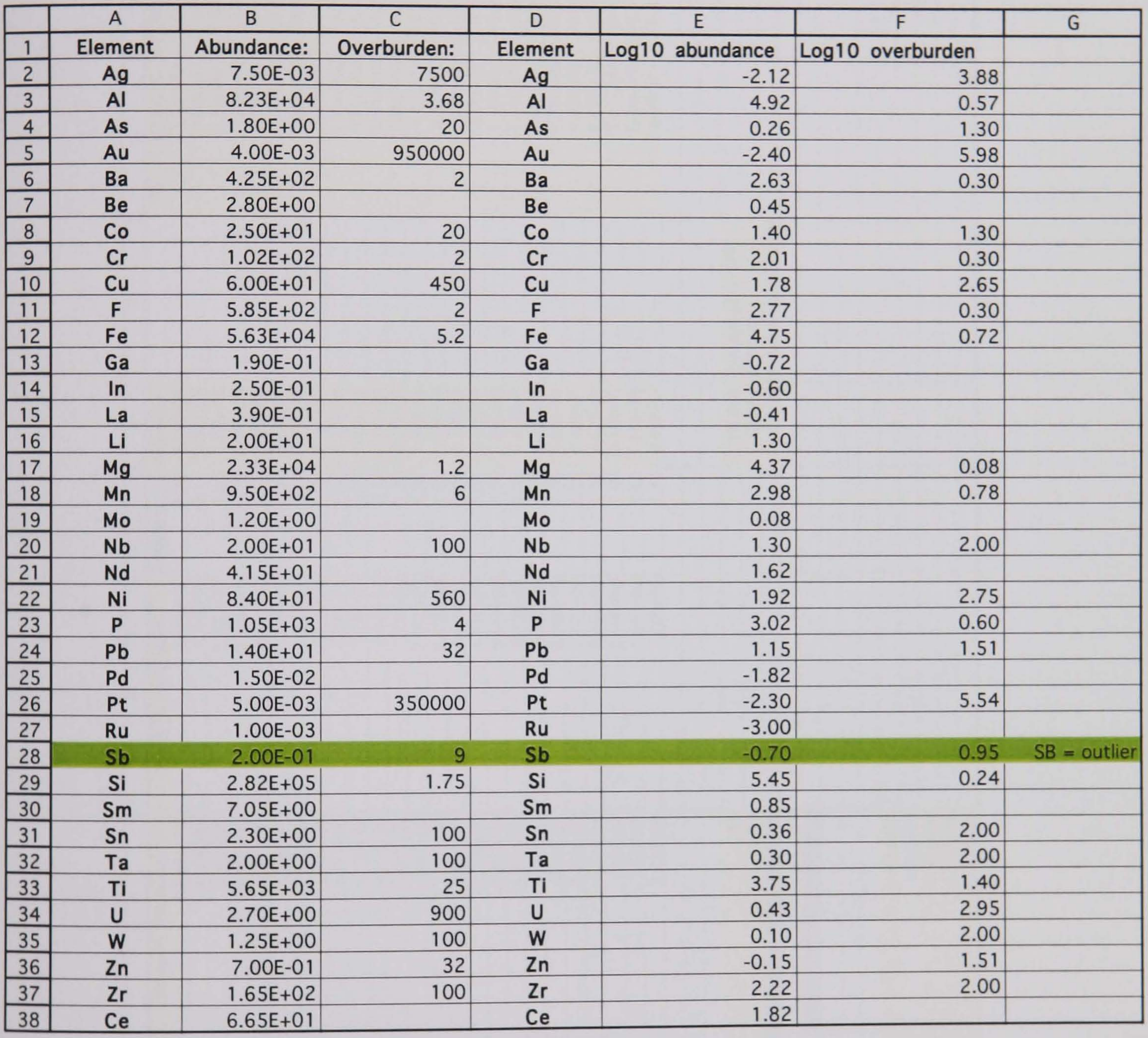
Ag (7500)
Au (950000)
Hg
In
Sb (9)

Group < 1ppm
rare
(Ag after Schmidt-Bleek, 1997)

Ir
Os
Pd
Pt (350000)
Rh
Ru

PGM - Group: E-03 to E-02 ppm
Platinum Group metals (PGM) use Pt overburden
(350000 after Schmidt-Bleek, 1997)

Abundance and overburden/rucksacks



	A	B	C	D	E	F	G
1	Element	Abundance:	Overburden:	Element	Log10 abundance	Log10 overburden	
2	Ag	7.50E-03	7500	Ag	-2.12	3.88	
3	Al	8.23E+04	3.68	Al	4.92	0.57	
4	As	1.80E+00	20	As	0.26	1.30	
5	Au	4.00E-03	950000	Au	-2.40	5.98	
6	Ba	4.25E+02	2	Ba	2.63	0.30	
7	Be	2.80E+00		Be	0.45		
8	Co	2.50E+01	20	Co	1.40	1.30	
9	Cr	1.02E+02	2	Cr	2.01	0.30	
10	Cu	6.00E+01	450	Cu	1.78	2.65	
11	F	5.85E+02	2	F	2.77	0.30	
12	Fe	5.63E+04	5.2	Fe	4.75	0.72	
13	Ga	1.90E-01		Ga	-0.72		
14	In	2.50E-01		In	-0.60		
15	La	3.90E-01		La	-0.41		
16	Li	2.00E+01		Li	1.30		
17	Mg	2.33E+04	1.2	Mg	4.37	0.08	
18	Mn	9.50E+02	6	Mn	2.98	0.78	
19	Mo	1.20E+00		Mo	0.08		
20	Nb	2.00E+01	100	Nb	1.30	2.00	
21	Nd	4.15E+01		Nd	1.62		
22	Ni	8.40E+01	560	Ni	1.92	2.75	
23	P	1.05E+03	4	P	3.02	0.60	
24	Pb	1.40E+01	32	Pb	1.15	1.51	
25	Pd	1.50E-02		Pd	-1.82		
26	Pt	5.00E-03	350000	Pt	-2.30	5.54	
27	Ru	1.00E-03		Ru	-3.00		
28	Sb	2.00E-01	9	Sb	-0.70	0.95	SB = outlier
29	Si	2.82E+05	1.75	Si	5.45	0.24	
30	Sm	7.05E+00		Sm	0.85		
31	Sn	2.30E+00	100	Sn	0.36	2.00	
32	Ta	2.00E+00	100	Ta	0.30	2.00	
33	Ti	5.65E+03	25	Ti	3.75	1.40	
34	U	2.70E+00	900	U	0.43	2.95	
35	W	1.25E+00	100	W	0.10	2.00	
36	Zn	7.00E-01	32	Zn	-0.15	1.51	
37	Zr	1.65E+02	100	Zr	2.22	2.00	
38	Ce	6.65E+01		Ce	1.82		

Estimated standard error (SE) for predicted (observed) overburden/rucksack values

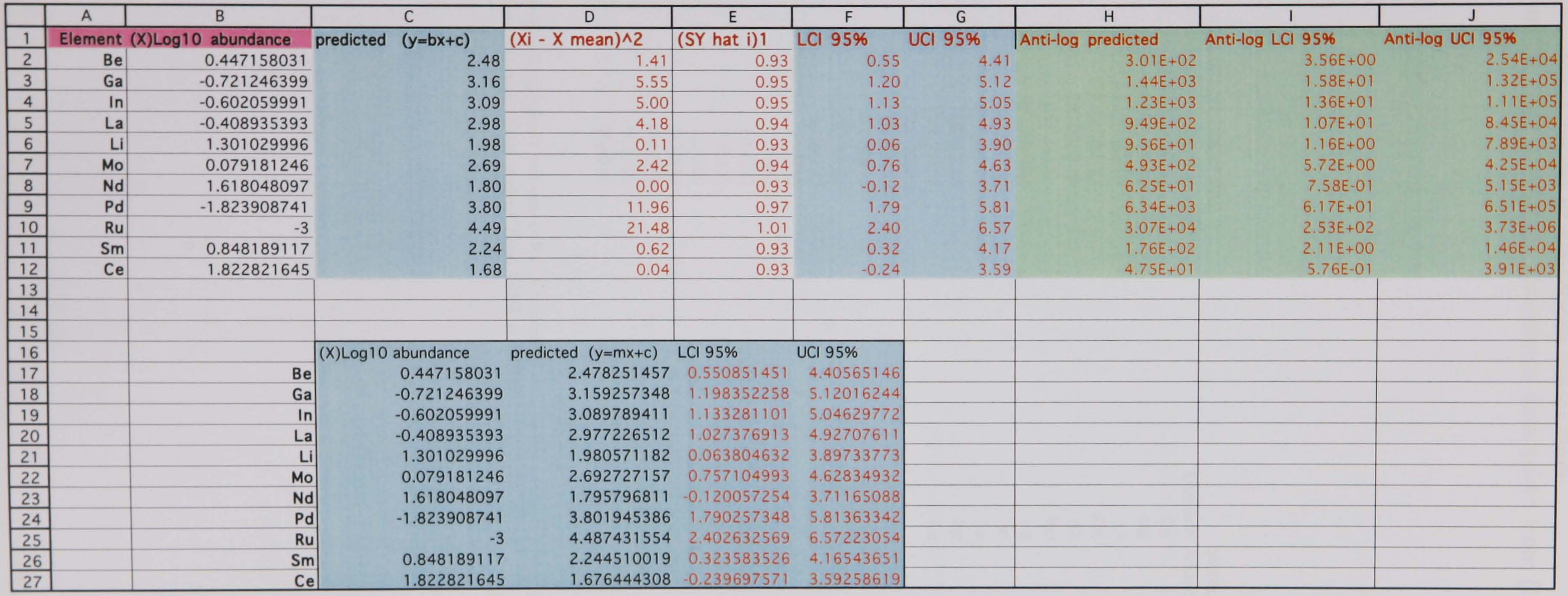
	A	B	C	D	E	F	G	H	I	J
1	Element	(X)Log10 abundance	(Y)Log10 overburden	Predicted y (\	Residuals		(Xi - X mean)^2	(SY hat i)1	LCI 95%	UCI 95%
2	Ag	-2.12E+00	3.88E+00	3.98	-1.02E-01		1.41E+01	9.80E-01	1.95E+00	6.01E+00
3	Al	4.92E+00	5.66E-01	-0.13	6.92E-01		1.08E+01	9.68E-01	-2.13E+00	1.88E+00
4	As	2.55E-01	1.30E+00	2.59	-1.29E+00		1.90E+00	9.34E-01	6.59E-01	4.52E+00
5	Au	-2.40E+00	5.98E+00	4.14	1.84E+00		1.63E+01	9.88E-01	2.09E+00	6.18E+00
6	Ba	2.63E+00	3.01E-01	1.21	-9.06E-01		9.87E-01	9.30E-01	-7.17E-01	3.13E+00
8	Co	1.40E+00	1.30E+00	1.92	-6.23E-01		5.61E-02	9.26E-01	7.77E-03	3.84E+00
9	Cr	2.01E+00	3.01E-01	1.57	-1.27E+00		1.40E-01	9.27E-01	-3.49E-01	3.49E+00
10	Cu	1.78E+00	2.65E+00	1.70	9.51E-01		2.05E-02	9.26E-01	-2.14E-01	3.62E+00
11	F	2.77E+00	3.01E-01	1.13	-8.25E-01		1.28E+00	9.31E-01	-8.00E-01	3.05E+00
12	Fe	4.75E+00	7.16E-01	-0.03	7.46E-01		9.71E+00	9.64E-01	-2.02E+00	1.96E+00
17	Mg	4.37E+00	7.92E-02	0.19	-1.14E-01		7.47E+00	9.55E-01	-1.78E+00	2.17E+00
18	Mn	2.98E+00	7.78E-01	1.00	-2.25E-01		1.80E+00	9.33E-01	-9.27E-01	2.93E+00
20	Nb	1.30E+00	2.00E+00	1.98	1.94E-02		1.11E-01	9.26E-01	6.38E-02	3.90E+00
22	Ni	1.92E+00	2.75E+00	1.62	1.13E+00		8.38E-02	9.26E-01	-2.99E-01	3.53E+00
23	P	3.02E+00	6.02E-01	0.98	-3.76E-01		1.92E+00	9.34E-01	-9.54E-01	2.91E+00
24	Pb	1.15E+00	1.51E+00	2.07	-5.66E-01		2.39E-01	9.27E-01	1.53E-01	3.99E+00
26	Pt	-2.30E+00	5.54E+00	4.08	1.46E+00		1.55E+01	9.86E-01	2.04E+00	6.12E+00
28	Si	5.45E+00	2.43E-01	-0.44	6.81E-01		1.46E+01	9.82E-01	-2.47E+00	1.59E+00
30	Sn	3.62E-01	2.00E+00	2.53	-5.28E-01		1.62E+00	9.32E-01	5.99E-01	4.46E+00
31	Ta	3.01E-01	2.00E+00	2.56	-5.63E-01		1.78E+00	9.33E-01	6.33E-01	4.49E+00
32	Ti	3.75E+00	1.40E+00	0.55	8.46E-01		4.48E+00	9.44E-01	-1.40E+00	2.50E+00
33	U	4.31E-01	2.95E+00	2.49	4.67E-01		1.45E+00	9.32E-01	5.60E-01	4.42E+00
34	W	9.69E-02	2.00E+00	2.68	-6.82E-01		2.37E+00	9.35E-01	7.47E-01	4.62E+00
35	Zn	-1.55E-01	1.51E+00	2.83	-1.32E+00		3.20E+00	9.39E-01	8.87E-01	4.77E+00
36	Zr	2.22E+00	2.00E+00	1.45	5.54E-01		3.39E-01	9.27E-01	-4.72E-01	3.37E+00
45										
46										
47										
48	SLOPE (b) xls:	-0.58			18.963	Sum(residuals^2)				
49	INTERCEPT (c) xls:	2.74			0.908	SERR (S):				
50	Standard Error (S)	0.908			0.824	Residual MS (S2 Y.X)				
51	Observations:	25								
52	t(level,2,(n-2))	2.069								
53										
54										
55										
56	MEAN:	1.63E+00								
57	VARIANCE	4.67E+00								
58	Sum (X^2)	1.79E+02								
59	(Sum X)^2	1.67E+03								
60	Sum x^2	1.12E+02								

Variables

Variables needed to calculate unknown overburden/rucksacks

slope	-0.583
intercept	2.739
X mean	1.635
SE	0.908
residual MS (S2 Y.X)	0.824
n	25
Sum x^2	112.171
t(0.05(2),(n-2))	2.069

Calculation of unknown overburden/rucksack values and their upper and lower 95% confidence limits



	A	B	C	D	E	F	G	H	I	J
1	Element	(X)Log10 abundance	predicted (y=bx+c)	(Xi - X mean)^2	(SY hat i)1	LCI 95%	UCI 95%	Anti-log predicted	Anti-log LCI 95%	Anti-log UCI 95%
2	Be	0.447158031	2.48	1.41	0.93	0.55	4.41	3.01E+02	3.56E+00	2.54E+04
3	Ga	-0.721246399	3.16	5.55	0.95	1.20	5.12	1.44E+03	1.58E+01	1.32E+05
4	In	-0.602059991	3.09	5.00	0.95	1.13	5.05	1.23E+03	1.36E+01	1.11E+05
5	La	-0.408935393	2.98	4.18	0.94	1.03	4.93	9.49E+02	1.07E+01	8.45E+04
6	Li	1.301029996	1.98	0.11	0.93	0.06	3.90	9.56E+01	1.16E+00	7.89E+03
7	Mo	0.079181246	2.69	2.42	0.94	0.76	4.63	4.93E+02	5.72E+00	4.25E+04
8	Nd	1.618048097	1.80	0.00	0.93	-0.12	3.71	6.25E+01	7.58E-01	5.15E+03
9	Pd	-1.823908741	3.80	11.96	0.97	1.79	5.81	6.34E+03	6.17E+01	6.51E+05
10	Ru	-3	4.49	21.48	1.01	2.40	6.57	3.07E+04	2.53E+02	3.73E+06
11	Sm	0.848189117	2.24	0.62	0.93	0.32	4.17	1.76E+02	2.11E+00	1.46E+04
12	Ce	1.822821645	1.68	0.04	0.93	-0.24	3.59	4.75E+01	5.76E-01	3.91E+03
13										
14										
15										
16			(X)Log10 abundance	predicted (y=mx+c)	LCI 95%	UCI 95%				
17		Be	0.447158031	2.478251457	0.550851451	4.40565146				
18		Ga	-0.721246399	3.159257348	1.198352258	5.12016244				
19		In	-0.602059991	3.089789411	1.133281101	5.04629772				
20		La	-0.408935393	2.977226512	1.027376913	4.92707611				
21		Li	1.301029996	1.980571182	0.063804632	3.89733773				
22		Mo	0.079181246	2.692727157	0.757104993	4.62834932				
23		Nd	1.618048097	1.795796811	-0.120057254	3.71165088				
24		Pd	-1.823908741	3.801945386	1.790257348	5.81363342				
25		Ru	-3	4.487431554	2.402632569	6.57223054				
26		Sm	0.848189117	2.244510019	0.323583526	4.16543651				
27		Ce	1.822821645	1.676444308	-0.239697571	3.59258619				

Range of abundance values from which overburden were predicted. Abundance data taken from [Lide, 1998].

non-blanks (observed OB)

Element	**Abundance (normal values)**
Si	282000.0000
Al	82300.0000
Fe	56300.0000
Mg	23300.0000
Ti	5650.0000
P	1050.0000
Mn	950.0000
F	585.0000
Ba	425.0000
Zr	165.0000
Cr	102.0000
Ni	84.0000
Cu	60.0000
Co	25.0000
Nb	20.0000
Pb	14.0000
U	2.7000
Sn	2.3000
Ta	2.0000
As	1.8000
W	1.2500
Zn	0.7000
Ag	0.0075
Pt	0.0050
Au	0.0040

blanks (predicted OB)

Element	**Abundance (normal values)**
Ce	66.5000
Nd	41.5000
Li	20.0000
Sm	7.0500
Be	2.8000
Mo	1.2000
La	0.3900
In	0.2500
Ga	0.1900
Pd	0.0150
Ru	0.0010

It is generally unsafe to predict Y hat values for X values outside the observed range of the given X (Zar, 1999, p. 267)

Descending order overburden values and percentage of reference materials

Element	Descending order observed/ pred. OB (raw data)		Predicted (% of reference mat.)	LCI		UCI	
Au	9.50E+05						
Pt	3.50E+05						
Ru	3.07E+04						
Ag	7.50E+03						
Pd	6.34E+03						
Ga	1.44E+03		392	4	*Alu	35836	*Alu
In	1.23E+03		38	42	% of Zn	3477	* Zn
La	9.49E+02		13	0.14	% of Ag	11	*Ag
U	9.00E+02						
Ni	5.60E+02						
Mo	4.93E+02						
Cu	4.50E+02						
Be	3.01E+02		67	0.8	% of Cu	57	* Cu
Sm	1.76E+02		39	0.5	% of Cu	33	* Cu
Nb	1.00E+02						
Sn	1.00E+02						
Ta	1.00E+02						
W	1.00E+02						
Zr	1.00E+02						
Li	9.56E+01						
Nd	6.25E+01		62	0.8	% of Sn	51	
Ce	4.75E+01						
Pb	3.20E+01						
Zn	3.20E+01						
Ti	2.50E+01						
As	2.00E+01						
Co	2.00E+01						
Mn	6.00E+00						
Fe	5.20E+00						
P	4.00E+00						
Al	3.68E+00						
Ba	2.00E+00						
Cr	2.00E+00						
F	2.00E+00						
Si	1.75E+00						
Mg	1.20E+00						

	LCI OB	UCI OB
Be	3.56E+00	2.54E+04
Ce	5.76E-01	3.91E+03
Ga	1.58E+01	1.32E+05
In	1.36E+01	1.11E+05
La	1.07E+01	8.45E+04
Li	1.16E+00	7.89E+03
Mo	5.72E+00	4.25E+04
Nd	7.58E-01	5.15E+03
Pd	6.17E+01	6.51E+05
Ru	2.53E+02	3.73E+06
Sm	2.11E+00	1.46E+04

Predicted overburden values are compared to their reference materials and their ratio is established.

Summary ratios as used in TEAM:

Element	predicted	LCL	UCL
Be [Cu]	*0.67	*0.008	*57
Ga [Al]	*392	*4	*3.58E+4
In [Zn]	*38	*0.42	*3477
Nd [Sn]	*0.62	*0.008	*51
Sm [Cu]	*0.39	* 0.005	*33
La [Ag]	* 0.13	* 0.0014	*11

Appendix D

10.4. Energy analysis of phone

```
System Description
        | Phone life cycle
        |         | 1. Raw material production
        |         |         | CuNi18Sn20 production
        |         |         | 74 Reflector
        |         |         | 40 Cerfilt
        |         |         | 274 Tungsten (W): Production.1
        |         |         | E_274 Aluminium (Al) - M33
        |         |         | GaP production
        |         |         | 15 Chipcap
        |         |         | E_274 Gold (Au) - M43
        |         |         | 10 Chipcap
        |         |         | 274 Lead (Pb): Production.1
        |         |         | 37 Plussa
        |         |         | S_241I 'Diethylene glycol' : Production
        |         |         | 86 Frame
        |         |         | Ceramics (LaTiO4) production
        |         |         | 63 Microboot
        |         |         | 49 SWtact
        |         |         | 44 Sawfilt
        |         |         | 26 Emi
        |         |         | 1b Chipres
        |         |         | 53 SMsystem
        |         |         | E_241 Polyoxymethylene (POM) - M13
        |         |         | 62 Condmic
        |         |         | S_'Niobium orTantalum'
        |         |         | 5 Chipres
        |         |         | Ag-epoxy production
        |         |         | S_241 'Polyvinylacohol' (PVAL) - M14.1
        |         |         | 33 Eeprom
        |         |         | 54 SMbatt
        |         |         | E_241 Silicone Rubber - M27
        |         |         | 45 Sawfilt
        |         |         | 6a Chipres
        |         |         | 81 TR
        |         |         | 78 Display
        |         |         | 58 PCB
        |         |         | 41 Sawfilt
        |         |         | FeNi42 production
        |         |         | E_241 Liquid Crystal Polymer (LCP) - M26
        |         |         | 66 Screw
        |         |         | 274 Palladium (Pd): Production.1
        |         |         | BaTiO3-production
        |         |         | 274 Manganese (Mn): Production.1
        |         |         | 274 Tin (Sn): Production.1
        |         |         | FeZn5 production
        |         |         | 39 RF
        |         |         | SnPb17 production
        |         |         | 6 Chipres
        |         |         | 59 Antenna
        |         |         | 88 Keymat
        |         |         | 31 Sram
        |         |         | 68 Jsert
        |         |         | 274 Aluminium Oxide (Al2O3): Production.1
        |         |         | E_271 Iron (Pure) - M28
        |         |         | 7 Res Network
        |         |         | 1a Chipres
        |         |         | CaO-production
        |         |         | 60 Battery
        |         |         | E_241 Polyester Resin (melamined modified) - M83
        |         |         | RuO2 production
        |         |         | SnPb20 production
        |         |         | LiNbO3-production
        |         |         | 57 SMDshield
        |         |         | 70 Bcover
        |         |         | Phosphorus production
        |         |         | 32 TC7W
```

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|         |         | S_241 Polymer(PP) - M14.1
|         |         | 69 IrWindow
|         |         | AgPd44 production
|         |         | 72 PainAcover
|         |         | 36 CRFU
|         |         | SnAg4 production
|         |         | 56 SMDshield
|         |         | 9b Chipcap
|         |         | FeNi29Co17 production
|         |         | E_241 Polyurethane (PU, rigid foam) - M25
|         |         | 75 Lightguide
|         |         | 241 Polyethylene (PE, All Grades): Production.1
|         |         | 61 Speaker
|         |         | 241 Acrylonitrile Butadiene Styrene  (ABS): Production
|         |         | SnPb37 production
|         |         | 274 Nickel (Ni): Production.1
|         |         | S_241 'Polybutylene' (PB)- M14.1
|         |         | 11 Chipcap
|         |         | 274 Cobalt (Co): Production.1
|         |         | PbSn6 production
|         |         | NdBFe - production
|         |         | 89 Solder
|         |         | 79 DIX2
|         |         | 29 TR
|         |         | 9 Chipcap
|         |         | GaAs production
|         |         | E_274 Lead Oxide (PbO) - M45
|         |         | 51 SMcoax
|         |         | E_241 Polyimide (PI) - M79
|         |         | S_epoxy+GF
|         |         | 55 Barcode
|         |         | Polymer Al-coated
|         |         | SnPb40 production
|         |         | 274 Copper (Cu): Production.1
|         |         | 14 Chipcap
|         |         | E_241 Polycarbonates (PC) - M8
|         |         | 52 SMconn
|         |         | Sb2O3 production
|         |         | 67 Dustcap
|         |         | LiPF6 production
|         |         | E_241 Polytetrafluoroethylene (PTFE) - M17
|         |         | 16 Chipcap
|         |         | CuZn15 production
|         |         | E_271 Steel Plate - M164
|         |         | E_241 Polybutylene Terephtalate (PBT) - M7
|         |         | S_241 Acrylic resin: Production.1
|         |         | 43 Crystal
|         |         | 24 Cap
|         |         | E_241 Magnesium Oxide (MgO) - M54
|         |         | FeSn5 production
|         |         | AuSn20-production
|         |         | Chromium production
|         |         | 84 Buzzer
|         |         | 18 Filz
|         |         | 27 TVS
|         |         | 23 Schdix
|         |         | SmCo production
|         |         | 2 NTC res
|         |         | 85 PCB
|         |         | 20 Chipcoil
|         |         | 80 Varistor
|         |         | E_241 Silica (SiO2) - M56-66
|         |         | 82 LED
|         |         | 13 Chipcap
|         |         | 77 ProtFoil
|         |         | SnPb30 production
```

```
|          |          | 46 Dupl
|          |          | 5a Chipres
|          |          | SnPb16 production
|          |          | 71 Sidekeymat
|          |          | 9a Chipcap
|          |          | CuNi18Zn20 production
|          |          | E_261 Glass Fibers - M60
|          |          | E_241 Polyphenylene Sulphide (PPS) - M23
|          |          | 22 Chipcoil
|          |          | 35 Chaps
|          |          | 'ITO' Production
|          |          | Beryllium production
|          |          | Pb88Sn10Ag2 production
|          |          | 50 SIM
|          |          | S_144 Sodium (Na): Production.1
|          |          | 274 Molybdenum (Mo): Production.1
|          |          | 28 TR
|          |          | LiTaO3 production
|          |          | E_241 Polypropylene (PP) - M14
|          |          | PZTproduction
|          |          | 87 Powkeymat
|          |          | 34 VCO
|          |          | 64 Screw
|          |          | 83 LED
|          |          | S_241 PAI: Production.1
|          |          | 30 Flash
|          |          | 73 DSL lcd
|          |          | 47 TFDU
|          |          | 274 Silver (Ag): Production.1
|          |          | 12 Chipcap
|          |          | 65 Screw
|          |          | 1 Chipres
|          |          | SnPb15 production
|          |          | 19 Filt
|          |          | E_241 Polyamide Resin (PA66) - M6
|          |          | 4 Chipres
|          |          | 274 Zinc (Zn): Production.1
|          |          | 38 Mad
|          |          | E_265 Talc - M61
|          |          | 42 VCTCXO
|          |          | E_241 Epoxy Resin - M76
|          |          | 76 Elasto
|          |          | 17 Ferrite bead
|          |          | CuZn38Pb1.5 production
|          |          | SnPb10 production.1
|          |          | Connection 1
|          |          | CuSn6 production
|          | 2. Parts and phone manufacture
|          |          | 401 Electricity (Chinese Taipei, 1996): Production.1
|          |          | 401 Electricity (European Union, 1996): Production.1
|          |          | 401 Electricity (European Union, 1996): Production.2
|          |          | 401 Electricity (Hong-Kong, 1996): Production.1
|          |          | 401 Electricity (Japan, 1996): Production.1
|          |          | 401 Electricity (Korea, 1996): Production.1
|          |          | 403I Natural Gas: Combustion.1
|          |          | connection and parts manufacture node
|          |          | E_401 Electricity (USA, 1998) - Europe consistent - M19
|          |          | Nokia assembly plant
|          | 3. Use
|          |          | use phase
|          |          | 401 Electricity (European Union, 1996): Production.1
|          | 4. End of Life
|          |          | End of life path
|          |          | To landfill
|          |          | To recycle
```

Appendix E

10.5. *EF calculations for mobile phone*

DLU Case A, BC

Inputs phone to produce required materials and components (kg)	Phone life cycle	Direct land use [m2/phone	Assumption:		1. Raw mat	Direct land use [m2/phone	2. Parts and	Direct land use [m2/phone	3. Use	Direct land use [m2/phone	4. End of Li	Direct land use [m2/phone
(r) Barium Sulphate (BaSO4, in ground)	7.33E-03	7.33E-06	as Barites		3.22E-03	3.22E-06	2.26E-03	2.26E-06	1.96E-03	1.96E-06	-1.05E-04	-1.05E-07
(r) Bauxite (Al2O3, ore)	1.96E-03	4.11E-06			2.15E-03	4.52E-06	8.42E-05	1.77E-07	8.70E-05	1.82E-07	-3.66E-04	-7.68E-07
(r) Bentonite (Al2O3.4SiO2.H2O, in ground)	4.59E-04	2.44E-07			1.00E-04	5.34E-08	2.13E-04	1.13E-07	1.85E-04	9.87E-08	-4.05E-05	-2.15E-08
(r) Calcium Sulphate (CaSO4, ore)	1.96E-05	3.52E-09	as gypsum		4.47E-06	8.05E-10	1.65E-05	2.97E-09	0.00E+00	0.00E+00	-1.38E-06	-2.49E-10
(r) Carbon Dioxide (CO2, in ground)	1.21E-04				1.21E-04		0.00E+00		0.00E+00		0.00E+00	
(r) Chromium (Cr, ore)	1.70E-05	3.78E-10	mined from FeCr2O4, treated as Fe with OB of 2		2.50E-05	5.55E-10	4.34E-07	9.63E-12	3.77E-07	8.38E-12	-8.79E-06	-1.95E-10
(r) Clay (in ground)	9.04E-03	1.63E-06			2.29E-04	4.12E-08	4.10E-03	7.38E-07	4.83E-03	8.69E-07	-1.20E-04	-2.17E-08
(r) Coal (in ground)	1.16E+01	5.83E-03	as Hardcoal S		2.18E-01	1.09E-04	6.99E+00	3.51E-03	4.48E+00	2.25E-03	-1.00E-01	-5.03E-05
(r) Cobalt (Co, ore)	3.08E-05				3.08E-05		0.00E+00		0.00E+00		0.00E+00	
(r) Copper (Cu, ore)	3.70E-03	1.07E-03			1.36E-02	3.93E-03	2.21E-06	6.37E-07	1.92E-06	5.54E-07	-9.93E-03	-2.86E-03
(r) Dolomite (CaCO3.MgCO3, in ground)	2.26E-06	3.08E-11	as Lime		2.27E-06	3.08E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-3.28E-09	-4.45E-14
(r) Feldspar (ore)	2.14E-09	3.85E-13	as clay		2.14E-09	3.85E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Fluorspar (CaF2, ore)	1.28E-05				1.28E-05		0.00E+00		0.00E+00		-2.29E-08	
(r) Gold (Au, ore)	7.16E-06				5.66E-05		0.00E+00		0.00E+00		-4.94E-05	
(r) Gravel (unspecified)	2.52E-03	4.54E-07			4.61E-04	8.30E-08	2.25E-03	4.06E-07	0.00E+00	0.00E+00	-1.89E-04	-3.40E-08
(r) Ilmenite (FeO.TiO2, ore)	4.23E-04				4.23E-04		0.00E+00		0.00E+00		0.00E+00	
(r) Iron (Fe, ore)	4.03E-02	4.47E-07			7.63E-03	8.47E-08	1.95E-02	2.17E-07	1.63E-02	1.81E-07	-3.16E-03	-3.50E-08
(r) Iron Sulphate (FeSO4, ore)	3.71E-04	4.12E-09			1.83E-06	2.03E-11	2.26E-04	2.51E-09	1.45E-04	1.61E-09	-1.44E-06	-1.60E-11
(r) Kaolin (Al2O3.2SiO2.2H2O, ore)	5.09E-03	9.16E-07			5.09E-03	9.16E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Lead (Pb, ore)	1.16E-04				1.16E-04		6.89E-07		6.00E-07		-9.30E-07	
(r) Lignite (in ground)	5.44E+00	1.91E-03			9.44E-02	3.31E-05	1.81E+00	6.36E-04	3.59E+00	1.26E-03	-5.52E-02	-1.94E-05
(r) Limestone (CaCO3, in ground)	1.86E+00	2.53E-05			1.58E-02	2.15E-07	1.08E+00	1.47E-05	7.66E-01	1.04E-05	-2.09E-03	-2.84E-08
(r) Magnesium (Mg, ore)	2.65E-04				2.65E-04		0.00E+00		0.00E+00		0.00E+00	
(r) Manganese (Mn, ore)	5.56E-05	1.41E-07			6.50E-05	1.65E-07	2.53E-07	6.41E-10	2.20E-07	5.58E-10	-9.89E-06	-2.51E-08
(r) Molybdenum (Mo, ore)	2.00E-06				2.00E-06		0.00E+00		0.00E+00		0.00E+00	
(r) Natural Gas (in ground)	2.95E+00	5.99E-03			1.63E-01	3.31E-04	1.52E+00	3.10E-03	1.31E+00	2.66E-03	-5.20E-02	-1.06E-04
(r) Nickel (Ni, ore)	1.32E-03				1.32E-03		1.47E-07		1.28E-07		-6.97E-07	
(r) Oil (in ground)	1.95E+00	1.08E-02			8.91E-02	4.96E-04	9.72E-01	5.40E-03	9.27E-01	5.15E-03	-3.74E-02	-2.08E-04
(r) Olivine ((Mg,Fe)2SiO4, ore)	3.92E-07	7.06E-11	treat as aggregates		3.94E-07	7.09E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.64E-09	-2.95E-13
(r) Palladium (Pd, ore)	2.73E-05				6.30E-05		0.00E+00		0.00E+00		-3.57E-05	
(r) Perlite (SiO2, ore)	8.68E-03	1.56E-06	as sand/gravel		8.68E-03	1.56E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Phosphate Rock (in ground)	4.04E-05	7.26E-09	as sand/gravel		4.04E-05	7.26E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Potassium Chloride (KCl, as K2O, in ground)	4.12E-04				4.12E-04		0.00E+00		0.00E+00		-1.64E-08	
(r) Pyrite (FeS2, ore)	1.13E-02	1.25E-07	as iron ore		1.10E-02	1.22E-07	3.62E-03	4.01E-08	3.15E-03	3.49E-08	-6.45E-03	-7.16E-08
(r) Sand (in ground)	6.23E-03	1.12E-06			1.70E-03	3.06E-07	2.02E-03	3.64E-07	3.33E-03	6.00E-07	-8.27E-04	-1.49E-07
(r) Serpentine (3MgO.2SiO2.2H2O, ore)	3.29E-08	5.93E-12	as aggregates		3.29E-08	5.93E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Silver (Ag, ore)	7.35E-05				5.66E-04		1.09E-08		9.52E-09		-4.92E-04	
(r) Sodium Chloride (NaCl, in ground or in sea)	2.96E-02				1.99E-02		5.84E-03		4.67E-03		-8.22E-04	
(r) Sulphur (in natural gas)	1.01E-04				1.01E-04		0.00E+00		0.00E+00		0.00E+00	
(r) Sulphur (S, in ground)	2.02E-01				2.02E-01		0.00E+00		0.00E+00		-4.58E-05	
(r) Talcum (4SiO2.3MgO.H2O, ore)	7.36E-04	1.32E-07			7.36E-04	1.32E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Tin (Sn, ore)	1.12E-03				1.12E-03		0.00E+00		0.00E+00		0.00E+00	
(r) Titanium (Ti, ore)	6.12E-07	1.70E-10	as iron ore with OB 25 (DL, 1998)		6.12E-07	1.70E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Tungsten (W, ore)	6.39E-05				6.39E-05		0.00E+00		0.00E+00		0.00E+00	
(r) Uranium (U, ore)	5.50E-04	2.15E+00			1.17E-05	4.55E-02	2.43E-04	9.47E-01	3.01E-04	1.17E+00	-5.16E-06	-2.01E-02
(r) Zinc (Zn, ore)	9.56E-04				9.56E-04		1.60E-08		1.40E-08		-1.14E-10	
Boron Oxide (B2O3)	1.15E-06				1.15E-06		0.00E+00		0.00E+00		0.00E+00	
Explosive (unspecified)	1.10E-03				1.10E-03		0.00E+00		0.00E+00		0.00E+00	
Ferromanganese (Fe, Mn, C)	1.67E-08	3.20E-11	50/50 Fe/Mn		1.67E-08	3.20E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fluorspar (CaF2)	9.81E-06				1.19E-05		0.00E+00		0.00E+00		-2.05E-06	
Iron Scrap	3.36E-03	2.20E-06			1.93E-04	1.26E-07	1.84E-03	1.20E-06	1.50E-03	9.82E-07	-1.80E-04	-1.18E-07
Lead Scrap	1.11E-04				1.11E-04		0.00E+00		0.00E+00		0.00E+00	
Magnesium (Mg)	3.13E-05				3.13E-05		0.00E+00		0.00E+00		0.00E+00	
Magnesium Scrap	8.96E-05				8.96E-05		0.00E+00		0.00E+00		0.00E+00	
Raw Materials (unspecified)	5.13E-01				5.82E-03		2.99E-01		2.09E-01		-1.67E-04	
Recovered Matter: Non Ferrous Metals	5.52E-06				5.52E-06		0.00E+00		0.00E+00		0.00E+00	
S_'Antimony' (ore)	2.86E-06				2.86E-06		0.00E+00		0.00E+00		0.00E+00	
S_'Arsenic' (ore)	1.04E-09				1.04E-09		0.00E+00		0.00E+00		0.00E+00	
S_'Beryllium' (ore)	6.70E-06				6.70E-06		0.00E+00		0.00E+00		0.00E+00	
S_'Gallium' (ore)	9.73E-07				9.73E-07		0.00E+00		0.00E+00		0.00E+00	
S_Indium (ore)	3.50E-07				3.50E-07		0.00E+00		0.00E+00		0.00E+00	
S_Lanthanum (ore)	7.48E-05				7.48E-05		0.00E+00		0.00E+00		0.00E+00	
S_NbTa (ore)	4.21E-04				4.21E-04		0.00E+00		0.00E+00		0.00E+00	
S_'Ruthenium' (ore)	7.46E-06				7.46E-06		0.00E+00		0.00E+00		0.00E+00	
S_Samarium (ore)	1.13E-04				1.13E-04		0.00E+00		0.00E+00		0.00E+00	
S_Tin (ore)	4.08E-04				4.08E-04		0.00E+00		0.00E+00		0.00E+00	
Steel	5.51E-11	7.21E-14	as pig iron		5.51E-11	7.21E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Used (total) litres = kg	9.54E+01				2.99E+01		4.23E+01		4.34E+01		-2.01E+01	
Water: Public Network	5.47E-01				6.28E-01		0.00E+00		0.00E+00		-8.11E-02	
Water: River	6.33E-02				6.33E-02		0.00E+00		0.00E+00		-4.59E-08	
Water: Sea	1.39E-02				1.39E-02		0.00E+00		0.00E+00		-4.26E-05	
Water: Unspecified Origin	9.47E+01				2.91E+01		4.23E+01		4.34E+01		-2.01E+01	
Water: Well	4.18E-03				4.18E-03		0.00E+00		0.00E+00		-5.24E-07	
Wood	6.19E-02	5.63E-02			2.33E-03	2.12E-03	3.67E-02	3.34E-02	2.35E-02	2.14E-02	-6.81E-04	-6.20E-04
Sum raw materials/ m2:		**2.23E+00**				**5.25E-02**		**9.93E-01**		**1.21E+00**		**-2.40E-02**
Sum raw materials/m2 w/o wood:		2.17E+00				5.04E-02		9.60E-01		1.19E+00		-2.34E-02
						2		45		54		-1

	Sum Blanks (kg)			
	1.21E-04			
	3.08E-05			
	1.28E-05			
	7.16E-06	Sum non-blank flows [kg]		
	4.23E-04	7.33E-03		
	1.16E-04	1.96E-03		
	2.65E-04	4.59E-04		
	2.00E-06	1.96E-05		
	1.32E-03	1.70E-05		
	2.73E-05	9.04E-03		
	4.12E-04	1.16E+01		
	7.35E-05	3.70E-03		
	2.96E-02	2.26E-06		
	1.01E-04	2.14E-09		
	2.02E-01	2.52E-03		
	1.12E-03	4.03E-02		
	6.39E-05	3.71E-04		
	9.56E-04	5.09E-03		
	1.15E-06	5.44E+00		
	1.10E-03	1.86E+00		
	9.81E-06	5.56E-05		
	1.11E-04	2.95E+00		
	3.13E-05	1.95E+00		
	8.96E-05	3.92E-07		
	5.13E-01	8.68E-03		
	5.52E-06	4.04E-05		
	2.86E-06	1.13E-02		
	1.04E-09	6.23E-03		
	6.70E-06	3.29E-08		
	9.73E-07	7.36E-04		
	3.50E-07	6.12E-07	wood:	% wood
	7.48E-05	5.50E-04	6.19E-02	2.59E-01
	4.21E-04	1.67E-08		
	7.46E-06	3.36E-03		
	1.13E-04	5.51E-11		
	4.08E-04		1.00E+00	
w/o water:	**7.53E-01**	**2.39E+01**	**2.46E+01**	
including water (litres = kg):		9.69E+01		
		% of analysis		

DLU Case A, LCL

Inputs phone to produce required materials and components (kg)	Phone life cycle	Direct land use [m2/phone	Assumption:	Direct land use [m2/phone	2. Parts and phone manufacture	Direct land use [m2/phone	3. Use	Direct land use [m2/phone	4. End of Life	Direct land use [m2/phone
(r) Barium Sulphate (BaSO4, in ground)	7.33E-03	7.33E-06		3.22E-06	2.26E-03	2.26E-06	1.96E-03	1.96E-06	-1.05E-04	-1.05E-07
(r) Bauxite (Al2O3, ore)	1.96E-03	4.11E-06		4.52E-06	8.42E-05	1.77E-07	8.70E-05	1.82E-07	-3.66E-04	-7.68E-07
(r) Bentonite (Al2O3.4SiO2.H2O, in ground)	4.58E-04	2.44E-07		5.33E-08	2.13E-04	1.13E-07	1.85E-04	9.87E-08	-4.05E-05	-2.15E-08
(r) Calcium Sulphate (CaSO4, ore)	1.96E-05	3.52E-09	as gypsum	8.05E-10	1.65E-05	2.97E-09	0.00E+00	0.00E+00	-1.38E-06	-2.49E-10
(r) Carbon Dioxide (CO2, in ground)	1.21E-04				0.00E+00		0.00E+00		0.00E+00	
(r) Chromium (Cr, ore)	1.70E-05	3.78E-10	mined from FeCr2O4, treated as Fe with OB of 2	5.55E-10	4.34E-07	9.63E-12	3.77E-07	8.38E-12	-8.79E-06	-1.95E-10
(r) Clay (in ground)	9.04E-03	1.63E-06		4.12E-08	4.10E-03	7.38E-07	4.83E-03	8.69E-07	-1.20E-04	-2.17E-08
(r) Coal (in ground)	1.16E+01	5.83E-03	assumed to be used in power plant	1.09E-04	6.99E+00	3.51E-03	4.48E+00	2.25E-03	-1.00E-01	-5.03E-05
(r) Cobalt (Co, ore)	3.08E-05				0.00E+00		0.00E+00		0.00E+00	
(r) Copper (Cu, ore)	3.70E-03	1.07E-03		3.93E-03	2.21E-06	6.37E-07	1.92E-06	5.54E-07	-9.93E-03	-2.86E-03
(r) Dolomite (CaCO3.MgCO3, in ground)	2.26E-06	3.08E-11	as Lime	3.08E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-3.28E-09	-4.45E-14
(r) Feldspar (ore)	2.14E-09	3.85E-13	as clay	3.85E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Fluorspar (CaF2, ore)	1.28E-05				0.00E+00		0.00E+00		-2.29E-08	
(r) Gold (Au, ore)	7.16E-06				0.00E+00		0.00E+00		-4.94E-05	
(r) Gravel (unspecified)	2.52E-03	4.54E-07		8.30E-08	2.25E-03	4.06E-07	0.00E+00	0.00E+00	-1.89E-04	-3.40E-08
(r) Ilmenite (FeO.TiO2, ore)	4.23E-04				0.00E+00		0.00E+00		0.00E+00	
(r) Iron (Fe, ore)	4.03E-02	4.47E-07		8.46E-08	1.95E-02	2.17E-07	1.63E-02	1.81E-07	-3.16E-03	-3.50E-08
(r) Iron Sulphate (FeSO4, ore)	3.71E-04	4.12E-09		2.03E-11	2.26E-04	2.51E-09	1.45E-04	1.61E-09	-1.44E-06	-1.60E-11
(r) Kaolin (Al2O3.2SiO2.2H2O, ore)	5.09E-03	9.16E-07		9.16E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Lead (Pb, ore)	1.16E-04				6.89E-07		6.00E-07		-9.30E-07	
(r) Lignite (in ground)	5.44E+00	1.91E-03		3.31E-05	1.81E+00	6.36E-04	3.59E+00	1.26E-03	-5.52E-02	-1.94E-05
(r) Limestone (CaCO3, in ground)	1.86E+00	2.53E-05		2.14E-07	1.08E+00	1.47E-05	7.66E-01	1.04E-05	-2.09E-03	-2.84E-08
(r) Magnesium (Mg, ore)	2.65E-04				0.00E+00		0.00E+00		0.00E+00	
(r) Manganese (Mn, ore)	5.56E-05	1.41E-07		1.65E-07	2.53E-07	6.41E-10	2.20E-07	5.58E-10	-9.89E-06	-2.51E-08
(r) Molybdenum (Mo, ore)	2.00E-06				0.00E+00		0.00E+00		0.00E+00	
(r) Natural Gas (in ground)	2.94E+00	5.99E-03		3.30E-04	1.52E+00	3.10E-03	1.31E+00	2.66E-03	-5.20E-02	-1.06E-04
(r) Nickel (Ni, ore)	1.32E-03				1.47E-07		1.28E-07		-6.97E-07	
(r) Oil (in ground)	1.95E+00	1.08E-02		4.90E-04	9.72E-01	5.40E-03	9.27E-01	5.15E-03	-3.74E-02	-2.08E-04
(r) Olivine ((Mg,Fe)2SiO4, ore)	3.92E-07	7.06E-11	treat as aggregates	7.09E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.64E-09	-2.95E-13
(r) Palladium (Pd, ore)	2.73E-05				0.00E+00		0.00E+00		-3.57E-05	
(r) Perlite (SiO2, ore)	8.68E-03	1.56E-06	as sand/gravel	1.56E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Phosphate Rock (in ground)	4.04E-05	7.26E-09	as sand/gravel	7.26E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Potassium Chloride (KCl, as K2O, in ground)	4.12E-04				0.00E+00		0.00E+00		-1.64E-08	
(r) Pyrite (FeS2, ore)	1.12E-02	1.25E-07	as iron ore	1.21E-07	3.62E-03	4.01E-08	3.15E-03	3.49E-08	-6.45E-03	-7.16E-08
(r) Sand (in ground)	6.23E-03	1.12E-06		3.06E-07	2.02E-03	3.64E-07	3.33E-03	6.00E-07	-8.27E-04	-1.49E-07
(r) Serpentine (3MgO.2SiO2.2H2O, ore)	3.29E-08	5.93E-12	as aggregates	5.93E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Silver (Ag, ore)	7.35E-05				1.09E-08		9.52E-09		-4.92E-04	
(r) Sodium Chloride (NaCl, in ground or in sea)	2.96E-02				5.84E-03		4.67E-03		-8.22E-04	
(r) Sulphur (in natural gas)	1.01E-04				0.00E+00		0.00E+00		0.00E+00	
(r) Sulphur (S, in ground)	2.02E-01				0.00E+00		0.00E+00		-4.58E-05	
(r) Talcum (4SiO2.3MgO.H2O, ore)	7.36E-04	1.32E-07		1.32E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Tin (Sn, ore)	8.71E-04				0.00E+00		0.00E+00		0.00E+00	
(r) Titanium (Ti, ore)	6.12E-07	1.70E-10	as iron ore with OB 25 (DL, 1998)	1.70E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Tungsten (W, ore)	6.39E-05				0.00E+00		0.00E+00		0.00E+00	
(r) Uranium (U, ore)	5.50E-04	2.15E+00		4.53E-02	2.43E-04	9.47E-01	3.01E-04	1.17E+00	-5.16E-06	-2.01E-02
(r) Zinc (Zn, ore)	9.56E-04				1.60E-08		1.40E-08		-1.14E-10	
Boron Oxide (B2O3)	1.15E-06				0.00E+00		0.00E+00		0.00E+00	
Explosive (unspecified)	3.67E-04				2.76E-04		8.60E-05		-1.77E-05	
Ferromanganese (Fe, Mn, C)	1.67E-08	3.20E-11	50/50 Fe/Mn	3.20E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fluorspar (CaF2)	2.20E-07				0.00E+00		0.00E+00		-2.05E-06	
Iron Scrap	3.36E-03	2.20E-06		1.26E-07	1.84E-03	1.20E-06	1.50E-03	9.82E-07	-1.80E-04	-1.18E-07
Lead Scrap	1.11E-04				0.00E+00		0.00E+00		0.00E+00	
Magnesium (Mg)	3.13E-05				0.00E+00		0.00E+00		0.00E+00	
Magnesium Scrap	8.96E-05				0.00E+00		0.00E+00		0.00E+00	
Raw Materials (unspecified)	5.13E-01				2.99E-01		2.09E-01		-1.67E-04	
Recovered Matter: Non Ferrous Metals	5.52E-06				0.00E+00		0.00E+00		0.00E+00	
S_'Antimony' (ore)	2.86E-06				0.00E+00		0.00E+00		0.00E+00	
S_'Arsenic' (ore)	1.04E-09				0.00E+00		0.00E+00		0.00E+00	
S_'Beryllium' (ore)	6.70E-06				0.00E+00		0.00E+00		0.00E+00	
S_'Gallium' (ore)	9.73E-07				0.00E+00		0.00E+00		0.00E+00	
S_Indium (ore)	3.50E-07				0.00E+00		0.00E+00		0.00E+00	
S_Lanthanum (ore)	7.48E-05				0.00E+00		0.00E+00		0.00E+00	
S_NbTa (ore)	4.21E-04				0.00E+00		0.00E+00		0.00E+00	
S_'Ruthenium' (ore)	7.46E-06				0.00E+00		0.00E+00		0.00E+00	
S_Samarium (ore)	1.13E-04				0.00E+00		0.00E+00		0.00E+00	
S_Tin (ore)	4.08E-04				0.00E+00		0.00E+00		0.00E+00	
Steel	5.51E-11	7.21E-14	as pig iron	7.21E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Used (total) litres = kg	9.54E+01				4.23E+01		4.34E+01		-2.01E+01	
Water: Public Network	5.47E-01				0.00E+00		0.00E+00		-8.11E-02	
Water: River	6.33E-02				0.00E+00		0.00E+00		-4.59E-08	
Water: Sea	1.39E-02				0.00E+00		0.00E+00		-4.26E-05	
Water: Unspecified Origin	9.47E+01				4.23E+01		4.34E+01		-2.01E+01	
Water: Well	4.18E-03				0.00E+00		0.00E+00		-5.24E-07	
Wood	6.19E-02	5.63E-02		2.11E-03	3.67E-02	3.34E-02	2.35E-02	2.14E-02	-6.81E-04	-6.20E-04
Sum raw materials/ m2:		**2.23E+00**		**5.23E-02**	**9.73E+01**	**9.93E-01**	**9.81E+01**	**1.21E+00**	**-4.05E+01**	**-2.40E-02**
Sum raw materials/m2 w/o wood:		2.17E+00		5.02E-02		9.60E-01		1.19E+00		-2.34E-02
				2		45		54		-1

DLU Case A, UCL

Inputs phone to produce required materials and components (kg)	Phone life cycle	Direct land use [m2/phone	Assumption:	1. Raw material	Direct land use [m2/phone	2. Parts and phone	Direct land use [m2/phone	3. Use	Direct land use [m2/phone	4. End of Life	Direct land use [m2/phone
(r) Barium Sulphate (BaSO4, in ground)	7.35E-03	7.35E-06		3.23E-03	3.23E-06	2.26E-03	2.26E-06	1.96E-03	1.96E-06	-1.05E-04	-1.05E-07
(r) Bauxite (Al2O3, ore)	1.97E-03	4.13E-06		2.16E-03	4.54E-06	8.42E-05	1.77E-07	8.70E-05	1.82E-07	-3.66E-04	-7.68E-07
(r) Bentonite (Al2O3.4SiO2.H2O, in ground)	4.64E-04	2.47E-07		1.06E-04	5.63E-08	2.13E-04	1.13E-07	1.85E-04	9.87E-08	-4.05E-05	-2.15E-08
(r) Calcium Sulphate (CaSO4, ore)	1.96E-05	3.52E-09	as gypsum	4.47E-06	8.05E-10	1.65E-05	2.97E-09	0.00E+00	0.00E+00	-1.38E-06	-2.49E-10
(r) Carbon Dioxide (CO2, in ground)	1.21E-04			1.21E-04		0.00E+00		0.00E+00		0.00E+00	
(r) Chromium (Cr, ore)	1.70E-05	3.78E-10	mined from FeCr2O4, treated as Fe with OB of 2	2.50E-05	5.55E-10	4.34E-07	9.63E-12	3.77E-07	8.38E-12	-8.79E-06	-1.95E-10
(r) Clay (in ground)	9.06E-03	1.63E-06		2.48E-04	4.47E-08	4.10E-03	7.38E-07	4.83E-03	8.69E-07	-1.20E-04	-2.17E-08
(r) Coal (in ground)	1.17E+01	5.89E-03	assumed to be used in power plant	3.37E-01	1.69E-04	6.99E+00	3.51E-03	4.48E+00	2.25E-03	-1.00E-01	-5.03E-05
(r) Cobalt (Co, ore)	3.08E-05			3.08E-05		0.00E+00		0.00E+00		0.00E+00	
(r) Copper (Cu, ore)	4.08E-03	1.18E-03		1.40E-02	4.04E-03	2.21E-06	6.37E-07	1.92E-06	5.54E-07	-9.93E-03	-2.86E-03
(r) Dolomite (CaCO3.MgCO3, in ground)	2.26E-06	3.08E-11	as Lime	2.27E-06	3.08E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-3.28E-09	-4.45E-14
(r) Feldspar (ore)	2.14E-09	3.85E-13	as clay	2.14E-09	3.85E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Fluorspar (CaF2, ore)	1.28E-05			1.28E-05		0.00E+00		0.00E+00		-2.29E-08	
(r) Gold (Au, ore)	7.16E-06			5.66E-05		0.00E+00		0.00E+00		-4.94E-05	
(r) Gravel (unspecified)	2.52E-03	4.54E-07		4.61E-04	8.30E-08	2.25E-03	4.06E-07	0.00E+00	0.00E+00	-1.89E-04	-3.40E-08
(r) Ilmenite (FeO.TiO2, ore)	4.23E-04			4.23E-04		0.00E+00		0.00E+00		0.00E+00	
(r) Iron (Fe, ore)	4.04E-02	4.49E-07		7.76E-03	8.62E-08	1.95E-02	2.17E-07	1.63E-02	1.81E-07	-3.16E-03	-3.50E-08
(r) Iron Sulphate (FeSO4, ore)	3.71E-04	4.12E-09		1.83E-06	2.03E-11	2.26E-04	2.51E-09	1.45E-04	1.61E-09	-1.44E-06	-1.60E-11
(r) Kaolin (Al2O3.2SiO2.2H2O, ore)	5.09E-03	9.16E-07		5.09E-03	9.16E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Lead (Pb, ore)	1.16E-04			1.16E-04		6.89E-07		6.00E-07		-9.30E-07	
(r) Lignite (in ground)	5.45E+00	1.91E-03		1.06E-01	3.71E-05	1.81E+00	6.36E-04	3.59E+00	1.26E-03	-5.52E-02	-1.94E-05
(r) Limestone (CaCO3, in ground)	1.87E+00	2.54E-05		2.19E-02	2.98E-07	1.08E+00	1.47E-05	7.66E-01	1.04E-05	-2.09E-03	-2.84E-08
(r) Magnesium (Mg, ore)	2.65E-04			2.65E-04		0.00E+00		0.00E+00		0.00E+00	
(r) Manganese (Mn, ore)	5.56E-05	1.41E-07		6.50E-05	1.65E-07	2.53E-07	6.41E-10	2.20E-07	5.58E-10	-9.89E-06	-2.51E-08
(r) Molybdenum (Mo, ore)	2.00E-06			2.00E-06		0.00E+00		0.00E+00		0.00E+00	
(r) Natural Gas (in ground)	3.00E+00	6.10E-03		2.16E-01	4.40E-04	1.52E+00	3.10E-03	1.31E+00	2.66E-03	-5.20E-02	-1.06E-04
(r) Nickel (Ni, ore)	1.32E-03			1.32E-03		1.47E-07		1.28E-07		-6.97E-07	
(r) Oil (in ground)	2.04E+00	1.13E-02		1.77E-01	9.84E-04	9.72E-01	5.40E-03	9.27E-01	5.15E-03	-3.74E-02	-2.08E-04
(r) Olivine ((Mg,Fe)2SiO4, ore)	3.92E-07	7.06E-11	treat as aggregates	3.94E-07	7.09E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.64E-09	-2.95E-13
(r) Palladium (Pd, ore)	2.73E-05			6.30E-05		0.00E+00		0.00E+00		-3.57E-05	
(r) Perlite (SiO2, ore)	8.68E-03	1.56E-06	as sand/gravel	8.68E-03	1.56E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Phosphate Rock (in ground)	4.04E-05	7.26E-09	as sand/gravel	4.04E-05	7.26E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Potassium Chloride (KCl, as K2O, in ground)	4.12E-04			4.12E-04		0.00E+00		0.00E+00		-1.64E-08	
(r) Pyrite (FeS2, ore)	1.35E-02	1.50E-07	as iron ore	1.32E-02	1.47E-07	3.62E-03	4.01E-08	3.15E-03	3.49E-08	-6.45E-03	-7.16E-08
(r) Sand (in ground)	6.36E-03	1.14E-06		1.83E-03	3.29E-07	2.02E-03	3.64E-07	3.33E-03	6.00E-07	-8.27E-04	-1.49E-07
(r) Serpentine (3MgO.2SiO2.2H2O, ore)	3.29E-08	5.93E-12	as aggregates	3.29E-08	5.93E-12	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Silver (Ag, ore)	7.35E-05			5.66E-04		1.09E-08		9.52E-09		-4.92E-04	
(r) Sodium Chloride (NaCl, in ground or in sea)	3.15E-02			2.18E-02		5.84E-03		4.67E-03		-8.22E-04	
(r) Sulphur (in natural gas)	1.01E-04			1.01E-04		0.00E+00		0.00E+00		0.00E+00	
(r) Sulphur (S, in ground)	2.03E-01			2.03E-01		0.00E+00		0.00E+00		-4.58E-05	
(r) Talcum (4SiO2.3MgO.H2O, ore)	7.36E-04	1.32E-07		7.36E-04	1.32E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Tin (Sn, ore)	2.17E-02			2.17E-02		0.00E+00		0.00E+00		0.00E+00	
(r) Titanium (Ti, ore)	6.12E-07	1.70E-10	as iron ore with OB 25 (DL, 1998)	6.12E-07	1.70E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
(r) Tungsten (W, ore)	6.39E-05			6.39E-05		0.00E+00		0.00E+00		0.00E+00	
(r) Uranium (U, ore)	5.54E-04	2.16E+00		1.57E-05	6.14E-02	2.43E-04	9.47E-01	3.01E-04	1.17E+00	-5.16E-06	-2.01E-02
(r) Zinc (Zn, ore)	9.56E-04			9.56E-04		1.60E-08		1.40E-08		-1.14E-10	
Boron Oxide (B2O3)	1.15E-06			1.15E-06		0.00E+00		0.00E+00		0.00E+00	
Explosive (unspecified)	3.67E-04			2.24E-05		2.76E-04		8.60E-05		-1.77E-05	
Ferromanganese (Fe, Mn, C)	1.67E-08	3.20E-11	50/50 Fe/Mn	1.67E-08	3.20E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fluorspar (CaF2)	8.85E-04			8.87E-04		0.00E+00		0.00E+00		-2.05E-06	
Iron Scrap	3.36E-03	2.20E-06		1.93E-04	1.26E-07	1.84E-03	1.20E-06	1.50E-03	9.82E-07	-1.80E-04	-1.18E-07
Lead Scrap	1.11E-04			1.11E-04		0.00E+00		0.00E+00		0.00E+00	
Magnesium (Mg)	3.13E-05			3.13E-05		0.00E+00		0.00E+00		0.00E+00	
Magnesium Scrap	8.96E-05			8.96E-05		0.00E+00		0.00E+00		0.00E+00	
Raw Materials (unspecified)	5.14E-01			6.18E-03		2.99E-01		2.09E-01		-1.67E-04	
Recovered Matter: Non Ferrous Metals	5.52E-06			5.52E-06		0.00E+00		0.00E+00		0.00E+00	
S_'Antimony' (ore)	2.86E-06			2.86E-06		0.00E+00		0.00E+00		0.00E+00	
S_'Arsenic' (ore)	1.04E-09			1.04E-09		0.00E+00		0.00E+00		0.00E+00	
S_'Beryllium' (ore)	6.70E-06			6.70E-06		0.00E+00		0.00E+00		0.00E+00	
S_'Gallium' (ore)	9.73E-07			9.73E-07		0.00E+00		0.00E+00		0.00E+00	
S_Indium (ore)	3.50E-07			3.50E-07		0.00E+00		0.00E+00		0.00E+00	
S_Lanthanum (ore)	7.48E-05			7.48E-05		0.00E+00		0.00E+00		0.00E+00	
S_NbTa (ore)	4.21E-04			4.21E-04		0.00E+00		0.00E+00		0.00E+00	
S_'Ruthenium' (ore)	7.46E-06			7.46E-06		0.00E+00		0.00E+00		0.00E+00	
S_Samarium (ore)	1.13E-04			1.13E-04		0.00E+00		0.00E+00		0.00E+00	
S_Tin (ore)	4.08E-04			4.08E-04		0.00E+00		0.00E+00		0.00E+00	
Steel	5.51E-11	7.21E-14	as pig iron	5.51E-11	7.21E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water Used (total) litres =	9.60E+01			3.05E+01		4.23E+01		4.34E+01		-2.01E+01	
Water: Public Network	5.47E-01			6.28E-01		0.00E+00		0.00E+00		-8.11E-02	
Water: River	6.33E-02			6.33E-02		0.00E+00		0.00E+00		-4.59E-08	
Water: Sea	1.39E-02			1.39E-02		0.00E+00		0.00E+00		-4.26E-05	
Water: Unspecified Origin	9.53E+01			2.98E+01		4.23E+01		4.34E+01		-2.01E+01	
Water: Well	4.18E-03			4.18E-03		0.00E+00		0.00E+00		-5.24E-07	
Wood	6.25E-02	5.69E-02		2.94E-03	2.67E-03	3.67E-02	3.34E-02	2.35E-02	2.14E-02	-6.81E-04	-6.20E-04
Sum raw materials/ m2:		**2.25E+00**			**6.97E-02**		**9.93E-01**		**1.21E+00**		**-2.40E-02**
Sum raw materials/m2 w/o wood:		2.19E+00			6.70E-02		9.60E-01		1.19E+00		-2.34E-02
					3.10E+00		4.42E+01		5.37E+01		-1.07E+00

DLU Case B, BC

Inputs phone to produce required materials and components (kg)	Phone life cycle	Direct land use [	Assumption:	1. Raw material	Direct land use [m2/ph	2. Parts and phone manuf	Direct land use [m2/p	3. Use	Direct land use [m2/ph	4. End of Life	Direct land use
(r) Barium Sulphate (BaSO4, in ground)	0.00698488	6.98E-06		0.00321564	3.22E-06	0.00191128	1.91E-06	0.0019634	1.96E-06	-0.00010542	-1.05E-07
(r) Bauxite (Al2O3, ore)	0.00194624	4.08E-06		0.00215377	4.52E-06	7.15E-05	1.50E-07	8.70E-05	1.82E-07	-0.000366011	-7.68E-07
(r) Bentonite (Al2O3.4SiO2.H2O, in ground)	0.00042589	2.27E-07		0.000100339	5.34E-08	0.000180547	9.61E-08	0.0001855	9.87E-08	-4.05E-05	-2.15E-08
(r) Calcium Sulphate (CaSO4, ore)	1.69E-05	3.04E-09	as gypsum	4.47E-06	8.05E-10	1.38E-05	2.48E-09	0	0.00E+00	-1.38E-06	-2.49E-10
(r) Carbon Dioxide (CO2, in ground)	0.000121348			0.000121348		0		0		0	
(r) Chromium (Cr, ore)	1.69E-05	3.76E-10	mined from FeCr2O4, treated as Fe with OB of 2	2.50E-05	5.55E-10	3.67E-07	8.16E-12	3.77E-07	8.38E-12	-8.79E-06	-1.95E-10
(r) Clay (in ground)	0.00842687	1.52E-06		0.000228897	4.12E-08	0.00348779	6.28E-07	0.0048305	8.69E-07	-0.00012029	-2.17E-08
(r) Coal (in ground)	10.5007	5.28E-03		0.217786	1.09E-04	5.89906	2.96E-03	4.48386	2.25E-03	-0.100009	-5.03E-05
(r) Cobalt (Co, ore)	3.08E-05			3.08E-05		0		0		0	
(r) Copper (Cu, ore)	0.00370233	1.07E-03		0.0136267	3.93E-03	1.87E-06	5.39E-07	1.92E-06	5.54E-07	-0.00992814	-2.86E-03
(r) Dolomite (CaCO3.MgCO3, in ground)	2.26E-06	3.08E-11	as Lime	2.27E-06	3.08E-11	0	0.00E+00	0	0.00E+00	-3.28E-09	-4.45E-14
(r) Feldspar (ore)	2.14E-09	3.85E-13	as clay	2.14E-09	3.85E-13	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Fluorspar (CaF2, ore)	1.28E-05			1.28E-05		0		0		-2.29E-08	
(r) Gold (Au, ore)	7.16E-06			5.66E-05		0		0		-4.94E-05	
(r) Gravel (unspecified)	0.00215484	3.88E-07		0.000460888	8.30E-08	0.0018828	3.39E-07	0	0.00E+00	-0.000188849	-3.40E-08
(r) Ilmenite (FeO.TiO2, ore)	0.000423006			0.000423006		0		0		0	
(r) Iron (Fe, ore)	0.0372912	4.14E-07		0.0076265	8.47E-08	0.0165268	1.83E-07	0.016294	1.81E-07	-0.00315606	-3.50E-08
(r) Iron Sulphate (FeSO4, ore)	0.000335651	3.73E-09		1.83E-06	2.03E-11	0.000190604	2.12E-09	0.0001447	1.61E-09	-1.44E-06	-1.60E-11
(r) Kaolin (Al2O3.2SiO2.2H2O, ore)	0.00508878	9.16E-07		0.00508878	9.16E-07	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Lead (Pb, ore)	0.000116343			0.000116089		5.84E-07		6.00E-07		-9.30E-07	
(r) Lignite (in ground)	5.18737	1.82E-03		0.0943595	3.31E-05	1.55881	5.47E-04	3.5894	1.26E-03	-0.0551994	-1.94E-05
(r) Limestone (CaCO3, in ground)	1.69531	2.31E-05		0.0157825	2.15E-07	0.915287	1.24E-05	0.766329	1.04E-05	-0.00208531	-2.84E-08
(r) Magnesium (Mg, ore)	0.000264503			0.000264503		0		0		0	
(r) Manganese (Mn, ore)	5.55E-05	1.41E-07		6.50E-05	1.65E-07	2.14E-07	5.43E-10	2.20E-07	5.58E-10	-9.89E-06	-2.51E-08
(r) Molybdenum (Mo, ore)	2.00E-06			2.00E-06		0		0		0	
(r) Natural Gas (in ground)	2.71183	5.52E-03		0.162635	3.31E-04	1.29139	2.63E-03	1.30978	2.66E-03	-0.0519772	-1.06E-04
(r) Nickel (Ni, ore)	0.00132394			0.00132439		1.24E-07		1.28E-07		-6.97E-07	
(r) Oil (in ground)	1.80279	1.00E-02		0.0891382	4.96E-04	0.824189	4.58E-03	0.92691	5.15E-03	-0.037446	-2.08E-04
(r) Olivine ((Mg,Fe)2SiO4, ore)	3.92E-07	7.06E-11	treat as aggregates	3.94E-07	7.09E-11	0	0.00E+00	0	0.00E+00	-1.64E-09	-2.95E-13
(r) Palladium (Pd, ore)	2.73E-05			6.30E-05		0		0		-3.57E-05	
(r) Perlite (SiO2, ore)	0.00868487	1.56E-06	as sand/gravel	0.00868487	1.56E-06	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Phosphate Rock (in ground)	4.04E-05	7.26E-09	as sand/gravel	4.04E-05	7.26E-09	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Potassium Chloride (KCl, as K2O, in ground)	0.000412255			0.000412271		0		0		-1.64E-08	
(r) Pyrite (FeS2, ore)	0.0107188	1.19E-07	as iron ore	0.0109568	1.22E-07	0.00306335	3.40E-08	0.0031469	3.49E-08	-0.00644819	-7.16E-08
(r) Sand (in ground)	0.00594125	1.07E-06		0.00170123	3.06E-07	0.00173476	3.12E-07	0.003332	6.00E-07	-0.00082678	-1.49E-07
(r) Serpentine (3MgO.2SiO2.2H2O, ore)	3.29E-08	5.93E-12	as aggregates	3.29E-08	5.93E-12	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Silver (Ag, ore)	7.35E-05			0.000565541		9.27E-09		9.52E-09		-0.0004921	
(r) Sodium Chloride (NaCl, in ground or in sea)	0.0287178			0.0199252		0.00494162		0.0046725		-0.000821502	
(r) Sulphur (in natural gas)	0.000101379			0.000101379		0		0		0	
(r) Sulphur (S, in ground)	0.202358			0.202404		0		0		-4.58E-05	
(r) Talcum (4SiO2.3MgO.H2O, ore)	0.000735893	1.32E-07		0.000735893	1.32E-07	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Tin (Sn, ore)	0.00112079			0.00112079		0		0		0	
(r) Titanium (Ti, ore)	6.12E-07	1.70E-10	as iron ore with OB 25 (DL, 1998)	6.12E-07	1.70E-10	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Tungsten (W, ore)	6.39E-05			6.39E-05		0		0		0	
(r) Uranium (U, ore)	0.000514273	2.01E+00		1.17E-05	4.55E-02	0.000206804	8.07E-01	0.000301	1.17E+00	-5.16E-06	-2.01E-02
(r) Zinc (Zn, ore)	0.000955826			0.000955798		1.36E-08		1.40E-08		-1.14E-10	
Boron Oxide (B2O3)	1.15E-06			1.15E-06		0		0		0	
Explosive (unspecified)	0.000322342			2.24E-05		0.000231589		8.60E-05		-1.77E-05	
Ferromanganese (Fe, Mn, C)	1.67E-08	3.20E-11	50/50 Fe/Mn	1.67E-08	3.20E-11	0	0.00E+00	0	0.00E+00	0	0.00E+00
Fluorspar (CaF2)	9.81E-06			1.19E-05		0		0		-2.05E-06	
Iron Scrap	0.00307438	2.01E-06		0.000193306	1.26E-07	0.0015589	1.02E-06	0.0015023	9.82E-07	-0.000180086	-1.18E-07
Lead Scrap	0.000111374			0.000111374		0		0		0	
Magnesium (Mg)	3.13E-05			3.13E-05		0		0		0	
Magnesium Scrap	8.96E-05			8.96E-05		0		0		0	
Raw Materials (unspecified)	0.467008			0.0058186		0.252602		0.208755		-0.000167497	
Recovered Matter: Non Ferrous Metals	5.52E-06			5.52E-06		0		0		0	
S_'Antimony' (ore)	2.86E-06			2.86E-06		0		0		0	
S_'Arsenic' (ore)	1.04E-09			1.04E-09		0		0		0	
S_'Beryllium' (ore)	6.70E-06			6.70E-06		0		0		0	
S_'Gallium' (ore)	9.73E-07			9.73E-07		0		0		0	
S_Indium (ore)	3.50E-07			3.50E-07		0		0		0	
S_Lanthanum (ore)	7.48E-05			7.48E-05		0		0		0	
S_NbTa (ore)	0.000421226			0.000421226		0		0		0	
S_'Ruthenium' (ore)	7.46E-06			7.46E-06		0		0		0	
S_Samarium (ore)	0.0001127			0.0001127		0		0		0	
S_Tin (ore)	0.0004083			0.0004083		0		0		0	
Steel	5.51E-11	7.21E-14	as pig iron	5.51E-11	7.21E-14	0	0.00E+00	0	0.00E+00	0	0.00E+00
Water Used (total) litres	88.9828			29.8583		35.8795		43.378		-20.1331	
Water: Public Network	0.547004			0.628065		0		0		-0.081061	
Water: River	0.063282			0.0632821		0		0		-4.59E-08	
Water: Sea	0.0138633			0.0139058		0		0		-4.26E-05	
Water: Unspecified Origin	88.3358			29.1488		35.8693		43.3696		-20.0519	
Water: Well	0.00417966			0.00418018		0		0		-5.24E-07	
Wood	5.62E-02	5.11E-02		2.33E-03	2.12E-03	3.10E-02	2.82E-02	2.35E-02	2.14E-02	-6.81E-04	-6.20E-04
Sum raw materials/ m2:		**2.08E+00**			**5.25E-02**		**8.45E-01**		**1.21E+00**		**-2.40E-02**
Sum raw materials/m2 w/o wood:		2.03E+00			5.04E-02		8.17E-01		1.19E+00		-2.34E-02

DLU Case B, LCL

Inputs phone to produce required materials and components (kg)	Phone life cycle	Direct land use [m2/phone	Assumption:	1. Raw material	Direct land use [m2/pl	2. Parts and phone	Direct land use [m2/ph	3. Use	Direct land use [m2/ph	4. End of Life	Direct land use [m2/
(r) Barium Sulphate (BaSO4, in ground)	0.00698468	6.98E-06		0.00321544	3.22E-06	0.00191128	1.91E-06	0.0019634	1.96E-06	-0.00010542	-1.05E-07
(r) Bauxite (Al2O3, ore)	0.00194613	4.08E-06		0.00215366	4.52E-06	7.15E-05	1.50E-07	8.70E-05	1.82E-07	-0.000366011	-7.68E-07
(r) Bentonite (Al2O3.4SiO2.H2O, in ground)	0.000425826	2.27E-07		0.000100275	5.33E-08	0.000180547	9.61E-08	0.0001855	9.87E-08	-4.05E-05	-2.15E-08
(r) Calcium Sulphate (CaSO4, ore)	1.69E-05	3.04E-09	as gypsum	4.47E-06	8.05E-10	1.38E-05	2.48E-09	0	0.00E+00	-1.38E-06	-2.49E-10
(r) Carbon Dioxide (CO2, in ground)	0.000121348			0.000121348		0		0		0	
(r) Chromium (Cr, ore)	1.69E-05	3.76E-10	mined from FeCr2O4, treated as Fe with OB of 2	2.50E-05	5.55E-10	3.67E-07	8.16E-12	3.77E-07	8.38E-12	-8.79E-06	-1.95E-10
(r) Clay (in ground)	0.00842665	1.52E-06		0.000228673	4.12E-08	0.00348779	6.28E-07	0.0048305	8.69E-07	-0.00012029	-2.17E-08
(r) Coal (in ground)	10.4993	5.28E-03	assumed to be used in power plant	0.216415	1.09E-04	5.89906	2.96E-03	4.48386	2.25E-03	-0.100009	-5.03E-05
(r) Cobalt (Co, ore)	3.08E-05			3.08E-05		0		0		0	
(r) Copper (Cu, ore)	0.00369789	1.07E-03		0.0136222	3.93E-03	1.87E-06	5.39E-07	1.92E-06	5.54E-07	-0.00992814	-2.86E-03
(r) Dolomite (CaCO3.MgCO3, in ground)	2.26E-06	3.08E-11	as Lime	2.27E-06	3.08E-11	0	0.00E+00	0	0.00E+00	-3.28E-09	-4.45E-14
(r) Feldspar (ore)	2.14E-09	3.85E-13	as clay	2.14E-09	3.85E-13	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Fluorspar (CaF2, ore)	1.28E-05			1.28E-05		0		0		-2.29E-08	
(r) Gold (Au, ore)	7.16E-06			5.66E-05		0		0		-4.94E-05	
(r) Gravel (unspecified)	0.00215484	3.88E-07		0.000460888	8.30E-08	0.0018828	3.39E-07	0	0.00E+00	-0.000188849	-3.40E-08
(r) Ilmenite (FeO.TiO2, ore)	0.000423006			0.000423006		0		0		0	
(r) Iron (Fe, ore)	0.0372897	4.14E-07		0.00762495	8.46E-08	0.0165268	1.83E-07	0.016294	1.81E-07	-0.00315606	-3.50E-08
(r) Iron Sulphate (FeSO4, ore)	0.000335651	3.73E-09		1.83E-06	2.03E-11	0.000190604	2.12E-09	0.0001447	1.61E-09	-1.44E-06	-1.60E-11
(r) Kaolin (Al2O3.2SiO2.2H2O, ore)	0.00508878	9.16E-07		0.00508878	9.16E-07	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Lead (Pb, ore)	0.000116343			0.000116089		5.84E-07		6.00E-07		-9.30E-07	
(r) Lignite (in ground)	5.18724	1.82E-03		0.0942337	3.31E-05	1.55881	5.47E-04	3.5894	1.26E-03	-0.0551994	-1.94E-05
(r) Limestone (CaCO3, in ground)	1.69525	2.31E-05		0.0157152	2.14E-07	0.915287	1.24E-05	0.766329	1.04E-05	-0.00208531	-2.84E-08
(r) Magnesium (Mg, ore)	0.000264503			0.000264503		0		0		0	
(r) Manganese (Mn, ore)	5.55E-05	1.41E-07		6.50E-05	1.65E-07	2.14E-07	5.43E-10	2.20E-07	5.58E-10	-9.89E-06	-2.51E-08
(r) Molybdenum (Mo, ore)	2.00E-06			2.00E-06		0		0		0	
(r) Natural Gas (in ground)	2.7112	5.52E-03		0.162001	3.30E-04	1.29139	2.63E-03	1.30978	2.66E-03	-0.0519772	-1.06E-04
(r) Nickel (Ni, ore)	0.00132394			0.00132439		1.24E-07		1.28E-07		-6.97E-07	
(r) Oil (in ground)	1.80178	1.00E-02		0.0881278	4.90E-04	0.824189	4.58E-03	0.92691	5.15E-03	-0.037446	-2.08E-04
(r) Olivine ((Mg,Fe)2SiO4, ore)	3.92E-07	7.06E-11	treat as aggregates	3.94E-07	7.09E-11	0	0.00E+00	0	0.00E+00	-1.64E-09	-2.95E-13
(r) Palladium (Pd, ore)	2.73E-05			6.30E-05		0		0		-3.57E-05	
(r) Perlite (SiO2, ore)	0.00868487	1.56E-06	as sand/gravel	0.00868487	1.56E-06	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Phosphate Rock (in ground)	4.04E-05	7.26E-09	as sand/gravel	4.04E-05	7.26E-09	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Potassium Chloride (KCl, as K2O, in ground)	0.000412255			0.000412271		0		0		-1.64E-08	
(r) Pyrite (FeS2, ore)	0.0106921	1.19E-07	as iron ore	0.0109301	1.21E-07	0.00306335	3.40E-08	0.0031469	3.49E-08	-0.00644819	-7.16E-08
(r) Sand (in ground)	0.0059398	1.07E-06		0.00169978	3.06E-07	0.00173476	3.12E-07	0.003332	6.00E-07	-0.00082678	-1.49E-07
(r) Serpentine (3MgO.2SiO2.2H2O, ore)	3.29E-08	5.93E-12	as aggregates	3.29E-08	5.93E-12	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Silver (Ag, ore)	7.35E-05			0.000565541		9.27E-09		9.52E-09		-0.0004921	
(r) Sodium Chloride (NaCl, in ground or in sea)	0.0286971			0.0199045		0.00494162		0.0046725		-0.000821502	
(r) Sulphur (in natural gas)	0.000101379			0.000101379		0		0		0	
(r) Sulphur (S, in ground)	0.202354			0.2024		0		0		-4.58E-05	
(r) Talcum (4SiO2.3MgO.H2O, ore)	0.000735893	1.32E-07		0.000735893	1.32E-07	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Tin (Sn, ore)	0.000870908			0.000870908		0		0		0	
(r) Titanium (Ti, ore)	6.12E-07	1.70E-10	as iron ore with OB 25 (DL, 1998)	6.12E-07	1.70E-10	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Tungsten (W, ore)	6.39E-05			6.39E-05		0		0		0	
(r) Uranium (U, ore)	0.000514226	2.01E+00		1.16E-05	4.53E-02	0.000206804	8.07E-01	0.000301	1.17E+00	-5.16E-06	-2.01E-02
(r) Zinc (Zn, ore)	0.000955826			0.000955798		1.36E-08		1.40E-08		-1.14E-10	
Boron Oxide (B2O3)	1.15E-06			1.15E-06		0		0		0	
Explosive (unspecified)	0.000322342			2.24E-05		0.000231589		8.60E-05		-1.77E-05	
Ferromanganese (Fe, Mn, C)	1.67E-08	3.20E-11	50/50 Fe/Mn	1.67E-08	3.20E-11	0	0.00E+00	0	0.00E+00	0	0.00E+00
Fluorspar (CaF2)	2.20E-07			2.27E-06		0		0		-2.05E-06	
Iron Scrap	0.00307438	2.01E-06		0.000193306	1.26E-07	0.0015589	1.02E-06	0.0015023	9.82E-07	-0.000180086	-1.18E-07
Lead Scrap	0.000111374			0.000111374		0		0		0	
Magnesium (Mg)	3.13E-05			3.13E-05		0		0		0	
Magnesium Scrap	8.96E-05			8.96E-05		0		0		0	
Raw Materials (unspecified)	0.467004			0.0058146		0.252602		0.208755		-0.000167497	
Recovered Matter: Non Ferrous Metals	5.52E-06			5.52E-06		0		0		0	
S_'Antimony' (ore)	2.86E-06			2.86E-06		0		0		0	
S_'Arsenic' (ore)	1.04E-09			1.04E-09		0		0		0	
S_'Beryllium' (ore)	6.70E-06			6.70E-06		0		0		0	
S_'Gallium' (ore)	9.73E-07			9.73E-07		0		0		0	
S_Indium (ore)	3.50E-07			3.50E-07		0		0		0	
S_Lanthanum (ore)	7.48E-05			7.48E-05		0		0		0	
S_NbTa (ore)	0.000421226			0.000421226		0		0		0	
S_'Ruthenium' (ore)	7.46E-06			7.46E-06		0		0		0	
S_Samarium (ore)	0.0001127			0.0001127		0		0		0	
S_Tin (ore)	0.0004083			0.0004083		0		0		0	
Steel	5.51E-11	7.21E-14	as pig iron	5.51E-11	7.21E-14	0	0.00E+00	0	0.00E+00	0	0.00E+00
Water Used (total)	88.9758			29.8513		35.8795		43.378		-20.1331	
Water: Public Network	0.547004			0.628065		0		0		-0.081061	
Water: River	0.063282			0.0632821		0		0		-4.59E-08	
Water: Sea	0.0138633			0.0139058		0		0		-4.26E-05	
Water: Unspecified Origin	88.3287			29.1418		35.8693		43.3696		-20.0519	
Water: Well	0.00417966			0.00418018		0		0		-5.24E-07	
Wood	5.61E-02	5.11E-02		2.32E-03	2.11E-03	3.10E-02	2.82E-02	2.35E-02	2.14E-02	-6.81E-04	-6.20E-04
Sum raw materials/ m2:		**2.08E+00**			**5.23E-02**		**8.45E-01**		**1.21E+00**		**-2.40E-02**
Sum raw materials/m2 w/o wood:		2.03E+00			5.02E-02		8.17E-01		1.19E+00		-2.34E-02

DLU Case B, UCL

Inputs phone to produce required materials and components (kg)	Phone life cycle	Direct land use [m2/ph	Assumption:	1. Raw material prod	Direct land use [m2/ph	2. Parts and	Direct land use [m2/ph	3. Use	Direct land use [m2/ph	4. End of Life	Direct land use [m2/ph
(r) Barium Sulphate (BaSO4, in ground)	0.00700188	7.00E-06		3.23E-03	3.23E-06	0.00191128	1.91E-06	0.001963	1.96E-06	-0.00010542	-1.05E-07
(r) Bauxite (Al2O3, ore)	0.00195606	4.10E-06		2.16E-03	4.54E-06	7.15E-05	1.50E-07	8.70E-05	1.82E-07	-0.000366011	-7.68E-07
(r) Bentonite (Al2O3.4SiO2.H2O, in groun	0.0004314	2.30E-07		1.06E-04	5.62E-08	0.00018055	9.61E-08	0.000185	9.87E-08	-4.05E-05	-2.15E-08
(r) Calcium Sulphate (CaSO4, ore)	1.69E-05	3.04E-09	as gypsum	4.47E-06	8.05E-10	1.38E-05	2.48E-09	0	0.00E+00	-1.38E-06	-2.49E-10
(r) Carbon Dioxide (CO2, in ground)	0.000121348			1.21E-04		0		0		0	
(r) Chromium (Cr, ore)	1.69E-05	3.76E-10	mined from FeCr2O4, treated as Fe with OB of 2	2.50E-05	5.55E-10	3.67E-07	8.16E-12	3.77E-07	8.38E-12	-8.79E-06	-1.95E-10
(r) Clay (in ground)	0.00844604	1.52E-06		2.48E-04	4.46E-08	0.00348779	6.28E-07	0.00483	8.69E-07	-0.00012029	-2.17E-08
(r) Coal (in ground)	10.6196	5.34E-03	as Hardcoal S	3.34E-01	1.68E-04	5.89906	2.96E-03	4.48386	2.25E-03	-0.100009	-5.03E-05
(r) Cobalt (Co, ore)	3.08E-05			3.08E-05		0		0		0	
(r) Copper (Cu, ore)	0.00407974	1.18E-03		1.40E-02	4.04E-03	1.87E-06	5.39E-07	1.92E-06	5.54E-07	-0.00992814	-2.86E-03
(r) Dolomite (CaCO3.MgCO3, in ground)	2.26E-06	3.08E-11	as Lime	2.27E-06	3.08E-11	0	0.00E+00	0	0.00E+00	-3.28E-09	-4.45E-14
(r) Feldspar (ore)	2.14E-09	3.85E-13	as clay	2.14E-09	3.85E-13	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Fluorspar (CaF2, ore)	1.28E-05			1.28E-05		0		0		-2.29E-08	
(r) Gold (Au, ore)	7.16E-06			5.66E-05		0		0		-4.94E-05	
(r) Gravel (unspecified)	0.00215484	3.88E-07		4.61E-04	8.30E-08	0.0018828	3.39E-07	0	0.00E+00	-0.000188849	-3.40E-08
(r) Ilmenite (FeO.TiO2, ore)	0.000423006			4.23E-04		0		0		0	
(r) Iron (Fe, ore)	0.0374269	4.15E-07		7.76E-03	8.61E-08	0.0165268	1.83E-07	0.016294	1.81E-07	-0.00315606	-3.50E-08
(r) Iron Sulphate (FeSO4, ore)	0.000335651	3.73E-09		1.83E-06	2.03E-11	0.0001906	2.12E-09	0.000145	1.61E-09	-1.44E-06	-1.60E-11
(r) Kaolin (Al2O3.2SiO2.2H2O, ore)	0.00508878	9.16E-07		5.09E-03	9.16E-07	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Lead (Pb, ore)	0.000116343			1.16E-04		5.84E-07		6.00E-07		-9.30E-07	
(r) Lignite (in ground)	5.19862	1.83E-03		1.05E-01	3.69E-05	1.55881	5.47E-04	3.5894	1.26E-03	-0.0551994	-1.94E-05
(r) Limestone (CaCO3, in ground)	1.70145	2.31E-05		2.16E-02	2.94E-07	0.915287	1.24E-05	0.766329	1.04E-05	-0.00208531	-2.84E-08
(r) Magnesium (Mg, ore)	0.000264503			2.65E-04		0		0		0	
(r) Manganese (Mn, ore)	5.55E-05	1.41E-07		6.50E-05	1.65E-07	2.14E-07	5.43E-10	2.20E-07	5.58E-10	-9.89E-06	-2.51E-08
(r) Molybdenum (Mo, ore)	2.00E-06			2.00E-06		0		0		0	
(r) Natural Gas (in ground)	2.76546	5.63E-03		2.16E-01	4.39E-04	1.29139	2.63E-03	1.30978	2.66E-03	-0.0519772	-1.06E-04
(r) Nickel (Ni, ore)	0.00132394			1.32E-03		1.24E-07		1.28E-07		-6.97E-07	
(r) Oil (in ground)	1.89072	1.05E-02		1.75E-01	9.72E-04	0.824189	4.58E-03	0.92691	5.15E-03	-0.037446	-2.08E-04
(r) Olivine ((Mg,Fe)2SiO4, ore)	3.92E-07	7.06E-11	treat as aggregates	3.94E-07	7.09E-11	0	0.00E+00	0	0.00E+00	-1.64E-09	-2.95E-13
(r) Palladium (Pd, ore)	2.73E-05			6.30E-05		0		0		-3.57E-05	
(r) Perlite (SiO2, ore)	0.00868487	1.56E-06	as sand/gravel	8.68E-03	1.56E-06	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Phosphate Rock (in ground)	4.04E-05	7.26E-09	as sand/gravel	4.04E-05	7.26E-09	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Potassium Chloride (KCl, as K2O, in gr	0.000412255			4.12E-04		0		0		-1.64E-08	
(r) Pyrite (FeS2, ore)	0.0129895	1.44E-07	as iron ore	1.32E-02	1.46E-07	0.00306335	3.40E-08	0.003147	3.49E-08	-0.00644819	-7.16E-08
(r) Sand (in ground)	0.00606862	1.09E-06		1.82E-03	3.28E-07	0.00173476	3.12E-07	0.003332	6.00E-07	-0.00082678	-1.49E-07
(r) Serpentine (3MgO.2SiO2.2H2O, ore)	3.29E-08	5.93E-12	as aggregates	3.29E-08	5.93E-12	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Silver (Ag, ore)	7.35E-05			5.66E-04		9.27E-09		9.52E-09		-0.0004921	
(r) Sodium Chloride (NaCl, in ground or in	0.0306024			2.17E-02		0.00494162		0.004672		-0.000821502	
(r) Sulphur (in natural gas)	0.000101379			1.01E-04		0		0		0	
(r) Sulphur (S, in ground)	0.202696			2.03E-01		0		0		-4.58E-05	
(r) Talcum (4SiO2.3MgO.H2O, ore)	0.000735893	1.32E-07		7.36E-04	1.32E-07	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Tin (Sn, ore)	0.0216909			2.20E-02		0		0		0	
(r) Titanium (Ti, ore)	6.12E-07	1.70E-10	as iron ore with OB 25 (DL, 1998)	6.12E-07	1.70E-10	0	0.00E+00	0	0.00E+00	0	0.00E+00
(r) Tungsten (W, ore)	6.39E-05			6.39E-05		0		0		0	
(r) Uranium (U, ore)	0.000518345	2.02E+00		1.56E-05	6.08E-02	0.0002068	8.07E-01	0.000301	1.17E+00	-5.16E-06	-2.01E-02
(r) Zinc (Zn, ore)	0.000955826			9.56E-04		1.36E-08		1.40E-08		-1.14E-10	
Boron Oxide (B2O3)	1.15E-06			1.15E-06		0		0		0	
Explosive (unspecified)	0.000322342			2.24E-05		0.00023159		8.60E-05		-1.77E-05	
Ferromanganese (Fe, Mn, C)	1.67E-08	3.20E-11	50/50 Fe/Mn	1.67E-08	3.20E-11	0	0.00E+00	0	0.00E+00	0	0.00E+00
Fluorspar (CaF2)	0.000884853			8.42E-04		0		0		-2.05E-06	
Iron Scrap	0.00307438	2.01E-06		1.93E-04	1.26E-07	0.0015589	1.02E-06	0.001502	9.82E-07	-0.000180086	-1.18E-07
Lead Scrap	0.000111374			1.11E-04		0		0		0	
Magnesium (Mg)	3.13E-05			3.13E-05		0		0		0	
Magnesium Scrap	8.96E-05			8.96E-05		0		0		0	
Raw Materials (unspecified)	0.467373			6.16E-03		0.252602		0.208755		-0.000167497	
Recovered Matter: Non Ferrous Metals	5.52E-06			5.52E-06		0		0		0	
S_'Antimony' (ore)	2.86E-06			2.86E-06		0		0		0	
S_'Arsenic' (ore)	1.04E-09			1.04E-09		0		0		0	
S_'Beryllium' (ore)	6.70E-06			6.70E-06		0		0		0	
S_'Gallium' (ore)	9.73E-07			9.73E-07		0		0		0	
S_Indium (ore)	3.50E-07			3.50E-07		0		0		0	
S_Lanthanum (ore)	7.48E-05			7.48E-05		0		0		0	
S_NbTa (ore)	0.000421226			4.21E-04		0		0		0	
S_'Ruthenium' (ore)	7.46E-06			7.46E-06		0		0		0	
S_Samarium (ore)	0.0001127			1.13E-04		0		0		0	
S_Tin (ore)	0.0004083			4.08E-04		0		0		0	
Steel	5.51E-11	7.21E-14	as pig iron	5.51E-11	7.21E-14	0	0.00E+00	0	0.00E+00	0	0.00E+00
Water Used (total)	89.5926			3.04E+01		35.8795		43.378		-20.1331	
Water: Public Network	0.547004			6.28E-01		0		0		-0.081061	
Water: River	0.063282			6.33E-02		0		0		-4.59E-08	
Water: Sea	0.0138633			1.39E-02		0		0		-4.26E-05	
Water: Unspecified Origin	88.9456			2.97E+01		35.8693		43.3696		-20.0519	
Water: Well	0.00417966			4.18E-03		0		0		-5.24E-07	
Wood	5.68E-02	5.16E-02		2.90E-03	2.64E-03	3.10E-02	2.82E-02	2.35E-02	2.14E-02	-6.81E-04	-6.20E-04
Sum raw materials/ m2:		**2.10E+00**			**6.91E-02**		**8.45E-01**		**1.21E+00**		**-2.40E-02**
Sum raw materials/m2 w/o wood:		2.05E+00			6.65E-02		8.17E-01		1.19E+00		-2.34E-02

Case A, DLU ranks BC

	Total		raw m.extraction		manufacture		use		eol
Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:
(r) Uranium (U, ore)	2.15E+00	(r) Uranium (U, ore)	4.55E-02	(r) Uranium (U, ore)	9.47E-01	(r) Uranium (U, ore)	1.17E+00	(r) Uranium (U, ore)	-2.01E-02
Wood	5.63E-02	(r) Copper (Cu, ore)	3.93E-03	Wood	3.34E-02	Wood	2.14E-02	(r) Copper (Cu, ore)	-2.86E-03
(r) Oil (in ground)	1.08E-02	Wood	2.12E-03	(r) Oil (in ground)	5.40E-03	(r) Oil (in ground)	5.15E-03	Wood	-6.20E-04
(r) Natural Gas (in ground	5.94E-03	(r) Oil (in ground)	4.95E-04	(r) Coal (in ground)	3.51E-03	(r) Natural Gas (in ground	2.64E-03	(r) Oil (in ground)	-2.08E-04
(r) Coal (in ground)	5.83E-03	(r) Natural Gas (in ground	3.28E-04	(r) Natural Gas (in ground	3.07E-03	(r) Coal (in ground)	2.25E-03	(r) Natural Gas (in ground	-1.05E-04
(r) Lignite (in ground)	1.91E-03	(r) Coal (in ground)	1.09E-04	(r) Lignite (in ground)	6.36E-04	(r) Lignite (in ground)	1.26E-03	(r) Coal (in ground)	-5.03E-05
(r) Copper (Cu, ore)	1.07E-03	(r) Lignite (in ground)	3.31E-05	(r) Limestone (CaCO3, in	1.47E-05	(r) Limestone (CaCO3, in	1.04E-05	(r) Lignite (in ground)	-1.94E-05
(r) Limestone (CaCO3, in	2.53E-05	(r) Bauxite (Al2O3, ore)	4.52E-06	(r) Barium Sulphate (BaS	2.26E-06	(r) Barium Sulphate (BaS	1.96E-06	(r) Bauxite (Al2O3, ore)	-7.68E-07
(r) Barium Sulphate (BaS	7.33E-06	(r) Barium Sulphate (BaS	3.22E-06	Iron Scrap	1.20E-06	Iron Scrap	9.82E-07	(r) Sand (in ground)	-1.49E-07
(r) Bauxite (Al2O3, ore)	4.11E-06	(r) Perlite (SiO2, ore)	1.56E-06	(r) Clay (in ground)	7.38E-07	(r) Clay (in ground)	8.69E-07	Iron Scrap	-1.18E-07
Iron Scrap	2.20E-06	(r) Kaolin (Al2O3.2SiO2.2	9.16E-07	(r) Copper (Cu, ore)	6.37E-07	(r) Sand (in ground)	6.00E-07	(r) Barium Sulphate (BaS	-1.05E-07
(r) Clay (in ground)	1.63E-06	(r) Sand (in ground)	3.06E-07	(r) Gravel (unspecified)	4.06E-07	(r) Copper (Cu, ore)	5.54E-07	(r) Pyrite (FeS2, ore)	-7.16E-08
(r) Perlite (SiO2, ore)	1.56E-06	(r) Limestone (CaCO3, in	2.15E-07	(r) Sand (in ground)	3.64E-07	(r) Bauxite (Al2O3, ore)	1.82E-07	(r) Iron (Fe, ore)	-3.50E-08
(r) Sand (in ground)	1.12E-06	(r) Manganese (Mn, ore)	1.65E-07	(r) Iron (Fe, ore)	2.17E-07	(r) Iron (Fe, ore)	1.81E-07	(r) Gravel (unspecified)	-3.40E-08
(r) Kaolin (Al2O3.2SiO2.2	9.16E-07	(r) Talcum (4SiO2.3MgO.	1.32E-07	(r) Bauxite (Al2O3, ore)	1.77E-07	(r) Bentonite (Al2O3.4Si	9.87E-08	(r) Limestone (CaCO3, in	-2.84E-08
(r) Gravel (unspecified)	4.55E-07	Iron Scrap	1.26E-07	(r) Bentonite (Al2O3.4Si	1.13E-07	(r) Pyrite (FeS2, ore)	3.49E-08	(r) Manganese (Mn, ore)	-2.51E-08
(r) Iron (Fe, ore)	4.47E-07	(r) Pyrite (FeS2, ore)	1.22E-07	(r) Pyrite (FeS2, ore)	4.01E-08	(r) Iron Sulphate (FeSO4,	1.61E-09	(r) Clay (in ground)	-2.17E-08
(r) Bentonite (Al2O3.4Si	2.44E-07	(r) Iron (Fe, ore)	8.47E-08	(r) Calcium Sulphate (CaS	2.97E-09	(r) Manganese (Mn, ore)	5.58E-10	(r) Bentonite (Al2O3.4Si	-2.15E-08
(r) Manganese (Mn, ore)	1.41E-07	(r) Gravel (unspecified)	8.30E-08	(r) Iron Sulphate (FeSO4,	2.51E-09	(r) Chromium (Cr, ore)	8.38E-12	(r) Calcium Sulphate (CaS	-2.49E-10
(r) Talcum (4SiO2.3MgO.	1.32E-07	(r) Bentonite (Al2O3.4Si	5.34E-08	(r) Manganese (Mn, ore)	6.41E-10	(r) Calcium Sulphate (CaS	0.00E+00	(r) Chromium (Cr, ore)	-1.95E-10
(r) Pyrite (FeS2, ore)	1.25E-07	(r) Clay (in ground)	4.12E-08	(r) Chromium (Cr, ore)	9.63E-12	(r) Dolomite (CaCO3.MgC	0.00E+00	(r) Iron Sulphate (FeSO4,	-1.60E-11
(r) Phosphate Rock (in gr	7.26E-09	(r) Phosphate Rock (in gr	7.26E-09	(r) Dolomite (CaCO3.MgC	0.00E+00	(r) Feldspar (ore)	0.00E+00	(r) Olivine ((Mg,Fe)2SiO4	-2.95E-13
(r) Iron Sulphate (FeSO4,	4.12E-09	(r) Calcium Sulphate (CaS	8.05E-10	(r) Feldspar (ore)	0.00E+00	(r) Gravel (unspecified)	0.00E+00	(r) Dolomite (CaCO3.MgC	-4.45E-14
(r) Calcium Sulphate (CaS	3.52E-09	(r) Chromium (Cr, ore)	5.55E-10	(r) Kaolin (Al2O3.2SiO2.2	0.00E+00	(r) Kaolin (Al2O3.2SiO2.2	0.00E+00	(r) Feldspar (ore)	0.00E+00
(r) Chromium (Cr, ore)	3.78E-10	(r) Titanium (Ti, ore)	1.70E-10	(r) Olivine ((Mg,Fe)2SiO4	0.00E+00	(r) Olivine ((Mg,Fe)2SiO4	0.00E+00	(r) Kaolin (Al2O3.2SiO2.2	0.00E+00
(r) Titanium (Ti, ore)	1.70E-10	(r) Olivine ((Mg,Fe)2SiO4	7.09E-11	(r) Perlite (SiO2, ore)	0.00E+00	(r) Perlite (SiO2, ore)	0.00E+00	(r) Perlite (SiO2, ore)	0.00E+00
(r) Olivine ((Mg,Fe)2SiO4	7.06E-11	Ferromanganese (Fe, Mn,	3.20E-11	(r) Phosphate Rock (in gr	0.00E+00	(r) Phosphate Rock (in gr	0.00E+00	(r) Phosphate Rock (in gr	0.00E+00
Ferromanganese (Fe, Mn,	3.20E-11	(r) Dolomite (CaCO3.MgC	3.08E-11	(r) Serpentine (3MgO.2Si	0.00E+00	(r) Serpentine (3MgO.2Si	0.00E+00	(r) Serpentine (3MgO.2Si	0.00E+00
(r) Dolomite (CaCO3.MgC	3.08E-11	(r) Iron Sulphate (FeSO4,	2.03E-11	(r) Talcum (4SiO2.3MgO.	0.00E+00	(r) Talcum (4SiO2.3MgO.	0.00E+00	(r) Talcum (4SiO2.3MgO.	0.00E+00
(r) Serpentine (3MgO.2Si	5.93E-12	(r) Serpentine (3MgO.2Si	5.93E-12	(r) Titanium (Ti, ore)	0.00E+00	(r) Titanium (Ti, ore)	0.00E+00	(r) Titanium (Ti, ore)	0.00E+00
(r) Feldspar (ore)	3.85E-13	(r) Feldspar (ore)	3.85E-13	Ferromanganese (Fe, Mn,	0.00E+00	Ferromanganese (Fe, Mn,	0.00E+00	Ferromanganese (Fe, Mn,	0.00E+00
Steel	7.21E-14	Steel	7.21E-14	Steel	0.00E+00	Steel	0.00E+00	Steel	0.00E+00
SUM x-check	2.23E+00		5.25E-02		9.93E-01		1.21E+00		-2.40E-02

Case A, DLU ranks LCL

Total		raw m.extraction		manufacture		use		eol	
Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	**Inputs phone to produce required materials and components (kg)**	DLU [m2/phone LC]:	**Inputs phone to produce required materials and components (kg)**	DLU [m2/phone LC]:	**Inputs phone to produce required materials and components (kg)**	DLU [m2/phone LC]:	**Inputs phone to produce required materials and components (kg)**	DLU [m2/phone LC]:
(r) Uranium (U, ore)	2.15E+00	(r) Uranium (U, ore)	4.53E-02	(r) Uranium (U, ore)	9.47E-01	(r) Uranium (U, ore)	1.17E+00	(r) Uranium (U, ore)	-2.01E-02
Wood	5.63E-02	(r) Copper (Cu, ore)	3.93E-03	Wood	3.34E-02	Wood	2.14E-02	(r) Copper (Cu, ore)	-2.86E-03
(r) Oil (in ground)	1.08E-02	Wood	2.11E-03	(r) Oil (in ground)	5.40E-03	(r) Oil (in ground)	5.15E-03	Wood	-6.20E-04
(r) Natural Gas (in gro	5.94E-03	(r) Oil (in ground)	4.90E-04	(r) Coal (in ground)	3.51E-03	(r) Natural Gas (in gro	2.64E-03	(r) Oil (in ground)	-2.08E-04
(r) Coal (in ground)	5.83E-03	(r) Natural Gas (in gro	3.27E-04	(r) Natural Gas (in gro	3.07E-03	(r) Coal (in ground)	2.25E-03	(r) Natural Gas (in gro	-1.05E-04
(r) Lignite (in ground)	1.91E-03	(r) Coal (in ground)	1.09E-04	(r) Lignite (in ground)	6.36E-04	(r) Lignite (in ground)	1.26E-03	(r) Coal (in ground)	-5.03E-05
(r) Copper (Cu, ore)	1.07E-03	(r) Lignite (in ground)	3.31E-05	(r) Limestone (CaCO3,	1.47E-05	(r) Limestone (CaCO3,	1.04E-05	(r) Lignite (in ground)	-1.94E-05
(r) Limestone (CaCO3,	2.53E-05	(r) Bauxite (Al2O3, ore	4.52E-06	(r) Barium Sulphate (B	2.26E-06	(r) Barium Sulphate (B	1.96E-06	(r) Bauxite (Al2O3, ore	-7.68E-07
(r) Barium Sulphate (B	7.33E-06	(r) Barium Sulphate (B	3.22E-06	Iron Scrap	1.20E-06	Iron Scrap	9.82E-07	(r) Sand (in ground)	-1.49E-07
(r) Bauxite (Al2O3, ore	4.11E-06	(r) Perlite (SiO2, ore)	1.56E-06	(r) Clay (in ground)	7.38E-07	(r) Clay (in ground)	8.69E-07	Iron Scrap	-1.18E-07
Iron Scrap	2.20E-06	(r) Kaolin (Al2O3.2SiO	9.16E-07	(r) Copper (Cu, ore)	6.37E-07	(r) Sand (in ground)	6.00E-07	(r) Barium Sulphate (B	-1.05E-07
(r) Clay (in ground)	1.63E-06	(r) Sand (in ground)	3.06E-07	(r) Gravel (unspecified	4.06E-07	(r) Copper (Cu, ore)	5.54E-07	(r) Pyrite (FeS2, ore)	-7.16E-08
(r) Perlite (SiO2, ore)	1.56E-06	(r) Limestone (CaCO3,	2.14E-07	(r) Sand (in ground)	3.64E-07	(r) Bauxite (Al2O3, ore	1.82E-07	(r) Iron (Fe, ore)	-3.50E-08
(r) Sand (in ground)	1.12E-06	(r) Manganese (Mn, ore	1.65E-07	(r) Iron (Fe, ore)	2.17E-07	(r) Iron (Fe, ore)	1.81E-07	(r) Gravel (unspecified	-3.40E-08
(r) Kaolin (Al2O3.2SiO	9.16E-07	(r) Talcum (4SiO2.3Mg	1.32E-07	(r) Bauxite (Al2O3, ore	1.77E-07	(r) Bentonite (Al2O3.4	9.87E-08	(r) Limestone (CaCO3,	-2.84E-08
(r) Gravel (unspecified	4.55E-07	Iron Scrap	1.26E-07	(r) Bentonite (Al2O3.4	1.13E-07	(r) Pyrite (FeS2, ore)	3.49E-08	(r) Manganese (Mn, ore	-2.51E-08
(r) Iron (Fe, ore)	4.47E-07	(r) Pyrite (FeS2, ore)	1.21E-07	(r) Pyrite (FeS2, ore)	4.01E-08	(r) Iron Sulphate (FeSC	1.61E-09	(r) Clay (in ground)	-2.17E-08
(r) Bentonite (Al2O3.4	2.44E-07	(r) Iron (Fe, ore)	8.46E-08	(r) Calcium Sulphate (	2.97E-09	(r) Manganese (Mn, ore	5.58E-10	(r) Bentonite (Al2O3.4	-2.15E-08
(r) Manganese (Mn, ore	1.41E-07	(r) Gravel (unspecified	8.30E-08	(r) Iron Sulphate (FeSC	2.51E-09	(r) Chromium (Cr, ore)	8.38E-12	(r) Calcium Sulphate (	-2.49E-10
(r) Talcum (4SiO2.3Mg	1.32E-07	(r) Bentonite (Al2O3.4	5.34E-08	(r) Manganese (Mn, ore	6.41E-10	(r) Calcium Sulphate (	0.00E+00	(r) Chromium (Cr, ore)	-1.95E-10
(r) Pyrite (FeS2, ore)	1.25E-07	(r) Clay (in ground)	4.12E-08	(r) Chromium (Cr, ore)	9.63E-12	(r) Dolomite (CaCO3.M	0.00E+00	(r) Iron Sulphate (FeSC	-1.60E-11
(r) Phosphate Rock (in	7.26E-09	(r) Phosphate Rock (in	7.26E-09	(r) Dolomite (CaCO3.M	0.00E+00	(r) Feldspar (ore)	0.00E+00	(r) Olivine ((Mg,Fe)2Si	-2.95E-13
(r) Iron Sulphate (FeSC	4.12E-09	(r) Calcium Sulphate (	8.05E-10	(r) Feldspar (ore)	0.00E+00	(r) Gravel (unspecified	0.00E+00	(r) Dolomite (CaCO3.M	-4.45E-14
(r) Calcium Sulphate (	3.52E-09	(r) Chromium (Cr, ore)	5.55E-10	(r) Kaolin (Al2O3.2SiO	0.00E+00	(r) Kaolin (Al2O3.2SiO	0.00E+00	(r) Feldspar (ore)	0.00E+00
(r) Chromium (Cr, ore)	3.78E-10	(r) Titanium (Ti, ore)	1.70E-10	(r) Olivine ((Mg,Fe)2Si	0.00E+00	(r) Olivine ((Mg,Fe)2Si	0.00E+00	(r) Kaolin (Al2O3.2SiO	0.00E+00
(r) Titanium (Ti, ore)	1.70E-10	(r) Olivine ((Mg,Fe)2Si	7.09E-11	(r) Perlite (SiO2, ore)	0.00E+00	(r) Perlite (SiO2, ore)	0.00E+00	(r) Perlite (SiO2, ore)	0.00E+00
(r) Olivine ((Mg,Fe)2Si	7.06E-11	Ferromanganese (Fe, M	3.20E-11	(r) Phosphate Rock (in	0.00E+00	(r) Phosphate Rock (in	0.00E+00	(r) Phosphate Rock (in	0.00E+00
Ferromanganese (Fe, M	3.20E-11	(r) Dolomite (CaCO3.M	3.08E-11	(r) Serpentine (3MgO.	0.00E+00	(r) Serpentine (3MgO.	0.00E+00	(r) Serpentine (3MgO.	0.00E+00
(r) Dolomite (CaCO3.M	3.08E-11	(r) Iron Sulphate (FeSC	2.03E-11	(r) Talcum (4SiO2.3Mg	0.00E+00	(r) Talcum (4SiO2.3Mg	0.00E+00	(r) Talcum (4SiO2.3Mg	0.00E+00
(r) Serpentine (3MgO.	5.93E-12	(r) Serpentine (3MgO.	5.93E-12	(r) Titanium (Ti, ore)	0.00E+00	(r) Titanium (Ti, ore)	0.00E+00	(r) Titanium (Ti, ore)	0.00E+00
(r) Feldspar (ore)	3.85E-13	(r) Feldspar (ore)	3.85E-13	Ferromanganese (Fe, M	0.00E+00	Ferromanganese (Fe, M	0.00E+00	Ferromanganese (Fe, M	0.00E+00
Steel	7.21E-14	Steel	7.21E-14	Steel	0.00E+00	Steel	0.00E+00	Steel	0.00E+00
SUM x-check m2	2.23E+00		5.23E-02		9.93E-01		1.21E+00		-2.40E-02

Case A, DLU ranks UCL

	Total	raw m.extraction		manufacture		use		eol	
Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:
(r) Uranium (U, ore)	2.16E+00	(r) Uranium (U, ore)	6.14E-02	(r) Uranium (U, ore)	9.47E-01	(r) Uranium (U, ore)	1.17E+00	(r) Uranium (U, ore)	-2.01E-02
Wood	5.69E-02	(r) Copper (Cu, ore)	4.04E-03	Wood	3.34E-02	Wood	2.14E-02	(r) Copper (Cu, ore)	-2.86E-03
(r) Oil (in ground)	1.13E-02	Wood	2.67E-03	(r) Oil (in ground)	5.40E-03	(r) Oil (in ground)	5.15E-03	Wood	-6.20E-04
(r) Natural Gas (in grou	6.04E-03	(r) Oil (in ground)	9.84E-04	(r) Coal (in ground)	3.51E-03	(r) Natural Gas (in grou	2.64E-03	(r) Oil (in ground)	-2.08E-04
(r) Coal (in ground)	5.89E-03	(r) Natural Gas (in grou	4.36E-04	(r) Natural Gas (in grou	3.07E-03	(r) Coal (in ground)	2.25E-03	(r) Natural Gas (in grou	-1.05E-04
(r) Lignite (in ground)	1.91E-03	(r) Coal (in ground)	1.69E-04	(r) Lignite (in ground)	6.36E-04	(r) Lignite (in ground)	1.26E-03	(r) Coal (in ground)	-5.03E-05
(r) Copper (Cu, ore)	1.18E-03	(r) Lignite (in ground)	3.71E-05	(r) Limestone (CaCO3,	1.47E-05	(r) Limestone (CaCO3,	1.04E-05	(r) Lignite (in ground)	-1.94E-05
(r) Limestone (CaCO3,	2.54E-05	(r) Bauxite (Al2O3, ore	4.54E-06	(r) Barium Sulphate (B	2.26E-06	(r) Barium Sulphate (B	1.96E-06	(r) Bauxite (Al2O3, ore	-7.68E-07
(r) Barium Sulphate (B	7.35E-06	(r) Barium Sulphate (B	3.23E-06	Iron Scrap	1.20E-06	Iron Scrap	9.82E-07	(r) Sand (in ground)	-1.49E-07
(r) Bauxite (Al2O3, ore	4.13E-06	(r) Perlite (SiO2, ore)	1.56E-06	(r) Clay (in ground)	7.38E-07	(r) Clay (in ground)	8.69E-07	Iron Scrap	-1.18E-07
Iron Scrap	2.20E-06	(r) Kaolin (Al2O3.2SiO	9.16E-07	(r) Copper (Cu, ore)	6.37E-07	(r) Sand (in ground)	6.00E-07	(r) Barium Sulphate (B	-1.05E-07
(r) Clay (in ground)	1.63E-06	(r) Sand (in ground)	3.28E-07	(r) Gravel (unspecified	4.06E-07	(r) Copper (Cu, ore)	5.54E-07	(r) Pyrite (FeS2, ore)	-7.16E-08
(r) Perlite (SiO2, ore)	1.56E-06	(r) Limestone (CaCO3,	2.94E-07	(r) Sand (in ground)	3.64E-07	(r) Bauxite (Al2O3, ore	1.82E-07	(r) Iron (Fe, ore)	-3.50E-08
(r) Sand (in ground)	1.14E-06	(r) Manganese (Mn, ore	1.65E-07	(r) Iron (Fe, ore)	2.17E-07	(r) Iron (Fe, ore)	1.81E-07	(r) Gravel (unspecified	-3.40E-08
(r) Kaolin (Al2O3.2SiO	9.16E-07	(r) Pyrite (FeS2, ore)	1.46E-07	(r) Bauxite (Al2O3, ore	1.77E-07	(r) Bentonite (Al2O3.4	9.87E-08	(r) Limestone (CaCO3,	-2.84E-08
(r) Gravel (unspecified	4.54E-07	(r) Talcum (4SiO2.3Mg	1.32E-07	(r) Bentonite (Al2O3.4	1.13E-07	(r) Pyrite (FeS2, ore)	3.49E-08	(r) Manganese (Mn, ore	-2.51E-08
(r) Iron (Fe, ore)	4.49E-07	Iron Scrap	1.26E-07	(r) Pyrite (FeS2, ore)	4.01E-08	(r) Iron Sulphate (FeSO	1.61E-09	(r) Clay (in ground)	-2.17E-08
(r) Bentonite (Al2O3.4	2.47E-07	(r) Iron (Fe, ore)	8.61E-08	(r) Calcium Sulphate (	2.97E-09	(r) Manganese (Mn, ore	5.58E-10	(r) Bentonite (Al2O3.4	-2.15E-08
(r) Pyrite (FeS2, ore)	1.50E-07	(r) Gravel (unspecified	8.30E-08	(r) Iron Sulphate (FeSO	2.51E-09	(r) Chromium (Cr, ore)	8.38E-12	(r) Calcium Sulphate (	-2.49E-10
(r) Manganese (Mn, ore	1.41E-07	(r) Bentonite (Al2O3.4	5.62E-08	(r) Manganese (Mn, ore	6.41E-10	(r) Calcium Sulphate (	0.00E+00	(r) Chromium (Cr, ore)	-1.95E-10
(r) Talcum (4SiO2.3Mg	1.32E-07	(r) Clay (in ground)	4.46E-08	(r) Chromium (Cr, ore)	9.63E-12	(r) Dolomite (CaCO3.M	0.00E+00	(r) Iron Sulphate (FeSO	-1.60E-11
(r) Phosphate Rock (in	7.26E-09	(r) Phosphate Rock (in	7.26E-09	(r) Dolomite (CaCO3.M	0.00E+00	(r) Feldspar (ore)	0.00E+00	(r) Olivine ((Mg,Fe)2Si	-2.95E-13
(r) Iron Sulphate (FeSO	4.12E-09	(r) Calcium Sulphate (	8.05E-10	(r) Feldspar (ore)	0.00E+00	(r) Gravel (unspecified	0.00E+00	(r) Dolomite (CaCO3.M	-4.45E-14
(r) Calcium Sulphate (	3.52E-09	(r) Chromium (Cr, ore)	5.55E-10	(r) Kaolin (Al2O3.2SiO	0.00E+00	(r) Kaolin (Al2O3.2SiO	0.00E+00	(r) Feldspar (ore)	0.00E+00
(r) Chromium (Cr, ore)	3.78E-10	(r) Titanium (Ti, ore)	1.70E-10	(r) Olivine ((Mg,Fe)2Si	0.00E+00	(r) Olivine ((Mg,Fe)2Si	0.00E+00	(r) Kaolin (Al2O3.2SiO	0.00E+00
(r) Titanium (Ti, ore)	1.70E-10	(r) Olivine ((Mg,Fe)2Si	7.09E-11	(r) Perlite (SiO2, ore)	0.00E+00	(r) Perlite (SiO2, ore)	0.00E+00	(r) Perlite (SiO2, ore)	0.00E+00
(r) Olivine ((Mg,Fe)2Si	7.06E-11	Ferromanganese (Fe, M	3.20E-11	(r) Phosphate Rock (in	0.00E+00	(r) Phosphate Rock (in	0.00E+00	(r) Phosphate Rock (in	0.00E+00
Ferromanganese (Fe, M	3.20E-11	(r) Dolomite (CaCO3.M	3.08E-11	(r) Serpentine (3MgO.2	0.00E+00	(r) Serpentine (3MgO.2	0.00E+00	(r) Serpentine (3MgO.2	0.00E+00
(r) Dolomite (CaCO3.M	3.08E-11	(r) Iron Sulphate (FeSO	2.03E-11	(r) Talcum (4SiO2.3Mg	0.00E+00	(r) Talcum (4SiO2.3Mg	0.00E+00	(r) Talcum (4SiO2.3Mg	0.00E+00
(r) Serpentine (3MgO.2	5.93E-12	(r) Serpentine (3MgO.2	5.93E-12	(r) Titanium (Ti, ore)	0.00E+00	(r) Titanium (Ti, ore)	0.00E+00	(r) Titanium (Ti, ore)	0.00E+00
(r) Feldspar (ore)	3.85E-13	(r) Feldspar (ore)	3.85E-13	Ferromanganese (Fe, M	0.00E+00	Ferromanganese (Fe, M	0.00E+00	Ferromanganese (Fe, M	0.00E+00
Steel	7.21E-14	Steel	7.21E-14	Steel	0.00E+00	Steel	0.00E+00	Steel	0.00E+00
SUM x-check	2.25E+00		6.97E-02		9.93E-01		1.21E+00		-2.40E-02

Case B, DLU ranks BC

	Total	raw m.extraction		manufacture		use		eol	
Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:
(r) Uranium (U, ore)	2.01E+00	(r) Uranium (U, ore)	4.55E-02	(r) Uranium (U, ore)	8.06E-01	(r) Uranium (U, ore)	1.17E+00	(r) Uranium (U, ore)	-2.01E-02
Wood	5.11E-02	(r) Copper (Cu, ore)	3.93E-03	Wood	2.82E-02	Wood	2.14E-02	(r) Copper (Cu, ore)	-2.86E-03
(r) Oil (in ground)	1.00E-02	Wood	2.12E-03	(r) Oil (in ground)	4.58E-03	(r) Oil (in ground)	5.15E-03	Wood	-6.20E-04
(r) Natural Gas (in gro	5.46E-03	(r) Oil (in ground)	4.95E-04	(r) Coal (in ground)	2.96E-03	(r) Natural Gas (in gro	2.64E-03	(r) Oil (in ground)	-2.08E-04
(r) Coal (in ground)	5.28E-03	(r) Natural Gas (in gro	3.28E-04	(r) Natural Gas (in gro	2.60E-03	(r) Coal (in ground)	2.25E-03	(r) Natural Gas (in gro	-1.05E-04
(r) Lignite (in ground)	1.82E-03	(r) Coal (in ground)	1.09E-04	(r) Lignite (in ground)	5.47E-04	(r) Lignite (in ground)	1.26E-03	(r) Coal (in ground)	-5.03E-05
(r) Copper (Cu, ore)	1.07E-03	(r) Lignite (in ground)	3.31E-05	(r) Limestone (CaCO3,	1.24E-05	(r) Limestone (CaCO3,	1.04E-05	(r) Lignite (in ground)	-1.94E-05
(r) Limestone (CaCO3,	2.31E-05	(r) Bauxite (Al2O3, ore	4.52E-06	(r) Barium Sulphate (B	1.91E-06	(r) Barium Sulphate (B	1.96E-06	(r) Bauxite (Al2O3, ore	-7.68E-07
(r) Barium Sulphate (B	6.98E-06	(r) Barium Sulphate (B	3.22E-06	Iron Scrap	1.02E-06	Iron Scrap	9.82E-07	(r) Sand (in ground)	-1.49E-07
(r) Bauxite (Al2O3, ore	4.08E-06	(r) Perlite (SiO2, ore)	1.56E-06	(r) Clay (in ground)	6.28E-07	(r) Clay (in ground)	8.69E-07	Iron Scrap	-1.18E-07
Iron Scrap	2.01E-06	(r) Kaolin (Al2O3.2SiO	9.16E-07	(r) Copper (Cu, ore)	5.39E-07	(r) Sand (in ground)	6.00E-07	(r) Barium Sulphate (B	-1.05E-07
(r) Perlite (SiO2, ore)	1.56E-06	(r) Sand (in ground)	3.06E-07	(r) Gravel (unspecified	3.39E-07	(r) Copper (Cu, ore)	5.54E-07	(r) Pyrite (FeS2, ore)	-7.16E-08
(r) Clay (in ground)	1.52E-06	(r) Limestone (CaCO3,	2.15E-07	(r) Sand (in ground)	3.12E-07	(r) Bauxite (Al2O3, ore	1.82E-07	(r) Iron (Fe, ore)	-3.50E-08
(r) Sand (in ground)	1.07E-06	(r) Manganese (Mn, ore	1.65E-07	(r) Iron (Fe, ore)	1.83E-07	(r) Iron (Fe, ore)	1.81E-07	(r) Gravel (unspecified	-3.40E-08
(r) Kaolin (Al2O3.2SiO	9.16E-07	(r) Talcum (4SiO2.3Mg	1.32E-07	(r) Bauxite (Al2O3, ore	1.50E-07	(r) Bentonite (Al2O3.4	9.87E-08	(r) Limestone (CaCO3,	-2.84E-08
(r) Iron (Fe, ore)	4.14E-07	Iron Scrap	1.26E-07	(r) Bentonite (Al2O3.4	9.60E-08	(r) Pyrite (FeS2, ore)	3.49E-08	(r) Manganese (Mn, ore	-2.51E-08
(r) Gravel (unspecified	3.88E-07	(r) Pyrite (FeS2, ore)	1.22E-07	(r) Pyrite (FeS2, ore)	3.40E-08	(r) Iron Sulphate (FeSC	1.61E-09	(r) Clay (in ground)	-2.17E-08
(r) Bentonite (Al2O3.4	2.26E-07	(r) Iron (Fe, ore)	8.47E-08	(r) Calcium Sulphate (	2.48E-09	(r) Manganese (Mn, ore	5.58E-10	(r) Bentonite (Al2O3.4	-2.15E-08
(r) Manganese (Mn, ore	1.41E-07	(r) Gravel (unspecified	8.30E-08	(r) Iron Sulphate (FeSC	2.11E-09	(r) Chromium (Cr, ore)	8.38E-12	(r) Calcium Sulphate (	-2.49E-10
(r) Talcum (4SiO2.3Mg	1.32E-07	(r) Bentonite (Al2O3.4	5.34E-08	(r) Manganese (Mn, ore	5.43E-10	(r) Calcium Sulphate (	0.00E+00	(r) Chromium (Cr, ore)	-1.95E-10
(r) Pyrite (FeS2, ore)	1.19E-07	(r) Clay (in ground)	4.12E-08	(r) Chromium (Cr, ore)	8.15E-12	(r) Dolomite (CaCO3.M	0.00E+00	(r) Iron Sulphate (FeSC	-1.60E-11
(r) Phosphate Rock (in	7.26E-09	(r) Phosphate Rock (in	7.26E-09	(r) Dolomite (CaCO3.M	0.00E+00	(r) Feldspar (ore)	0.00E+00	(r) Olivine ((Mg,Fe)2Si	-2.95E-13
(r) Iron Sulphate (FeSC	3.72E-09	(r) Calcium Sulphate (	8.05E-10	(r) Feldspar (ore)	0.00E+00	(r) Gravel (unspecified	0.00E+00	(r) Dolomite (CaCO3.M	-4.45E-14
(r) Calcium Sulphate (	3.04E-09	(r) Chromium (Cr, ore)	5.55E-10	(r) Kaolin (Al2O3.2SiO	0.00E+00	(r) Kaolin (Al2O3.2SiO	0.00E+00	(r) Feldspar (ore)	0.00E+00
(r) Chromium (Cr, ore)	3.76E-10	(r) Titanium (Ti, ore)	1.70E-10	(r) Olivine ((Mg,Fe)2Si	0.00E+00	(r) Olivine ((Mg,Fe)2Si	0.00E+00	(r) Kaolin (Al2O3.2SiO	0.00E+00
(r) Titanium (Ti, ore)	1.70E-10	(r) Olivine ((Mg,Fe)2Si	7.09E-11	(r) Perlite (SiO2, ore)	0.00E+00	(r) Perlite (SiO2, ore)	0.00E+00	(r) Perlite (SiO2, ore)	0.00E+00
(r) Olivine ((Mg,Fe)2Si	7.06E-11	Ferromanganese (Fe, M	3.20E-11	(r) Phosphate Rock (in	0.00E+00	(r) Phosphate Rock (in	0.00E+00	(r) Phosphate Rock (in	0.00E+00
Ferromanganese (Fe, M	3.20E-11	(r) Dolomite (CaCO3.M	3.08E-11	(r) Serpentine (3MgO.2	0.00E+00	(r) Serpentine (3MgO.2	0.00E+00	(r) Serpentine (3MgO.2	0.00E+00
(r) Dolomite (CaCO3.M	3.08E-11	(r) Iron Sulphate (FeSC	2.03E-11	(r) Talcum (4SiO2.3Mg	0.00E+00	(r) Talcum (4SiO2.3Mg	0.00E+00	(r) Talcum (4SiO2.3Mg	0.00E+00
(r) Serpentine (3MgO.2	5.93E-12	(r) Serpentine (3MgO.2	5.93E-12	(r) Titanium (Ti, ore)	0.00E+00	(r) Titanium (Ti, ore)	0.00E+00	(r) Titanium (Ti, ore)	0.00E+00
(r) Feldspar (ore)	3.85E-13	(r) Feldspar (ore)	3.85E-13	Ferromanganese (Fe, M	0.00E+00	Ferromanganese (Fe, M	0.00E+00	Ferromanganese (Fe, M	0.00E+00
Steel	7.21E-14	Steel	7.21E-14	Steel	0.00E+00	Steel	0.00E+00	Steel	0.00E+00
SUM x-check	2.08E+00		5.25E-02		8.45E-01		1.21E+00		-2.40E-02

Case B, DLU ranks LCL

Total		raw m.extraction		manufacture		use		eol	
Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:
(r) Uranium (U, ore)	2.01E+00	(r) Uranium (U, ore)	4.53E-02	(r) Uranium (U, ore)	8.06E-01	(r) Uranium (U, ore)	1.17E+00	(r) Uranium (U, ore)	-2.01E-02
Wood	5.11E-02	(r) Copper (Cu, ore)	3.93E-03	Wood	2.82E-02	Wood	2.14E-02	(r) Copper (Cu, ore)	-2.86E-03
(r) Oil (in ground)	1.00E-02	Wood	2.11E-03	(r) Oil (in ground)	4.58E-03	(r) Oil (in ground)	5.15E-03	Wood	-6.20E-04
(r) Natural Gas (in gro	5.46E-03	(r) Oil (in ground)	4.90E-04	(r) Coal (in ground)	2.96E-03	(r) Natural Gas (in gro	2.64E-03	(r) Oil (in ground)	-2.08E-04
(r) Coal (in ground)	5.28E-03	(r) Natural Gas (in gro	3.27E-04	(r) Natural Gas (in gro	2.60E-03	(r) Coal (in ground)	2.25E-03	(r) Natural Gas (in gro	-1.05E-04
(r) Lignite (in ground)	1.82E-03	(r) Coal (in ground)	1.09E-04	(r) Lignite (in ground)	5.47E-04	(r) Lignite (in ground)	1.26E-03	(r) Coal (in ground)	-5.03E-05
(r) Copper (Cu, ore)	1.07E-03	(r) Lignite (in ground)	3.31E-05	(r) Limestone (CaCO3	1.24E-05	(r) Limestone (CaCO3	1.04E-05	(r) Lignite (in ground)	-1.94E-05
(r) Limestone (CaCO3	2.31E-05	(r) Bauxite (Al2O3, or	4.52E-06	(r) Barium Sulphate (	1.91E-06	(r) Barium Sulphate (	1.96E-06	(r) Bauxite (Al2O3, or	-7.68E-07
(r) Barium Sulphate (	6.98E-06	(r) Barium Sulphate (	3.22E-06	Iron Scrap	1.02E-06	Iron Scrap	9.82E-07	(r) Sand (in ground)	-1.49E-07
(r) Bauxite (Al2O3, or	4.08E-06	(r) Perlite (SiO2, ore)	1.56E-06	(r) Clay (in ground)	6.28E-07	(r) Clay (in ground)	8.69E-07	Iron Scrap	-1.18E-07
Iron Scrap	2.01E-06	(r) Kaolin (Al2O3.2Si	9.16E-07	(r) Copper (Cu, ore)	5.39E-07	(r) Sand (in ground)	6.00E-07	(r) Barium Sulphate (	-1.05E-07
(r) Perlite (SiO2, ore)	1.56E-06	(r) Sand (in ground)	3.06E-07	(r) Gravel (unspecifie	3.39E-07	(r) Copper (Cu, ore)	5.54E-07	(r) Pyrite (FeS2, ore)	-7.16E-08
(r) Clay (in ground)	1.52E-06	(r) Limestone (CaCO3	2.14E-07	(r) Sand (in ground)	3.12E-07	(r) Bauxite (Al2O3, or	1.82E-07	(r) Iron (Fe, ore)	-3.50E-08
(r) Sand (in ground)	1.07E-06	(r) Manganese (Mn, or	1.65E-07	(r) Iron (Fe, ore)	1.83E-07	(r) Iron (Fe, ore)	1.81E-07	(r) Gravel (unspecifie	-3.40E-08
(r) Kaolin (Al2O3.2Si	9.16E-07	(r) Talcum (4SiO2.3M	1.32E-07	(r) Bauxite (Al2O3, or	1.50E-07	(r) Bentonite (Al2O3.	9.87E-08	(r) Limestone (CaCO3	-2.84E-08
(r) Iron (Fe, ore)	4.14E-07	Iron Scrap	1.26E-07	(r) Bentonite (Al2O3.	9.60E-08	(r) Pyrite (FeS2, ore)	3.49E-08	(r) Manganese (Mn, or	-2.51E-08
(r) Gravel (unspecifie	3.88E-07	(r) Pyrite (FeS2, ore)	1.21E-07	(r) Pyrite (FeS2, ore)	3.40E-08	(r) Iron Sulphate (FeS	1.61E-09	(r) Clay (in ground)	-2.17E-08
(r) Bentonite (Al2O3.	2.26E-07	(r) Iron (Fe, ore)	8.46E-08	(r) Calcium Sulphate (	2.48E-09	(r) Manganese (Mn, or	5.58E-10	(r) Bentonite (Al2O3.	-2.15E-08
(r) Manganese (Mn, or	1.41E-07	(r) Gravel (unspecifie	8.30E-08	(r) Iron Sulphate (FeS	2.11E-09	(r) Chromium (Cr, ore	8.38E-12	(r) Calcium Sulphate (	-2.49E-10
(r) Talcum (4SiO2.3M	1.32E-07	(r) Bentonite (Al2O3.	5.34E-08	(r) Manganese (Mn, or	5.43E-10	(r) Calcium Sulphate (	0.00E+00	(r) Chromium (Cr, ore	-1.95E-10
(r) Pyrite (FeS2, ore)	1.19E-07	(r) Clay (in ground)	4.12E-08	(r) Chromium (Cr, ore	8.15E-12	(r) Dolomite (CaCO3.	0.00E+00	(r) Iron Sulphate (FeS	-1.60E-11
(r) Phosphate Rock (i	7.26E-09	(r) Phosphate Rock (i	7.26E-09	(r) Dolomite (CaCO3.	0.00E+00	(r) Feldspar (ore)	0.00E+00	(r) Olivine ((Mg,Fe)2S	-2.95E-13
(r) Iron Sulphate (FeS	3.72E-09	(r) Calcium Sulphate (	8.05E-10	(r) Feldspar (ore)	0.00E+00	(r) Gravel (unspecifie	0.00E+00	(r) Dolomite (CaCO3.	-4.45E-14
(r) Calcium Sulphate (	3.04E-09	(r) Chromium (Cr, ore	5.55E-10	(r) Kaolin (Al2O3.2Si	0.00E+00	(r) Kaolin (Al2O3.2Si	0.00E+00	(r) Feldspar (ore)	0.00E+00
(r) Chromium (Cr, ore	3.76E-10	(r) Titanium (Ti, ore)	1.70E-10	(r) Olivine ((Mg,Fe)2S	0.00E+00	(r) Olivine ((Mg,Fe)2S	0.00E+00	(r) Kaolin (Al2O3.2Si	0.00E+00
(r) Titanium (Ti, ore)	1.70E-10	(r) Olivine ((Mg,Fe)2S	7.09E-11	(r) Perlite (SiO2, ore)	0.00E+00	(r) Perlite (SiO2, ore)	0.00E+00	(r) Perlite (SiO2, ore)	0.00E+00
(r) Olivine ((Mg,Fe)2S	7.06E-11	Ferromanganese (Fe,	3.20E-11	(r) Phosphate Rock (i	0.00E+00	(r) Phosphate Rock (i	0.00E+00	(r) Phosphate Rock (i	0.00E+00
Ferromanganese (Fe,	3.20E-11	(r) Dolomite (CaCO3.	3.08E-11	(r) Serpentine (3MgO.	0.00E+00	(r) Serpentine (3MgO.	0.00E+00	(r) Serpentine (3MgO.	0.00E+00
(r) Dolomite (CaCO3.	3.08E-11	(r) Iron Sulphate (FeS	2.03E-11	(r) Talcum (4SiO2.3M	0.00E+00	(r) Talcum (4SiO2.3M	0.00E+00	(r) Talcum (4SiO2.3M	0.00E+00
(r) Serpentine (3MgO.	5.93E-12	(r) Serpentine (3MgO.	5.93E-12	(r) Titanium (Ti, ore)	0.00E+00	(r) Titanium (Ti, ore)	0.00E+00	(r) Titanium (Ti, ore)	0.00E+00
(r) Feldspar (ore)	3.85E-13	(r) Feldspar (ore)	3.85E-13	Ferromanganese (Fe,	0.00E+00	Ferromanganese (Fe,	0.00E+00	Ferromanganese (Fe,	0.00E+00
Steel	7.21E-14	Steel	7.21E-14	Steel	0.00E+00	Steel	0.00E+00	Steel	0.00E+00
SUM x-check	2.08E+00		5.23E-02		8.45E-01		1.21E+00		-2.40E-02

Case B, DLU ranks UCL

	Total		raw m.extraction		manufacture		use		eol
Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:	Inputs phone to produce required materials and components (kg)	DLU [m2/phone LC]:
(r) Uranium (U, ore)	2.02E+00	(r) Uranium (U, ore)	6.08E-02	(r) Uranium (U, ore)	8.06E-01	(r) Uranium (U, ore)	1.17E+00	(r) Uranium (U, ore)	-2.01E-02
Wood	5.16E-02	(r) Copper (Cu, ore)	4.04E-03	Wood	2.82E-02	Wood	2.14E-02	(r) Copper (Cu, ore)	-2.86E-03
(r) Oil (in ground)	1.05E-02	Wood	2.64E-03	(r) Oil (in ground)	4.58E-03	(r) Oil (in ground)	5.15E-03	Wood	-6.20E-04
(r) Natural Gas (in gro	5.57E-03	(r) Oil (in ground)	9.72E-04	(r) Coal (in ground)	2.96E-03	(r) Natural Gas (in gro	2.64E-03	(r) Oil (in ground)	-2.08E-04
(r) Coal (in ground)	5.34E-03	(r) Natural Gas (in gro	4.35E-04	(r) Natural Gas (in gro	2.60E-03	(r) Coal (in ground)	2.25E-03	(r) Natural Gas (in gro	-1.05E-04
(r) Lignite (in ground)	1.83E-03	(r) Coal (in ground)	1.68E-04	(r) Lignite (in ground)	5.47E-04	(r) Lignite (in ground)	1.26E-03	(r) Coal (in ground)	-5.03E-05
(r) Copper (Cu, ore)	1.18E-03	(r) Lignite (in ground)	3.69E-05	(r) Limestone (CaCO3	1.24E-05	(r) Limestone (CaCO3	1.04E-05	(r) Lignite (in ground)	-1.94E-05
(r) Limestone (CaCO3	2.31E-05	(r) Bauxite (Al2O3, or	4.54E-06	(r) Barium Sulphate (E	1.91E-06	(r) Barium Sulphate (E	1.96E-06	(r) Bauxite (Al2O3, or	-7.68E-07
(r) Barium Sulphate (E	7.00E-06	(r) Barium Sulphate (E	3.23E-06	Iron Scrap	1.02E-06	Iron Scrap	9.82E-07	(r) Sand (in ground)	-1.49E-07
(r) Bauxite (Al2O3, or	4.10E-06	(r) Perlite (SiO2, ore)	1.56E-06	(r) Clay (in ground)	6.28E-07	(r) Clay (in ground)	8.69E-07	Iron Scrap	-1.18E-07
Iron Scrap	2.01E-06	(r) Kaolin (Al2O3.2SiO	9.16E-07	(r) Copper (Cu, ore)	5.39E-07	(r) Sand (in ground)	6.00E-07	(r) Barium Sulphate (E	-1.05E-07
(r) Perlite (SiO2, ore)	1.56E-06	(r) Sand (in ground)	3.28E-07	(r) Gravel (unspecified	3.39E-07	(r) Copper (Cu, ore)	5.54E-07	(r) Pyrite (FeS2, ore)	-7.16E-08
(r) Clay (in ground)	1.52E-06	(r) Limestone (CaCO3	2.94E-07	(r) Sand (in ground)	3.12E-07	(r) Bauxite (Al2O3, or	1.82E-07	(r) Iron (Fe, ore)	-3.50E-08
(r) Sand (in ground)	1.09E-06	(r) Manganese (Mn, or	1.65E-07	(r) Iron (Fe, ore)	1.83E-07	(r) Iron (Fe, ore)	1.81E-07	(r) Gravel (unspecified	-3.40E-08
(r) Kaolin (Al2O3.2SiO	9.16E-07	(r) Pyrite (FeS2, ore)	1.46E-07	(r) Bauxite (Al2O3, or	1.50E-07	(r) Bentonite (Al2O3.4	9.87E-08	(r) Limestone (CaCO3	-2.84E-08
(r) Iron (Fe, ore)	4.15E-07	(r) Talcum (4SiO2.3Mg	1.32E-07	(r) Bentonite (Al2O3.4	9.60E-08	(r) Pyrite (FeS2, ore)	3.49E-08	(r) Manganese (Mn, or	-2.51E-08
(r) Gravel (unspecified	3.88E-07	Iron Scrap	1.26E-07	(r) Pyrite (FeS2, ore)	3.40E-08	(r) Iron Sulphate (FeS(	1.61E-09	(r) Clay (in ground)	-2.17E-08
(r) Bentonite (Al2O3.4	2.30E-07	(r) Iron (Fe, ore)	8.61E-08	(r) Calcium Sulphate (	2.48E-09	(r) Manganese (Mn, or	5.58E-10	(r) Bentonite (Al2O3.4	-2.15E-08
(r) Pyrite (FeS2, ore)	1.44E-07	(r) Gravel (unspecified	8.30E-08	(r) Iron Sulphate (FeS(	2.11E-09	(r) Chromium (Cr, ore	8.38E-12	(r) Calcium Sulphate (	-2.49E-10
(r) Manganese (Mn, or	1.41E-07	(r) Bentonite (Al2O3.4	5.62E-08	(r) Manganese (Mn, or	5.43E-10	(r) Calcium Sulphate (	0.00E+00	(r) Chromium (Cr, ore	-1.95E-10
(r) Talcum (4SiO2.3Mg	1.32E-07	(r) Clay (in ground)	4.46E-08	(r) Chromium (Cr, ore	8.15E-12	(r) Dolomite (CaCO3.N	0.00E+00	(r) Iron Sulphate (FeS(	-1.60E-11
(r) Phosphate Rock (ir	7.26E-09	(r) Phosphate Rock (ir	7.26E-09	(r) Dolomite (CaCO3.N	0.00E+00	(r) Feldspar (ore)	0.00E+00	(r) Olivine ((Mg,Fe)2Si	-2.95E-13
(r) Iron Sulphate (FeS(	3.73E-09	(r) Calcium Sulphate (	8.05E-10	(r) Feldspar (ore)	0.00E+00	(r) Gravel (unspecified	0.00E+00	(r) Dolomite (CaCO3.N	-4.45E-14
(r) Calcium Sulphate (	3.04E-09	(r) Chromium (Cr, ore	5.55E-10	(r) Kaolin (Al2O3.2SiO	0.00E+00	(r) Kaolin (Al2O3.2SiO	0.00E+00	(r) Feldspar (ore)	0.00E+00
(r) Chromium (Cr, ore	3.76E-10	(r) Titanium (Ti, ore)	1.70E-10	(r) Olivine ((Mg,Fe)2Si	0.00E+00	(r) Olivine ((Mg,Fe)2Si	0.00E+00	(r) Kaolin (Al2O3.2SiO	0.00E+00
(r) Titanium (Ti, ore)	1.70E-10	(r) Olivine ((Mg,Fe)2Si	7.09E-11	(r) Perlite (SiO2, ore)	0.00E+00	(r) Perlite (SiO2, ore)	0.00E+00	(r) Perlite (SiO2, ore)	0.00E+00
(r) Olivine ((Mg,Fe)2Si	7.06E-11	Ferromanganese (Fe, N	3.20E-11	(r) Phosphate Rock (ir	0.00E+00	(r) Phosphate Rock (ir	0.00E+00	(r) Phosphate Rock (ir	0.00E+00
Ferromanganese (Fe, N	3.20E-11	(r) Dolomite (CaCO3.N	3.08E-11	(r) Serpentine (3MgO.	0.00E+00	(r) Serpentine (3MgO.	0.00E+00	(r) Serpentine (3MgO.	0.00E+00
(r) Dolomite (CaCO3.N	3.08E-11	(r) Iron Sulphate (FeS(	2.03E-11	(r) Talcum (4SiO2.3Mg	0.00E+00	(r) Talcum (4SiO2.3Mg	0.00E+00	(r) Talcum (4SiO2.3Mg	0.00E+00
(r) Serpentine (3MgO.	5.93E-12	(r) Serpentine (3MgO.	5.93E-12	(r) Titanium (Ti, ore)	0.00E+00	(r) Titanium (Ti, ore)	0.00E+00	(r) Titanium (Ti, ore)	0.00E+00
(r) Feldspar (ore)	3.85E-13	(r) Feldspar (ore)	3.85E-13	Ferromanganese (Fe, N	0.00E+00	Ferromanganese (Fe, N	0.00E+00	Ferromanganese (Fe, N	0.00E+00
Steel	7.21E-14	Steel	7.21E-14	Steel	0.00E+00	Steel	0.00E+00	Steel	0.00E+00
SUM x-check	2.10E+00		6.91E-02		8.45E-01		1.21E+00		-2.40E-02

Flowcalculation A&B

	Input raw material flows in kg	
DLU Case A [kg	w/o wood	wood
BC	2.39E+01	6.19E-02
LCL	2.39E+01	6.19E-02
UCL	2.42E+01	6.25E-02
DLU Case B [kg]		
BC	2.20E+01	5.61E-02
LCL	2.20E+01	5.61E-02
UCL	2.23E+01	5.67E-02
	ca. 97% by weight	ca. 0.3% by weight

Wood [m2 phone-1 yr]						
A		Direct land use [m2]:	Direct land use [m2]:	Direct land use [m2]:	Direct land use [m2]:	x-check:
	Total	Raw material extraction	Parts and phone manufct.	Use	Eol	
BC	0.06	2.12E-03	3.34E-02	2.14E-02	-6.20E-04	0.06
LCL	0.06	2.11E-03	3.34E-02	2.14E-02	-6.20E-04	0.06
UCL	0.06	2.67E-03	3.34E-02	2.14E-02	-6.20E-04	0.06
B						
	Total	Raw material extraction	Parts and phone manufct.	Use	Eol	
BC	0.05	2.12E-03	2.82E-02	2.14E-02	-6.20E-04	0.05
LCL	0.05	2.11E-03	2.82E-02	2.14E-02	-6.20E-04	0.05
UCL	0.05	2.64E-03	2.82E-02	2.14E-02	-6.20E-04	0.05
A %	BC	4	59	38	-1	100
	LCL	4	59	38	-1	100
	UCL	5	59	38	-1	100
B %	BC	4	55	42	-1	100
	LCL	4	55	42	-1	100
	UCL	5	55	41	-1	100

Wood (kg)						
	Total	1. Raw material production	2. Parts and phone manufacture	3. Use	4. End of Life	x-check:
A						
BC	0.06	2.33E-03	3.67E-02	2.35E-02	-6.81E-04	0.06
LCL	0.06	2.32E-03	3.67E-02	2.35E-02	-6.81E-04	0.06
UCL	0.06	2.94E-03	3.67E-02	2.35E-02	-6.81E-04	0.06
B						
BC	0.06	2.33E-03	3.10E-02	2.35E-02	-6.81E-04	0.06
LCL	0.06	2.32E-03	3.10E-02	2.35E-02	-6.81E-04	0.06
UCL	0.06	2.90E-03	3.10E-02	2.35E-02	-6.81E-04	0.06
A %	BC	4	59	38	-1	100
	LCL	4	59	38	-1	100
	UCL	5	59	38	-1	100
B %	BC	4	55	42	-1	100
	LCL	4	55	42	-1	100
	UCL	5	55	41	-1	100

% DLU, life cycle A&B

Case A, DLU						
BC						
total [m2 phone-1 yr-1]		extraction	manufacture	use	Eol	
	2.23E+00	5.25E-02	9.93E-01	1.21E+00	-2.40E-02	x-check
	100%	2	45	54	-1	100
LCL						
	2.23E+00	5.23E-02	9.93E-01	1.21E+00	-2.40E-02	x-check
	100%	2	45	54	-1	100
UCL						
	2.25E+00	6.97E-02	9.93E-01	1.21E+00	-2.40E-02	x-check
	100%	3	44	54	-1	100

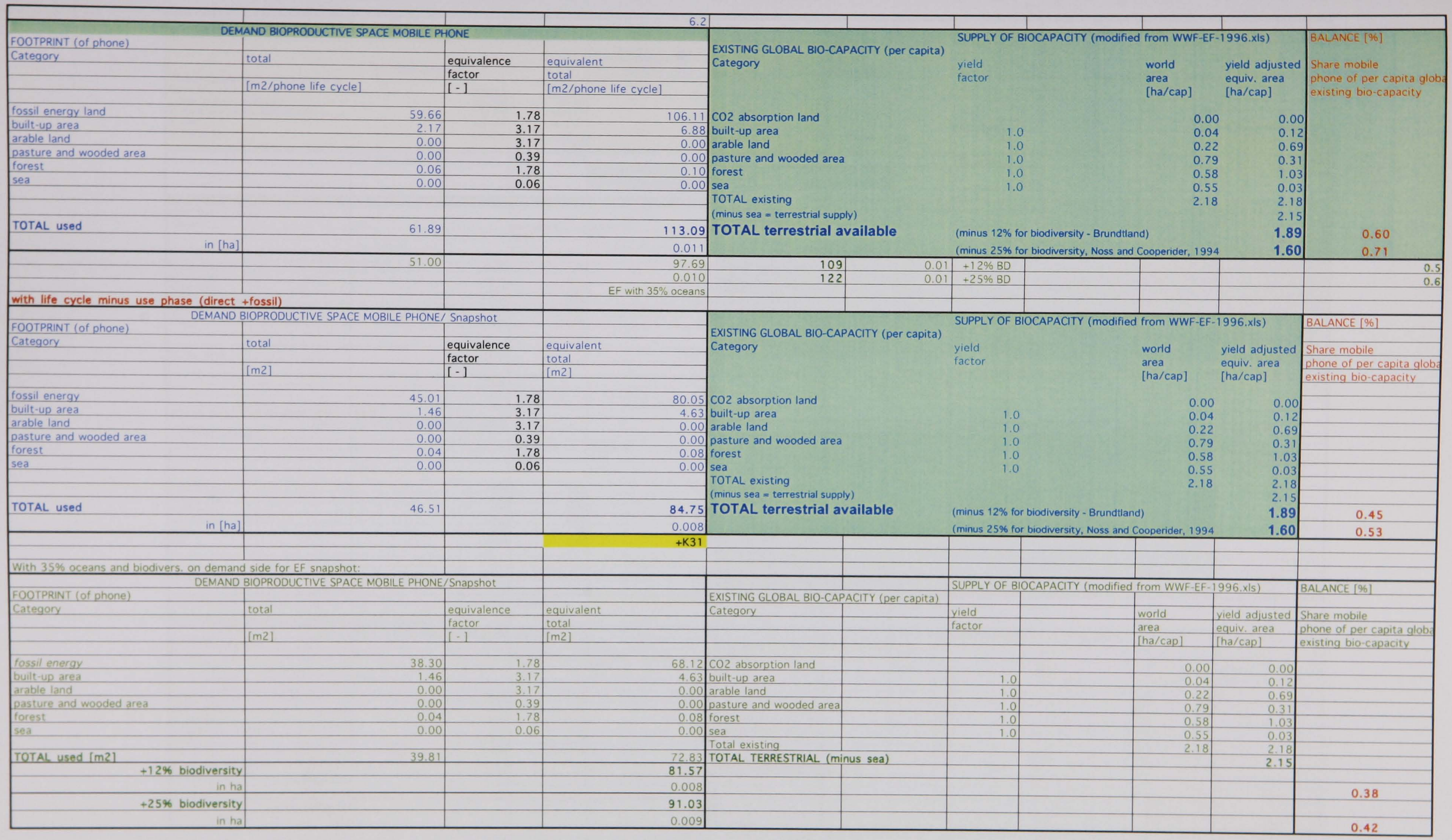
Case B, DLU						
BC						
total [m2 phone-1 yr-1]						
	2.08E+00	5.25E-02	8.45E-01	1.21E+00	-2.40E-02	x-check
	100%	2.5	40.6	58.0	-1.2	100
LCL						
	2.08E+00	5.23E-02	8.45E-01	1.21E+00	-2.40E-02	x-check
	100%	2.5	40.6	58.0	-1.2	100
UCL						
	2.10E+00	6.91E-02	8.45E-01	1.21E+00	-2.38E-02	x-check
	100%	3.3	40.3	57.5	-1.1	100

	Case A			Case B				
	BC	diff. m2 (within case)	in % within case		diff. m2 (within case)	in % within case	diff. A vs B in m2	in %
Total	**2.23**			**2.08**			-0.15	-7
1. Raw material production	0.05			0.05				
2. Parts and phone manufacture	0.99			0.85				-15
3. Use	1.21			1.21				
4. End of Life	-0.02			-0.02				
	LCL							
Total	**2.23**	0.00	0	**2.08**	0.00	0	-0.15	-7
1. Raw material production	0.05	0.00	0	0.05	0.00	0		
2. Parts and phone manufacture	0.99			0.85				-15
3. Use	1.21			1.21				
4. End of Life	-0.02			-0.02				
	UCL							
Total	**2.25**	0.02	1	**2.10**	0.02	1	-0.15	-7
1. Raw material production	0.07	0.02	33	0.07	0.02	32		
2. Parts and phone manufacture	0.99			0.85				-15
3. Use	1.21			1.21				
4. End of Life	-0.02			-0.02				

EF case A, BC

Carbon emission factors (CEF):	**gC/MJ**	**Carbon uptake in biomass [MJ m2^{-1} yr^{-1}]**			2.27 dtm/ha/yr [Wac. CO2-abs.xls]					
Jet kerosene	19.5	7.3	31.25 Nuclear		+25% roots (belowground biomass. Median of IPCC root-to-shoot ratios, p. 5/54)					
Diesel oil	20.2	7.0	0.77 Hydro		* 0.5 to convert from wood [dm] to carbon (default value IPCC p 5.20)					
Coking coal	25.8	5.5		(see EnergyEF.xls)	= 1.418 tC*ha^{-1}yr^{-1} [142gC m2$^{(-1)}$ yr^{-1}]					
Lignite	27.6	5.1		**Fuel specific**						
Crude oil (for fuel oil)	20.0	7.1		**footprints**						
Natural gas (dry)	15.3	9.3								
[IPCC, 1996. Workbook p 1.6]										
Sum different transports [MJ]					**30.47**					
MJ data and split from [Wright, 1999]										
TRANSPORT IS THE SAME FOR ALL CASES AND SCENARIOS										
Transport	**C [g/phone]**				**Sum [m2/phone]**					
Air	445.62	75 % by air	2.35		*2.04*	*Sum with 35% oceans*				
Truck / Ship	153.87	25% truck/ship	0.81	Sum includes 25% oceans	**3.17**					
			3.17							
			x-check							
2. EF-calculation by CO2-emissions:										
	CO2 [g/phone]	**C**	**Bioproductive space from carbon emissions phone life cycle [m2 phone-1 yr]**		**Carbon Footprint life cycle [m2 phone-1 yr]**					
Carbon Dioxide (CO2, fossil) from total Phone life cycle	39218.4	10695.93	56.49	includes 25% oceans	*48.96*	*Sum with 35% oceans*				
1. Raw material production	988.15	269.50	1.42							
2. Parts and phone manufacture	21715	5922.27	31.28				Use phase=			Use phase/yr with EQF:
3. Use	16954.2	4623.87	24.42		**56.49**		24.42			17.38
4. End of Life	-438.917	-119.70	-0.63				*21.17*	*th 35% oceans*		1.50
		3.667					Use phase=			0.02
	Sum carbon [kg]	11.30	**Direct land use:**		**2.17**		1.19			**18.89**
			Direct land use forests		**0.06**		0.02			
			DLU (%)							

EF case A, BC



			6.2							
DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE						SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)						
Category	total [m2/phone life cycle]	equivalence factor [-]	equivalent total [m2/phone life cycle]	Category		yield factor		world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita globa existing bio-capacity
fossil energy land	59.66	1.78	106.11	CO2 absorption land				0.00	0.00	
built-up area	2.17	3.17	6.88	built-up area		1.0		0.04	0.12	
arable land	0.00	3.17	0.00	arable land		1.0		0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area		1.0		0.79	0.31	
forest	0.06	1.78	0.10	forest		1.0		0.58	1.03	
sea	0.00	0.06	0.00	sea		1.0		0.55	0.03	
				TOTAL existing				2.18	2.18	
				(minus sea = terrestrial supply)					2.15	
TOTAL used	61.89		113.09	**TOTAL terrestrial available**		(minus 12% for biodiversity - Brundtland)			**1.89**	0.60
in [ha]			0.011			(minus 25% for biodiversity, Noss and Cooperider, 1994			**1.60**	0.71
	51.00		97.69	109	0.01	+12% BD				0.5
			0.010	122	0.01	+25% BD				0.6
			EF with 35% oceans							
with life cycle minus use phase (direct +fossil)										

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/ Snapshot						SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)						
Category	total [m2]	equivalence factor [-]	equivalent total [m2]	Category		yield factor		world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita globa existing bio-capacity
fossil energy	45.01	1.78	80.05	CO2 absorption land				0.00	0.00	
built-up area	1.46	3.17	4.63	built-up area		1.0		0.04	0.12	
arable land	0.00	3.17	0.00	arable land		1.0		0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area		1.0		0.79	0.31	
forest	0.04	1.78	0.08	forest		1.0		0.58	1.03	
sea	0.00	0.06	0.00	sea		1.0		0.55	0.03	
				TOTAL existing				2.18	2.18	
				(minus sea = terrestrial supply)					2.15	
TOTAL used	46.51		84.75	**TOTAL terrestrial available**		(minus 12% for biodiversity - Brundtland)			**1.89**	0.45
in [ha]			0.008			(minus 25% for biodiversity, Noss and Cooperider, 1994			**1.60**	0.53
			+K31							

With 35% oceans and biodivers. on demand side for EF snapshot:										
DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/Snapshot						SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)						
Category	total [m2]	equivalence factor [-]	equivalent total [m2]	Category		yield factor		world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita globa existing bio-capacity
fossil energy	38.30	1.78	68.12	CO2 absorption land				0.00	0.00	
built-up area	1.46	3.17	4.63	built-up area		1.0		0.04	0.12	
arable land	0.00	3.17	0.00	arable land		1.0		0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area		1.0		0.79	0.31	
forest	0.04	1.78	0.08	forest		1.0		0.58	1.03	
sea	0.00	0.06	0.00	sea		1.0		0.55	0.03	
				Total existing				2.18	2.18	
TOTAL used [m2]	39.81		72.83	TOTAL TERRESTRIAL (minus sea)					2.15	
+12% biodiversity			81.57							
in ha			0.008							0.38
+25% biodiversity			91.03							
in ha			0.009							0.42

EF case A, LCL

2. EF-calculation by CO2-emissions:									
	CO2 [g/phone]	C	Bioproductive space from carbon emissions phone life cycle [m2 phone-1 yr]		Footprint life cycle [m2 phone-1 yr]				
Carbon Dioxide (CO2, fossil) from total Phone life cycle	39210.3	10693.72	56.48	includes 25% oceans	48.95	Sum with 35% oceans			
1. Raw material production	980.059	267.29	1.41						
2. Parts and phone manufacture	21715	5922.27	31.28				Use phase=		Use phase/yr with EQF:
3. Use	16954.2	4623.87	24.42		56.48		24.42		17.38
4. End of Life	-438.917	-119.70	-0.63				21.17	use phase with 35% oceans	1.50
		3.667					Use phase=		0.02
	Sum carbon [kg]	11.29							18.89
			Direct land use:		2.17		1.19		
			Direct land use forests		0.06		0.02		

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE				SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)				
Category	total	equivalence factor	equivalent total	Category	yield factor	world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita global existing bio-capacity
	[m2/phone life cycle]	[-]	[m2/phone life cycle]					
fossil energy land	59.65	1.78	106.09	CO2 absorption land		0.00	0.00	
built-up area	2.17	3.17	6.88	built-up area	1.0	0.04	0.12	
arable land	0.00	3.17	0.00	arable land	1.0	0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area	1.0	0.79	0.31	
forest	0.06	1.78	0.10	forest	1.0	0.58	1.03	
sea	0.00	0.06	0.00	sea	1.0	0.55	0.03	
				TOTAL existing		2.18	2.18	
				(minus sea = terrestrial supply)			2.15	
TOTAL used	61.88		113.07	TOTAL terrestrial available	(minus 12% for biodiversity - Brundtland)		1.89	0.60
in [ha]			0.011		(minus 25% for biodiversity, Noss and Cooperider, 1994)		1.60	0.71
	50.99		97.67	109	0.01	+12% BD		0.5
			0.010	122	0.01	+25% BD		0.6
			EF with 35% oceans					

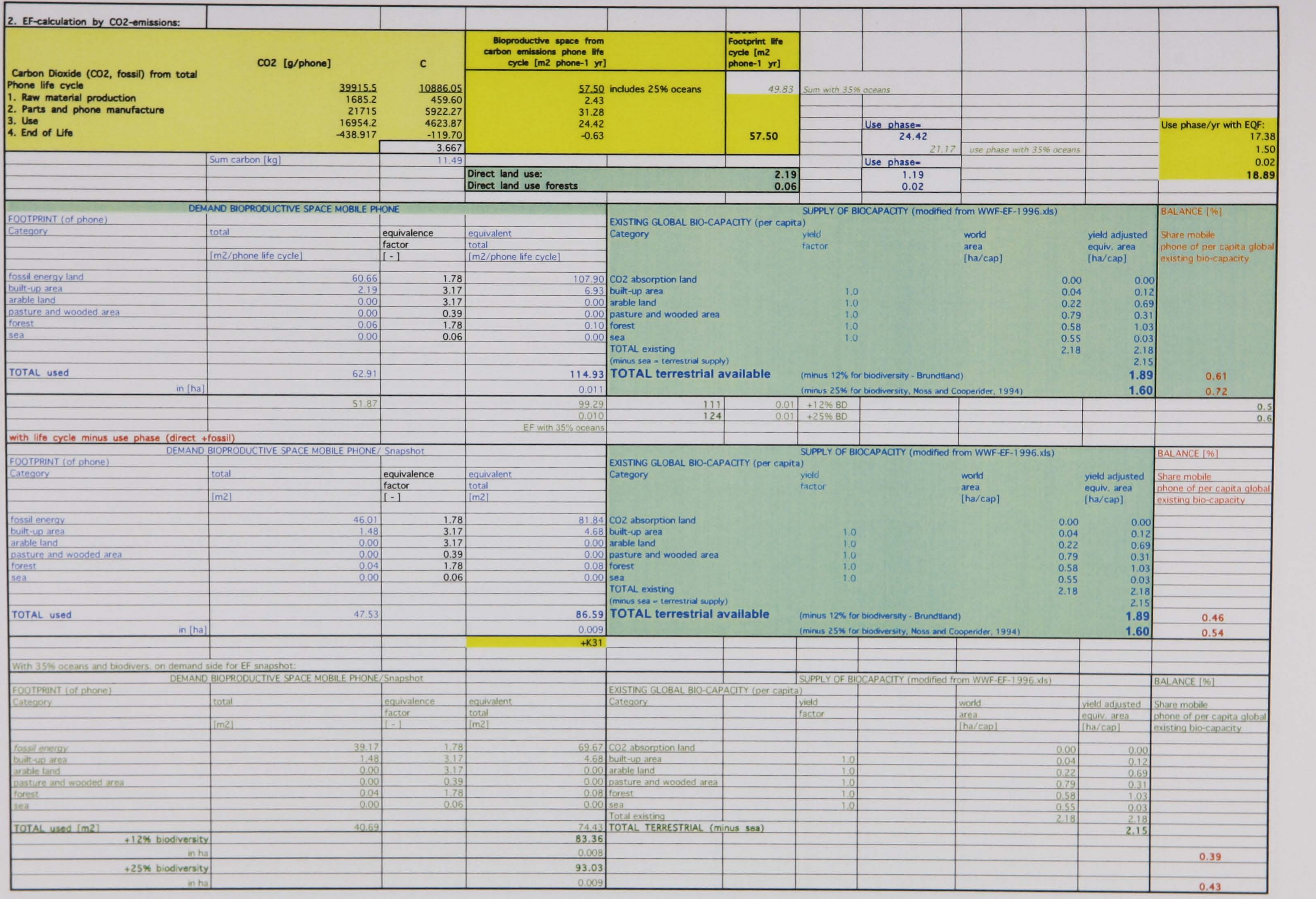
with life cycle minus use phase (direct +fossil)

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/ Snapshot				SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)				
Category	total	equivalence factor	equivalent total	Category	yield factor	world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita global existing bio-capacity
	[m2]	[-]	[m2]					
fossil energy	44.99	1.78	80.03	CO2 absorption land		0.00	0.00	
built-up area	1.46	3.17	4.62	built-up area	1.0	0.04	0.12	
arable land	0.00	3.17	0.00	arable land	1.0	0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area	1.0	0.79	0.31	
forest	0.04	1.78	0.08	forest	1.0	0.58	1.03	
sea	0.00	0.06	0.00	sea	1.0	0.55	0.03	
				TOTAL existing		2.18	2.18	
				(minus sea = terrestrial supply)			2.15	
TOTAL used	46.50		84.73	TOTAL terrestrial available	(minus 12% for biodiversity - Brundtland)		1.89	0.45
in [ha]			0.008		(minus 25% for biodiversity, Noss and Cooperider, 1994)		1.60	0.53
			+K31					

With 35% oceans and biodivers. on demand side for EF snapshot:

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/Snapshot				SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)				
Category	total	equivalence factor	equivalent total	Category	yield factor	world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita global existing bio-capacity
	[m2]	[-]	[m2]					
fossil energy	38.29	1.78	68.11	CO2 absorption land		0.00	0.00	
built-up area	1.46	3.17	4.62	built-up area	1.0	0.04	0.12	
arable land	0.00	3.17	0.00	arable land	1.0	0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area	1.0	0.79	0.31	
forest	0.04	1.78	0.08	forest	1.0	0.58	1.03	
sea	0.00	0.06	0.00	sea	1.0	0.55	0.03	
				Total existing		2.18	2.18	
TOTAL used [m2]	39.79		72.81	TOTAL TERRESTRIAL (minus sea)			2.15	
+12% biodiversity			81.54					
in ha			0.008					0.38
+25% biodiversity			91.01					
in ha			0.009					0.42

EF case A, UCL



2. EF-calculation by CO2-emissions:										
Carbon Dioxide (CO2, fossil) from total	CO2 [g/phone]	C	Bioproductive space from carbon emissions phone life cycle [m2 phone-1 yr]		Footprint life cycle [m2 phone-1 yr]					
Phone life cycle	39915.5	10886.05	57.50	includes 25% oceans	49.83	Sum with 35% oceans				
1. Raw material production	1685.2	459.60	2.43							
2. Parts and phone manufacture	21715	5922.27	31.28							
3. Use	16954.2	4623.87	24.42				Use phase=			Use phase/yr with EQF:
4. End of Life	-438.917	-119.70	-0.63		57.50		24.42			17.38
		3.667					21.17	use phase with 35% oceans		1.50
	Sum carbon [kg]	11.49					Use phase=			0.02
			Direct land use:		2.19		1.19			18.89
			Direct land use forests		0.06		0.02			
DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE						SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)						
Category	total [m2/phone life cycle]	equivalence factor [-]	equivalent total [m2/phone life cycle]	Category		yield factor		world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita global existing bio-capacity
fossil energy land	60.66	1.78	107.90	CO2 absorption land				0.00	0.00	
built-up area	2.19	3.17	6.93	built-up area		1.0		0.04	0.12	
arable land	0.00	3.17	0.00	arable land		1.0		0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area		1.0		0.79	0.31	
forest	0.06	1.78	0.10	forest		1.0		0.58	1.03	
sea	0.00	0.06	0.00	sea		1.0		0.55	0.03	
				TOTAL existing				2.18	2.18	
				(minus sea = terrestrial supply)					2.15	
TOTAL used	62.91		114.93	TOTAL terrestrial available		(minus 12% for biodiversity - Brundtland)			1.89	0.61
in [ha]			0.011			(minus 25% for biodiversity, Noss and Cooperider, 1994)			1.60	0.72
	51.87		99.29	111	0.01	+12% BD				0.5
			0.010	124	0.01	+25% BD				0.6
			EF with 35% oceans							
with life cycle minus use phase (direct +fossil)										
DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/ Snapshot						SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)						
Category	total [m2]	equivalence factor [-]	equivalent total [m2]	Category		yield factor		world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita global existing bio-capacity
fossil energy	46.01	1.78	81.84	CO2 absorption land				0.00	0.00	
built-up area	1.48	3.17	4.68	built-up area		1.0		0.04	0.12	
arable land	0.00	3.17	0.00	arable land		1.0		0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area		1.0		0.79	0.31	
forest	0.04	1.78	0.08	forest		1.0		0.58	1.03	
sea	0.00	0.06	0.00	sea		1.0		0.55	0.03	
				TOTAL existing				2.18	2.18	
				(minus sea = terrestrial supply)					2.15	
TOTAL used	47.53		86.59	TOTAL terrestrial available		(minus 12% for biodiversity - Brundtland)			1.89	0.46
in [ha]			0.009			(minus 25% for biodiversity, Noss and Cooperider, 1994)			1.60	0.54
			+K31							
With 35% oceans and biodivers. on demand side for EF snapshot:										
DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/Snapshot						SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)						
Category	total [m2]	equivalence factor [-]	equivalent total [m2]	Category		yield factor		world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita global existing bio-capacity
fossil energy	39.17	1.78	69.67	CO2 absorption land				0.00	0.00	
built-up area	1.48	3.17	4.68	built-up area		1.0		0.04	0.12	
arable land	0.00	3.17	0.00	arable land		1.0		0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area		1.0		0.79	0.31	
forest	0.04	1.78	0.08	forest		1.0		0.58	1.03	
sea	0.00	0.06	0.00	sea		1.0		0.55	0.03	
				Total existing				2.18	2.18	
TOTAL used [m2]	40.69		74.43	TOTAL TERRESTRIAL (minus sea)					2.15	
+12% biodiversity			83.36							
in ha			0.008							0.39
+25% biodiversity			93.03							
in ha			0.009							0.43

EF case B, BC

2. EF-calculation by CO2-emissions:

Carbon Dioxide (CO2, fossil) from total	**CO2 [g/phone]**	**C**	**Bioproductive space from carbon emissions phone life cycle [m2 phone-1 yr]**		**Carbon Footprint life cycle [m2 phone 1 yr]**	
Phone life cycle	35868.3	9782.26	51.67	includes 25% oceans	*44.78*	*Sum with 35% oceans*
1. Raw material production	988.15	269.50	1.42			
2. Parts and phone manufacture	18364.9	5008.61	26.45			
3. Use	16954.2	4623.87	24.42		**51.67**	
4. End of Life	-438.917	-119.70	-0.63			
		3.667				
Sum carbon [kg]		10.38				
			Direct land use:		**2.03**	
			Direct land use forests		**0.05**	

Use phase=		
24.42		
21.17	*use phase with 35% oceans*	
Use phase=		
1.19		
0.02		

Use phase/yr with EQF:
17.38
1.50
0.02
18.89

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE

FOOTPRINT (of phone) Category	total [m2/phone life cycle]	equivalence factor [-]	equivalent total [m2/phone life cycle]
fossil energy land	54.83	1.78	97.53
built-up area	2.03	3.17	6.43
arable land	0.00	3.17	0.00
pasture and wooded area	0.00	0.39	0.00
forest	0.05	1.78	0.09
sea	0.00	0.06	0.00
TOTAL used	56.91		104.05
in [ha]			0.010
4	46.82		89.79
6			0.009
			EF with 35% oceans

SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)

EXISTING GLOBAL BIO-CAPACITY (per capita) Category	yield factor	world area [ha/cap]	yield adjusted equiv. area [ha/cap]	BALANCE [%] Share mobile phone of per capita global existing bio-capacity
CO2 absorption land		0.00	0.00	
built-up area	1.0	0.04	0.12	
arable land	1.0	0.22	0.69	
pasture and wooded area	1.0	0.79	0.31	
forest	1.0	0.58	1.03	
sea	1.0	0.55	0.03	
TOTAL existing		2.18	2.18	
(minus sea = terrestrial supply)			2.15	
TOTAL terrestrial available	(minus 12% for biodiversity - Brundtland)		**1.89**	**0.55**
	(minus 25% for biodiversity, Noss and Cooperider, 1994)		**1.60**	**0.65**
101	0.01	+12% BD		0.5
112	0.01	+25% BD		0.5

with life cycle minus use phase (direct +fossil)

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/ Snapshot

FOOTPRINT (of phone) Category	total [m2]	equivalence factor [-]	equivalent total [m2]
fossil energy land	40.18	1.78	71.47
built-up area	1.32	3.17	4.17
arable land	0.00	3.17	0.00
pasture and wooded area	0.00	0.39	0.00
forest	0.04	1.78	0.07
sea	0.00	0.06	0.00
TOTAL used	41.54		75.71
in [ha]			0.008
			+K31

SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)

EXISTING GLOBAL BIO-CAPACITY (per capita) Category	yield factor	world area [ha/cap]	yield adjusted equiv. area [ha/cap]	BALANCE [%] Share mobile phone of per capita global existing bio-capacity
CO2 absorption land		0.00	0.00	
built-up area	1.0	0.04	0.12	
arable land	1.0	0.22	0.69	
pasture and wooded area	1.0	0.79	0.31	
forest	1.0	0.58	1.03	
sea	1.0	0.55	0.03	
TOTAL existing		2.18	2.18	
(minus sea = terrestrial supply)			2.15	
TOTAL terrestrial available	(minus 12% for biodiversity - Brundtland)		**1.89**	**0.40**
	(minus 25% for biodiversity, Noss and Cooperider, 1994)		**1.60**	**0.47**

With 35% oceans and biodivers. on demand side for EF snapshot:

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/Snapshot

FOOTPRINT (of phone) Category	total [m2]	equivalence factor [-]	equivalent total [m2]
fossil energy	34.12	1.78	60.68
built-up area	1.32	3.17	4.17
arable land	0.00	3.17	0.00
pasture and wooded area	0.00	0.39	0.00
forest	0.04	1.78	0.07
sea	0.00	0.06	0.00
TOTAL used [m2]	35.48		64.93
+12% biodiversity			**72.72**
in ha			0.007
+25% biodiversity			**81.16**
in ha			0.008

SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)

EXISTING GLOBAL BIO-CAPACITY (per capita) Category	yield factor	world area [ha/cap]	yield adjusted equiv. area [ha/cap]	BALANCE [%] Share mobile phone of per capita global existing bio-capacity
CO2 absorption land		0.00	0.00	
built-up area	1.0	0.04	0.12	
arable land	1.0	0.22	0.69	
pasture and wooded area	1.0	0.79	0.31	
forest	1.0	0.58	1.03	
sea	1.0	0.55	0.03	
Total existing		2.18	2.18	
TOTAL TERRESTRIAL (minus sea)			2.15	
				0.34
				0.38

EF case B, LCL

2. EF-calculation by CO2-emissions:										
Carbon Dioxide (CO2, fossil) from total	CO2 [g/phone]	C	Bioproductive space from carbon emissions phone life cycle [m2 phone-1 yr]		Carbon Footprint life cycle [m2 phone-1 yr]					
Phone life cycle	35860.2	9780.05	51.66	includes 25% oceans	44.77	Sum with 35% oceans				
1. Raw material production	980.059	267.29	1.41							
2. Parts and phone manufacture	18364.9	5008.61	26.45							
3. Use	16954.2	4623.87	24.42				Use phase=			Use phase/yr with EQF:
4. End of Life	-438.917	-119.70	-0.63		51.66		24.42			17.38
		3.667					21.17	use phase with 35% oceans		1.50
	Sum carbon [kg]	10.38					Use phase=			0.02
			Direct land use:		2.03		1.19			18.89
			Direct land use forests		0.05		0.02			
DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE						SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)						
Category	total	equivalence	equivalent	Category		yield		world	yield adiuste	Share mobile
		factor	total			factor		area	equiv. area	phone of per capita global
	[m2/phone life cycle]	[-]	[m2/phone life cycle]					[ha/cap]	[ha/cap]	existing bio-capacity
fossil energy land	54.82	1.78	97.51	CO2 absorption land				0.00	0.00	
built-up area	2.03	3.17	6.43	built-up area		1.0		0.04	0.12	
arable land	0.00	3.17	0.00	arable land		1.0		0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area		1.0		0.79	0.31	
forest	0.05	1.78	0.09	forest		1.0		0.58	1.03	
sea	0.00	0.06	0.00	sea		1.0		0.55	0.03	
				TOTAL existing				2.18	2.18	
				(minus sea = terrestrial supply)					2.15	
TOTAL used	56.90		104.02	TOTAL terrestrial available		(minus 12% for biodiversity - Brundtland)			1.89	0.55
in [ha]			0.010			(minus 25% for biodiversity, Noss and Cooperider, 1994)			1.60	0.65
	46.81		89.77	101	0.01	+12% BD				0.5
			0.009	112	0.01	+25% BD				0.5
			EF with 35% oceans							
with life cycle minus use phase (direct +fossil)										
DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/ Snapshot						SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)						
Category	total	equivalence	equivalent	Category		yield		world	yield adiuste	Share mobile
		factor	total			factor		area	equiv. area	phone of per capita global
	[m2]	[-]	[m2]					[ha/cap]	[ha/cap]	existing bio-capacity
fossil energy land	40.17	1.78	71.45	CO2 absorption land				0.00	0.00	
built-up area	1.32	3.17	4.17	built-up area		1.0		0.04	0.12	
arable land	0.00	3.17	0.00	arable land		1.0		0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area		1.0		0.79	0.31	
forest	0.04	1.78	0.07	forest		1.0		0.58	1.03	
sea	0.00	0.06	0.00	sea		1.0		0.55	0.03	
				TOTAL existing				2.18	2.18	
				(minus sea = terrestrial supply)					2.15	
TOTAL used	41.52		75.69	TOTAL terrestrial available		(minus 12% for biodiversity - Brundtland)			1.89	0.40
in [ha]			0.008			(minus 25% for biodiversity, Noss and Cooperider, 1994)			1.60	0.47
			+K31							
With 35% oceans and biodivers. on demand side for EF snapshot:										
DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/Snapshot						SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)						
Category	total	equivalence	equivalent	Category		yield		world	yield adiuste	Share mobile
		factor	total			factor		area	equiv. area	phone of per capita global
	[m2]	[-]	[m2]					[ha/cap]	[ha/cap]	existing bio-capacity
fossil energy	34.11	1.78	60.67	CO2 absorption land				0.00	0.00	
built-up area	1.32	3.17	4.17	built-up area		1.0		0.04	0.12	
arable land	0.00	3.17	0.00	arable land		1.0		0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area		1.0		0.79	0.31	
forest	0.04	1.78	0.07	forest		1.0		0.58	1.03	
sea	0.00	0.06	0.00	sea		1.0		0.55	0.03	
				TOTAL TERRESTRIAL (minus sea)				2.18	2.18	
TOTAL used [m2]	35.46		64.91						2.15	
+12% biodiversity			72.70							
in ha			0.007							0.34
+25% biodiversity			81.13							
in ha			0.008							0.38

EF case B, UCL

2. EF-calculation by CO2-emissions:									
	CO2 [g/phone]	C	Bioproductive space from carbon emissions phone life cycle [m2 phone-1 yr]		Carbon Footprint life cycle [m2 phone-1 yr]				
Carbon Dioxide (CO2, fossil) from total Phone life cycle	36565.4	9972.38	52.67	includes 25% oceans	45.65	Sum with 35% oceans			
1. Raw material production	1685.2	459.60	2.43						
2. Parts and phone manufacture	18364.9	5008.61	26.45				Use phase=		Use phase/yr with EQF:
3. Use	16954.2	4623.87	24.42				24.42		17.38
4. End of Life	-438.917	-119.70	-0.63		52.67				1.50
		3.667					21.17	use phase with 35% oceans	0.02
							Use phase=		18.89
	Sum carbon [kg]	10.57					1.19		
			Direct land use:		2.05				
			Direct land use forests		0.05		0.02		

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE				SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)				
Category	total	equivalence factor	equivalent total	Category	yield factor	world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita global existing bio-capacity
	[m2/phone life cycle]	[-]	[m2/phone life cycle]					
fossil energy land	55.84	1.78	99.31	CO2 absorption land		0.00	0.00	
built-up area	2.05	3.17	6.48	built-up area	1.0	0.04	0.12	
arable land	0.00	3.17	0.00	arable land	1.0	0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area	1.0	0.79	0.31	
forest	0.05	1.78	0.09	forest	1.0	0.58	1.03	
sea	0.00	0.06	0.00	sea	1.0	0.55	0.03	
				TOTAL existing		2.18	2.18	
				(minus sea = terrestrial supply)			2.15	
TOTAL used	57.94		105.88	TOTAL terrestrial available	(minus 12% for biodiversity - Brundtland)		1.89	0.56
in [ha]			0.011		(minus 25% for biodiversity, Noss and Cooperider, 1994)		1.60	0.66
	47.69		91.39	102	0.01	+12% BD		0.5
			0.009	114	0.01	+25% BD		0.5
			EF with 35% oceans					

with life cycle minus use phase (direct +fossil)

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/ Snapshot				SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)				
Category	total	equivalence factor	equivalent total	Category	yield factor	world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita global existing bio-capacity
	[m2]	[-]	[m2]					
fossil energy land	41.18	1.78	73.25	CO2 absorption land		0.00	0.00	
built-up area	1.33	3.17	4.23	built-up area	1.0	0.04	0.12	
arable land	0.00	3.17	0.00	arable land	1.0	0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area	1.0	0.79	0.31	
forest	0.04	1.78	0.07	forest	1.0	0.58	1.03	
sea	0.00	0.06	0.00	sea	1.0	0.55	0.03	
				TOTAL existing		2.18	2.18	
				(minus sea = terrestrial supply)			2.15	
TOTAL used	42.56		77.55	TOTAL terrestrial available	(minus 12% for biodiversity - Brundtland)		1.89	0.41
in [ha]			0.008		(minus 25% for biodiversity, Noss and Cooperider, 1994)		1.60	0.48
			+K31					

With 35% oceans and biodivers. on demand side for EF snapshot:

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/ Snapshot				SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)				
Category	total	equivalence factor	equivalent total	Category	yield factor	world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita global existing bio-capacity
	[m2]	[-]	[m2]					
fossil energy	34.99	1.78	62.23	CO2 absorption land		0.00	0.00	
built-up area	1.33	3.17	4.23	built-up area	1.0	0.04	0.12	
arable land	0.00	3.17	0.00	arable land	1.0	0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area	1.0	0.79	0.31	
forest	0.04	1.78	0.07	forest	1.0	0.58	1.03	
sea	0.00	0.06	0.00	sea	1.0	0.55	0.03	
				Total existing		2.18	2.18	
TOTAL used [m2]	36.36		66.53	TOTAL TERRESTRIAL (minus sea)			2.15	
+12% biodiversity			74.51					
in ha			0.007					0.35
+25% biodiversity			83.16					
in ha			0.008					0.39

EF 0.4W, BC

2. EF-calculation by CO2-emissions:									
Carbon Dioxide (CO2, fossil) from total Phone life cycle	**CO2 [g/phone]**	**C**	**Bioproductive space from carbon emissions phone life cycle [m2 phone-1 yr]**		**Carbon Footprint life cycle [m2 phone-1 yr]**				
		6985.98	36.90	includes 25% oceans	31.98	Sum with 35% oceans			
1. Raw material production		269.50	1.42						
2. Parts and phone manufacture		5008.61	26.45						
3. Use		1827.58	9.65				Use phase=		Use phase/yr with EQF:
4. End of Life		-119.70	-0.63		**36.90**		9.65		6.87
		3.667							
	Sum carbon [kg]	7.59					8.37	use phase with 35% oceans	1.50
							Use phase=		0.02
			Direct land use:		**2.03**		1.19		**8.38**
			Direct land use forests		**0.05**		0.02		

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE				EXISTING GLOBAL BIO-CAPACITY (per capita)	SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)			BALANCE [%]
FOOTPRINT (of phone)								
Category	total [m2/phone life cycle]	equivalence factor [-]	equivalent total [m2/phone life cycle]	Category	yield factor	world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita global existing bio-capacity
fossil energy land	40.06	1.78	71.26	CO2 absorption land		0.00	0.00	
built-up area	2.03	3.17	6.43	built-up area	1.0	0.04	0.12	
arable land	0.00	3.17	0.00	arable land	1.0	0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area	1.0	0.79	0.31	
forest	0.05	1.78	0.09	forest	1.0	0.58	1.03	
sea	0.00	0.06	0.00	sea	1.0	0.55	0.03	
				TOTAL existing		2.18	2.18	
				(minus sea = terrestrial supply)			2.15	
TOTAL used	42.14		77.78	**TOTAL terrestrial available**	(minus 12% for biodiversity - Brundtland)		**1.89**	0.41
in [ha]			0.008		(minus 25% for biodiversity, Noss and Cooperider, 1994)		**1.60**	0.49
	34.02		67.02	75	0.01	+12% BD		0.3
			0.007	84	0.01	+25% BD		0.4
			EF with 35% oceans					

with life cycle minus use phase (direct +fossil)

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/ Snapshot				EXISTING GLOBAL BIO-CAPACITY (per capita)	SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)			BALANCE [%]
FOOTPRINT (of phone)								
Category	total [m2]	equivalence factor [-]	equivalent total [m2]	Category	yield factor	world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita global existing bio-capacity
fossil energy land	34.27	1.78	60.96	CO2 absorption land		0.00	0.00	
built-up area	1.32	3.17	4.17	built-up area	1.0	0.04	0.12	
arable land	0.00	3.17	0.00	arable land	1.0	0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area	1.0	0.79	0.31	
forest	0.04	1.78	0.07	forest	1.0	0.58	1.03	
sea	0.00	0.06	0.00	sea	1.0	0.55	0.03	
				TOTAL existing		2.18	2.18	
				(minus sea = terrestrial supply)			2.15	
TOTAL used	35.63		65.20	**TOTAL terrestrial available**	(minus 12% for biodiversity - Brundtland)		**1.89**	0.35
in [ha]			0.007		(minus 25% for biodiversity, Noss and Cooperider, 1994)		**1.60**	0.41
			+K31					

With 35% oceans and biodivers. on demand side for EF snapshot:

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/Snapshot				EXISTING GLOBAL BIO-CAPACITY (per capita)	SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)			BALANCE [%]
FOOTPRINT (of phone)								
Category	total [m2]	equivalence factor [-]	equivalent total [m2]	Category	yield factor	world area [ha/cap]	yield adjusted equiv. area [ha/cap]	Share mobile phone of per capita global existing bio-capacity
fossil energy	29.00	1.78	51.58	CO2 absorption land		0.00	0.00	
built-up area	1.32	3.17	4.17	built-up area	1.0	0.04	0.12	
arable land	0.00	3.17	0.00	arable land	1.0	0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area	1.0	0.79	0.31	
forest	0.04	1.78	0.07	forest	1.0	0.58	1.03	
sea	0.00	0.06	0.00	sea	1.0	0.55	0.03	
				Total existing		2.18	2.18	
TOTAL used [m2]	30.36		55.82	TOTAL TERRESTRIAL (minus sea)			2.15	
+12% biodiversity			62.52					
in ha			0.006					0.29
+25% biodiversity			69.78					
in ha			0.007					0.32

EF 0.4W, LCL

2. EF-calculation by CO2-emissions:

Carbon Dioxide (CO2, fossil) from total	CO2 [g/phone]	C	Bioproductive space from carbon emissions phone life cycle [m2 phone-1 yr]		Carbon Footprint life cycle [m2 phone-1 yr]	
Phone life cycle		6983.77	36.89	includes 25% oceans	31.97	Sum with 35% oceans
1. Raw material production		267.29	1.41			
2. Parts and phone manufacture		5008.61	26.45			
3. Use		1827.58	9.65			
4. End of Life		-119.70	-0.63		36.89	
		3.667				
	Sum carbon [kg]	7.58				
			Direct land use:		2.03	
			Direct land use forests		0.05	

Use phase=		
9.65		
8.37	use phase with 35% oceans	
Use phase=		
1.19		
0.02		

Use phase/yr with EQF:
6.87
1.50
0.02
8.38

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE

FOOTPRINT (of phone) Category	total [m2/phone life cycle]	equivalence factor [-]	equivalent total [m2/phone life cycle]
fossil energy land	40.05	1.78	71.24
built-up area	2.03	3.17	6.42
arable land	0.00	3.17	0.00
pasture and wooded area	0.00	0.39	0.00
forest	0.05	1.78	0.09
sea	0.00	0.06	0.00
TOTAL used	42.13		77.75
in [ha]			0.008
	34		67
			0
			EF with 35% oceans

SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)

EXISTING GLOBAL BIO-CAPACITY (per capita) Category	yield factor		world area [ha/cap]	yield adjuste equiv. area [ha/cap]	BALANCE [%] Share mobile phone of per capita global existing bio-capacity
CO2 absorption land			0.00	0.00	
built-up area	1.0		0.04	0.12	
arable land	1.0		0.22	0.69	
pasture and wooded area	1.0		0.79	0.31	
forest	1.0		0.58	1.03	
sea	1.0		0.55	0.03	
TOTAL existing			2.18	2.18	
(minus sea = terrestrial supply)				2.15	
TOTAL terrestrial available	(minus 12% for biodiversity - Brundtland)			**1.89**	0.41
	(minus 25% for biodiversity, Noss and Cooperider, 1994)			**1.60**	0.49
75	0	+12% BD			0.35
84	0	+25% BD			0.39

with life cycle minus use phase (direct +fossil)

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/ Snapshot

FOOTPRINT (of phone) Category	total [m2]	equivalence factor [-]	equivalent total [m2]
fossil energy land	34.26	1.78	60.94
built-up area	1.32	3.17	4.17
arable land	0.00	3.17	0.00
pasture and wooded area	0.00	0.39	0.00
forest	0.04	1.78	0.07
sea	0.00	0.06	0.00
TOTAL used	35.62		65.18
in [ha]			0.007
			+K31

SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)

EXISTING GLOBAL BIO-CAPACITY (per capita) Category	yield factor	world area [ha/cap]	yield adjuste equiv. area [ha/cap]	BALANCE [%] Share mobile phone of per capita global existing bio-capacity
CO2 absorption land		0.00	0.00	
built-up area	1.0	0.04	0.12	
arable land	1.0	0.22	0.69	
pasture and wooded area	1.0	0.79	0.31	
forest	1.0	0.58	1.03	
sea	1.0	0.55	0.03	
TOTAL existing		2.18	2.18	
(minus sea = terrestrial supply)			2.15	
TOTAL terrestrial available	(minus 12% for biodiversity - Brundtland)		**1.89**	0.35
	(minus 25% for biodiversity, Noss and Cooperider, 1994)		**1.60**	0.41

With 35% oceans and biodivers. on demand side for yearly EF:

DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/ Snapshot

FOOTPRINT (of phone) Category	total [m2]	equivalence factor [-]	equivalent total [m2]
fossil energy	28.99	1.78	51.56
built-up area	1.32	3.17	4.17
arable land	0.00	3.17	0.00
pasture and wooded area	0.00	0.39	0.00
forest	0.04	1.78	0.07
sea	0.00	0.06	0.00
TOTAL used [m2]	30.34		55.80
+12% biodiversity			62.50
in ha			0.006
+25% biodiversity			69.75
in ha			0.007

SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)

EXISTING GLOBAL BIO-CAPACITY (per capita) Category	yield factor	world area [ha/cap]	yield adjuste equiv. area [ha/cap]	BALANCE [%] Share mobile phone of per capita global existing bio-capacity
CO2 absorption land		0.00	0.00	
built-up area	1.0	0.04	0.12	
arable land	1.0	0.22	0.69	
pasture and wooded area	1.0	0.79	0.31	
forest	1.0	0.58	1.03	
sea	1.0	0.55	0.03	
TOTAL TERRESTRIAL (minus sea)		2.18	2.18	
			2.15	
				0.29
				0.32

EF 0.4W, UCL

2. EF-calculation by CO2-emissions:										
	CO2 [g/phone]	C	Bioproductive space from carbon emissions phone life cycle [m2 phone-1 yr]		Carbon Footprint life cycle [m2 phone-1 yr]					
Carbon Dioxide (CO2, fossil) from total Phone life cycle		7176.08	37.90	includes 25% oceans	32.85	Sum with 35% oceans				
1. Raw material production		459.60	2.43							
2. Parts and phone manufacture		5008.61	26.45							
3. Use		1827.58	9.65				Use phase=			Use phase/yr with EQF:
4. End of Life		-119.70	-0.63		37.90		9.65			6.87
		3.667					8.37	use phase with 35% oceans		1.50
	Sum carbon [kg]	7.78					Use phase=			0.02
			Direct land use:		2.05		1.19			8.38
			Direct land use forests		0.05		0.02			
	DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE					SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)						
Category	total	equivalence	equivalent	Category		yield		world	yield adjuste	Share mobile
		factor	total			factor		area	equiv. area	phone of per capita global
	[m2/phone life cycle]	[-]	[m2/phone life cycle]					[ha/cap]	[ha/cap]	existing bio-capacity
fossil energy land	41.07	1.78	73.05	CO2 absorption land				0.00	0.00	
built-up area	2.05	3.17	6.48	built-up area		1.0		0.04	0.12	
arable land	0.00	3.17	0.00	arable land		1.0		0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area		1.0		0.79	0.31	
forest	0.05	1.78	0.09	forest		1.0		0.58	1.03	
sea	0.00	0.06	0.00	sea		1.0		0.55	0.03	
				TOTAL existing				2.18	2.18	
				(minus sea = terrestrial supply)					2.15	
TOTAL used	43.17		79.62	TOTAL terrestrial available		(minus 12% for biodiversity - Brundtland)			1.89	0.42
in [ha]			0.008			(minus 25% for biodiversity, Noss and Cooperider, 1994)			1.60	0.50
	34.89		68.62	77	0.01	+12% BD				0.4
			0.007	86	0.01	+25% BD				0.4
			EF with 35% oceans							
with life cycle minus use phase (direct +fossil)										
	DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/ Snapshot					SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)						
Category	total	equivalence	equivalent	Category		yield		world	yield adjuste	Share mobile
		factor	total			factor		area	equiv. area	phone of per capita global
	[m2]	[-]	[m2]					[ha/cap]	[ha/cap]	existing bio-capacity
fossil energy land	35.28	1.78	62.74	CO2 absorption land				0.00	0.00	
built-up area	1.33	3.17	4.23	built-up area		1.0		0.04	0.12	
arable land	0.00	3.17	0.00	arable land		1.0		0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area		1.0		0.79	0.31	
forest	0.04	1.78	0.07	forest		1.0		0.58	1.03	
sea	0.00	0.06	0.00	sea		1.0		0.55	0.03	
				TOTAL existing				2.18	2.18	
				(minus sea = terrestrial supply)					2.15	
TOTAL used	36.65		67.04	TOTAL terrestrial available		(minus 12% for biodiversity - Brundtland)			1.89	0.36
in [ha]			0.007			(minus 25% for biodiversity, Noss and Cooperider, 1994)			1.60	0.42
			+K31							
With 35% oceans and biodivers. on demand side for EF snapshot:										
	DEMAND BIOPRODUCTIVE SPACE MOBILE PHONE/ Snapshot					SUPPLY OF BIOCAPACITY (modified from WWF-EF-1996.xls)				BALANCE [%]
FOOTPRINT (of phone)				EXISTING GLOBAL BIO-CAPACITY (per capita)						
Category	total	equivalence	equivalent	Category		yield		world	yield adjuste	Share mobile
		factor	total			factor		area	equiv. area	phone of per capita global
	[m2]	[-]	[m2]					[ha/cap]	[ha/cap]	existing bio-capacity
fossil energy	29.87	1.78	53.13	CO2 absorption land				0.00	0.00	
built-up area	1.33	3.17	4.23	built-up area		1.0		0.04	0.12	
arable land	0.00	3.17	0.00	arable land		1.0		0.22	0.69	
pasture and wooded area	0.00	0.39	0.00	pasture and wooded area		1.0		0.79	0.31	
forest	0.04	1.78	0.07	forest		1.0		0.58	1.03	
sea	0.00	0.06	0.00	sea		1.0		0.55	0.03	
				Total existing				2.18	2.18	
TOTAL used [m2]	31.24		57.42	TOTAL TERRESTRIAL (minus sea)					2.15	
+12% biodiversity			64.31							
in ha			0.006							0.30
+25% biodiversity			71.78							
in ha			0.007							0.33

EF comparisons

Case A	total EF [m2]	diff. m2 (within case)	in % within case	diff. A vs B in m2	in %	Case A	Fair earth share (-12)%	Fair earth share (-25)%	1.89
BC	113.09					BC	0.6	0.7	1.60
LCL	113.07	-0.02				LCL	0.6	0.7	
UCL	114.93	1.84	2			UCL	0.6	0.7	
Case B						Case B			
BC	104.05			-9	-8	BC	0.6	0.6	
LCL	104.02	-0.02	0	-9	-8	LCL	0.6	0.6	
UCL	105.88	1.84	2	-9	-8	UCL	0.6	0.7	
							size mobile ca. 8.3x17cm	0.01411	m2
								7371	times bigger than
	Share energy land in EF		Share direct land use					8150	actual size
Case A	fossil m2	(%)	m2	(%)					
BC	106	94	7.0	6					
LCL	106	94	7.0	6					
UCL	108	94	7.0	6					
Case B									
BC	98	94	6.5	6					
LCL	98	94	6.5	6					
UCL	99	94	6.6	6					
	all including equivalence factors								
Use phase CO2 savings with 0.4 W charger (estimate)									
MJ	CO2 [g]								
115.75	16954	*CO2 from TEAM output*	use phase=	C use phase:	-25% oceans				
45.75	6701	39.52	% of old charger value	1827.6	1371				
70	10253				-35% oceans				
				3.67	1188				
		0.4W	0.4W	0.4W					
	Carbon B-BC/ 1.3W	BC	LCL	UCL					
Total	9782	6986	6984	7176					
rm	269	269	267	460					
manu	5009	5009	5009	5009					
use	4624	1828	1828	1828					
eol	-120	-120	-120	-120					
Estimate EF for 0.4 W phone (scenarios):									
Case B	total CO2 [g]	- difference = new total							
BC	35868	6986							
LCL	35860	6984							
UCL	36565	7176							
		3.67							

EF comparisons

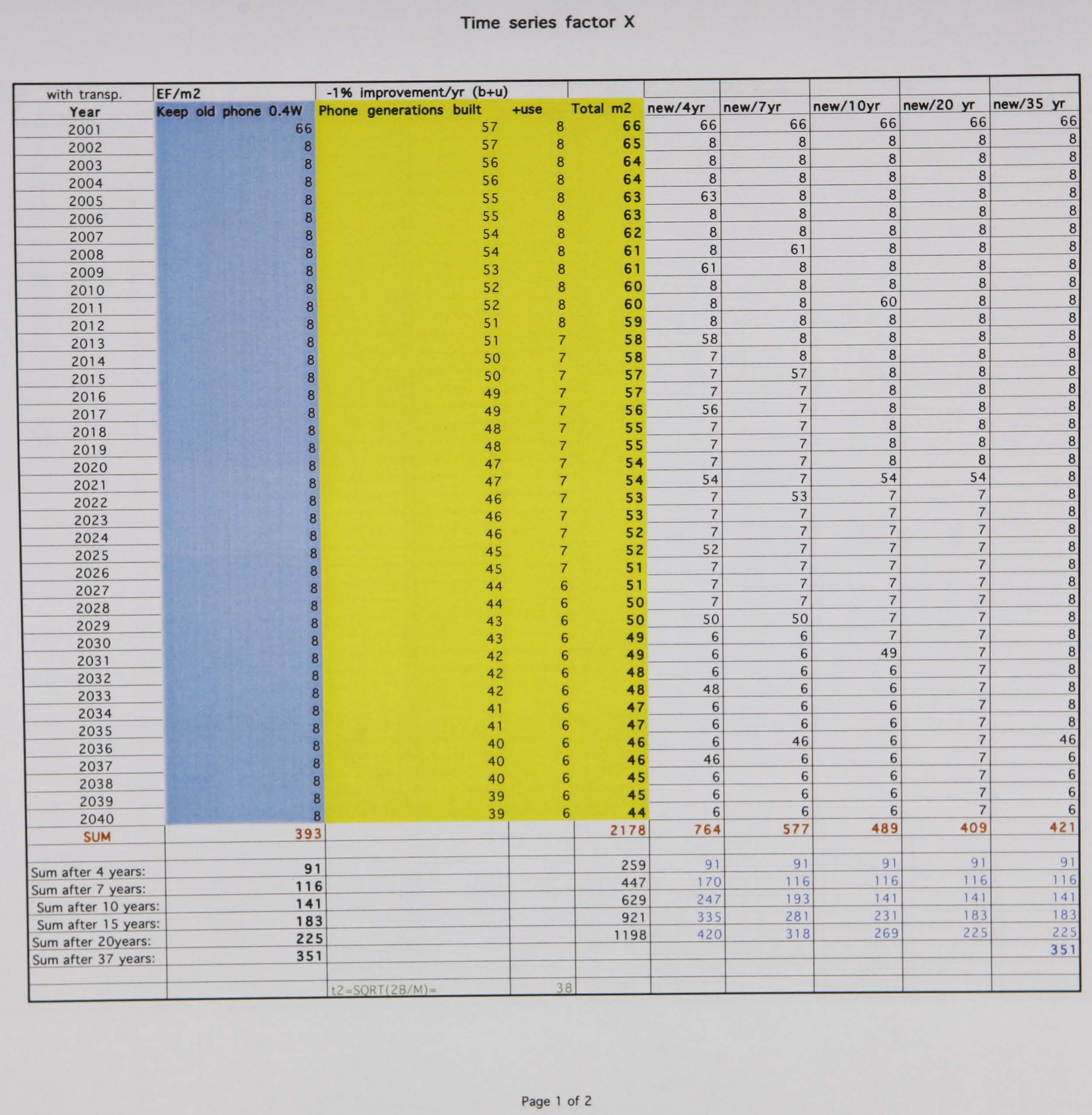
Comparison: total EF [m2/phone]		
Case A		
BC	113.1	
LCL	113.1	
UCL	114.9	
Case B		
BC	104.0	
LCL	104.0	
UCL	105.9	
Case 0.4 W		
BC	77.8	
LCL	77.8	
UCL	79.6	
Saved vs. Ca:	-25	=8.3 per cent over 3 yrs.(1998-2001)
Saved vs. Ca:	-26	

Time series A and B and 0.4W -25% oceans)		EF yr 1[m2]	EF use yr n [m2]	Fair earth share (	Fair earth share	+n Share world per cap.	Share world per cap. (-25)
Case A	BC	85	19	0.4	0.5	0.1	0.1
	LCL	85	19	0.4	0.5	0.1	0.1
	UCL	87	19	0.5	0.5	0.1	0.1
Case B	BC	76	19	0.4	0.5		
	LCL	76	19	0.4	0.5		
	UCL	78	19	0.4	0.5		
"Case 0.4 W"						EF % -reduction to B	
	BC	65	8	0.35	0.41	-14	
	LCL	65	8	0.35	0.41	-14	
	UCL	67	8	0.36	0.42	-14	
		66					

Total EF [m2/phone] with 35% oceans/12% BD:				
		Vgl. 25 to 35% oceans LC:		
Case A				
BC	109.4		113.1	-3
LCL	109.4		113.1	-3
UCL	111.1		114.9	-3
Case B				
BC	100.5		104.0	-3
LCL	100.5		104.0	-3
UCL	102.3		105.9	-3
"Case 0.4 W"				
BC	75		77.8	-3
LCL	75		77.8	-3
UCL	77		79.6	-3

Phone replacement every four years at 10 and 20% efficiency rates

Year	Keep old phone	new/4yr (-10% p.a.)	new/4yr (-20% p.a.)
1	66	66	66
2	8	8	8
3	8	8	8
4	8	8	8
5	8	43	27
6	8	6	3
7	8	6	3
8	8	6	3
9	8	28	11
10	8	4	1
Total	**141**	**183**	**141**



Time series factor X

with transp.	EF/m2	-1% improvement/yr (b+u)							
Year	Keep old phone 0.4W	Phone generations built	+use	Total m2	new/4yr	new/7yr	new/10yr	new/20 yr	new/35 yr
2001	66	57	8	66	66	66	66	66	66
2002	8	57	8	65	8	8	8	8	8
2003	8	56	8	64	8	8	8	8	8
2004	8	56	8	64	8	8	8	8	8
2005	8	55	8	63	63	8	8	8	8
2006	8	55	8	63	8	8	8	8	8
2007	8	54	8	62	8	8	8	8	8
2008	8	54	8	61	8	61	8	8	8
2009	8	53	8	61	61	8	8	8	8
2010	8	52	8	60	8	8	8	8	8
2011	8	52	8	60	8	8	60	8	8
2012	8	51	8	59	8	8	8	8	8
2013	8	51	7	58	58	8	8	8	8
2014	8	50	7	58	7	8	8	8	8
2015	8	50	7	57	7	57	8	8	8
2016	8	49	7	57	7	7	8	8	8
2017	8	49	7	56	56	7	8	8	8
2018	8	48	7	55	7	7	8	8	8
2019	8	48	7	55	7	7	8	8	8
2020	8	47	7	54	7	7	8	8	8
2021	8	47	7	54	54	7	54	54	8
2022	8	46	7	53	7	53	7	7	8
2023	8	46	7	53	7	7	7	7	8
2024	8	46	7	52	7	7	7	7	8
2025	8	45	7	52	52	7	7	7	8
2026	8	45	7	51	7	7	7	7	8
2027	8	44	6	51	7	7	7	7	8
2028	8	44	6	50	7	7	7	7	8
2029	8	43	6	50	50	50	7	7	8
2030	8	43	6	49	6	6	7	7	8
2031	8	42	6	49	6	6	49	7	8
2032	8	42	6	48	6	6	6	7	8
2033	8	42	6	48	48	6	6	7	8
2034	8	41	6	47	6	6	6	7	8
2035	8	41	6	47	6	6	6	7	8
2036	8	40	6	46	6	46	6	7	46
2037	8	40	6	46	46	6	6	7	6
2038	8	40	6	45	6	6	6	7	6
2039	8	39	6	45	6	6	6	7	6
2040	8	39	6	44	6	6	6	7	6
SUM	393			2178	764	577	489	409	421
Sum after 4 years:	91			259	91	91	91	91	91
Sum after 7 years:	116			447	170	116	116	116	116
Sum after 10 years:	141			629	247	193	141	141	141
Sum after 15 years:	183			921	335	281	231	183	183
Sum after 20years:	225			1198	420	318	269	225	225
Sum after 37 years:	351								351
		t2=SQRT(2B/M)=	38						

Page 1 of 2

Time series factor X

-10% improvement/yr (b+u) Phone generations built	+use	Total m2	new/4yr	new/7yr	new/10yr	new/12yr
57	8	**66**	66	66	66	66
52	8	**59**	8	8	8	8
47	7	**53**	8	8	8	8
42	6	**48**	8	8	8	8
38	6	**43**	43	8	8	8
34	5	**39**	6	8	8	8
31	4	**35**	6	8	8	8
27	4	**31**	6	31	8	8
25	4	**28**	28	4	8	8
22	3	**25**	4	4	8	8
20	3	**23**	4	4	23	8
18	3	**21**	4	4	3	8
16	2	**19**	19	4	3	19
15	2	**17**	2	4	3	2
13	2	**15**	2	15	3	2
12	2	**14**	2	2	3	2
11	2	**12**	12	2	3	2
10	1	**11**	2	2	3	2
9	1	**10**	2	2	3	2
8	1	**9**	2	2	3	2
7	1	**8**	8	2	8	2
6	1	**7**	1	7	1	2
6	1	**6**	1	1	1	2
5	1	**6**	1	1	1	2
5	1	**5**	5	1	1	5
4	1	**5**	1	1	1	1
4	1	**4**	1	1	1	1
3	0	**4**	1	1	1	1
3	0	**3**	3	3	1	1
3	0	**3**	0	0	1	1
2	0	**3**	0	0	3	1
2	0	**3**	0	0	0	1
2	0	**2**	2	0	0	1
2	0	**2**	0	0	0	1
2	0	**2**	0	0	0	1
1	0	**2**	0	2	0	1
1	0	**1**	1	0	0	1
1	0	**1**	0	0	0	0
1	0	**1**	0	0	0	0
1	0	**1**	0	0	0	0
			261	**219**	**214**	**217**
		226	91	91	91	91
		343	145	116	116	116
		429	183	156	141	141
		523	213	187	176	181
		578	232	196	191	193
	12					

-20% improvement/yr (b+u) Phone generations built	+use	Total m2	new/4yr	new/7yr	new/10yr
57	8	**66**	66	66	66
46	7	**53**	8	8	8
37	5	**42**	8	8	8
29	4	**34**	8	8	8
24	3	**27**	27	8	8
19	3	**22**	3	8	8
15	2	**17**	3	8	8
12	2	**14**	3	14	8
10	1	**11**	11	2	8
8	1	**9**	1	2	8
6	1	**7**	1	2	7
5	1	**6**	1	2	1
4	1	**5**	5	2	1
3	0	**4**	1	2	1
3	0	**3**	1	3	1
2	0	**2**	1	0	1
2	0	**2**	2	0	1
1	0	**1**	0	0	1
1	0	**1**	0	0	1
1	0	**1**	0	0	1
1	0	**1**	1	0	1
1	0	**1**	0	1	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
0	0	**0**	0	0	0
			154	**147**	**158**
		194	91	91	91
		260	125	116	116
		294	**141**	133	141
		317	149	143	152
		325	152	145	156
	8				

Appendix F

10.6. Extrapolation EF to worldwide sales of mobile phones

Extrapolation World

Nokia: sold 77 million mobiles in 1999, which was 27% of total mobile phone sales world wide (Oiva et al., 2000).							
	EF B/BC (life cycle)	m2	ha	no. of FES or w/a citizens		Employees at Nokia?	EF employees
77000000	104.05	8.01E+09	8.01E+05	**4.24E+05**			
(27%)	EF B/BC (snapshot)						
	75.71	5.83E+09	5.83E+05	3.08E+05			
	EF 0.4W/BC (snapshot)						
	65.2	5.02E+09	5.02E+05	**2.66E+05**			
World (1999):	EF B/BC (life cycle)						
285185185.2	104.05	2.97E+10	2.97E+06	**1.57E+06**			
(100%)	EF B/BC (snapshot)						
	75.71	2.16E+10	2.16E+06	**1.14E+06**			
	EF 0.4W/BC (snapshot)						
	65.2	1.86E+10	1.86E+06	**9.84E+05**			
Zogbi, in: Passive component industry, Sept./Oct. 2001, p.4: Actual production in 2000 = 430m, to be sold in 2001 = 340m.							
World (2001):							
340000000		2.22E+10	2.22E+06	**1.17E+06**	1.17 mio w/a citizens		

Appendix G

10.7. Publications

- Ecological footprint of a mobile phone. United Nations Environment Programme (UNEP). Production and Consumption Unit (28 December 2001) at http://www.uneptie.org/pc/sustain/sc-net/sc-net.htm.

- Frey, S., Harrison, D.J., Billett, E.H (2001). Environmental assessment of a mobile phone using ecological footprint analysis. In: The Science and Culture of Industrial Ecology, International Society of Industrial Ecology, The Netherlands, 12-14 November 2001. 31-32.

- Abstracts on PC and mobile phone study on Best Foot Forward's website (spring and winter 2001 newsletter) at: http://www.bestfootforward.com/FootprintNews/EFNews211101.htm.

- Frey, S., Harrison, D.J., Billett, E.H (2000). Environmental assessment using LCA and ecological footprint. *In: Joint International Congress and Exhibition. Electronics goes green 2000,* Berlin, Germany, 11-13 September. 253-258.

- Frey, S., Harrison, D.J., Billett, E.H (2000). Integrated product policy and ecological footprint of electronic products. In: International Symposium on Electronics and the Environment. Institute of Electrical and Electronic Engineers. San Francisco, 8-10 May 2000.

UNEP
Production and Consumption Unit
Sustainable Consumption [SC]

Ecological footprint of a mobile phone

Sibylle Frey, 19/12/2001

Mobile phones have become a necessity that is almost taken for granted in industrialised countries. Sibylle Frey, with Brunel University, prepared a study to estimate the bio-productive space needed to appropriate the resources and emissions of a mobile phone based on life cycle energy analyses.

Initial results suggest that the footprint of a mobile phone is between 0.6 (older models) and 0.4 (newer models) per cent of the global terrestrial supply of bio-capacity per capita. For direct land use, the methodology includes area estimates based on the density of materials, size of ore bodies, overburden, and biomass accumulation.

As electronic products contain a wide range of materials including precious and rare earth metals, they have made statistical approximations regarding energy requirements and overburden arising from extraction processes. For indirect land use, fuel specific carbon sequestration by forests and estimates for the oceans' carbon absorption capacity were included.

The study group used a single indicator to make the results comparable to the global supply of bio-productive space of 1.92 hectares per person based on 1996 data (Wackernagel et al) or 1.89 hectares without sea space. The results should be viewed as a snapshot of a mobile phone's demand for ecosystem services.

This study was conducted in collaboration with Nokia Mobile Phones.

For more information please contact Ms. Sibylle Frey e-mail Sibylle.Frey@brunel.ac.uk

International Society for Industrial Ecology

The Science & Culture of Industrial Ecology

Abstracts from the inaugural meeting

12-14 November 2001—The Netherlands

can work together towards possible solutions.

In the view of globalisation and increasing interdependencies amongst societal actors we have to address complex issues from a multidisciplinary point of view and be aware of the interrelations that exist between, for example, the fields of economy and ecology. On a smaller scale, this multidisciplinary approach also presupposes the interaction between economical, ecological, societal and political actors. Thus, policy-making in general has to consider these features of modern society. Our proposed concept of transition management as a policy-option to address structural and complex problems is primarily based upon the notion of multi-actor, multi-domain and multi-level interactions. We state that because of these interactions policy-makers have to develop policies in collaboration with the relevant societal actors.

The recent agricultural crises and the growing concern with the (over)use of energy resources in modern society are triggers for structural societal transformation processes and open up options for policy-makers that were until now unrecognised. We argue that by constructing interdisciplinary networks we can formulate long-term goals from which we derive short-term actions. In order to really manage such transition processes diverse tools have been developed such as network- and actor analysis, the facilitation of interactive and participative processes, the use of scenario's and models and so on. The paper will specifically address these policy-options of transition management and thus the relevancy of the concept for policy-making in the field of environmental issues.

The focus of the research presented in the paper is on the concept of transition management. The main objective of this research however is to make these ideas applicable to the practice of policy making. Based on the transition concept we have to change the way in which we define societal problems and the way in which we construct solutions for these problems. By combining different observations and options, linked to everyday policy-making (interactionism, multilevel governance) we can construct a theoretical framework which allows us to structure and organize policy-making processes. The thus structured, goal-oriented and multi-actor transition process overcomes criticism on the current practice of policy-making that it would be undemocratic and that there is no ground for legitimizing of the interactive policy-making practiced, for example, by the European Commission.

Long-term Energy Efficiency Agreements Between Dutch Industry and Government

Ton van Dril and Leon van der Palen

Full paper available: No

With the start of a new round of long term agreements with industry on energy efficiency, the Dutch government has introduced the option of improving energy efficiency in production chains. Companies can now be credited for innovations that save energy elsewhere, outside plant limits. These innovations include material efficiency and substitution, energy savings in the use phase of their product, extending the lifetime of components and improving recycling. This research on present experiences with this type of energy chain management focuses on implementation within the company organisation. Research has been done on the paper and metal chain. LTA-efforts up to now have a strong engineering focus on energy equipment within the company. A broader scope of energy efficiency in production chains requires specific efforts from sales, purchases and design departments, and a firm commitment from company management. The findings are that there are surprisingly few technological barriers for implementation, but a firm policy incentive and knowledge of energy accounting is still lacking.

Life Cycle Assessment Cases

The Ecological Footprint of a Mobile Phone

Sibylle Frey, David J. Harrison and Eric H. Billett

Full paper available: No

The Ecological Footprint (EF) is a conservative estimate of human pressure on global ecosystems and has often been suggested as a sustainability indicator for the human impact on Earth [1]. The EF represents the total productive area of land and water ecosystems required to sustain the resources, wastes, and emissions of a population wherever that land may be located. The world's EF changes proportionally with global population size, per capita consumption, and intensity of the used resource technologies [2]. Traditionally, the EF has been applied to global or other geographic levels.

In this paper, we will discuss how the EF can be applied to electronic products. Based on life cycle energy assessment methodology, we used a bottom-up approach to estimate the bioproductive space needed to appropriate the resources and emissions of a mobile phone. For the direct land use, the methodology includes estimates from the density of materials, size of ore bodies, overburden, and biomass accumulation. As electronic products contain a wide range of materials including precious and rare earth metals, we have made statistical estimates regarding the energy and overburden arising from extraction and processing. For indirect land use, fuel specific carbon sequestration by forests and estimates for the oceans' carbon absorption capacity were included. We also use area as a single indicator to make our results comparable to the world-average bioproductive space of 1.92 hectares per person based on 1996 data or 1.89 hectares without sea space [3]. The results will give a snapshot of a mobile phone's demand for ecosystem services. Our previous estimates [4] suggested that the EF of a PC is about 9 per cent of the terrestrial area of a world-average citizen, which is probably underestimated. Although the results of this case study are a crude approximation, they indicate the magnitude of human appropriation of ecosystems by a single product.

References:

1 Wackernagel, M., Lewan, L. Borgstöm Hansson, C. (1999). Evaluating the use of natural capital with the ecological footprint. Royal Swedish Academy of Sciences. Ambio. 28 (7) 604-12.

2 WWF- World WildLife Fund For Nature (2000). Living Planet Report. http://panda.org/livingplanet/lpr00/download.cfm

3 Wackernagel, M., Callejas, A. Deumling, D. (2000). World of EF-1996-sumaries-WWF.xls. http://www.rprogress.org/ef/LPR2000/. Redefining Progress, USA; Centre for Sustainability Studies, Mexico.

4 Frey, S.D,. Harrison, D.J,. Billett, E. (2000). Environmental assessment of electronic products using LCA and ecological footprint. In: Joint International Congress and Exhibition. Electronics goes green 2000, Berlin, Germany, 11-13 September 2000. 253-258.

Greening of the Ivory Tower

Thomas Gloria and Greg Norris

Full paper available: Yes

Purchases by US colleges and universities exceed $60 billion annually. This research demonstrates the capability to identify which of the nearly 500 categories of college and university purchasing activities reported by the US Bureau of Economic Analysis (BEA) carry the greatest share of direct and upstream environmental life-cycle burdens related to climate change for the average US university, and for specific universities on a case-by-case basis.

The contribution of emissions from upstream production activities can be enormous. In a recent investigation of the nearly 500 sectors of the US economy the following surprising results were found:

- for a majority of sectors, upstream emissions exceed direct emissions;
- for many sectors upstream emission are 5-10 times direct emissions; and,
- the largest sector in terms of upstream emissions is the construction sector with upstream emissions 5 times its direct emissions.

This effort is an initial step to build collaboration among universities to collectively measure their environmental burdens. The approach will allow universities to determine a comprehensive benchmark to measure improvements over time, critical in the process to prioritize long-term strategies. Further, the results of this method would assist universities in establishing purchasing priorities to effectively reduce environmental harm.

There is an urgent need for universities to educate future generations of environmental leaders that will
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Footprint News

Ecological Footprinting & Regions

Issue 2 Winter 2001

Return to Best Foot Forward home page

Regional projects

South East Mass Balance Project, UK

***Melanie Sealey**, EcoSys Environmental Management & Education*

In October this year, Best Foot Forward began a 2-year project with EcoSys Environmental Management & Education, supported by public sector organisations, to produce a mass balance assessment and ecological footprint of the South East. The majority funding is from Biffaward, a multi-million pound environment fund utilising landfill tax credits donated by Biffa Waste Services and The South East England Development Agency. The Ecological Footprint developed will become a cornerstone for regional activity on sustainability.

For further information on Ecosys, visit their website http://www.greenbusiness.org.uk/

Flows of construction minerals and solid waste, UK

Using a mass balance approach, the 4sight project has looked in particular at the flows of construction minerals and solid waste in and around a regional system, using the North West as a case study. Research undertaken as part of 4sight has contributed to the more sustainable management of resource flows.

Further details available at http://www.4sight.org.uk and from Mary Parkinson on 0161 295 5276

Sustainable Sonoma County, *USA*

Ann Hancock

Sustainable Sonoma County has recently been awarded $10,000 from the U.S. Environmental Protection Agency to calculate the per capita Ecological Footprint for Sonoma County and conduct a public information program to disseminate the results. Mathis Wackernagel of Redefining Progress will oversee the calculation. Two panels will then be convened to review and comment on the results. A report will be written and a conference convened to disseminate the results. For more information, please visit: www.sustainablesonoma.org or email: jtrav@wco.com

Research

Best Foot Forward win
Biffaward Awards 2001

BFF Director, Nicky Chambers (right), with project team members from Imperial College, London, and UK Environment Minister, Michael Meacher (left)

The **Isle of Wight's 'Ecological-footprint'** has certainly made its mark on the environment sector by scooping top slot to become Research & Development category and Overall Winner at the major environmental Biffaward Awards 2001.

Download a copy of the winning report
www.bestfootforward.com

Other BFF news ...

Regional Stepwise

Interested in conducting a regional ecological footprint, similar to the Isle of Wight study?

Best Foot Forward have developed a tool to calculate regional footprints. The tool is a good starting point for anyone interested in footprinting regions. It provides information on two regional case studies, tips on how to gather and enter data.

If you are interested in finding out more about Regional Stepwise, contact Nicola Jenkin at nicola@bestfootforward.com

City Limits project

This innovative, year long project was

The Ecological Footprint of a Mobile Phone

***Sibylle Frey**, Brunel University*

This study has attempted to estimate the bioproductive space needed to appropriate the resources and emissions of a mobile phone based on life cycle energy analysis. First results suggest that the footprint of a mobile phone is between 0.6 (older models) and 0.4 (newer models) per cent of the global terrestrial supply of biocapacity per capita. For direct land use, the methodology includes area estimates based on the density of materials, size of ore bodies, overburden, and biomass accumulation. As electronic products contain a wide range of materials including precious and rare earth metals, we have made statistical approximations regarding energy requirements and overburden arising from extraction processes. For indirect land use, fuel specific carbon sequestration by forests and estimates for the oceans' carbon absorption capacity were included.

We used area as a single indicator to make our results comparable to the global supply of bioproductive space of 1.92 hectares per person based on 1996 data (Wackernagel et al) or 1.89 hectares without sea space. The results should be viewed as a snapshot of a mobile phone's demand for ecosystem services. Our previous estimates (Frey, Harrison I Billett, 2000) suggested that the footprint of a PC is about 9 per cent of the global terrestrial bioproductive space per capita, which is probably underestimated. Although the results of these studies are a first approximation only, they indicate the magnitude of human appropriation of ecosystems by products.

Sibylle Frey can be contacted for further information by e-mail Sibylle.Frey@brunel.ac.uk

This study was conducted in collaboration with Nokia Mobile Phones. For more details on Nokia's environmental work, please visit http://www.nokia.com/insight/environmental/index.html

For more details on the PC study, please visit http://www.brunel.ac.uk:8080/research/cleaner/GreenBusiness.html

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Oslo workshop on Ecological Footprinting, EU

***Ingrid Thorsen Norland**, ProSus, University of Oslo*

Report from the Oslo Workshop on Ecological Footprint (24-26 August 2001) is available: http://www.prosus.uio.no/english/sus_dev/tools/oslows/index.htm
The expert workshop gathered the leading researchers in the area of Ecological Footprinting in Europe and local authority representatives from several European cities. Co-sponsors of the workshop were: ProSus, the Western Norway Research Institute, ENSURE and Ambiente Italia / European Common Indicator Project.

For a copy of the Oslo Report *Ecological footprint & biocapacity analyses as sustainability indicators for sub-national geographical areas: A way forward*, by Lillemor Lewan & Craig Simmons, contact Nicola Jenkin nicola@bestfootforward.com

For further information on the co-sponsors, visit their websites:
ProSus: www.prosus.uio.no
Western Norway Research Institute: www.vestforsk.no
ENSURE: http://www.european-association.org/ensure/index.html
Ambiente Italia: http://www.ambienteitalia.it/
European Common Indicator Project: http://www.sustainable-cities.org/indicators/

An Ecological Footprint Analysis using GIS at a Sub-national Geographic Area, *Australia*

***Arvind Kamar**, University of New South Wales, Sydney*

This doctoral research project aims to develop a decision support system for assessing the impact of the built environment on urban ecology by using Ecological Footprinting Analysis (EFA) and Geographical Information Systems (GIS). The launched in July 2001. We are currently gathering data and plan to complete and make the final report publicly available in July 2002. Information on the City Limits project can be found at www.citylimitslondon.com

South East Region Mass Balance & Ecological Footprint Analysis

As reported in the main body of this newsletter, Best Foot Forward will be working with Ecosys Environmental Management & Education to conduct an 18 month long resource flow and ecological footprint analysis of the South East Region, UK. The project is in the early stages with completion planned for February 2003.

Recent projects completed ...

European Union Sustainable Cities

Craig Simmons - a Director of BFF, and Lillemor Lewan (Lund University, Sweden) have recently authored *The use of Ecological Footprint & Biocapaicty Analyses as Sustainability Indicators for Sub-national Geographical Areas: A recommended way forward.* A report produced as an outcome from an EU Sustainable Cities workshop held in Oslo, August 2001.

Ambiente Italia have kindly agreed to the report being more widely available. Copies are available on request from Nicola Jenkin, nicola@bestfootforward.com

Footprint of Wales

WWF Cymru and Best Foot Forward, in partnership with The National Assembly for Wales have constructed the first ecological footprint for Wales.

The Assembly is the first administration in the world to use footprinting as an indicator of 'real progress' for its overarching Sustainable Development Scheme.

Herefordshire Footprint

BFF has recently completed a regional footprint of Herefordshire, England. It can be deduced that if everyone on the planet consumed the same as the average Herefordshire resident, we would need around one and a half additional Earths to support current global demand.

Holiday Footprinting

With funding from WWF-UK, we recently completed a footprint of two Mediterranean tourist destinations. Presenting the results at the World Travel Market, London. Accompanying the report is a computer-based tool, using the two tourist destinations as case studies.

For further information contact either Best Foot Forward or Justin Woolford, WWF-UK, jwoolford@wwf.org.uk

Footprint News

Ecological Footprinting & Business

Issue 1 Spring 2001

News

Anglian Water

The ecological footprint and AWG
Anglian Water Services, a subsidiary of AWG, and Best Foot Forward are working in partnership to develop a tool that will clearly communicate environmental performance to stakeholders and monitor progress in reducing ecological impacts. The Ecological Footprint (EF) provides such a tool. **FULL STORY**

Sibylle Frey
Brunel University

A PC's terrestrial ecological footprint
A Life Cycle Analysis-based exploratory study at Brunel University of a personal computer (PC) showed, as a first snapshot, that a PC's terrestrial Ecological Footprint (EF) is about 9% the space of the world average citizen. This result was obtained using the following methodology:

1. Calculating the direct land use of different materials through
   a) using density of materials, size of orebodies, overburden/'rucksacks'
   b) affected production areas divided by output
   c) Intergovernmental Panel on Climate Change (IPCC) data for biomass accumulation.
2. To account for emissions, up to now we have only included CO_2. We used fuel specific carbon sequestration by forests and a 25%carbon absorption rate by oceans. Current research addresses the EF of mobile phones.

For more details on the PC study, please visit
http://www.brunel.ac.uk:8080/research/cleaner/GreenBusiness.html

John Barrett
York University

Ecological footprint of Liverpool
The component ecological footprint project of Liverpool has now finished and the full report will soon be available from http://www.regionalsustainability.org/

Summary report: Northwest Development Agency
A summary report is also going to be available in a couple of months, funded by the Government Office for the Northwest Development Agency.

I'm off to Sweden in a couple of weeks to discuss future footprinting with Carl Folke and Roger Kasperson (Exec Director of SEI).

David Burdick
Sustainable Steps

Sustainable Steps
Sustainable Steps is a consulting firm dedicated to helping corporations move towards sustainability. One of the steps on this path consists of defining what corporate ecological sustainability is. This is accomplished by determining the company's *maximum sustainable consumption* of the earth's resources and comparing it to the company's products' *actual consumption*. Calculations are based on equivalents of land, air, water and solar power.

Further information can be found at: http://www.sustainablesteps.com
or contact: Dburdick@sustainablesteps.com

Best Foot Forward

Publications

Ecological Footprint Analysis: Towards a sustainability indicator for business
Nicky Chambers & Kevin Lewis
Published by: ACCA

Download available from 'Published Research' at the ACCA website: http://www.accaglobal.com/research.html

Sharing Nature's Interest is a new book on ecological footprinting by Nicky Chambers, Craig Simmons and Mathis Wackernagel. Further details are available online.

Released mid-March in USA!!!

*** Oxford Book launch ***
Nicky Chambers & Craig Simmons
will be signing and introducing their book at
Borders – Oxford
(Magdalen St [off Commarket])

Thursday, 19th April 2001
7:00pm

VDE VERLAG

Herbert Reichl, Hansjörg Griese (Editors)

Joint International Congress and Exhibition

ELECTRONICS GOES GREEN 2000+

A Challenge for the Next Millennium

Proceedings Volume 1
Technical Lectures

CARE INNOVATION 2000, Europe

EcoDesign

ECO DESIGN, Japan

IEEE, USA
TC Electronics and the Environment

September 11–13, 2000
Berlin, Germany

Environmental Assessment of Electronic Products using LCA and Ecological footprint

S.D. Frey, Dr. D. J. Harrison, Prof. E. H Billett, Brunel University, Cleaner Electronics Research Group, Runnymede Campus, Egham, UK. Sibylle.Frey@Brunel.ac.uk

Abstract

The Ecological Footprint (EF) methodology, developed by Wackernagel and Rees, has often been suggested as a sustainability indicator for the human impact on earth. Efs, expressed as area, sum up the total productive area of land and water ecosystems required to sustain the resources, wastes, and emissions of a population wherever that land may be located. Thus, EFs can be established on a global or other geographic level. In this paper, we discuss whether the EF can be applied to electronic products. Based on a LCA study, we used a bottom-up approach for estimating the bioproductive space needed to appropriate the resources and emissions of a personal computer (PC). We also used area as a single indicator to make results comparable to the current terrestrial world-average footprint. Our estimates suggest that the EF of a PC is about 9 per cent of the terrestrial EF of a world-average citizen, which is probably underestimated. Although the results of this case study are a first approximation only, they indicate the magnitude of human appropriation of ecosystems by a single product.

1 Background

The key question behind the EF is whether nature's productivity is sufficient to satisfy present and future demands of the economy indefinitely. The EF method assumes that every category of energy and material consumption and waste requires the productive or absorptive capacity of a finite area of land or water [21]. The EF of a state or region sums up the biologically productive areas of consumption and waste absorption wherever on Earth that land or water may be located [10]. Previous studies based on United Nations statistics have shown that man's use of natural resources exceeds the earth's carrying capacity by more than a third [19].

If global biologically productive sea and land space on earth are divided by the global population, the average space per capita is 2.2 hectares (ha) per person. Without the sea, average land space is around 1.7 ha per capita [19]. The Brundtland Commission suggested a figure of 12 per cent for the other 10 to 30 million species on the planet, which might be politically feasible but will probably not be enough for securing long-term biodiversity [10]. From this, approximately 1.5 hectares per capita are left [20]. With an anticipated number of ten billion people by 2050, the available productive land and sea space will be reduced to 1.2 hectares world wide [20]. These figures are likely to be underestimated as to date, apart from CO_2, other emissions, toxins and wastes are not included in the calculations [21]. Recent work in EF assessments for products has been done by Buitenkamp and Spapens for a detergent and a photocopier [2]. In our case study, we tried to estimate how much bioproductive space is needed to appropriate the resources and emissions of a PC. We used a LCA based, bottom-up approach for matching our findings with the present, terrestrial footprint of a world-average citizen, based on [20]. This required aggregating the resources and emissions and appropriating these into area-units-equivalents.

2 Experiments

2.1 Methodology and assumptions for resource consumption

The data for this footprint analysis was taken from a LCA report on a generic PC from 1998 [1], carried out on behalf of the EC. The equipment was based on the assumptions shown in table 1. The impact assessment data was used for converting primary energy consumption into land space. The direct land-use data for the LCI materials was calculated from Frischknecht [7], which is mostly site-specific. Using the direct consumption of land space takes into account that even with recultivation measures after mining operations, the original environment with its species and habitats cannot be re-installed [17], Globally, recultivation efforts are very patchy due to the high costs involved [15].

200MHz CPU and cooler	Power supply
16MB EDO RAM	Mini tower cabinet
4 MB RAM graphics adapter	CD-ROM drive
3 GB IDE hard disk	15" SVGA colour monitor
3.5" floppy drive	Keyboard and mouse
Power consumption Monitor and Control Unit (incl. Keyboard)	100 and 60 Watts
Lifetime	3 years (230 days or 5520 hours)
Transport distance truck / van	525 km
Disposal routes Europe	63% land-filled, 22% incineration with 75% heat recovery, 15% recycling
Recovery rates metals	Steel 97%, Al 95%, other 100%

Tab. 1. Generic PC data according to [10].

The separate LCI inputs were appropriated to land areas. No generic assumptions can be made with regard to the land affected through mining operations, as they differ between mines and sites. Due to limited data available, we used data from mining sites, orebodies, density of materials, and overburden as a first approximation for the collateral impact from materials extraction. Overburden data was mainly collected from Douglas and Lawson [5], and Schmidt-Bleek [16]. Other mining data was mainly obtained from Frischknecht [7]. In our calculations the higher overburden values were used as they were sometimes given as an ore to commodity ratio, or included all material movements associated with extraction. An example is given in **Tab. 2**.

Material:	**Aluminium**	**Copper**	**Hard coal**
Land use (m^2/kg)	5.49E-04 ^{a}	6.41E-04 ^{a}	1.80E-04 ^{a}
Overburden factor:	3.68 ^{b}	450 ^{c}	4.87 ^{c}
^{a} Calculated from FK 1996; ^{b} FK 1996; ^{c} DL 1998			

Tab. 2. Example commodities and their overburden.

For some raw materials the land space required for processing steps after the extraction phase could be included, such as for oil, coal, and natural gas. For gas and oil pipelines, space for infrastructure could not be established due to lack of data. The embedded energy was included in the LCA for all LCI inputs [14]. Some metals where found not to be included in the LCI, such as some Gold (0.8g), Silver (0.97 g), Beryllium (0.13g) and some Cadmium. Water was not included in this EF assessment, although we know from the LCA that approximately 74000 litres are consumed over a PC's life-time [1]. Therefore, land for resource consumption is believed to be highly underestimated.

2.2 Methodology and assumptions for estimation of CO_2 absorption areas

Fossil-energy-land is the land to be reserved for CO_2 absorption and refers to the spatial impact of fossil fuel use. As a minimum requirement, the fossil carbon added to the carbon cycle of the biosphere through burning must be sequestered if we assume that added anthropogenic CO_2 to the atmosphere should be curbed. This is, however, a strong sustainability assumption. Hence, the EF for fossil fuels is probably overestimated. Today, the only sequestering technique applied (and to a very limited extent) is growing forest that will not be harvested. Such land serves as a carbon dioxide sink during a period of 40 to 100 years, depending on climate and tree species. In order not to release the fixed CO_2, the mature forest would have to be maintained for the future without human intervention, spontaneously renewing itself. Harvesting is only possible with little wastage and if most of the biomass is transformed in long-lasting products [8]. To avoid increasing levels of CO_2 in the atmosphere in case of continued fossil fuel use, additional areas would have to be set aside for sequestration. These are not included in the calculations [20]. Here, a world -average carbon absorption of 1.42 tonnes per hectare and year including root mass, was applied, based on FAO data [20]. The latest data from the Intergovernmental Panel on Climate Change, IPCC [8, 9] have been used to calculate the fossil fuel specific carbon uptake by forests. No other terrestrial carbon sinks have been included so far. As oceans are a major sink for CO_2, they have been accounted for in the calculations. However, data for the amount of anthropogenic carbon which is fixed by the sea is based on complex models which can vary significantly. The Hadley Centre for Climate Prediction and Research at the British Meteorological Office assumes a figure of 25 to 33 per cent for anthropogenic carbon dioxide uptake by oceans [13] which is in line with the literature. However, should the oceans warm substantially, an opposite effect may counterbalance this absorption to some extent because warming water emits CO_2 into the air [12]. Here we used an absorption rate of 25 per cent of CO_2 per year. **Tab. 3** gives an overview on carbon absorption by forests per area. As other impacts such as acidification and eutrophication are not yet included in the calculations, the overall results are probably underestimated.

World average carbon absorption by forests:
1.42 tonnes of carbon [t/ha/yr] including roots (Wac et al. 1999)

	^{a}CEF [t C/ TJ]	GJ/ ha/ yr:	MJ/ m^2/ yr	^{b}NCV	MJ per m^2
Crude oil	20	71	7.10	67	6.75
Coal	26	55	5.50	52	5.23
Nat.gas	15.3	93	9.30	84	8.37

[a] Carbon emission factors (IPCC 1997 a)

[b] Net Calorific Values for fossil fuels: 95% of liquid and solid fossil and biomass fuels, 90% of natural gas (IPCC1997 a)

Tab. 3. Fuel specific carbon absorption by forests.

3 Results and Discussion:

3.1 Land-use of resource consumption by PC system

By comparing the LCA amounts of resources with their respective land use, quantities and land-space do not change proportionally as overburdens are included for "non-renewables". This is especially visible in the case of copper with an overburden of 450 kg per kg copper derived from surface mining. Biomass was calculated as wood with a growth of 0.5 kg dry matter per m^2/year from IPCC data [8, 9]. The primary reason fossil fuels absorb so much space is related to the very high amount consumed. In the case of the keyboard, the relative high amounts of the raw materials crude oil and natural gas are due to the plastic ABS. The metals-to-plastic ratio is higher in the Monitor and Control Unit, which explains their higher presence in the land use data.

Tab. 4 shows the hierarchy for the top four resources from both studies. As these values represent the physical amounts taken from the earth only, and do not account for areas from associated wastes and emissions, these results are significantly underestimated. However, they serve as a valuable first approximation.

3.2 Land-space of resource consumption over a PC's life cycle

Fig. 1 shows the results for Monitor, Control Unit and Keyboard. For all three PC systems the material production determines the footprint-size with 53, 71 and 93 per cent. The use phase follows with 44 and 22 per cent of land consumption. Between 3 and 8 per cent of land-space are credited for recycling, which is 6 to 12 per cent of the space for material production. Land-space for material production was mainly determined by copper extraction, whereas fossil fuels determined the use phase.

It should be mentioned here that the credited land space is rather to be interpreted as space saved from further material extraction due to recycling, and not as a reconstitution of the original environment. Even if the environmental "rucksacks" are put back into the hole they have been taken from, they alter the sustainability of the area affected as they affect future erosion and slope stability of the respective site [4].

	LCA results	EF- results
Monitor	1. Hard coal, fuel 2. Lignite, fuel 3. Natural gas, fuel 4. Crude oil, fuel	1. Crude oil, fuel 2. Copper 3. Hard coal, fuel 4. Lignite, fuel
Control Unit	1. Hard coal, fuel 2. Lignite, fuel 3. Crude oil, fuel 4. Natural gas, fuel	1. Unspecified bm f 2. Copper 3. Crude oil, fuel 4. Wood, fuel
Keyboard	1. Hard coal, fuel 2. Crude oil 3. Crude oil raw m. 4. Natural gas, r.m.	1. Copper 2. Wood, fuel 3. Crude oil, fuel 4. Crude oil, raw m.

Tab. 4. Hierarchy of resources for LCA and EF.

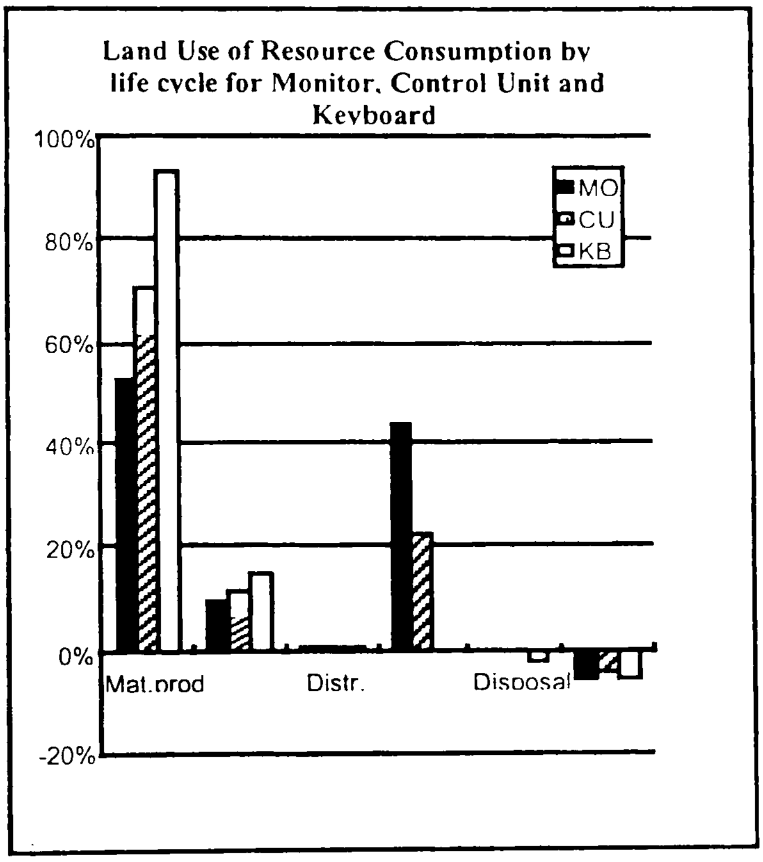

Fig. 1. Land use of resource consumption

3.3 Land-space for fossil-energy over life cycle

3.3.1 Materials-energy

Some fuel specific carbon emission factors and their appropriated space for CO_2-sequestration are shown in table 3. Because the overall results reflect the primary energy values from the LCA given in Mega Joules, the required land space for CO_2 sequestration is allocated pro rata.

If the primary energy for *materials* is appropriated into land space, the material production phase requires about 26 m^2, or more than 99 per cent of land-space in the Monitor, Control Unit and Keyboard. This reflects the relatively high energy costs in the extraction of non-renewable resources including the removal of overburden. However, land appropriated for materials energy only accounts for 1.5 per cent of the land for process energy.

3.3.2 Process-energy

Regarding *process* energy, the land-use is highest in the use phase for Monitor and Control Unit - it takes up 1340 m^2 (80 and 72 per cent). Manufacturing comes second with 340 m^2 (18 and 21 per cent for Monitor and Control Unit, 49 per cent for the Keyboard). Material production uses about 88 m^2 (3, 7 and 56 per cent). Around 9 m^2 are credited for recycling, which is 7, 12 and 3 per cent of material production, respectively.

Overall, the use phase consumes the lion's share of land-space for absorbing CO_2 emissions from material and process energy. Manufacturing consumes 25 per cent, and material production only 9 per cent of the land-space consumed for the use phase. Thus, the Monitor has the largest energy-footprint from use and manufacture (1070 m^2), followed by the Control Unit with 703 m^2, and the Keyboard with the smallest energy-footprint (15 m^2) from material production and manufacture. Including resource consumption, the EF of the total PC so far is 1790 m^2, or 0.18 ha. If 25 per cent of anthropogenic CO_2 emissions are absorbed by oceans, the PC's footprint on earth is still 1342 m^2 (0.13 ha) over its assumed life time of three years. **Fig. 2** and **3** show the energy footprints from materials and processes, and the overall results are summarised in **Tab. 5**.

Because CO_2-emissions associated with nuclear energy are low, it is sometimes suggested as a solution to global warming. However, there are reasons to consider nuclear energy as unsustainable [16].[1]

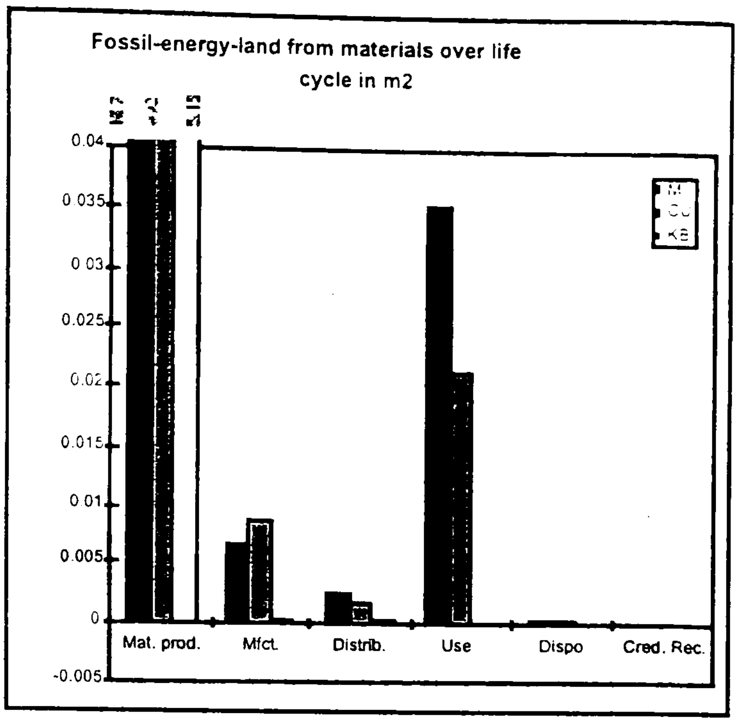

Fig. 2. Land-space from materials energy (Monitor, Control Unit, and Keyboard).

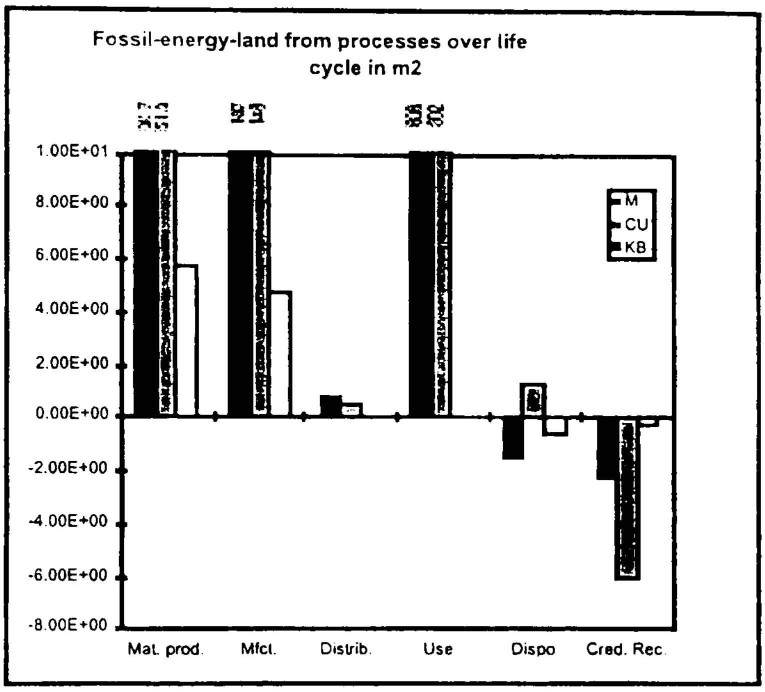

Fig. 3. Land-space from process energy (Monitor, Control Unit, Keyboard).

Totals (m2)	**Footprint res. cons.**	**Footprint energy**	**Ecological Footprint PC**
Control Unit	6.87E-01	6.99E+02	
Monitor	5.79E-01	1.07E+03	
Keyboard	3.27E-02	7.11E+00	
Total	**1.30E+00**	**1.77E+03**	**0.18 ha**

Tab. 5. Results and EF of a PC

4 Summary and Conclusions

In summary, a PC has a footprint of 1790 m^2, or 0.18 ha over its lifetime of three years. It exceeds its own physical size by more than a thousandfold. A PC's footprint is almost exclusively determined by fossil fuel use. This is about 9 per cent of the EF of the world average citizen, and is assumed to be very high for a single product in relation to other activities people pursue, such as heating, lighting, driving. However, these 9 per cent do not account for other outputs from resource consumption, such as emissions other than CO_2. This needs further investigation.

The results reconfirm the use phase as the main culprit, followed by manufacturing and material production. However, manufacture and material production account only for 25 and 9 per cent of the use phase, respectively. Using energy efficiency measures, for example the US EPA Energy Star requirements, could probably reduce the footprint size significantly.

The results also show that small amounts of resources extracted can have a high consumption of land-space, which was based on relatively high materials energy in the material production phase. However, this is offset by process energy in the use and manufacturing phase.

On the basis of the factors included in this study, the footprint from the resource consumption of raw materials appears to be negligible in comparison to the footprint from energy consumption. However, calculations suggest that at least 57 x 10^9 tonnes of material are dug from the earth's surface per year, of which 19.7 x 10^9 tonnes are minerals which are used, and 37.5 x 10^9 tonnes of which are waste or overburden. Apart from the energy associated with these material flows they also cause significant environmental site and off-site impacts [5, 18]. Ideally, these direct and indirect effects should be included in EFs.

At present, post-extraction data could only be included for a few non-renewable resources. Apart from overburden, no land use data was found for elements such as Gold, Silver, Tin, Lead and Zinc. They are present in PCs and have high environmental rucksacks, which must be seen in context with the impacts from global material flows. The study also shows that it is mainly the output side of resource use that creates pressures on the biosphere. Therefore, the present bioproductive space appropriated for the physical resource consumption can only be interpreted as a first approximation for the "hidden" areas required for impacts from materials extraction. The high amount of water consumed over the PC's life cycle (about 74000 litres) has not yet been appropriated into land area. This also suggests that the footprint for resource consumption is significantly underestimated.

Estimates of any heterogeneous process on a global scale are inevitably based on data with high uncertainties. Our estimates take a static snapshot of what is actually a highly complex dynamic ecosystem. But although not comprehensive, the results indicate the magnitude of human appropriation of ecosystems by a product. The EF for products can be very effective for giving an overview of a product's consumption in relation to a human's "fair earth share" as implied in the EF concept for populations. As an aggregate, single indicator, the EF communicates the resource consumption on a product level through links with the global level of world-average resource consumption. Used in this way, the EF holds the potential for measuring space-efficient technology. The EF does not compete with other assessment tools, but should rather be seen complementary. The above findings suggest that EFs have their role in the sustainability dialogue.

5. Acknowledgements

Special thanks to Prof. Lillemor Lewan from Lund University, Sweden, for her kind support in obtaining data for the footprint calculation, and to Diana Deumling from Redefining Progress, San Francisco. This work has partly been funded by the EPSRC Design for Life Cycle Program.

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[1] These are for example problems and risks associated with uranium production from uranium-ore processing and reprocessing, and unsolved problems with the long-term storage of radioactive waste [11, 20, 21]. There are also political and economic objectives such as the global implication of nuclear energy with military use [21] and high capital and operation costs [22, 23]. Other studies show that a focus on nuclear energy inhibits the development of more sustainable energy sources [11]. Wackernagel et al. assume that nuclear energy has the same footprint as fossil energy: rough calculations suggest that the lost ecological bio-production caused by the Chernobyl accident compared to the total nuclear power produced since the 1970s leads to nuclear per [MJ] footprints larger than those of fossil fuel. As nuclear energy is not even economically competitive with fossil fuel, it will most likely be replaced in the short run with fossil fuel based energy [7]. If this is taken into account, the EF of the PC would increase by about 160 m^2, assuming a 12 per cent share of nuclear in an average European energy mix.

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INTEGRATED PRODUCT POLICY AND ECOLOGICAL FOOTPRINT OF ELECTRONIC PRODUCTS

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Introduction

Integrated Product Policy (IPP) is a relatively new field in environmental policy developed to contribute to sustainable development as defined in the Brundtland-Report [1]. As such, its global objective is to improve resource efficiency and the environmental impact from the consumption of goods and sèrvices [2] and to 'green' the marketplace through the supply and demand chain [4,3]. The concept of IPP differs from the conventional approach in that it covers all product systems and their environmental effects by pursuing a life-cycle (LC)-thinking, thus avoiding shifting environmental problems between different stages of the life cycle. Within IPP, all existing management and regulation tools will still be valid but their use might be reassessed within a new framework in which all stakeholders are incorporated and new instruments may be developed [1]. Five IPP measures have been identified: 1. Measures aimed at reducing and managing wastes generated through the consumption of products 2. Encouragement for the innovation of more environmentally sound products 3. Creating markets for those products 4. Transmission of information along the product chain 5. Allocation of product responsibility for environmental burdens [2]. IPP will therefore encourage changes in behaviour within all stakeholders [1].

However, there are many challenges and questions which have to be solved in implementing IPP. These are seen, for example, in the co-operation of different stakeholders, in the key focus on products, in what tools there are to reveal the link between a product and its environmental impact, and in balancing market forces and sustainable development [1]. But there is still some confusion about what IPP could be and how the impact of such an approach would look like - for example when moving away from a product-focused towards a service-focused industry. The European Commission (EC) is going to address the main issues and problems by further research based on joint pilot projects within stakeholders [1].

The Ecological Footprint (EF) methodology, developed by Wackernagel and Rees, is already a very effective sustainability indicator for the human impact on earth. EF are calculated by dividing the biologically productive land and sea space of the earth by its population. Thus, EF can be established on a global or other geographic level. In this paper, we discuss whether the EF can be brought down to a product level to assess the sustainability of a Personal Computer (PC). We also used land-space as a single indicator to make results comparable to the current world-average footprint. Recent work in this sector has been done by Buitenkamp and Spapens [5]. This paper extends their research.

I Background

The key question behind the EF is whether naturesí productivity is sufficient to satisfy present and future demands of the economy indefinitely. The EF method assumes that every category of energy and material consumption and waste requires the productive or absorptive capacity of a finite area of land or water [6]. EFs sum up the biologically productive areas of consumption and waste where ever that land or water may be located on the planet [9 Previous studies based on United Nations statistics have shown that man's use of natural resources exceeds the earth's carrying capacity by more than a third [8].

If global biologically productive sea and land space on earth are divided by the global population , the average space per capita is 2.2 hectares (ha) per person. Without the sea, average land space is around 1.7 ha per capita [8]. The Brundtland Commission suggested a figure of 12 per cent for the other 10 to 30 million species on the planet, which might be politically feasible but will probably not be enough for securing long-term biodiversity [9]. From this, approximately 1.5 hectares per capita are left [7]. With an anticipated number of ten billion people by 2050, the available space will be reduced to 1.2 hectares world wide, including the productive areas of the seas [7]. These figures are likely to be underestimated as to date, apart from CO_2, other emissions, toxins and wastes are not included in the calculations [6].

II Experiments

A. Methodology resource consumption:

The data for this footprint analysis was taken from a LCA report on a generic PC from 1998 [10], carried out on behalf of the EC. The equipment was based on the following assumptions:

200MHz CPU and cooler	Power supply
16MB EDO RAM	Mini tower cabinet
4 MB RAM graphics adapter	CD-ROM drive
3 GB IDE hard disk	15î SVGA colour monitor
3.5î floppy drive	Keyboard and mouse
Power consumption Monitor and Control Unit (incl. Keyboard)	100 and 60 Watts
Lifetime	3 years (230 days or 5520 hours)
Transport distance truck / van	525 km
Disposal routes Europe	63% landfilled, 22% incineration with 75% heat recovery, 15% recycling
Recovery rates metals	Steel 97%, Alu 95%, other 100%

Tab. 1. Generic PC data according to [10].

The impact assessment data was used for translating primary energy consumption into land space. The direct land-use data for the LCI materials was calculated from Frischknecht [11], which is mostly site-specific. Using the direct consumption of land space takes into account that even with recultivation measures after mining operations, the original environment with its species and habitats cannot be re-installed [12].

The separate LCI inputs were appropriated to land areas. No generic information is available with regard to the land affected through mining operations, as they differ between sites. Where possible, overburden were included and added to the extraction data. Overburden data was collected from Douglas and Lawson [13], Schmidt-Bleek [14] and Frischknecht [11]. In our calculations the higher overburden values were used as they were sometimes given as an ore to commodity ratio, or included all material movements associated with extraction. An example is given in table 2.

Material:	Aluminium	Copper	Hardcoal
Land use (m^2/kg)	5.49E-04 ^{a}	6.41E-04 ^{a}	1.80E-04 ^{a}
Overburden factor:	3.68 ^{b}	450 ^{c}	4.87 ^{c}
^{a} Calculated from FK 1996; ^{b} FK 1996; ^{c} DL 1998			

Tab. 2. Example commodities and their overburden.

For some raw materials the land space required for processing steps after the extraction phase could be included, such as for oil, coal, and natural gas. For gas and oil pipelines, space for infrastructure could not be established due to lack of data. The embedded energy was included in the LCA for all LCI inputs (IPU, pers. comm.). Some metals where found not to be included in the LCI, such as some Gold (0.8g), Silver (0.97 g), Beryllium (0.13g) and some Cadmium. Water was not included in this EF assessment. Therefore, land for resource consumption is believed to be highly underestimated.

B. Methodology for carbon dioxide emissions

Fossil-energy-land is the land to be reserved for CO_2 absorption and refers to the spatial impact of fossil fuel use. As a minimum requirement, the fossil carbon added to the carbon cycle of the biosphere through burning must be sequestered. Today, the only sequestering technique applied is growing forest that will not be harvested. Such land serves as a carbon dioxide sink during a period of 40 to 100 years, depending on climate and tree species. In order not to release the fixed CO_2, the mature forest would have to be left for the future without human intervention, spontaneously renewing itself. Harvesting is only possible with little wastage and if most of the biomass is transformed in long-lasting products [16].To avoid increasing levels of CO_2 in the atmosphere in case of continued fossil fuel use, additional areas would have to be set aside for sequestration. This is not included in the calculations [7]. Here, a world average carbon absorption of 1.42 tonnes per hectare and year including root mass, is applied, based on FAO data [7]. The latest data from the Intergovernmental Panel on Climate Change [15, 16] have been used to calculate the fossil fuel specific carbon uptake by forests. As oceans are a major sink for CO_2, they have been included in the calculations. However, data for the amount of anthropogenic carbon which is fixed by the sea is based on complex models which can vary significantly. The Hadley Centre assumes a figure of 25 to 33 per cent for anthropogenic carbon dioxide uptake by oceans (Hadley Centre, pers. comm.,) which is in line with the literature. However, should the oceans warm substantially, an opposite effect may counterbalance this absorption to some extent because warming water emits CO_2 into the air [17]. Here we used an absorption rate of 25 per cent of CO_2 per year. Table 3 gives an overview on carbon absorption by forests.

World average carbon absorption by forests:					
1.42 tonnes of carbon [t/ha/yr] including roots (Wac et al. 1999)					
	[a] CEF [t C/ TJ]	GJ/ ha/ yr.	MJ/m²/ yr	[b]NCV	MJ per m²
Crude oil	20	71	7.10	67	6.75
Coal	26	55	5.50	52	5.23
Nat.gas	15.3	93	9.30	84	8.37
[a] Carbon emission factors (IPCC 1997 a)					
[b] Net Calorific Values for fossil fuels: 95% of liquid and solid fossil and biomass fuels, 90% of natural gas (IPCC1997 a)					

Tab. 3. Fuel specific carbon absorption by forests.

III Results and Discussion:

A. Resource consumption-land

1. Land-space of resource consumption by PC system:

By comparing the LCA amounts of resources with their respective land use, quantities and land-space do not change proportionally as overburdens are included for "non-renewables". This is especially visible in the case of copper with an overburden of 450 kg per kg copper derived from surface mining. Biomass was calculated as wood with a growth of 0.5 kg dry matter per m^2/year [15, 16]. The primary reason fossil fuels absorb so much space is related to the very high amount consumed. In the case of the keyboard, the relative high amounts of the raw materials crude oil and natural gas are due to the plastic ABS. The metals to plastic ratio is higher in the Monitor and Control Unit, which explains their higher presence in the land use data. Table 4 shows the hierarchy for the top four resources from both studies.

2. Land-space of resource consumption by life cycle

Fig. 1 shows the results for Monitor, Control Unit and Keyboard. For all three PC systems the material production determines the footprint-size with 53, 71 and 93 per cent. The use phase follows with 44 and 22 per cent of land consumption. Between 3 and 8 per cent of land-space are credited for recycling, which is 6 to 12 per cent of the space for material production. Land-space for material production was mainly determined by copper extraction, whereas fossil fuels determined the use phase.

It should be mentioned here that the credited land space is rather to be interpreted as space saved from further material extraction due to recycling, and not as a reconstitution of the original environment. Even if the environmental "rucksacks" are put back into the hole they have been taken from, they alter the sustainability of the area affected as they affect future erosion and slope stability of the respective site [13].

	LCA results	Land-use results
Monitor	1. Hard coal, fuel 2. Lignite, fuel 3. Natural gas, fuel 4. Crude oil, fuel	1. Crude oil, fuel 2. Copper 3. Hard coal, fuel 4. Lignite, fuel
Control Unit	1. Hard coal, fuel 2. Lignite, fuel 3. Crude oil, fuel 4. Natural gas, fuel	1. Unspecified bm f 2. Copper 3. Crude oil, fuel 4. Wood, fuel
Keyboard	1. Hard coal, fuel 2. Crude oil 3. Crude oil raw mat 4. Natural gas, raw material	1. Copper 2. Wood, fuel 3. Crude oil, fuel 4. Crude oil, raw material

Tab. 4. Hierarchy of resources LCA and land-use.

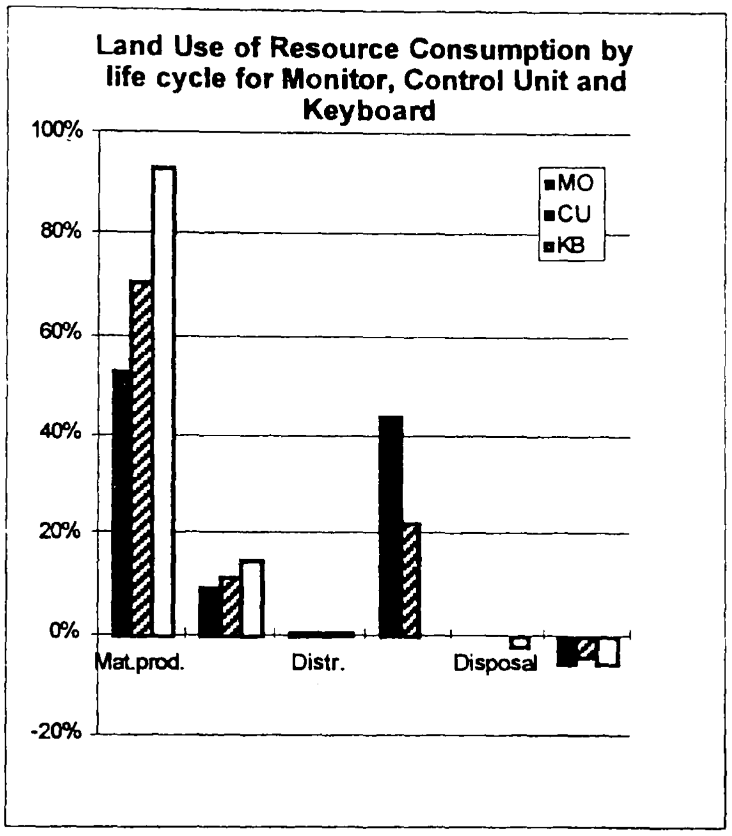

Fig. 1. Land use of resource consumption

B. Fossil-Energy-Land

1. Land-space for energy from materials by life cycle

As the results reflect the primary energy values from the LCA given in Mega Joules, the required land space for CO_2 sequestration is allocated pro rata.

If the primary energy for *materials* is appropriated into land space, the *material production* phase requires about 26 m^2, or more than 99 per cent of land-space in the Monitor, Control Unit and Keyboard. This reflects the relatively energy costs in the extraction of non-renewable resources including the removal of overburden. However, land for material energy only accounts for 1.5 per cent of the land for process energy.

2.Land-space for energy from processes by life cycle

Regarding process energy, the land-use is highest in the use phase for Monitor and Control Unit - it takes up 1340 m^2 (80 or 72 per cent). Manufacturing comes second with 340 m^2 (18 and 21 per cent for Monitor and Control Unit, 49 per cent for the Keyboard. Material production uses about 88 m^2 (3, 7 and 56 per cent). Around 9 m^2 credit are credited for recycling, which is 7, 12 and 3 per cent of material production respectively.

Overall, the use phase consumes the lion's share of land-space for absorbing CO_2 emissions from material and process energy. Manufacturing consumes 25 per cent, and material production only 9 per cent of the land-space consumed for the use phase. Thus, the Monitor has the largest energy-footprint from using and manufacturing it (1070 m^2). The Control Unit holds the second place with 703 m^2, and the Keyboard has the smallest energy-footprint (15 m^2) from material production and manufacture. Including resource consumption, the EF of the total PC is 1790 m^2, or 0.18 ha. If 25 per cent of anthropogenic CO_2 emissions are absorbed by oceans, the PC's footprint on earth is still 1342 m^2 (0.13 ha). Figures 2 and 3 show the energy footprints, and the results are summarised in table 5.

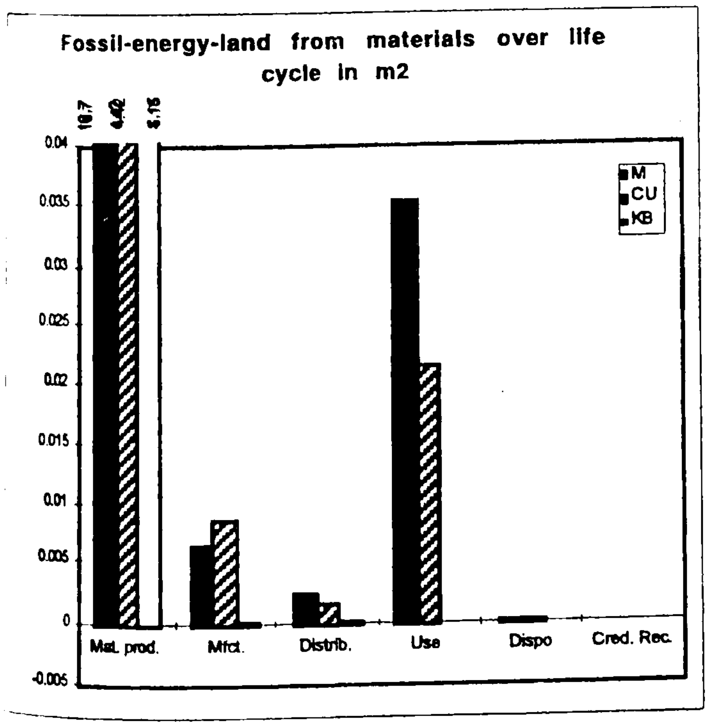

Fig. 2. Land-space from materials energy.

Totals (m2)	Footprint res. cons.	Footprint energy	Ecological Footprint PC
Control Unit	6.87E-01	6.99E+02	
Monitor	5.79E-01	1.07E+03	
Keyboard	3.27E-02	7.11E+00	
Total	**1.30E+00**	**1.77E+03**	**0.18 ha**

Tab. 5. Results and EF of a PC

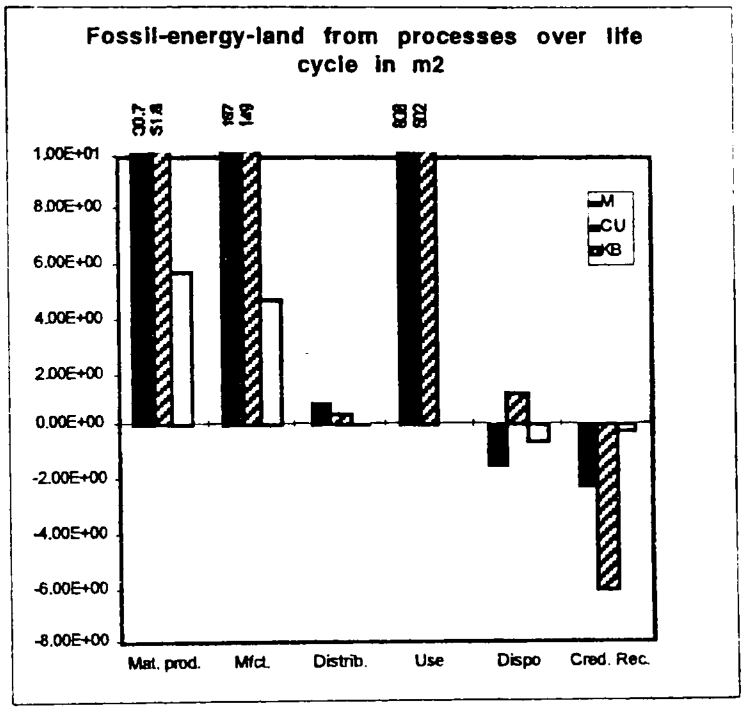

Fig. 3. Land-space from process energy.

Because CO_2-emissions associated with nuclear energy are low, it is sometimes suggested as a solution to global warming. However, there are reasons to consider nuclear energy as unsustainable [14].[1]

IV. Summary and Conclusions:

In summary, a PC has a footprint of 1790 m^2, or 0.18 ha over its lifetime of three years. It exceeds its own size by more than a thousandfold. A PC's footprint is almost exclusively determined by fossil fuel use. This is about 9 per cent of the EF of the world average citizen, and is assumed to be very high for a single product in relation to other activities people pursue, such as heating, lighting, driving. These 9 per cent do not account for other outputs from resource consumption.

The results reconfirm the use phase as the main culprit, followed by manufacturing and material production. However they account for only 25 and 9 per cent of the use phase. Due to energy efficiency measures, for example the US EPA Energy Star requirements, the footprint size could be reduced significantly.

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