ENVIRONMENTAL IMPACTS AND BENEFITS OF INFORMATION AND COMMUNICATION TECHNOLOGY INFRASTRUCTURE AND SERVICES, USING PROCESS AND INPUT-OUTPUT LIFE CYCLE ASSESSMENT

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Pour Flavie, Yohan et Stéphanie

“We don’t inherit the earth from our ancestors, we borrow it from our children”

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ABSTRACT

Sustainable development and the Information Society are two concepts that are not commonly associated. However, both could have a major impact on the other. Information and communication technologies (ICT) may have important negative impacts on the environment. At the same time, ICT can also bring improvements. To provide guidance on how ICT devices and applications can be oriented towards positive effects, new methodology and tools are needed to understand and assess these various effects. In that respect, Life Cycle Assessment (LCA) is a pertinent approach, potentially enabling a holistic and in-depth analysis. This thesis proposes to develop appropriate Life Cycle tools and methodology and to apply them to measure the sustainability of ICT devices and of their applications. Specific objectives are:

- to explore the possibilities of combining Process LCA (PLCA) and Input-Output LCA (IOLCA), and to develop an operational method for ICT applications;
- to apply the developed method to assess the direct impacts of a computer network, including software and maintenance and developing strategies, to account for the high renewal rate in ICT technologies;
- to extend the method to consider not only negative impacts, but also benefits of ICT;
- to develop a method to address effects on lifestyles and rebound effects, and apply it to assess the impacts and benefits of innovative ICT services;

Chapter 1 is a short introduction describing the environmental impacts of ICT and how this work addresses them. Chapter 2 presents the main methodological developments: It looks in detail at how PLCA and IOLCA can be compared and used in a complementary way. A method is developed to compare the two approaches in detail and to evaluate the cut-offs processes – the processes that are not traditionally considered in a PLCA - of two specific ecoinvent processes. The conclusions are that a full integration of PLCA and IOLCA remains difficult with our present level of knowledge. IOLCA could be use to complement PLCA when no other evaluation is available, but IOLCA should also be used as a quality check for PLCA and to determine priorities.

Chapter 3 assesses comprehensively the environmental impacts of the computer network of the Ecole Polytechnique Fédérale de Lausanne. The LCA shows that the computers have the highest environmental impact, but also that short-term technology changes can reduce significantly their impact. The use phase dominates the impacts, but the production phase is also significant. Finally, using the Input-Output (IO) approach leads us to the conclusion that the service-linked contribution included in the total cost of ownership - that is, all of the costs associated with the computer network - has a significant impact on the environment.

Chapter 4 evaluates the impacts and benefits of the ICT application to help the management of urban networks. The CREM, in Switzerland, uses a telemonitoring system to assess the water, electricity, district heating, and natural gas networks to increase the efficiency of their management. We want to know how the environmental and economical costs of the infrastructure and its maintenance compare with the savings. An LCA has been performed using a tiered hybrid approach. It shows that the savings overcome largely the cost and environmental impacts of the infrastructure.

Chapter 5 analyses an innovative service developed by France Telecom. The visiophonic station enables the substitution of physical interviews by virtual interviews. A PLCA of the service shows that the saved km due to the shift from physical to virtual interviews dominates the effects on the environment and that the potential savings are therefore important. However, depending on what is consumed when using the time and financial resources made available by the service, the related impacts counterbalance the savings. Rebound effects must therefore be considered, studied, and addressed in the development as well as the implementation of new ICT services.

Chapter 6 concludes with recommendations towards environmental beneficial uses of ICT and identifies what is needed for the necessary further LCA developments.

Keywords: Process Life Cycle Assessment, Input-Output, Information and communication technologies (ICT), environmental impacts and benefits, rebound effects

RÉSUMÉ

Le développement durable et la société de l'information sont deux concepts qui sont rarement associés. Pourtant, ils ont, chacun à leur manière, un impact clé sur l'autre. Les impacts des technologies de l'information et de la communication (TIC) sur l'environnement sont importants, mais, de la même manière, l'application des TIC peut aussi générer des bénéfices pour l'environnement. Pour pouvoir guider le développement des TIC et ainsi mettre en avant les bénéfices qu'on peut en tirer, des méthodes et des outils sont nécessaires. L'approche cycle de vie est une approche pertinente pour étudier cette problématique, car elle permet une analyse globale et en profondeur. Cette thèse propose de développer des outils et des méthodes d'analyse de cycle de vie (ACV) pour augmenter la fiabilité de ces analyses. Les objectifs sont :

- d'explorer les possibilités de combiner les approches processus et Input-Output pour les analyses de cycle de vie et développer une méthode opérationnelle y arriver ;
- d'appliquer cette méthode pour analyser les impacts directs d'un réseau informatique, en incluant les logiciels et la maintenance et développer des stratégies pour réduire les impacts environnementaux lors du renouvellement du parc informatique ;
- d'étendre les méthodes pour prendre en compte non seulement les impacts négatifs, mais aussi les bénéfices que peuvent apporter les TIC ;
- de développer une méthode pour analyser les effets rebonds et l'appliquer pour évaluer les impacts de services innovants ;

Le chapitre 1 est une courte introduction qui décrit les impacts sur l'environnement des TIC. Le chapitre 2 présente les développements méthodologiques : il étudie en détail comment une ACV par processus et par Input-Output peuvent être comparées et utilisées de manière complémentaire. Une méthode est développée pour comparer les approches et évaluer les processus non pris en compte par l'ACV par processus. La méthode est illustrée par l'application à deux processus de la base de données ecoinvent. Les conclusions montrent qu'une ACV par processus et par la méthode Input-Output ne peuvent pas être sérieusement combinées actuellement. L'ACV Input-Output devrait plutôt être utilisée comme complément à une ACV classique.

Le chapitre 3 étudie l'impact sur l'environnement du réseau informatique de l'Ecole Polytechnique fédérale de Lausanne. L'ACV montre que ce sont les ordinateurs qui ont l'impact le plus important, en particulier la phase utilisation, mais la phase production est significative. Des changements techniques pourraient, à court terme, réduire considérablement ces impacts. Finalement le coût total de fonctionnement du réseeau a été étudié, en incluant la maintenance, la recherche et le développement, etc... qui ont un impact non négligeable sur l'environnement.

Le chapitre 4 décrit l'application des TIC pour la gestion des réseaux urbains à Martigny. Le CREM et les services industriels de cette petite ville utilisent un système de télémonitoring afin de bien comprendre le fonctionnement des réseaux pour améliorer l'efficacité de leur

gestion. L'étude a permis de montrer que l'approche est bénéfique autant du point de vue économique qu'environnemental. L'utilisation d'une méthode hybride a permis de monter que les économies sur l'environnement compensent largement les coûts d'infrastructure.

Le chapitre 5 analyse un service innovant de France Telecom. La borne visiophonique permet de rempacer un entretien physique par un entretien virtuel. Dans un premier temps, une ACV par processus a montré que les km évités dominent largement les impacts supplémentaires liés à l'infrastructure de l'entretien virtuel et que le service permet une réduction des impacts. L'évaluation des effets rebonds, notamment l'impact résultant des activités et des achats effectués avec le temps et l'argent économisés montre que ces derniers peuvent être importants. Le choix du consommateur est alors crucial.

Le chapitre 6 conclut ce travail avec des recommandations pour maximiser les impacts bénéfiques et identifie les besoins futurs pour les développements des ACV.

Mots-clés: Analyse de Cycle de Vie, Input-Output, technologies de l'information et de la communication (TIC), impacts sur l'environnement, effets rebonds

1 INTRODUCTION

1.1 Context

The concept of "information society" is referring to a society in which the information and communication technologies (ICT) play a key role, in terms of economic and cultural activity, which is nowadays undoubtedly the fact in "developped" countries. Like with the discovery of electricity or the steam engine, the development of the ICT is changing the world we are living in. Telecommunications, informatics and Internet are moving toward applications that would never have been thought of a few decades ago. The power of computers and the possibilities we have to communicate, with e-mails, cell phones, or voice over IP are now fundamentally modifying the way people live and work. The "knowledge-based society" is another close concept, that does not focus on the flows of information, but on knowledge and creativity[1]. Although both are strongly interlinked, the concept of "knowledge-based society" is interested in the impacts of the diffusion of knowledge on the economical development, culture, etc. Their economic counterpart is the concept of knowledge-based economy, which refers to the use of knowledge to produce economic benefits. Various observers describe today's global economy as one in transition to a knowledge-based economy, where resources such as know-how are more critical than other economic resources.

At the same time, and for a few decades now, the term "sustainable development" gained in importance and became a concept to which everybody refers. What about the information society and sustainable development? Are these two paradigms compatible?

There are many definitions for the concept of sustainable development. It tries to provide a framework to assure the quality of life and the development opportunities for future generations. Sustainable development is composed of three dimensions: the economy, the society and the environment. These three interlinked dimensions should all be considered together and balanced to reach equilibrium. The present work will address only the environmental aspect of sustainable development in the context of the information society, by assessing the environmental impact of ICT infrastructure and services.

ICT have an impact on our environment through resource consumption and pollutant emissions. ICT equipments need energy and primary materials to be produced, and electricity to be used. Finally, there are risks that pollutants are released in the environment when the dismantling of this material is not correctly performed. However, ICT also have an incredible variety of applications that can improve sustainability. The negative impacts of ICT on our environment, as well as the positive applications, are relatively poorly known, although these technologies are seen to play an important role on our way towards sustainability.

[1] In particular the fact that flows of information increases knowledge is debated.

Are we going in a direction where flows of information replace material flows? What impact on the environment will the information age we are entering into have? In fact, this question is complex and difficult to approach because of the multiple implications of ICT on human behaviour. The information society has positive and negative impacts throught new applications and it indirectly affects the way we live and work. Including the concept of knowledge based society added others parameters. What will the increase of knowledge change in our lives? It can have an effect on how we see and understand the world, the feeling of personal freedom, or the perception of nature, which can have tremendous implications for the future of humans and the environment we are living in. What will we do with this knowledge and what will be the corresponding impacts?

"Understanding the social, environmental and cultural impacts of information infrastructure, the services it enables, and the cultural changes it will entail, is far beyond our current capacity. In part, this is due to base human psychology: we are able to conceptualise the future only in terms of the past.

But that does not mean we cannot begin to understand some of the dimensions of this technology, or to create an intellectual structure within which further learning can occur and be organised. It is important to begin thinking about these issues, because the evolution of the "infosphere" - the global infrastructure and the information that fill it - has enormous social and environmental applications."

(Allenby, 2001)

As pointed out by Brad Allenby in the above citation, we cannot predict the future, we can only imagine scenarios, which might be optimistic or pessimistic. However, I believe that the ICT have a great potential to reduce the environmental impact and therefore contribute to sustainable development. But they must evolve. That is, we need to decrease their environmental impact and promote their best applications. But to be able to make the best decisions we need to have detailed and reliable assessments of the environmental impacts of ICT as well as ICT applications.

This work will explore how the life cycle approach can be used on the one hand to help decrease the environmental impact of the equipment and on the other hand to analyse the effects of ICT applications and their potential. It will in particular address the following questions:

How can direct as well as indirect impacts be measured? What are the conditions and contexts that make information technologies beneficial for the environment, and which make ICT environmentally detrimental? What can be done to decrease their negative impacts and increase their benefits?

To address these questions, we will first identify and classify the different types of influences ICT has on the environment. We will then propose a systematic approach and roadmap to further develop and use life cycle analyses to evaluate the environmental impacts of ICT along their whole life cycle, to identify key parameters, and to compare alterative scenarios. This introduction and the literature review are kept short in the introduction, as a detailed state of the art is carried out in each chapter to conform to the "paper based" format of this thesis.

1.2 The impact of ICT on the environment

To evaluate the environmental impact of a product, its life cycle can be divided into three phases: the production, the use and the end-of-life. At all stages, resources extracted and emissions are inventoried to get a global picture of the environmental emissions and therefore the environmental impact of the product or the service. The impacts on the environment of ICT can be separated in three categories (Radermacher, 1999; Berkhout and Hertin, 2001; Fichter, 2001; Arnfalk, 2002):

- Direct effects: energy consumption, use of resources, emissions and pollution caused by the production, trade and transport of goods, and by the disposal and recycling at the end of the devices' life cycle use.
- Indirect effects: changes in the economic structure, changes of the production processes, trade and transportation systems. The most important effects in this context are dematerialization, virtualization and immobilization of goods.
- Effect on the people's lifestyle, social values, and the "rebound effect."[2]

1.2.1 Direct effects

The production of semiconductors requires a large amount of energy, water, and materials, as well as solvents and hazardous substances (Williams, 2003; Williams, 2004 (a)) . A personal computer (PC) is made up of more than a thousand of components among which quite a significant number are toxics, such as heavy metals (lead, cadmium, baryum, mercury, copper) (Silicon Valley Toxics Coalition). In the production phase, only 2% of the used materials compose the computer, the other 98% are wastes (Hilty and Ruddy, 2000).

[2] "Traditionally, the term rebound effect refers to an effective increase in the consumption of an energy service after its price decreases due to higher efficiency of the production of the service. If technological progress makes certain equipment more energy efficient, less energy is needed to produce the same amount of products or services, thus the cost per unit of production falls, which leads to increased demand for the product or the service."(Plepys, 2002)

The use of ICT also requires an always increasing amount of electricity. Although some technological progresses, like Liquid Crystal Display (LCD) screens or stand-by mode, tend to decrease the individual consumption of devices, the increasing number of computers counterbalance this benefit (Cole, 2003). The electricity consumption of the equipment in use as well as in stand-by (not only ICT but more generally all electrical appliances) consume, in the United-States, between 5% and 15% of the households electricity consumption (Berkhout and Hertin, 2001). In Germany, the energy demand for ICT is estimated by Geiger and Wittke at 1.5 % of the total final energy consumption and 7.1 % of the electricity consumption (Aebisher et al., 2002; Geiger and Wittke, 2002).

The hazardous substances used in the manufacturing of computers imply that they are difficult to recycle and landfilling them is not a sustainable solution. A report by the Silicon Valley Toxics coalition highlights the problems induced by the exportation of electronic waste from the United States (Silicon Valley Toxics Coalition and The Basel Action Network). They estimate that between 50 and 80% of these wastes, collected for recycling, are not treated in the US but exported to Asia. A large amount is then not treated very efficiently, but landfilled, with strong environmental impacts. Several organizations have expressed great concern about the export of electronic waste to developing countries and the disastrous conditions under which they are handled. Matthews says that 4% of the US municipal solid waste are electrical and electronic waste (Berkhout and Hertin, 2001).

Available studies assessing the environmental impact of PCs are very rare ((MCC), 1993; Atlantic Consulting, 1998; Williams, 2004 (c)), and almost unique for LCD monitors and notebooks (Tekawa et al., 1997; Leet Socolof et al., 2002). The available results are old and give very different values. In addition, they only use indicators such as the non-renewable primary energy and the CO_2 emission. The complexity of the studies, together with the fact that some data are confidential, makes them difficult to analyse. Due to this last issue, and the fact that computers are composed of hundreds of components, data gathering is very difficult. In chapter 3, we perform a Life Cycle Assessment (LCA) of a computer, Cathod Ray Tube (CRT) and LCD screens, as well as a notebook, and give values for other indicators such as the impact on human health or on ecosystem quality.

1.2.2 Indirect effects

ICT are present in our everyday life with many applications. Some have an interesting potential to trim down the use of resources and energy. Upon entering the Information Age the economic structure of the world has undergone a change. We sell and exchange ideas and information instead of goods and raw materials. Intelligent production processes, an intelligent product design (for example, the “sleep mode” for computers which are not used for a while) and intelligent logistics for the supply, production and transport of goods and services tend to de-materialize the economy. Many of these improvements are possible because of the use of ICT to manage and transmit the information.

The Japanese ministry of telecommunication has evaluated in 1997 that the combination of possible ICT applications could reduce CO2 emission in Japan by 7%. Several towns in Japan have tested the use of ICT, and their administrations (the so-called e-administration) in order to lessen their environmental impacts (Miura et al., 2002).

Virtualization is a complete de-materialization, or the conversion of a physical product to a virtual one. Software, for example, is nowadays sold more and more often via the Internet. Forrester Research forecasts that soon, half of all computer programs sold by Microsoft, Netscape and Oracle will be present in the Internet, saving transport, storage facilities, CDs and other raw materials. Catalogue dictionaries, newspapers, or telephone books also represent a great quantity of paper that could be saved. Right now, the telephone books discarded each year in the United Stated account for approximately 470'000 tons and yet only 10 percent are recycled. Other examples are the development of the MP3 music format and digital cameras (Cohen, 1999). E-banking and e-commerce also allow the trading of goods, money, stocks, and shares at home, saving paper, time, and transport (Berkhout and Hertin, 2001; Faucheux et al., 2001; Loerincik and Jolliet, 2002; Loerincik and Jolliet, 2002; Palmin et al., 2002). E-commerce, video conferencing, on-line money transfer, teleworking and telecommunications are other examples of dematerialisation opportunities. According to the American Bankers Association, half of all financial transactions in the U.S. will soon be conducted electronically, with one-third of all bank branches closing as a result (Faucheux et al., 2001). Rome-based Merloni Eletrrodomestici, the fourth largest household-appliance vendor in Europe, has developed a line of digital refrigerators, washing machines, and dishwashers with remote Internet-control features that save energy by allowing homeowners and local utilities to monitor the power consumption of each appliance. Using web-based micro-management, individual appliances can be powered-down during peak loads and programmed to operate during off-peak periods when utilities have excess generating capacity.

Unfortunately, negative aspects are also occuring. In certain cases, the environmental effects cannot be avoided even though de-materialization is taking place. For example, on the one hand, e-commerce is likely to reduce emissions caused by transportation and the demand for storage facilities because a “production-on-demand” is made possible. This might eventually lead to less overproduction and less waste. On the other hand, other forms of transportation (in particular, aerial transportation) increase, because the products have to be delivered more quickly, and e-commerce facilitates the access to more geographically remote markets. The production of packaging materials (which represent 30% of all American household waste) also increases if products are delivered to homes (Faucheux et al., 2001).

These studies show that there is a potential for lowering the environmental impact with ICT and ICT applications, but that we lack detailed results and practical examples. Several studies have shown that e-commerce and traditional commerce are fairly equivalent in terms of environmental impact (Matthews et al., 2002; Williams and Tagami, 2002; Norris et al., 2003). Telia evaluated that the energy consumed and the greenhouse gases produce by a classical answering machine along its life cycle are more than 200 times higher than for network services (GESI, 2002). Others have studied the environmental impact of digital versus printed media. Results show that the environmental performances depend on various parameters such as power consumption, the number of people reading the book or the newspaper or the fact that the information is printed or not (Gard and Keoleian, 2002; Hischier and Reichart, 2003). Although these studies performed LCA of ICT applications, they generally do not consider the environmental impact of the services-linked contributions, such as the marketing or the research and development, as well as the infrastructure which enables the communication. There are risks of negative effects. There is therefore a need to evaluate the environmental impact over the whole life cycle of ICT devices or applications. This is needed in order to analyse the balance between positive and negative effects comprehensively. The adequacy of present LCA methods to address these effects is discussed in section 1.1.4 below.

1.2.3 Rebound effect and effects on lifestyles

At the moment, the relations between the virtual and traditional economies are still very strong and there is the risk that a further growth in the virtual economy will be followed by a growth in the traditional economy. In many cases “virtual” products will not replace traditional ones, but will simply mean an alternative that only increases the user’s choice (Berkhout and Hertin, 2001). In addition, the substitution of physical by virtual goods is incomplete. For example, the paperless office that has been promised to us for several years does not seem to be a reality. During the last 15 years, Canada, the greatest paper exporting nation, has more than doubled its amount of paper sold (Park, 2001).

Human behaviour can also entail problems: Do we really waste less energy by not travelling to work? Or do we use time and money that are saved in using ICT for even more environmentally unsustainable activities? Rebound effects have been described by (Hofstetter and Madjar, 2003):

- direct rebound effects (substitution effect, pure price effect) occur when greater efficiency leads to lower prices of the service, which in turn induces an increase of the use of the cheaper service;
- rebound effects can be observed if the decrease in the price of one commodity induces an increase in the consumption of other goods or services;
- general equilibrium effect is observed if the direct and rebound effect lead to changed prices and consumption throughout the economy, which may increase or decrease production in distant sectors;

- transformational effect includes changes in consumer preferences, alteration of social institutions, etc.

The first challenge we face when we want to consider rebound effects is to identify them.

E-commerce implies a different logistic than traditional business, which might allow for lower prices. But will this in turn entail more consumption, and consequently more harmful effects? The same phenomenon can be observed in airplane transportation, where the spread of e-mail communication stimulates people to travel more. Can these trips be replaced by videoconferencing and teleworking? The latter allows us to skip travelling from home to work. It also limits the size of office buildings and in some cases it might even make it unnecessary to build new office blocks at all. On the other hand, will the fact that we travel less to go to work change our habits? A study done by Peter Arnfalk (Arnfalk, 2002) among teleworkers showed the following results: 45% of the participants said that teleworking had reduced their mileage travelled per year, 10% said that it had increased and 45% did not observe any difference. This is due to the fact that commuters often use their daily trip to work for other activities such as taking the children to school or shopping, which need to be done even on teleworking days. The actual effects of teleworking are therefore difficult to evaluate. The use of public transportation could become too costly, complicated, or unpractical if it is not done on a regular basis. Therefore, there is a risk that public transportation might be replaced by even more car travel. If the use of ICT allows us to save time and money, the question arises – how will the spared time and money be used?

Besides, the evolution towards an information society and the use of the technologies that accompany it, have an effect on our lifestyle, on our choice of, and on the organization of the society we live in, which in turn has positive and negative effects on the environment. The use of the ICT we make can affect our choice of where we live, which can (and already does) result in people moving further and further away from town centers, causing both expansions in the built surface area and changes in our social behaviour. An example raised by Brad Allenby, former Vice President of the Environment, Health and Safety Department at AT&T, one of the world's leading telecommunications firms, shows the difficulty in assessing the rebound effects and lifestyle environmental effects. For AT&T as a whole, from calculations based only on avoided commutes, teleworking enabled employees to avoid 110 million miles of unnecessary driving a year, conserving roughly 5.1 million gallons of petrol and the emission of 50,000 tons of carbon dioxide. However, Allenby's own experience in teleworking has led him to the conclusion that he did not save kilometers by not having to go to work. However, having no dress code obligation, he did observe a reduced use of his washing machine (Allenby)!! These studies show that rebound effects are difficult to predict. If we want to include them in LCA, we face a double challenge: to identify and to quantify them. The use of time and financial resources by consumers has been studied under the field of sustainable consumption (Heiskanen and Pantzar, 1997; Jalas, 2002; Hofstetter and Madjar, 2003). They use, for instance, household expenditures together with LCA data to evaluate the environmental impact per unit of money. These studies have to be applied to ICT in order to measure the environmental impact induced by these effects.

1.2.4 The application of Life Cycle Approaches to ICT

LCA is a methodology that permits one to evaluate the environmental performances of a product, a service, or a company. Two major methodologies co-exists, the Process LCA (PLCA) (Heijungs et al., 1992; Frischknecht and Kolm, 1995; Heijungs and Suh, 2002) and the Input-Output LCA (IOLCA) (Miller and Blair, 1985; Cobas et al., 1995; Joshi, 2000; Nielse et al., 2001; Suh et al., 2004). PLCA inventories all the necessary resource extractions and estimates the corresponding emissions based on physical process flows. Detailed descriptions and examples are available in (ISO, 1997; Jolliet et al., 2005). IOLCA is a method based on the monetary flows induced in the economy and throughout the supply chain by a product, process, or activity. It allows one to quantify energy consumption and pollutant releases that are linked to these monetary transactions according to the sectors (industries) to which these transactions are related. The IO table of direct requirement coefficients is needed to estimate the monetary flows induced throughout the economy by the "ripple effect" emanating from a given sector output. For each sector, average emissions and the energy consumption per economic unit of output are required to assess the total environmental burden. This methodology has already been used for the assessment of ICT and ICT application (Matthews et al., 2002; Norris et al., 2003). The advantage of PLCA is its precision. However, some contributions are difficult to include in the assessment. IOLCA automatically includes the whole economy, but products or services are linked to an industrial sector, which represents an average of many different products.

However the total cost of ownership, that is, all the costs associated with the setting up and the use of an ICT application, are not considered in these studies, nor are the indirect or rebound effects.

There have been attempt to merge both approaches (Suh and Huppes, 2002; Suh, 2004) to potentially take advantage of both methods. Practical application are, however, rather rare. We lack an operational methodology to compare in detail PLCA and IOLCA in order to better understand their differences and similarities. In particular, we do not know if PLCA and IOLCA can be applied in an integrated way in the field of ICT.

Important challenges are faced when trying to evaluate the environmental effect of ICT applications including indirect and rebound effects. The first challenge is to quantify and characterize these effects. But they can be hidden, are mostly unknown, and there is no general approach to investigate them. When performing a LCA, considering the indirect and the rebound effects of ICT means extending the system boundaries. However, these effects are generally not only the consequence of the ICT applications, but of various parameters. There's a strong need for understanding these effects and identifying their driven force and how they can be allocated to ICT. Finally, investigating these effects also raises the question of responsibility. Are companies responsible of the behaviour of consumers?

1.3 Objectives and focus of the work

This work focuses on developing life cycle tools and methods for assessing comprehensively the environmental impacts of setting up and using computer networks and Internet services. More specifically it will:

- Explore the possibilities of combining PLCA and IOLCA, and develop an operational method for ICT applications;
- Apply the developed method to assess the direct impacts of a computer network, including software and maintenance, and developing strategies to account for the high renewal rate in ICT technologies.
- Extend the method to consider not only negative impacts, but also benefits of ICT.
- Develop a method to address rebound effects and apply it to assess the impacts and benefits of innovative ICT services.

These steps will involve both methodological developments and case studies to ensure that these developments are indeed operational.

1.4 Roadmap

The work is divided into six chapters, the first being this introduction. The second chapter presents and develops the methodology. The three next chapters combine methodological developments with case studies where the questions raised in the introduction will be treated, leading to the concluding final chapter. Chapters 3 to 5 are written following a paper structure.

Chapter 1. Introduction: The present chapter has set the scene for the thesis, defined its objective and its roadmap

Chapter 2. Life cycle tools and methodologies: This chapter describes the existing tools and methodologies to assess the environmental impact of ICT and identifies in details the advantages and limitations of different approaches. It evaluates the impact of the so-called services and investigates new tools to extend the system boundary to better assess ICT applications. Two approaches for LCA the PLCA and the Input-Output IOLCA are used to assess ICT. The reliability of the IO LCA is compared to that of the PLCA as well as the consistency of IO environmental data. The hybrid methods merging Input-Output and PLCA are described, and a methodology to evaluate the cut-offs (the contributions not considered in a PLCA) is developed, based on the data available in the Input-Output table. Its application to two processes of the ecoinvent database, the polycrystalline silicon wafer, and the electricity production, permits one to understand in more detail how these two approaches compare, and to identify the missing contributions in a PLCA using Input-Output.

The following questions will be investigated throughout the chapter in order to address objective 1: How reliable are IO economical and environmental data? How does IO LCA compares with PLCA? Can we take profit of the advantages of both approaches? Is it possible to use the Input-Output table to determine the contributions not taken into account in PLCA? Can a PLCA database such as ecoinvent be linked to an Input-Output table? How and for which benefits?

Chapter 3. Evaluation of a Computer Network Infrastructure using Process and Input-Output LCA: The third chapter applies the process and the IOLCA described in chapter two to evaluate the environmental impact of a personal computer with a CRT and an LCD monitor, as well as a laptop and a university computer network. In particular, the large amount of data needed as well as the rather important contribution of the services will be assessed using these two methods. The concept of total cost of ownership, covering software, maintenance, and management, is introduced to extend the system boundaries, and its environmental impact is calculated using the IOLCA. Environmental impact decreases achieved through short-term technology changes are investigated.

To fulfill the second objective, the following questions will be addressed: How can we deal with the complexity of the system and the use of services? What are the impacts of Internet and PC networks? How can one better evaluate these impacts? What are the impacts of services and how can we evaluate them? What is the total cost of ownership made of and what are the corresponding impacts?

Chapter 4. Evaluation of the environmental impact and benefits of the telemonitoring system in the city of Martigny: The city of Martigny, Switzerland, is monitoring the flows of water, district heating, electricity and gas within the city, using microcomputers. Measuring, understanding and acting is the basis for the concept of urbistic, where information plays a key role. The impact of the infrastructure surrounding the computers and the measurement devices is balanced with the benefits produced by its use. Using PLCA and IOLCA we compare the impact of the infrastructure with the benefits and avoided consumption obtained in using this information.

Objective 4 is partially addressed in this chapter. The questions that will be investigated are: How far is the application of ICT and the use of the collected information beneficial from an economic and an environmental perspective in the case of the city of Martigny? Can ICT help to better manage industrial networks in cities?

Chapter 5. Assessing innovative Internet services and evaluating their direct, indirect, and rebound effects on the environment: Four services of France Telecom, the “Borne visiophonique, the gluconet, the teleechography, and the visadom (home care facility), were assessed using the process and the IOLCA approaches. The visiophonic station, an e-administration tool, is investigated in more detail using as a first step the IOLCA to extend the system boundary. Finally, a method is developed to account for rebound effects such as those induced by the money or the time saved by a client. The method is then applied to the considered innovative service.

The following questions drive this chapter which will investigate objectives 3 and 4. How can we assess the benefits of ICT? Where are the main impacts of the services in development? How do we take into account indirect and rebound effects? What recommendation can we give to decrease the environmental impact and increase the potential benefit of these technologies? Can we evaluate their environmental impact? Where do corporate and consumer care responsibilities start and stop?

Chapter 6. Conclusion and perspectives: The concluding chapter shortly reviews achievements, limitations and perspectives for further research, making recommendations towards a sustainable development of ICT.

2 LIFE CYCLE METHODS: COMBINING PROCESS LCA AND INPUT-OUTPUT LCA

2.1 Abstract

Combining IOLCA and process LCA (PLCA) is a promising approach that could allow one to benefit from the advantages of both methodologies. This chapter explores the possibility of merging the two approaches and identifies benefits and disadvantages of using both methodologies together for the database ecoinvent[3]. As a first step, the existing Input-Output economic and environmental data are analysed and compared to determine which dataset is the best adapted to carry out the analyses. Available Input-Output data are analysed and the US set is found to be the best suited when European data is used for sensitivity analyses. In the second part of the report, the Input-Output sectors corresponding to contributions that we consider to be out of the scope of a PLCA are removed and a new Input-Output table is defined. The contributions of the so-called service sectors are studied. They are found to be on average around 7 %.

A new methodology is then developed to compare PLCA and IOLCA and is applied to one particular process of the ecoinvent database, the pc-si wafer. To enable a correct comparison of PLCA and IOLCA, some of the ecoinvent processes are aggregated and the database of the Swiss custom agency is used to determine products prices. It permits one to compare IOLCA and PLCA in details. Results show a relatively good accordance when comparing the structure of the CO_2 emissions, but a difference in the absolute value of these emissions. The analysis shows that the difference can be due to the amount, in monetary terms, of the inputs to the pc-si wafer process when evaluated with the PLCA and IOLCA. It can also comes from an underestimation of the emission per kg products – e.g. for inorganic or organic chemical – when product grade is approximated by an average grade in PLCA. Low differences in the cumulative CO_2 emissions per monetary unit of these same inputs have been observed. The cut-offs processes - the inputs not considered in the PLCA - are determined using the Input-Output table. They are evaluated for two ecoinvent processes: “pc-si wafer, at plant” and “electricity production”. These cut-off processes increase the CO_2 emission by respectively 30% and 4%. Finally, some recommendations are given on how IOLCA and PLCA should be used in the context of ecoinvent. This study shows that IOLCA should be used to identify development priorities and potential data gaps. Therefore, a systematic comparison between IO and PLCA should be performed for ecoinvent, but a full merge of the process database and the Input-Output table is not recommended at this stage.

[3] www.ecoinvent.ch

2.2 Introduction

Evaluating the environmental impacts of a product or a service over its whole life cycle includes the extraction of raw materials, its processing, the manufacturing of products, the associated transport, its distribution, the use phase and the end-of-life treatment. LCA is a powerful and well developed approach to perform such an analysis (ISO, 1997; Nielse et al., 2001; Jolliet et al., 2005). An LCA considers all of the necessary contributions to the manufacturing of a product or the realisation of a service and estimates the corresponding emissions. The two main methodologies that are used are the PLCA (PLCA: (Heijungs et al., 1992; Frischknecht and Kolm, 1995; Heijungs and Suh, 2002)) and the IOLCA (Miller and Blair, 1985; Cobas et al., 1995; Joshi, 2000; Nielse et al., 2001; Suh et al., 2004). Whereas conventional process based LCA relies on the identification and quantification of physical flows of energy and matter, IOLCA is a method based on the monetary flows produced in the economy and through all the supply chain by a product, process or activity. It allows the quantification of energy consumption and pollutant releases that are linked to these monetary transactions according to the sectors (industries) to which these transactions are related. PLCA can be seen as a bottom-up approach whereas IOLCA is a top-down technique. Although both analyse the same product/service, they use a different methodology.

On the one hand, the advantage of PLCA is that it can be very precise when two products are to be compared and we are able to take into consideration geographical and technical differences. To help researchers large databases have been developed during the last few years (ecoinvent, Gabi, ...). On the other hand, it has been criticized because (Suh and Huppes, 2005):

- An LCA for a new product is difficult to construct (Lave et al., 1995). Depending on the product to be studied, it could therefore be expensive and time consuming (Cobas-Flores et al., 1996)[4];
- The definition of problem boundaries is arbitrary and controversial (Lenzen, 2001). Lave (Lave et al., 1995) states that « a narrow focus can ignore important effects and lead to qualitatively incorrect conclusions” (Cobas-Flores et al., 1996);

On the one hand, the IOLCA allows one to account for full direct and indirect impacts (the whole economy is taken into account) and it is quick and inexpensive to perform. On the other hand:

- An Input-Output table and an environmental matrix are required and specialists must work on the task if one wants to have reliable data;
- Environmental data are not available for all industry sectors and thus are often averaged (not possible to distinguish one specific facility);

[4] This statement has to be moderated. As it is true that an exhaustive LCA can be a long and expensive study, particularly when a complex product (the life of a computer for instance) is assessed, it can also be quick and inexpensive. For example, a couple of existing consulting firms are offering these quick and LCAs for a price between 2’000 and 3’000 CHF.

- Sectors include many type of equipment and therefore the data are averaged. As a consequence, the Input-Output does not allow the comparison of two very similar products included in the same sector (Lave et al., 1995);
- It is assumed that the relationship between price and environmental impact is linear;
- Activities associated with final consumers, such as energy for product use or wastes of product disposal are not considered (Lave et al., 1995);
- Imports are assumed to be produced within the country;
- The boundaries problem also exists, as sometime too many processes can be included in an IOLCA.

Avoiding some of these problems is possible by constructing a hybrid approach. There has been various attempts to link PLCA and IOLCA to take profit of both advantages to enhance the reliability of the assessment (Bullard et al., 1978; van Engelenburg et al., 1994; Marheineke et al., 1998; Joshi, 2000; Suh and Huppes, 2002; Suh, 2004). In any case, using one of these approaches necessitates comparing in detail the PLCA and the IOLCA to understand what is taken into account in both approaches and what is over- or underestimated.

Applying hybrid methods has been tried in various studies, however, very few papers present a thorough comparison between IOLCA and PLCA based on real processes, and study the way the method could be combined in practice. Recently Mongelli (Mongelli et al., 2005) has shown that “MIET 2.0 and the ETH 96 database show substantial similarities” but a detailed comparison of PLCA databases and the IOLCA is missing. It is particularly difficult to evaluate the compatibility of the two methods. Hybrid methodologies are interesting but there is a need to better analyse how these two approaches could be combined and what the benefits and the limitations of such a combined approach would be.

The following groups of questions need to be addressed in more detail:

a) What is the importance of the services in the overall impact in the case of Input-Output? How can we estimate the cut-off processes, or the contributions not taken into account by the PLCA?
b) How can we establish the correspondence between IOLCA individual sectors and PLCA individual processes? How important are the differences for the ecoinvent PLCA database compared to IOLCA and what are the causes of these differences?
c) How can we merge an Input-Output table with a PLCA database like ecoinvent, what are meaningful combinations, and how far can the combination of these methods enhance the LCA quality?

This work addresses these questions and can be seen as an exploration of the feasibility and usefulness of merging PLCA and IOLCA. In particular, the problems and benefits of this integration will be discussed.

The detailed objectives of this study are therefore to:

- Analyse in-depth the available Input-Output economical and environmental data for Switzerland, Europe, European countries and the US;
- Evaluate how relevant the service-linked emissions and those out of scope of PLCA are compared to the already considered emissions, using IOLCA.
- Develop an operational methodology to establish a detailed correspondence of two different ecoinvent processes with IO industrial sectors, and evaluate the problems and benefits of combining the two methods
- Discuss the possible ways to combine IOLCA and a PLCA database, in our case ecoinvent, to improve assessment quality.
- In addition, we will evaluate the time and work needed for integrating the two approaches and for the update of data. The possible future development, the corresponding costs and the potential benefits for the ecoinvent database will be described.

To reach this goal, we start by concisely presenting IOLCA and the different hybrid approaches. We then analyse the reliability of IO data and choose the best suited IO dataset to perform the analysis. The second step analyses within IOLCA the contributions of the services and of the processes that are traditionally not taken into account in PLCA[5]. This provides the basic information needed to further explain differences between PLCA and IOLCA. The third step is to develop and describe the methodology that can be used to perform a detailed comparison and establish the correspondence between both approaches. The comparison of both approaches in a specific case will give the opportunity to evaluate the pertinence and usefulness of combining both approaches. Finally, we will discuss how a PLCA database can benefit from the use of IOLCA. Although the approach is valid for any PLCA database, and because the case studies are based on the ecoinvent database, we write ecoinvent instead of PLCA database in the text below.

2.3 State of the art

2.3.1 Input-Output Life Cycle Assessment

The IOLCA is based on the following equation (Miller and Blair, 1985; Nielse et al., 2001) (Appendix A gives more information on IOLCA):

Equation 1[6]:

$$\vec{b}_{IOLCA} = B_{IOLCA} \cdot \vec{x}_{IOLCA} = B_{IOLCA} \cdot (I - A_{IOLCA})^{-1} \cdot \vec{y}_{IOLCA}$$

- $\vec{b}_{IOLCA}$ is an m vector of the total impacts, m being the number of assessed pollutants.

[5] See chapter 2.5 for more information on these processes.
[6] The suffix IOLCA refers here to Input-Output LCA with the traditional Input-Output method

- B_{IOLCA} is the environmental matrix; it is a m by n matrix representing the emissions per $ for all industrial sectors, n being the number of industrial sectors.
- $\vec{x}_{IOLCA}$ is an n vector that represents the total output, that is all inputs needed to produce $\vec{y}_{IOLCA}$;
- A_{IOLCA} is the matrix of the technology coefficient, a_{ij} = input of sector i to sector j in order to produce $1 of sector j.
- $\vec{y}_{IOLCA}$ is an n vector that represents what we need to buy in all sectors (the final demand by functional unit).

A PLCA can be written with a similar formula

Equation 2:

$$\vec{b}_{PLCA} = B_{PLCA} \cdot \vec{x}_{PLCA} = B_{PLCA} \cdot (I - A_{PLCA})^{-1} \cdot \vec{y}_{PLCA}$$

- $\vec{b}_{PLCA}$ = is a p vector of the total impacts, p being the number of pollutants assessed.
- B_{PLCA} is the ecoinvent environmental matrix; it is a q by p matrix representing the direct emissions per process, q being the number of processes considered.
- A_{PLCA} is the ecoinvent technology matrix. $A_{PLCA,\ ij}$ = input or quantity of process i to produce one unit of process j.
- $\vec{y}_{PLCA}$ = reference flows (amount consumed for each process to produce a functional unit).

2.3.2 Hybrid approaches to LCA

The first hybrid approach is to perform PLCA and IOLCA in parallel and to use the IOLCA as a quality check for the life cycle inventory (LCI). In this case, the IOLCA can help to identify important contributions that have been forgotten. The processes corresponding to these industrial sectors could then be modeled and added in the PLCA.

Suh classified the hybrid approaches (when PLCA and IOLCA are combined) in three other main categories (Suh et al., 2004; Suh and Huppes, 2005). :

a) Tiered hybrid analysis (Suh and Huppes, 2002): A tiered hybrid analysis uses the Input-Output methodology to evaluate the contributions that were not taken into account by a PLCA. Direct requirements, as well as some important lower order upstream requirements, are examined using a traditional PLCA. The other contributions are covered by Input-Output.
b) Input-Output based hybrid analysis (Joshi, 2000): In an input-output hybrid based analysis, new sectors are created and/or important sectors are disaggregated into more detailed sectors using PLCA.

c) Integrated hybrid analysis (Suh, 2004; Suh and Huppes, 2005): In this model, the process-based system is represented in a technology matrix[7] and the Input-Output system is represented by monetary units. The flows crossing the boundaries from one model to the other (monetary unit per physical unit for Input-Output data contributing to a process and physical unit per monetary unit for process data used in the Input-Output) are determined and the process technology matrix is integrated into the Input-Output framework. The Input-Output matrix is modified to avoid double-counting.

Additional information on the hybrid methods are presented in Appendix A. The combination of the advantages of both process and IOLCA in hybrid methodologies is, at least in theory, promising. It enables one to take profit of the precision of the PLCA while removing the limitation linked to the system boundary. Therefore, we are able to reduce the uncertainties coming from:

- the system boundaries definition in PLCA;
- the poor level of detail of economic sectors.

The general equations for hybrid analyses are proposed by Suh (Suh, 2004):

Equation 3:

$$\vec{b}_{hybrid} = B_{hybrid} \cdot \left(I - A_{hybrid}\right)^{-1} \cdot \vec{y}_{hybrid} = \begin{pmatrix} B_{PLCA} \\ B_{IOLCA} \end{pmatrix} \cdot \left(I - \begin{pmatrix} A_{PLCA} & D \\ C & A_{IOLCA} \end{pmatrix} \right)^{-1} \cdot \begin{pmatrix} \vec{y}_{PLCA} \\ \vec{y}_{IOLCA} \end{pmatrix}$$

In our case:

A_{PLCA} is the ecoinvent 2630 by 2630 matrix and $A_{PLCA,\ i,\ j}$ = contribution from process i to produce one unit of process j. A_{PLCA} is in physical units.

C (n x 2630 matrix in our case) represents the upstream cut-off flow to the PLCA system, that is the contributions of the Input-Output to the processes, $C_{i,\ j}$ = inputs from Input-Output sector i to process j (monetary value/physical unit). n is the size of the chosen IO table.

D (2630 x n matrix in our case) represents the downstream cut-off flows to the IO system, that is the contributions of the PLCA to the Input-Output, $D_{i,\ j}$ = inputs from Input-Output sector i to process j (physical unit/monetary value).

In equation 3, C and D are the two matrices that do not exist and need to be worked out. There are several case studies where C has been determined in order to evaluate, in an LCA, some of the contributions with the Input-Output (tiered hybrid approach, D = 0) (Suh and Huppes, 2002; Suh and Huppes, 2005; Loerincik et al.). However, merging an existing database and an

[7] A process technology matrix is a square matrix describing the flows from one process to the other. Typically a_{ij}= amount of process i to produce one unit of process j.

IO table has never been done. Determining *C* requires knowing what the cut-off processes are and which contributions were not considered in the PLCA for all the processes of the database. These cut-offs were not considered in the PLCA for various reasons. Some of these contributions might have been neglected and therefore we know they exist and that they should be considered. However, some are not known and one of the difficulties is discovering them. When we try to determine these cut-offs it is essential to understand what is included in the PLCA and how it can be compared to the IOLCA.

Determining *D* requires one to know the total annual production of one process of the PLCA and the distribution of the economic sectors that buy the process output. If that information is availabe, the IO table should be adapted, because some of the flows that were within the IO table become flows between *D* and the IO table. A methodology to perform such an adaptation has been developed by Suh (Suh, 2004; Suh et al., 2004). Applying such methods requires, therefore, a deep understanding of what is considered in both approaches, thus the detailed comparison developed in chapter 2.7.

2.4 Choosing an Input-Output dataset

In order to compare and possibly combine IOLCA and PLCA, this initial part aims to analyze which IO datasets are available and which are the best suited to carry out the comparison.

2.4.1 Selection criteria

Input-Output data are available for many countries, with different levels of detail and industry classification. The Input-Output data are collected at different rates, depending on the countries. Corresponding environmental data are sometimes available, the sources varying from governmental agency to researchers merging different official datasets and evaluating the missing impacts (Suh, 2004 (b)).

Different criteria will be applied to analyze the different methods in a two-stage procedure:

a) A simple pre-selection will be carried out based on an investigation of the availability and the level of detail of economic and environmental data per country as well as their similarity to the Swiss economy.

b) A more thorough selection process is then used to determine which datasets are the most appropriate to carry out the study, based on the following criteria: representativeness[8], availability, age, level of detail and exhaustiveness, as well as reliability, both of the economic and of the environmental data.

[8] Similarity with the Swiss economy.

2.4.2 Preselection of potential sets

a) Among the different sets available (see Appendix B for a more exhaustive description of the existing data), the pre-selection leads to 4 sets of data that could be used within this project: Switzerland, Germany, the Netherlands, and the US.

Switzerland is retained, as it is evidently the most representative set[9]. It has however been extrapolated from the German matrix for a limited number of sectors[10]. Germany and the Netherlands represent the European sets that have a wider number of sectors and at the same time a somewhat similar economic structure (Germany) or eco-efficient industry (the Netherland) to Switzerland. The US data is chosen because of its high level of detail with 500 sectors available and because it does not differ totally in its structure. This level of detail will be useful when comparing in detail PLCA with IO.

2.4.3 Detailed discussion of IO sets according to individual criteria

Advantages and disadvantages of individual sets are discussed in details according to each criteria, leading to a final discussion and recommendation summarized in Table 2:

a) Availability, age, and level of detail

Availability, age and detail of economic data: (the detailed results are presented in Appendix B) Data for all four countries are available. The US data have significantly higher resolution with a high level of detail for the IO table (about 500 industrial sectors), compared to the 71 of Germany, 105 of the Netherlands, and the 37 of Switzerland. The US, Germany and the Netherlands compile new data on a regular basis. The most recent datasets are from 1998 to 2000. The Input-Output data for Switzerland have been updated in 2004.

Availability and exhaustiveness of the environmental data: except for Switzerland, where no corresponding environmental data are available (except the energy consumption), all the other countries have environmental data. The US environmental table (Suh, 2004 (b); Suh, 2005) covers many more pollutants as well as impact factors (ecoindicator 99, CML 2001, etc...). The reliability of these environmental data have not been assessed, but as pointed out by Rebitzer (Rebitzer, 2005) "the toxic release inventory (TRI) in the US, which is often used for IOLCA, does not account for emissions of small and medium sized enterprises (SMEs) (Suh et al., 2004)", which possibly produces high uncertainties.

[9] The case studies presented in chapters 3 and 4 are from Switzerland and therefore one of the criteria for the choice of the IO data is the possibility to use the data in the context of Switzerland.
[10] This has been done by the researchers in charge of the construction of the Swiss IO table and is due to the limited number of data for Switzerland.

b) Representativeness

Representativeness of economic data: In terms of structure, the German economy is quite similar to Switzerland's, except for heavy industry. The Netherlands' economy is also not too different from Switzerland's, except for the maritime industry, which produces larger imports and exports. From the topographic and climate points of view, Germany is also closer to Switzerland than the Netherlands is. The differences between the US and Switzerland are numerous but include different production methods, different energy prices, different lawyer and insurance system, etc. Nevertheless, as pointed out by Mongelly (Mongelli et al., 2005), the US and western Europe are more similar than other parts of the world: "Firstly, the technological compositions of the two regions, which are the U.S. and western Europe, are more similar than any other regions in the world, except for a few sectors related to agriculture and energy for example,..." (Mongelli et al., 2005).

Representativeness of environmental data: In this case, we do compare the environmental emission per monetary unit for the four countries. For Switzerland no data are available (except for energy consumption). The Netherlands have, like Switzerland, a rather eco-efficient economy. Germany, with the inclusion of the eastern part is less efficient. The US is known to be less energy efficient and have different environmental regulation from European countries.

c) Reliability

Reliability of economic data: On the one hand, the reliability of the economic data cannot be easily differentiated between Germany, the Netherlands and the US. On the other hand, the data for Switzerland are less reliable than the others as they are more than 10 years old and were produced with various methods. This must be taken into account even if different, updated data are used to enhance the quality of the table (Nathani and Wickart, 2004).

Reliability of environmental data: As with the economic data, the reliability of the environmental data cannot be differentiated between Germany, the Netherlands, and the US. Data are inexistent (excepted for energy consumption) for Switzerland.

To further assess the reliability and the representativeness of the environmental data, as well as the level of detail of the economic data, three approaches have been used:

1. Comparison of the direct and cumulative CO_2 emissions between different sources for the US environmental data and with data for Germany and the Netherlands;
2. Comparison between the total CO2 emissions of the countries: the UNPCC data for Germany, the Netherlands, and the US were compared with the total CO2 emissions calculated with the IO data;

3. Comparison between NAMEAs[11] data and Corinair[12] (performed by Corbière (Corbière-Nicollier, 2005)): she compared the results presented in the NAMEAs with the measured data of Corinair.

2.4.3.1 Comparison of direct and cumulative CO2 emissions

Comparing different sets of data is not straightforward, as the classification of industries varies between the US and Europe. As the number of IO sectors for the US is much higher than for Germany or the Netherlands, various sectors for the US sometimes correspond to a single sector in European tables. Here, we are interested in the environmental impact for different type of products. Therefore, we compare the impacts created by 1 of a product for each industrial sector of the US economy with the corresponding sector using another emission data source for US or using data from another country. The comparison is carried out at two different levels: for direct[13] emissions produced by the considered sector, and for the cumulative[14] emissions of the sector integrating all upstream emissions linked to spending in the other sectors of the economy.

[11] The National Accounting Matrix with Environmental Accounts (NAMEA) consists of a conventional national accounting matrix extended to include environmental accounts in physical units.
[12] European Air Emissions for 1994, Under contract of the European Environment Agency, http://www.aeat.co.uk/netcen/corinair/94/
[13] The direct emissions of the sector i are the emissions induced by the production of 1 $ in sector i that are directly emitted by sector i.
[14] The cumulative emission of the sector i are the emissions induced by the $ produce in all sectors in the whole supply chain necessary to produce 1$ in sector i.

a) Comparison of direct emission

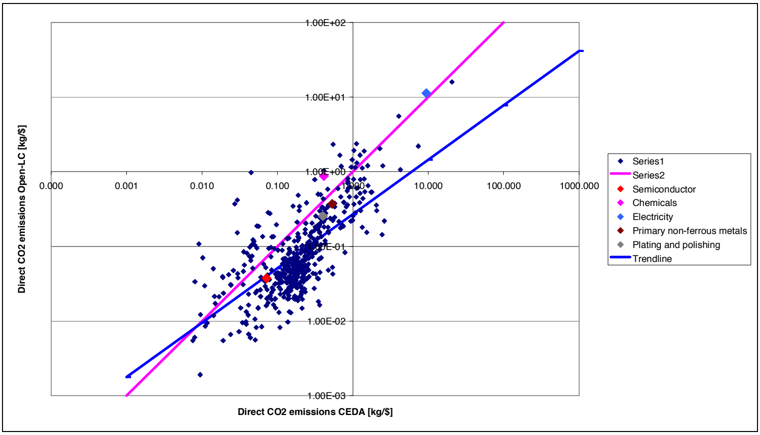


Figure 1: Comparison of the direct CO_2 emissions per sector between Open-LC and CEDA sources for the US economy. The sectors that contribute the most to the CO_2 emission of the pc-si wafer are marked with different colours.

Figure 1 shows a rather poor correspondence between the direct emissions of the US using two sources of data (Norris, 1998; Suh, 2005). The statistical analysis presented in Table 2 shows that the OPEN LC direct emissions are significantly lower than with CEDA. For some of the sectors the difference reaches a factor 10 or more. On the one hand Open-LC's data are higher by a factor 10 or so than the CEDA's data for the following sectors: water supply and sewerage systems, concrete products (except block and brick), mobile homes, prefabricated wood buildings and components, greeting cards, or U.S. postal service. On the other hand CEDA's data are higher than Open-LC's data by a factor 5 to 20 for sectors like religious organisations, legal services, pipelines, natural gas distribution, private libraries, or automotive rental and leasing (without drivers). The industrial sectors that have the highest direct emissions (>0.5 kg CO_2/$) are rather well distributed around the x = y line. This means that the average CO_2 emission per monetary unit for these sectors is similar for CEDA and Open-LC and that the cumulative emissions for all sectors are likely to be much closer than the direct contribution. For sectors that have lower direct emissions, CEDA's data are systematically higher than Open-LC. In the analysis, all data have been compared to CEDA's data, because they are the most recent and the most complete in terms of environmental substances.

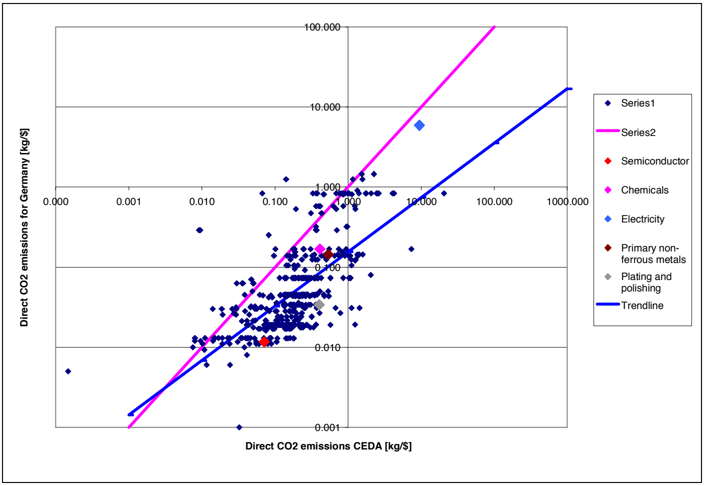


Figure 2: Comparison of the direct CO_2 emissions per sector between Germany and the US (CEDA). The sectors that contribute the most to the CO_2 emission of the pc-si wafer are marked with different colours

As the number of IO sectors for the US is much higher than for Germany, various values for the US data often correspond to a single sector in the German table. As in figure 1, a systematic difference is observed between the two sets of data: As confirmed by the statistical analysis and related discussion presented in table 2, the German direct emissions are up to 2 orders of magnitude lower than the US values for individual sectors. Different parameters could explain the higher values found in the US, like the electricity price or the industrial efficiency, but a more detailed analysis is necessary to characterise these influences with precisions.

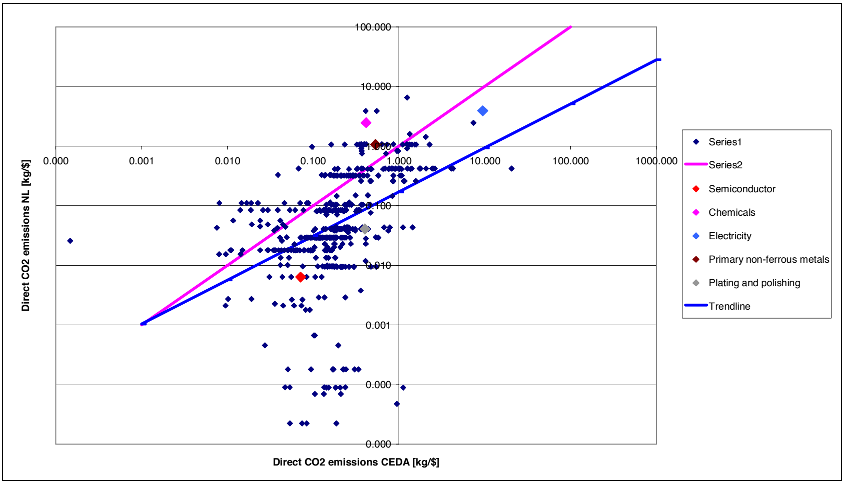


Figure 3: Comparison of the direct CO_2 emissions per sector between the Netherlands and the US (CEDA). The sectors that contribute the most to the CO_2 emission of the pc-si wafer are marked with different colours.

As the number of IO sectors for the US is also higher than for the Netherlands, various values for the US data often correspond to a single sector in the Netherlands table. Like in figure 1, a systematic difference is observed between the two sets of data. As confirmed by the statistical analysis and related discussion presented in table 2, the Dutch direct emissions are up to 4 orders of magnitude lower for individual sectors. Some of the industrial sectors of the Netherlands have very low values for direct CO_2 emissions per $. They are presented in table 1. If a study were to focus on these sectors, further examination would be needed to assess if there is a ground for such large differences, or if errors have been introduced in data handling.

Table 1: Compraison between NL and US data for industrial sectors that have very low direct CO_2 per $ emissions in the NL

Industrial sector	**Emissions NL [kg CO_2/$]**	**Emissions US [kg CO_2/$]**
Manufacture of fish products	0.000048	0.27 – 0.34
Manufacture of vegetables and fruit products	0.000049	0.35 – 0.57
Manufacture of animal feeds	0.000028	0.25 – 0.29
Manufacture of beverages	0.000089	0.14 – 0.20
Manufacture of tobacco products	0.000090	0.05 – 0.24
Manufacture of recorder media	0.000069	0.13 – 0.21
Manufacture of other basic chemicals	0.000047	0.17
Manufacture of train, trams, and aircraft	0.000022	0.022 – 0.028

b) Comparison of cumulative emissions

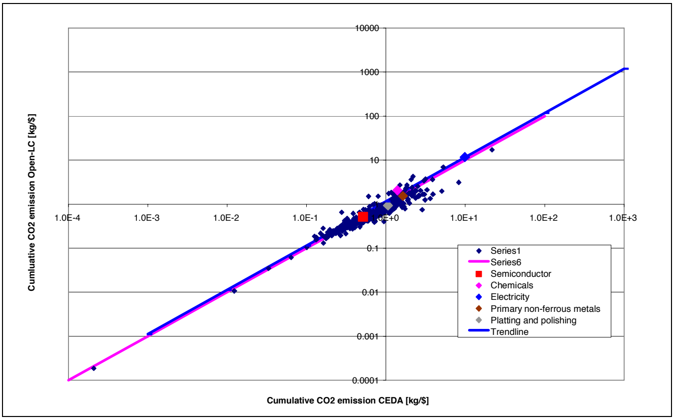


Figure 4: Comparison of the cumulative CO_2 emissions per sector between Open-LC and CEDA sources for the US economy. The sectors that contribute the most to the CO_2 emission of the pc-si wafer are marked with different colours

Figure 4 shows the cumulative CO_2 emission for the two sources for the US economy. Except for a few industrial sectors the results show a rather good agreement between the values (Intercept close to zero, slope of 1, R^2=0.92). It confirms that the good concordance in the two datasets for industrial sectors that have the highest direct emissions is driving the cumulative results for all other sectors and leads to a good agreement in cumulative emissions for all sectors.

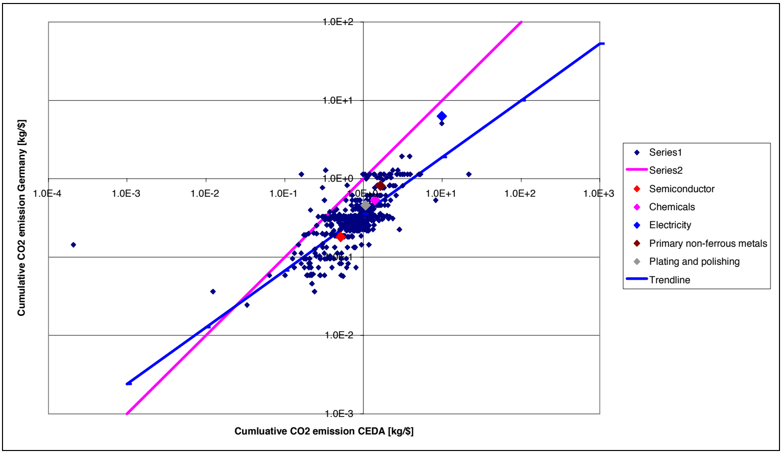


Figure 5: Comparison of the cumulative CO_2 emissions per sector between Germany and the US (CEDA) sources. The sectors that contribute the most to the CO_2 emission of the pc-si wafer are marked with different colours

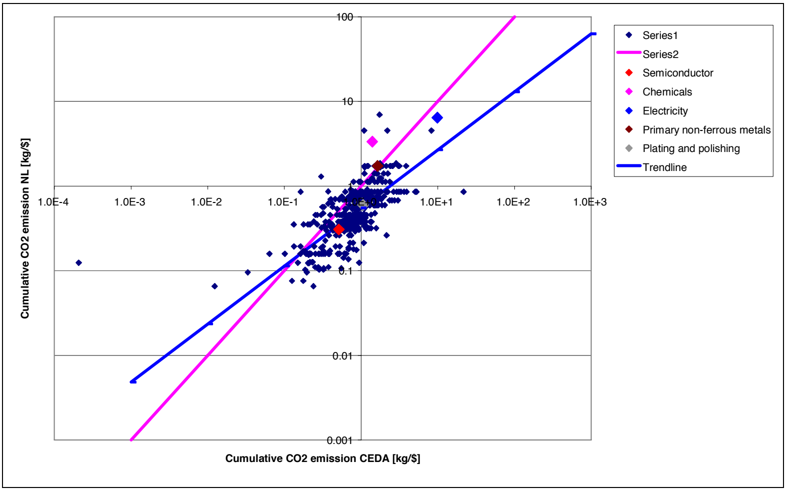


Figure 6: Comparison of the cumulative CO_2 emissions per sector between the Netherlands and the US (CEDA) sources. The sectors that contribute the most to the CO_2 emission of the pc-si wafer are marked with different colours.

Due to the much higher number of industrial sectors in the US Input-Output table, various values for the US can correspond to one value for Germany or the Netherlands. It shows that the consequence of the aggregation can lead to important uncertainties as values on the same horizontal line can be spread typically over one order of magnitude. Deviations are smaller for cumulative emissions than for direct emissions, but remain significant up to typically one order of magnitude higher or lower.

Table 2 summarises the correlation for the figures 1 to 6 providing the correlation coefficient R^2, the standard error on log value, as well as the slope and intercept of the linear regressions. The correlation coefficients have been calculated applying the related windows excel functions on the log values of the direct and the cumulative CO_2 emissions of the studied databases.

Table 2: Statistical analysis of the comparison between the US CEDA model and the US-Open LC, the German and the Dutch direct and cumulative emissions. Correlation coefficient, standard error on log, slope, standard error on slope, intercept and standard error on intercept for a linear regression.

Figure	**R^2**	**Standard error on log**	**Slope**	**Standard error on slope**	**Intercept (x = 0)**	**Standard error on intercept**
Direct emissions US CEDA– US OPEN LC (figure 1)	0.45	0.41	0.73	0.037	-0.58	0.033
Direct emissions US CEDA – Germany (figure 2)	0.41	0.42	0.68	0.037	-0.81	0.033
Direct emissions US CEDA – Netherlands (figure 3)	0.15	0.91	0.74	0.081	-0.77	0.073
Cumulative emissions US CEDA – US Open LC (figure 4)	0.92	0.10	1.00	0.014	0.060	0.0054
Cumulative emissions US CEDA – Germany (figure 5)	0.53	0.21	0.72	0.031	-0.45	0.010
Cumulative emissions US CEDA – Netherlands (figure 6)	0.48	0.22	0.69	0.033	-0.26	0.011

We observe a poor generation for the direct emissions between the reference data (US (CEDA)) and the others. The intercept value shows a systematic significant difference of up to a factor of 6.5 (log value of -0.81 at x=0), the US data from CEDA being systematically higher than the other. In addition, the correlation shows a rather high dispersion (R^2 between 0.15 and 0.45, standard error on log up to 0.4, thus, typically a factor 5 variation for the 95% confidence interval). Table 2 shows that the best agreement is between the two sets of US data, followed by Germany, and a very poor agreement between the US and the Netherlands. The picture is different for the cumulative CO_2 emissions. The correspondence between the cumulative CO_2 emissions evaluated with the two sets of US data shows a better agreement, with a trendline with a slope of 1 and an R^2 of 0.92. The intercept on the log is restricted to 0.06, showing only a 14% difference. This can be understood by the fact that the two sets show a good accordance for the IO sectors that have a high direct CO_2 emissions. The correlation between the US data and the German and Dutch data remains rather poor. The difference can particularly be observed with the slope of the trendlines (0.72 and 0.69) and the correlation coefficient R^2 (0.53 and 0.48).

2.4.3.2 Comparison of countries total CO2 emissions

The total CO2 emissions of the three countries (US, Germany and the Netherlands) are compared to the data given by the UNFCCC (United Nations Framework Convention on Climate Change, 2005) and to Eurostat, which provide reference[15] data. The UNFCCC data include household emissions, which is not the case for the Input-Output data; therefore a correcting factor has been defined using Eurostat data to evaluate the emissions linked to the economy excluding household transport and heating. Figure 7 shows the UNFCCC data and the UNFCCC corrected data, the Eurostat estimation with and without households emissions, as well as the result found using the IO table and the environmental data. The results show very similar values between IO and the UNFCC corrected or Eurostat without household data. This shows that the sectors contributing most to overall emissions are well described in the IO table and emissions. It provides however little verification on direct emission in less important sectors.

[15] Eurostat publishes data for each member state of the European Union and for Acceding and Candidate Countries as much as the information is available. Regarding products, Eurostat applies the CPA P60 classification that delineates sixty products. For the classification of industries, Eurostat uses NACE rev.1 A60 as a reference which distinguishes 60 industries. Figures are given for most of the variables of the tables 1500 "Supply Table", 1600 "Use Table", 1700 "Symmetric Input-Output Table", 1800 "Input-output Table for Domestic Output" and 1900 "Input-Output Table for Imports". The tables 1500 and 1600 are provided annually whereas the tables 1700 to 1900 are compiled in intervals of five years.
http://europa.eu.int/comm/eurostat/newcronos/reference/sdds/en/iot_sut/iot_sut_base.htm
http://europa.eu.int/comm/eurostat

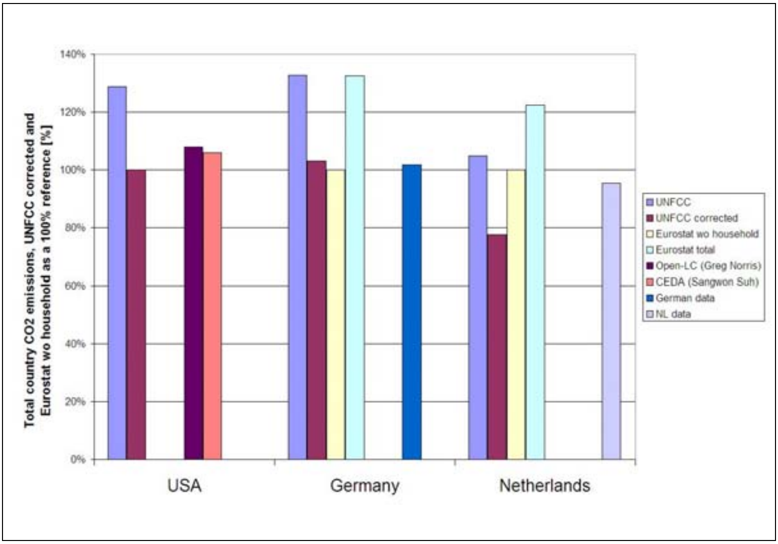


Figure 7: Comparison of the total CO_2 emission for the USA, Germany and the Netherlands given by the UNFCCC (or Eurostat) and calculation with Input-Output data.

2.4.3.3 Comparison between NAMEA and Corinair

Corbiere Nicollier (Corbière-Nicollier, 2005) compares the data from NAMEA[16] with the Corinair[17] database. Figure 8 shows a rather good agreement between NAMEA and Corinair data, apart from the Denmark situation, for which it appears that the NAMEA data for the NOx emissions have been significantly overestimated. The deeper analysis performed by Corbière shows that the contributions of the individual industrial sectors to the total CO_2 emissions can be rather different for NAMEAS and Corinair.

[16] The National Accounting Matrix with Environmental Accounts (NAMEA) consists of a conventional national accounting matrix extended to include environmental accounts in physical units.
[17] European Air Emissions for 1994, Under contract of the European Environment Agency, http://www.aeat.co.uk/netcen/corinair/94/

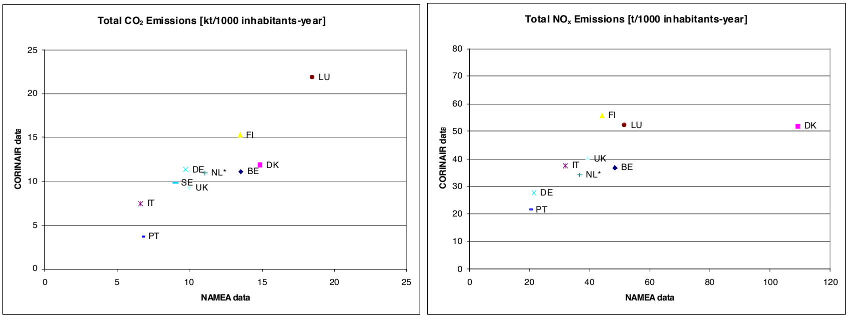


Figure 8: Comparison between NAMEA and Corinair for CO_2 and NO_x, graphics taken from Corbière (Corbière-Nicollier, 2005).

As a conclusion, Corbière recommends to use the median data of all European NAMEA's as a starting point and the German data where no other data are available.

2.4.3.4 Final discussion of the results and selection of an IO dataset

Table 3: Summary of the result of the Input-Output datasets analysis.

Input-Output datasets		**Switzerland**	**Germany**	**The Netherlands**	**USA**
Availability	economic (sectors)	37	71	105	480
	environmental (substances)	-	10	25	1344
Age	Economic	2004	2000	1995	1998
	Environmental	None	2000	1995	1998
Level of details of the economic data		-	+	+	++
Exhaustiveness of environmental data		None	+	+	++
Representativeness	Economic	++	++	+	+
	Environmental	none	+	++	-
Reliability	Economic	-	++	++	++
	Environmental	none	+	+	+

Figures 3 to 6 show the high uncertainty linked to the fact that a dataset is less detailed (has less sectors). Therefore this parameter has a higher influence on the choice of the dataset that the other, as long as we stay in OECD countries.

As a conclusion, US environmental data are the most appropriate for an initial assessment as they are more detailed (more industrial sectors and more pollutants) than European data. The choice of the IO US data, as the most detailed sets of data, minimises the uncertainties resulting from the inhomogeneity of industrial sectors. As a consequence, the US IO datasets will be used as an initial basis for the remainder of this study. Among IO datasets, CEDA was preferred, due to more detailed environmental data as well as more extensive metadata. The CEDA dataset is also more recent than the Open-LC dataset.

The high variation between environmental data suggests that sensitivity studies are necessary to test the results' robustness on the German set. The Swiss matrix is not retained here because of the lack of consistent environmental data. Ecoinvent data themselves are representative for many products of a European situation rather than of Swiss production.

2.5 Evaluation of the contribution of services and processes out of the scope of LCA

One source of difference in the comparison of PLCA and IOLCA results is the level of comprehensiveness in assessing the supply chain[18]. Several contributions that are supposed to be restricted are often not considered in PLCA, including the inputs known as services. As a basis for further interpretation, we characterize this difference by evaluating the contributions of the services and of the inputs out of the scope of LCA.

2.5.1 Methodology

Rebitzer (Rebitzer, 2005) divides the contributions to one functional unit in three categories:

1. Out of the scope of LCA because it is exclusively private consumption and assumed to be independent from industrial activity. This includes sectors exclusively related to residential housing, human food, clothing and accessories, vacation, body care, medical treatments, and leisure activities. We assume that these activities would be performed anyway and should therefore not be taken into account in a PLCA[19]. As a consequence, these lines and columns are set to 0 in the Input-Output table. It is however not straightforward that the contributions from industrial sectors identified as "exclusively related to private consumption" does not include additional special contributions related to industrial activities. However, to make a sensitivity analysis of the importance of these "out of scope" contributions, the sectors were set to 0 and the results calculated.
2. Industrial sectors that are generally not considered in PLCA due to a missing material/energy flow link, like banking, advertising, infrastructure maintenance, etc. Some

[18] In an IOLCA, the whole economy is included in the evaluation, while in PLCA one considers "only" the processes described in the process tree.

[19] Not all LCA practitioners are convinced that some of the IO industrial sectors should be excluded from an LCA, as IO is meant to describe an economy and not private consumption. This project will enable us to characterize these contributions and is the basis for further discussion. The question whether "too much" is included in an IOLCA requires further analysis, identifying in details what is really used in addition to the personal consumption.

of these sectors are included in the so-called services[20] category. To simplify the discussion, this category will be called services in the text below.

3. All the other contributions that are not included in the two first categories and that should theoretically be considered in a theoretical PLCA. That is everything that contribute to the realisation of the functional unit.

As proposed by Rebitzer and Kaenzig (Rebitzer, 2005), it is possible to define two new IO matrix $A_{IOLCA\text{-}OS}$ (Out of the Scope) and $A_{IOLCA\text{-}S}$ (Service), where $a_{ij} = 0$ when i corresponds to a sector that is out of the scope and that we do not want to take into account in PLCA, respectively to sectors considered as services (categories 1 and 2 above).

The cumulative CO_2 emissions have been calculated for all IO sectors with the three matrices, A_{IOLCA}, $A_{IOLCA\text{-}OS}$ and $A_{IOLCA\text{-}S}$ and the results are presented in figure 9.

In this work, A_{IO} is replaced by $A_{IO\text{-}OS}$ as we do not want to consider processes that are normally not taken into account in PLCA. Equation 3 becomes:

Equation 4

$$\vec{b}_{hybrid} = B_{hybrid} \cdot \left(I - A_{hybrid}\right)^{-1} \cdot \vec{y}_{hybrid} = \begin{pmatrix} B_{PLCA} \\ B_{IOLCA} \end{pmatrix} \cdot \left(I - \begin{pmatrix} A_{PLCA} & D \\ C & A_{IOLCA-OS} \end{pmatrix} \right)^{-1} \cdot \begin{pmatrix} \vec{y}_{PLCA} \\ \vec{y}_{IOLCA} \end{pmatrix}$$

2.5.2 Results

Figures 9 and 10 below show the difference when the cumulative CO_2 emission is calculated for all the IO sectors with*:* the conventional Input-Ouput matrix *(*A_{IO}*),* the corrected IO matrix that does not consider the sectors out of scope of PLCA ($A_{IOLCA\text{-}OS}$*),* and with the corrected matrix that further removes the services ($A_{IOLCA\text{-}S}$) from $A_{IOLCA\text{-}OS}$. Let's call these emissions $CO_{2\ IO}$, $CO_{2\ IOLCA\text{-}OS}$ and $CO_{2\ IOLCA\text{-}S}$.

Figure 9 shows the cumulative $CO_{2\ IO}$, $CO_{2\ IOLCAOS}$ as well as $CO_{2\ IOLCA\text{-}S}$ emissions for all sectors, listed on the x axis from the sector emitting the lowest to the sector emitting the highest quantity of CO_2 per \$. The correlation between the cumulative CO_2 emissions of one sector and the reduction when calculating the emission without the out of the scope sectors and the services can be seen.

[20] Nevertheless the missing material/energy flow does not serve as the definition of services, which can also include sectors like transportation or landfill.

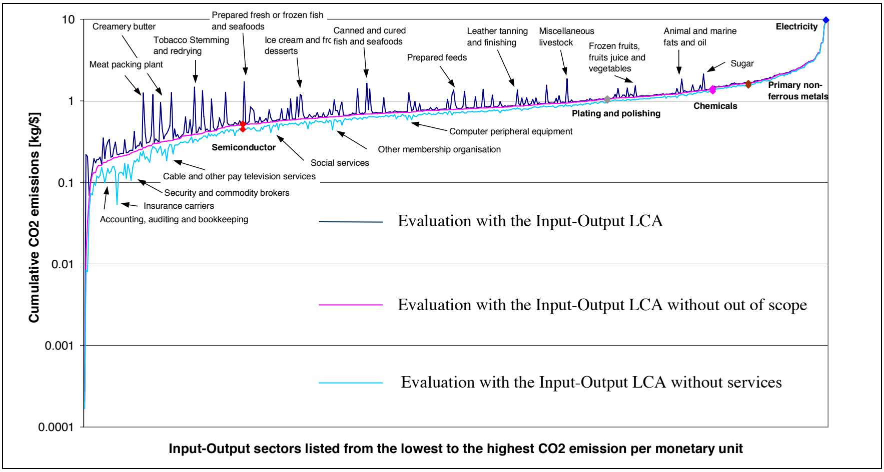


Figure 9: Cumulative emissions $CO_{2\ IO}$, $CO_{2\ IOLCA\text{-}OS}$ as well as $CO_{2\ IOLCA\text{-}S}$ for all sectors, sorted from the sector emitting the lowest to the sector emitting the highest quantity of $CO_{2\ IOLCA\text{-}OS}$ per \$. In addition, the ratio of the cumulative CO_2 emission to the US total CO_2 emission is plotted below.

On average, if we remove the industrial sectors that correspond to the out of the scope contributions that we do not want to take into account in PLCA, the CO_2 emissions decrease by 8.9% (the lowest value is 0.1% and the highest 94.4%). Nevertheless, a closer look shows that the sectors for which the reduction is important are producing food products and are therefore using as primary materials products from industrial sectors that were considered out of the scope of LCA.

Figure 10 shows the relationship between the contribution of services ($CO_{2\ IOLCA\text{-}OS}$ -$CO_{2\ IOLCA\text{-}S}$) and the cumulative CO_2 emissions for all 480 industrial sectors of the Input-Output table. The results show an important correlation between these two values. Not considering the services can lead to high uncertainties as seen is figure 9, up to 75% for some particular industrial sectors such as owner-occupied dwellings or insurance carriers. The average contribution, when considering the CO_2 emissions for all sectors, is 7.3%.

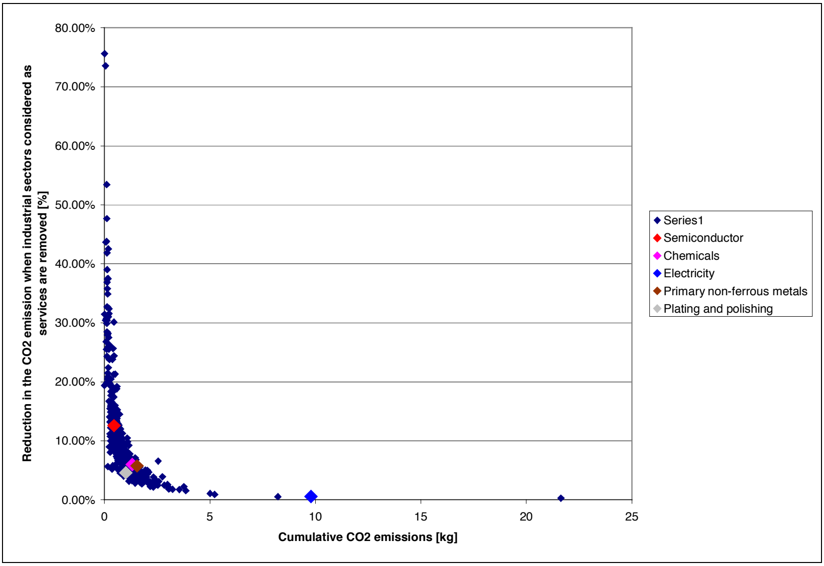


Figure 10: Reduction in CO_2 emission when the industrial sectors identified as services are removed as a function of the cumulative CO_2 emission per $ for the different US industrial sectors.

Results for the NO_x and the SO_2 are similar and lead to the same conclusions.

2.5.3 Discussion of the results

The methodology developed by Rebitzer (Rebitzer, 2005) permits one to reduce the system boundaries in order to exclude from the study some contributions that are considered to be out of the scope of LCA and thus generally not considered. Some examples are hairdresser, leisure, etc. The results show that these processes contribute, on average, to less than 10% of the total CO_2 emission.

The sectors considered as services are further removed from the Input-Output table. The estimation of these services' share shows that these further contribute, on average, to less than 10%, which is in accordance with Rebitzer's results.

"However, it is also evident that the overall contributions of the service sectors are not that large. For instance already that sector which is still in the top 10% of sectors in regards to contribution of services (40 sectors out of 490) only shows an absolute contribution of services of around 20%." (Rebitzer, 2005).

Figure 11 shows that the absolute CO_2 reduction is rather constant for a high number of industrial sectors, thus representing a higher percentage for sectors with a restricted impact. The CO_2 is reduced by 0.05 to 0.07 kg per $ when services are removed.

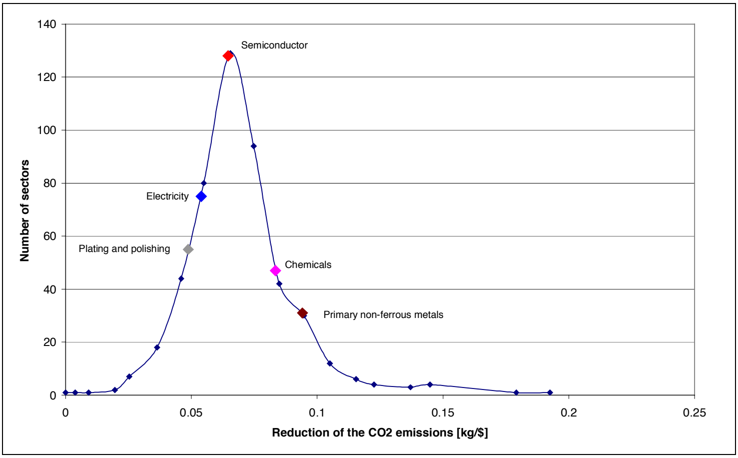


Figure 11: Reduction in CO_2 emissions when services are not included. The y axis shows the number of industrial sectors for which the CO_2 reduction is between x and x + 0.01 kg/$.

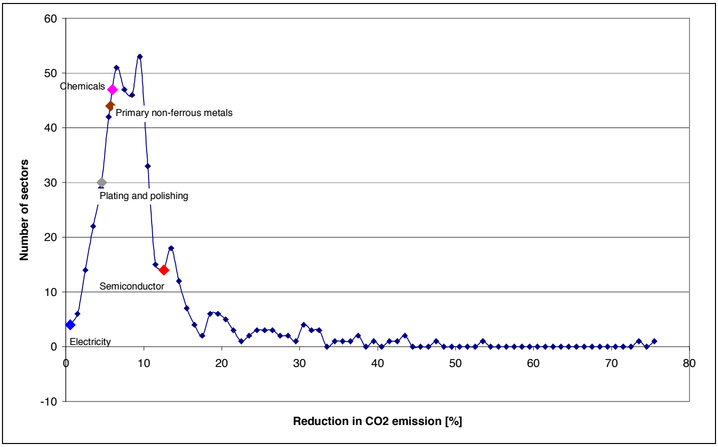


Figure 12: Reduction in CO_2 emissions when services are not included. The y axis shows the number of industrial sectors for which the CO_2 reduction is between x and x+1 %.

2.6 Detailed correspondence between Input-Output and Process LCA: evaluation of the cut-offs processes

As a follow up to the previous section, we compare IO and PLCA results for different individual sectors to analyse how far the difference between the methods corresponds to the quantity of services not considered in PLCA. To achieve this, a comparison will be performed on a practical case study, analysing in detail the correspondence between methods.

The cut-off processes are defined as the contributions to a functional unit that are not considered when performing a PLCA. The reason can be that the contributions are not identified as such (for instance the computer use for industrial production like aluminium or copper), are considered to be negligible or that no data are available.

The objective of this chapter is to set a methodology that enables an adequate comparison between IO and PLCA. This is not obvious as the structure of the IO table varies quite a bit from the PLCA databases structure, like in ecoinvent.

2.6.1 Methodology for the detailed comparison

In a traditional PLCA, the inputs to a particular process can be divided into the considered inputs, the known and not considered inputs, and the unknown inputs (Marheineke et al., 1998). In our case, we estimated that there are no known and not considered inputs[21] and we will speak in this report of considered and not considered inputs.

Figure 13 illustrates the difficulty behind this structural difference. For the two ecoinvent processes "electricity, medium voltage, production UCTE, at grid" and "electricity, production mix DE", the direct inputs to the process do not reflect the direct inputs to the IO industrial sector in which the two processes are included (electric services). More specifically, some of the processes contributing directly are included in the same industrial sector as the main process assessed, but without having any corresponding economic flows. As a consequence, some of the inputs to the IO industrial sector correspond to indirect inputs to the process. In order to solve the problem and enable an adequate and detailed correspondence, the ecoinvent processes are aggregated until none of the direct inputs are delivered by the same industrial sector corresponding to the studied process. This procedure is illustrated with an example in figures 14a and b for the production of pc-si silicon wafers.

[21] These contributions are not difficult to take into account either by using process or Input-Output LCA.

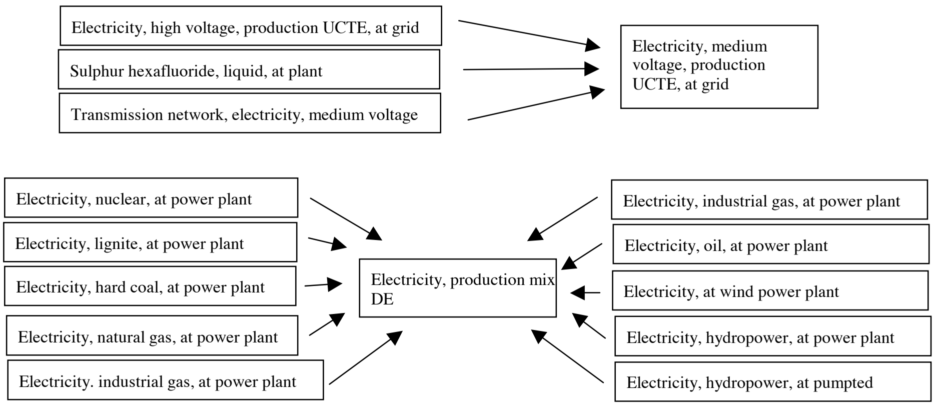
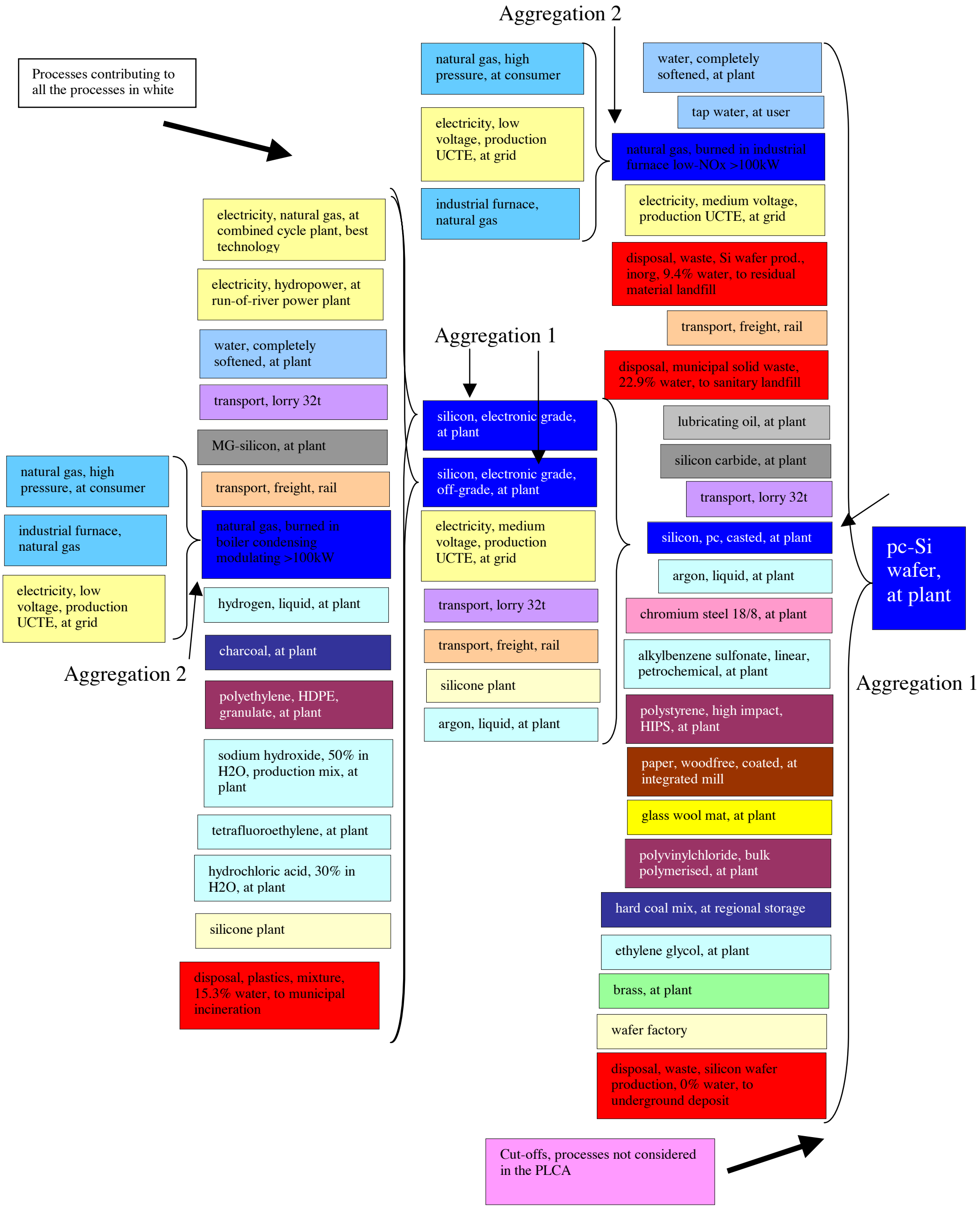


Figure 13: Example of the direct contributions for two processes of ecoinvent, electricity, production mix DE and electricity, medium voltage, production UCTE, at grid


Aggregation 2
Processes contributing to all the processes in white
natural gas, high pressure, at consumer
electricity, low voltage, production UCTE, at grid
industrial furnace, natural gas
water, completely softened, at plant
tap water, at user
natural gas, burned in industrial furnace low-NOx >100kW
electricity, medium voltage, production UCTE, at grid
disposal, waste, Si wafer prod., inorg, 9.4% water, to residual material landfill
transport, freight, rail
Aggregation 1
disposal, municipal solid waste, 22.9% water, to sanitary landfill
electricity, natural gas, at combined cycle plant, best technology
electricity, hydropower, at run-of-river power plant
water, completely softened, at plant
transport, lorry 32t
MG-silicon, at plant
transport, freight, rail
natural gas, burned in boiler condensing modulating >100kW
hydrogen, liquid, at plant
charcoal, at plant
polyethylene, HDPE, granulate, at plant
sodium hydroxide, 50% in H2O, production mix, at plant
tetrafluoroethylene, at plant
hydrochloric acid, 30% in H2O, at plant
silicone plant
disposal, plastics, mixture, 15.3% water, to municipal incineration
natural gas, high pressure, at consumer
industrial furnace, natural gas
electricity, low voltage, production UCTE, at grid
Aggregation 2
silicon, electronic grade, at plant
silicon, electronic grade, off-grade, at plant
electricity, medium voltage, production UCTE, at grid
transport, lorry 32t
transport, freight, rail
silicone plant
argon, liquid, at plant
lubricating oil, at plant
silicon carbide, at plant
transport, lorry 32t
silicon, pc, casted, at plant
argon, liquid, at plant
chromium steel 18/8, at plant
alkylbenzene sulfonate, linear, petrochemical, at plant
polystyrene, high impact, HIPS, at plant
paper, woodfree, coated, at integrated mill
glass wool mat, at plant
polyvinylchloride, bulk polymerised, at plant
hard coal mix, at regional storage
ethylene glycol, at plant
brass, at plant
wafer factory
disposal, waste, silicon wafer production, 0% water, to underground deposit
pc-Si wafer, at plant
Aggregation 1
Cut-offs, processes not considered in the PLCA

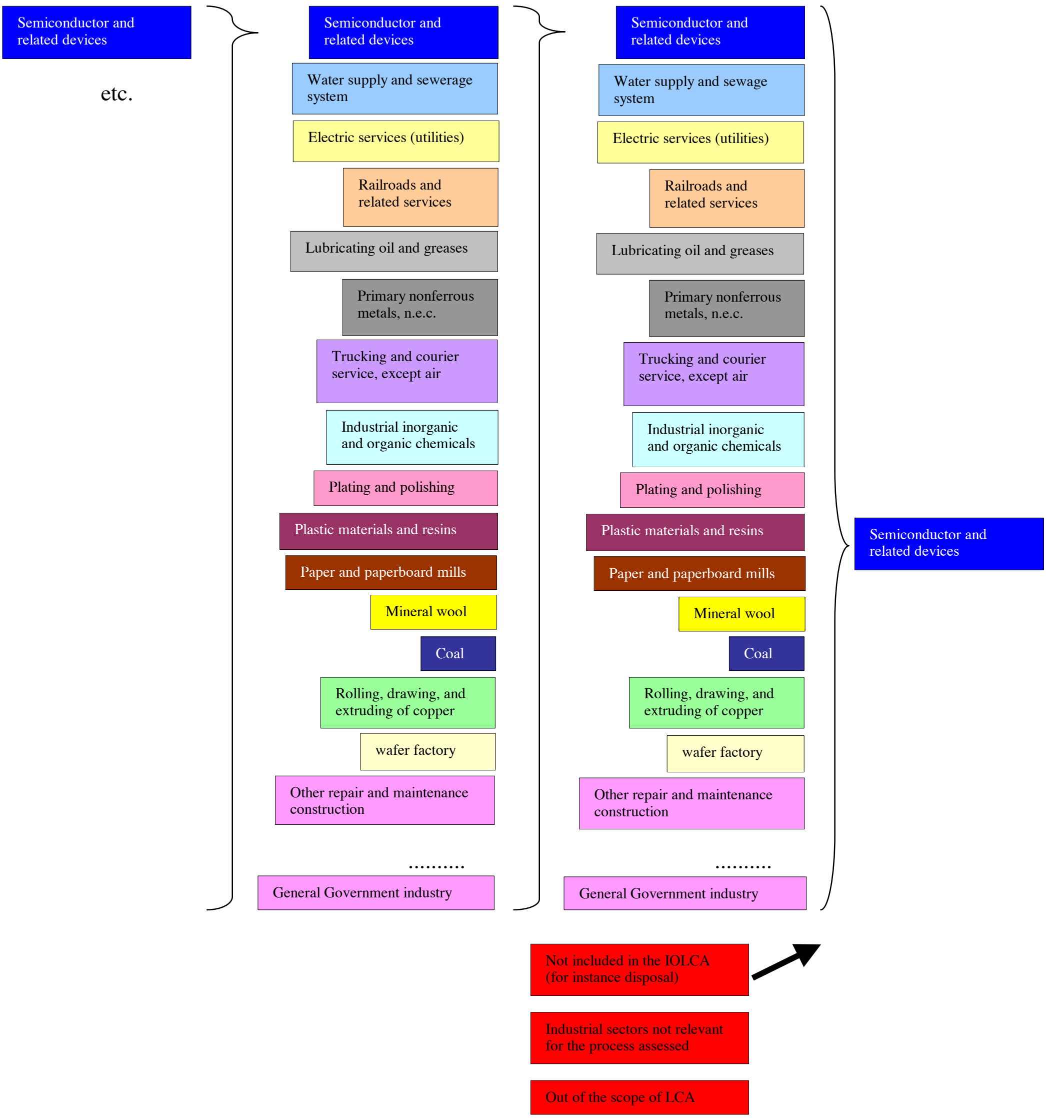


Figure 14a and 14b: Illustration of the aggregation scheme for the process pc-si wafer, at plant. Three steps are necessary to reach an adequate correspondence between the process and the Input-Output contributions. Processes in blue are those whose contributions are aggregated with the main process pc-Si wafer. Figure 14a above shows the scheme for ecoinvent and figure 14b for the IO table. The colors show the correspondence between the PLCA processes and the IO sectors.

The objective is to compare the cumulative contributions of the first tier of PLCA processes (figure 14a above) with the cumulative contributions of the first tier of I/O sectors (figure 14b).

The starting basis is the non-aggregated contributions of the first tier processes as presented in the first bar of figure 16.

To enable the comparison with Input-Output, two aggregation steps are carried out successively:
1) A first aggregation (1) is performed, adding up the direct emissions of the initial process (pc-Si wafer, at plant) with the direct emissions of the other silicon processes. These include:

- silicon, pc, casted at plant;
- silicon, electronic grade, at plant;
- silicon, electronic grade, off-grade, at plant;

The cumulative emissions of the first tier inputs to these processes are then added up to the first tier processes that provide inputs to the initial process.
2) One problem we have to face is the fact that one ecoinvent process can be included in various IO sectors. Typically heat production is a process that is normally performed directly within many of the IO sectors and the corresponding emissions are attributed to the IO sectors. Therefore, processes like natural gas, burned in industrial furnace low-NOx >100kW, and natural gas, burned in boiler condensing modulating >100kW, can be potentially part of various IO sectors. In the case of the pc-si wafer, at plant, they were also considered to be processes part of the semiconductor industrial sector and related devices. In the second aggregation step, the direct combustion emissions linked to natural gas were, therefore, added to the direct emissions of the silicon sectors. The cumulative first tier processes supplying the natural gas combustion are then also added to the first tier inputs of the pc-Si wafer.

A similar transformation is carried out on the IO matrix (figure 14b):

The $A_{IOLCA\text{-}OS}$ matrix is aggregated in the same way as that which has been done for the PLCA. We add the contribution to the sector I_1, coming from the same sector. To achieve this, we divided $A_{IOLCA\text{-}OS,j}$ by $(1\text{-}a_{jj})$ to take into account the inputs from all the tiers. For the Input-Output, if we apply it to a specific process, there is a series of sector contributions that are not relevant. For example, the wholesale contribution is not relevant for the “pc-Si wafer, at plant” where its contribution is likely to be negligible. These contributions should, therefore, be assessed separately.

A generalisation of this approach is illustrated in figures 15a and b.

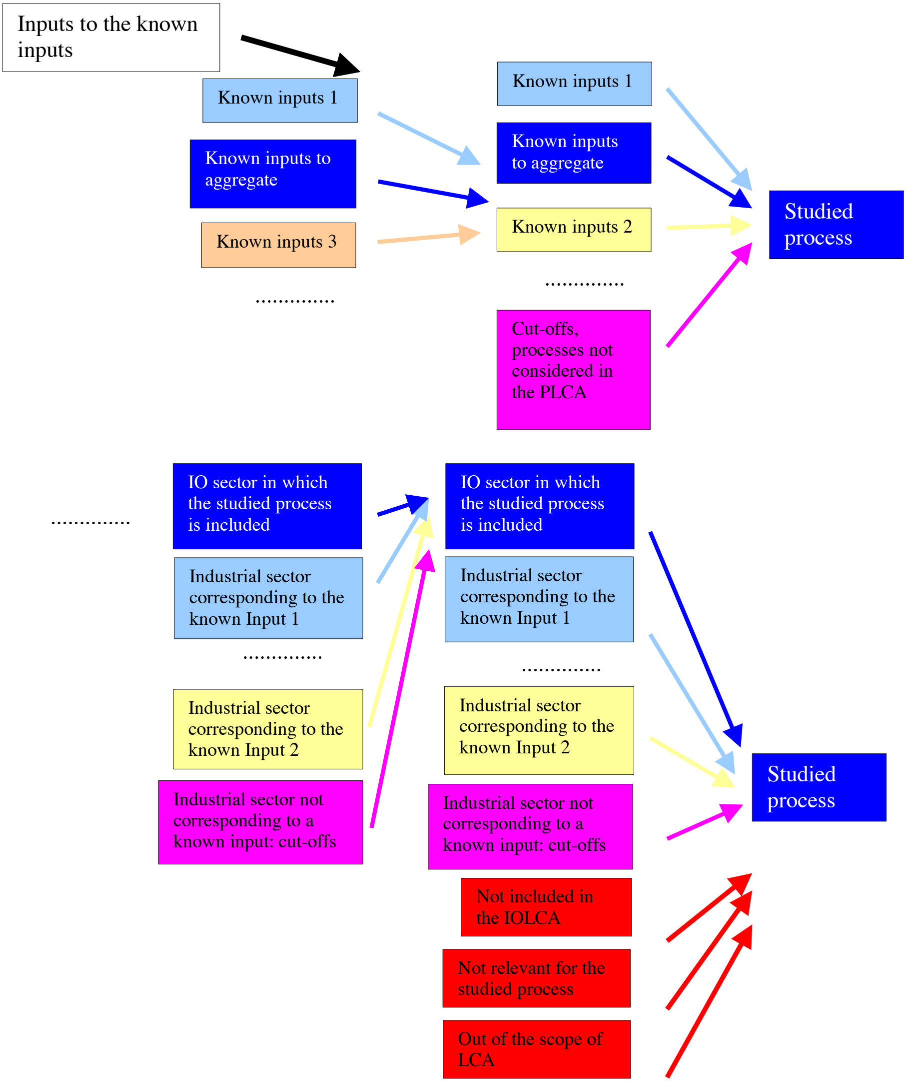


Figure 15a and 15b: Structure of the ecoinvent database and its relation to the input-output table. In dark blue are the processes to aggregate, in different colors the known inputs 1...n and in pink the cut-offs. In 15b the same colors indicate the corresponding IO sectors. Red is for contributions to the studied process that are not considered or should not be considered in the PLCA (not included in the IOLCA, not relevant for the studied process and out of the scope of LCA).

The figures 15a and b shows in blue the processes that we aggregate because they are included in the same IO sector as the studied process. In different colors, one finds the known inputs contributing to the studied process. The cut-offs are in pink, and in red one finds the contributions that are not or should not be included in the IOLCA (waste treatment, not relevant for the process, or out of the scope of LCA).

The aggregation enables the determination of a new set of processes P_k that contributes to the new constructed process called P_a. These will be compared to the inputs derived from the IO table.

2.6.2 Detailed comparison of wafer results

Figures 14 a and b shows the ecoinvent processes contributing to the process studied, as well as the correspondence between the PLCA and the IOLCA for the process pc-si wafer, at plant. Figure 16 compares the cumulative CO_2 emissions of this process using PLCA and IOLCA. The cumulative CO_2 emissions for all direct contributions, on the one hand to the ecoinvent processes, and on the other hand to the IO sectors, are presented. These direct contributions can be identified in figures 14a and b.

To enable a quantitative comparison between the PLCA and the IOLCA, the first data required is the price of a pc-si wafer, at plant. Table 4 provides a median estimate as well as a range for the wafer price, based on different data.

Table 4: Analysis of the price of a silicon wafer using various sources.

Si wafer description	**Price [$]**	**Source**
Diameter 100 mm, Dopant (Arsenic, Phos., Sb, Boron)	10 – 30	(Wafer World Inc., 2005)
100 mm x 100 mm, 4in Silicon Wafers	9.75 – 13.5	(Silicon Quest International, 2005)
100 mm x 100 mm, based on the annual reported production and value	22.8	(Williams, 2000)
Final range	**9.75 – 30**	
Median	**20**	

The median price corresponding to one pc-silicon wafer has been evaluated to be \$20, with a typical uncertainty range of +/- \$10. The producer price is calculated using the margin[22] given by Suh (Suh, 2001).

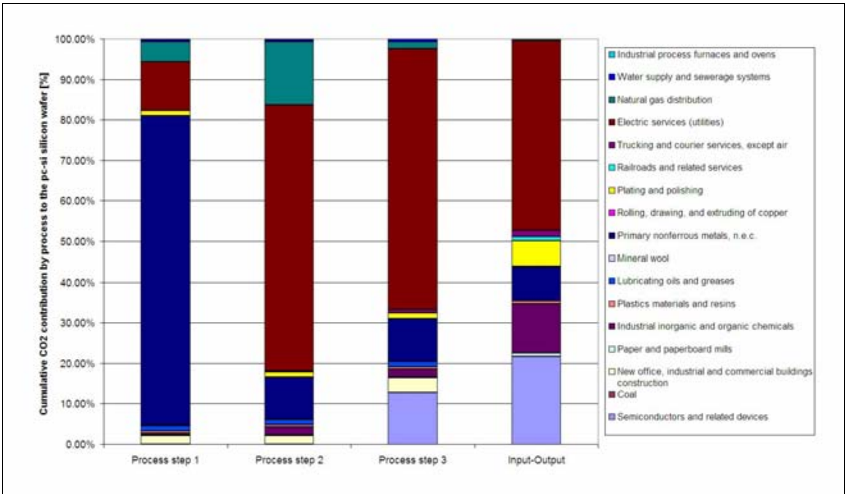


Figure 16: Cumulative CO_2 emissions produced by the contributions of the first tier for the PLCA and the IOLCA. The three levels of the aggregation of the PLCA are shown (no aggregation, aggregation 1 for all Si based processes, agregation 2 of silicon-based+natural gas combustion). Notice that the structure of the contributions for the process step 3 becomes consistent with the structure of the IO.

[22] The data used to evaluate the margin are specific to the different industrial sectors and are not an average for all sectors.

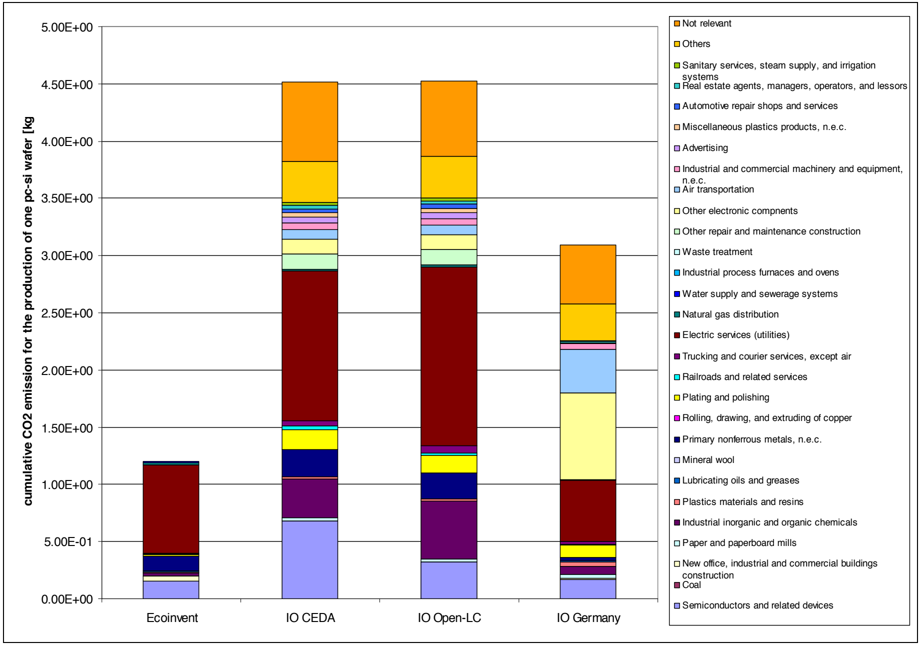


Figure 17: Absolute cumulative CO_2 emissions for the pc-si wafer, evaluated with the PLCA and the IOLCA (CEDA, Open-LC and the German data) using the minimum price for the pc-si wafer.

The results for the two aggregation steps presented in figure 16 show that the aggregation leads to better correspondence between the PLCA and the IOLCA. The direct emissions due to natural gas combustion that are added in the 2nd aggregation step represent the dominant direct contribution of the Silicon sector. The repartition of the induced CO_2 emission in the third step and in the IOLCA show a good accordance, although the absolute values are rather different. We can make several conclusions:

- The CO_2 emissions evaluated with the PLCA and the IOLCA are different from a factor of 4.7;
- One possible source of error is the price chosen for the pc-si wafer;
- The structure of the contribution to the CO_2 emissions shows a good accordance, although this is not sufficient for a good combination of the methods.

If the price is correct, the difference is likely to come from the following sectors that are responsible for the highest share in impact: electric services, plating and polishing, industrial inorganic and organic chemicals, semiconductors and related devices, and primary non-ferrous metals.

The differences between Open-LC and CEDA's data are very small. They come from an increase of the impact of the electricity consumption and a decrease in the estimation of the direct semiconductor and related device emissions.

The total cumulative CO_2 emissions evaluated with the German data is very similar to ecoinvent. Nevertheless, the structure of the contribution does not show a very good agreement, and it is, therefore, not correct to say that both evaluate the same contributions. The large difference in the cut-offs between the US' and Germany's data come from two sectors: air transportation and other electronic components. To produce $1 of semiconductor and related devices in the US, one spends $0.00565 in the sector air transportation. In Germany, the industry spends $0.03 in the air transportation sector to produce $1 of manufactured office machinery and computers. Producing and selling computers and final products (to be sold directly to the consumer) require much more air transportation (more assembly of products, etc.) than the semiconductor industry. The explanation is similar for the sector of other electronic equipment. Therefore, the cut-offs of the US are certainly more realistic for the considered process. The analysis and comparison of more processes should be realised if one would like to confirm the close results between the German IO and ecoinvent.

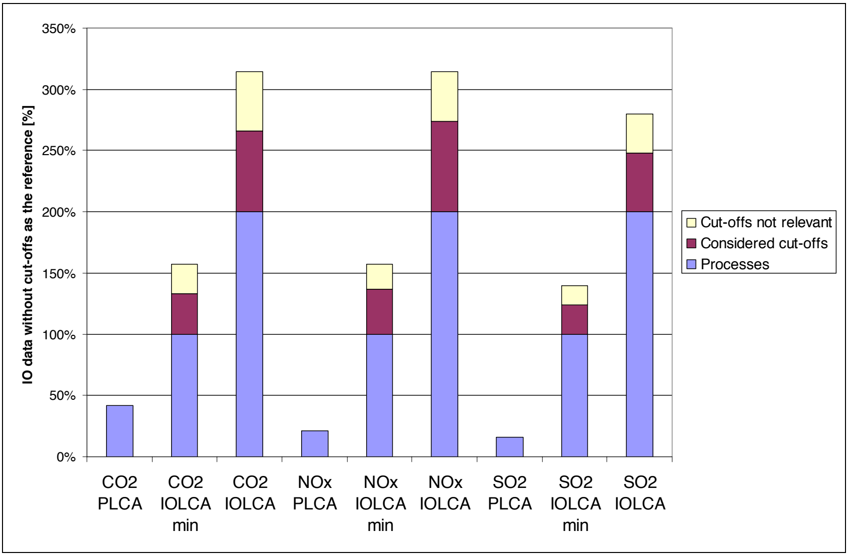


Figure 18:CO_2, NO_x and SO_2 emissions comparison between the IO and PLCA. The absolute values are given as well as the estimation of the cut-off processes taken into account and the cut-offs considered to be not relevant (these are the same as in figure 16)

Table 5: The ten highest contributions of the cut-off processes to be considered and the five highest contributions of the cut-offs considered to be not relevant for the pc-si wafer[23]. The minimum price for the si wafer was used to calculate the contributions presented in this table.

Industrial sector		Contribution	Contribution[24]
		[kg]	[%]
Additional cut-offs processes to be considered			
120300	Other repair and maintenance construction	1.4 E-1	14.3
570300	Other electronic components	1.3 E-1	13.3
650500	Air transportation	8.5 E-2	9.0
500400	Industrial and commercial machinery and equipment, n.e.c.	5.8 E-2	6.1
730200	Advertising	5.0 E-2	5.3
320400	Miscellaneous plastics products, n.e.c.	4.0 E-2	4.2
750002	Automotive repair shops and services	3.3 E-2	3.5
710201	Real estate agents, managers, operators, and lessors	3.0 E-2	3.2

[23] The cut-offs considered to be not relevant for the pc-si wafer are not the processes out of the scope of LCA described above. When evaluating the cut-offs, one makes a selection of the relevant processes. This selection is performed on the basis of expert evaluation.
[24] Ratio (in %) of the cumulative CO_2 of the Input-Output sector to the total contribution of the cut-off processes that should be added to the PLCA.

730104	Computer and data processing services; including own-account software	2.6 E-2	2.7
680302	Sanitary services, steam supply, and irrigation systems	2.3 E-2	2.4
Total		6.1 E-1	64.0
Others		3.4 E-1	36.0
Total		9.5 E-1	100.0
Cut-offs estimated to be not relevant for the considered process and product			
Industrial sector		Contribution	Contribution[25]
		[kg]	[%]
690100	Wholesale trade	1.6 E-1	22.5
420402	Coating, engraving, and allied services, n.e.c.	1.2 E-1	16.9
270406	Chemicals and chemical preparations, n.e.c.	5.9 E-2	8.2
410203	Metal stampings, n.e.c.	4.6 E-2	6.5
381000	Nonferrous wiredrawing and insulating	3.2 E-2	4.5
Total		4.2 E-1	60.4
Others		2.7 E-1	39.6
Total		6.9 E-1	100.0

As described in the methodological part, some of the cut-offs are not considered because they are evaluated to irrelevant for the ecoinvent process studied. The evaluation of the cut-offs considered or not has been done based on an expert evaluation[26].

From figures 16, 17 and 18, we can deduce some important results:

- The CO_2, NO_x, and SO_2 emissions evaluated with the IOLCA for the silicon wafer is much higher than with the PLCA (the ratios are respectively 7.4, 15.0 and 14.9);
- The structure of the contributions shows a rather good agreement with the PLCA and the IOLCA, although the importance of some of the contributions are very different;
- The contributions of the cut-offs processes not considered in the PLCA are important and represent an increase between 32% and 36%.

The cut-offs processes not considered in the PLCA are the contributions of all the IO sectors that do not have any correspondence in the PLCA direct inputs.

[25] Ratio (in %) of the cumulative CO_2 of the Input-Output sector to the total contribution of the IO that are considered to be not relevant among the cut-off processes.
[26] These cut-offs not relevant for the process studied should not be confused with the IO sectors out of the scope of PLCA described in the chapter 6. These processes not relevant are estimated on an expert basis. Although they are in the scope of LCA they are judged to be not relevant for the studied process, due to the aggregation of products or services in one IO sector.

In the following section, we concentrate on analysing in more details CO_2 emissions and explaining the observed differences. These different points will be treated below, first theoretically (section 2.6.3) and then through the wafer example (section 2.6.4). The aim behind the assessment of these results is to evaluate whether PLCA and IOLCA are compatible and if ecoinvent can improve in quality by using IOLCA.

2.6.3 Explaining the differences: theoretical bases

Considering the first result, the high difference between both approaches for the pc-si wafer can have various sources:

1. the price chosen for the process pc-si wafer, at plant;
2. the cumulative CO_2 emissions induced by the different inputs (see graphic) is either underestimated in ecoinvent or overestimated in the Input-Output data (that will be discussed below);
3. the fact that the pc-si wafer, at plant, is not representative of the average of the IO sectors semiconductor and related devices. This could for instance appear as an over- or underestimation of one of the direct contributions;

To better understand the role of each parameter, it is interesting to look at the different parameters involved in the IOLCA and PLCA calculation of the cumulative contributions of a given sector. The cumulative CO_2 emission for one of the direct contributors to the process we are studying can be evaluated with the IOLCA and the PLCA. We have the following relationship:

Equation 5

$$CO_{2i,IOLCA}[kg] = \varepsilon_i[kg/\$]\cdot A_i[\$/\$]\cdot p_i[\$]\begin{pmatrix} < \\ = \\ > \end{pmatrix}\sum_j P_j[PH]\cdot \alpha_j[kg/PH] = CO_{2i,PLCA}[kg]$$ [27]

Where:

- $CO_{2i,\ IOLCA}$ is the cumulative CO_2 emissions induced by the contribution of the IO sector i
- ε_i is the cumulative emissions linked to \$1 of the output of sector i
- A_i is the amount of money from sector i to produce \$1 of the chosen process
- p_i is the price of the product (the price of the pc-si wafer, at plant)
- P_j is the amount of the contribution of the process j (physical unit) to the process studied, j characterises all the processes contributing to the process studied classified in the IO sector i
- α_j is the cumulative emissions linked to the production of one unit of P_j
- $CO_{2i,\ PLCA}$ is the cumulative CO_2 emissions linked to the processes classified in the IO sector i.

[27] [PH] means physical unit

If $CO_{2i,\ IOLCA}$ is higher or lower than $CO_{2i,\ PLCA}$ then the following explanations are possible:

a. the price of the pc-si wafer p_i is over- or underestimated;
b. A_i is over- or underestimated: this can be the case if the process we are studying is not in the average of the industrial sector;
c. the cumulative CO_2 emissions for sector i ε_i is too high or too low;
d. the contribution from sector j P_j is under- or overestimated;
e. the emissions α_j is under- or overestimated.

Let us assume that there is only one single process j. We can have two particular situations:

1. A good agreement on the emissions:

Equation 6

$$\varepsilon_i[kg/\$] = \cdot \frac{\alpha_i[kg/PH]}{\beta_i[\$/PH]}$$

2. A good agreement on the contributions, which can be translated as:

Equation 7

$$A_i[\$/\$] \cdot p_i[\$]/\beta_i[\$/PH] = P_j[PH]$$

Where β_i is the price of one physical unit of the process P_i.

If the evaluation of the IO is higher than the PLCA, we have:

Situation 1: good agreement on the emissions

If equation 6 is approximately satisfied, it can be introduced in equation 5, yielding:

Equation 8

$$B_{i,IOLCA}[kg] = A_i[\$/\$] \cdot p_i[\$] > P_j[PH] \cdot \beta_i[\$/PH] = B_{i,PLCA}[kg]$$

In this case, the difference between the PLCA and the IOLCA can therefore come from the following reasons:

a. The amount of money from sector i to produce \$1 of the chosen process, A_i, is overestimated. This can be the case if the process we are studying is not in the average of the industrial sector;
b. The price of the product p_i is overestimated;
c. The amount of the contribution of the process j (physical unit) to the process studied, P_j, is underestimated;
d. The price of one physical unit of the process $P_{i,}$ β_i, is underestimated (that is the price per physical unit is underestimated).

But if β_i the price per physical unit is underestimated, that would mean, according to equation 6, that α_i - the kg emitted per physical unit - is also underestimated. This makes sense in the case of very pure materials where both prices and environmental impacts are higher than average as reflected in the IO paradigm. This situation could occur when using an average process in the PLCA when specific data are not available for the considered process. For example, if a purer material is effectively used in the process to replace a given chemical, it can be more expensive and responsible for larger environmental impacts.

Situation 2: good agreement on the contributions

If equation 7 is approximately satisfied, it can be introduced in equation 5, yielding:

Equation 9

$$B_{i,IOLCA}[kg] = \varepsilon_i[kg/\$] \cdot \beta_j[\$/PH] \cdot P_j[PH] > \alpha_j[kg/PH] \cdot P_j[PH] = B_{i,PLCA}[kg]$$

In this situation, the difference between the PLCA and the IOLCA can possibly come from the following reasons:

a. ε_i is overestimated;
b. the emissions α_j is underestimated;

Table 6 summarises the potential sources for differences and their respective role:

Table 6: Summary of the important parameters that could explain the differences between IOLCA and PLCA when evaluating the environmental impact of one particular process using the developed methodology.

Parameter	**Potential explanation**
the price of the studied process p_i (in our case the pc-si wafer)	This parameter is a key parameter and has an influence on the total environmental impact, not on the structure nor on the relative contributions. It is never easy to find the right price corresponding to a process, especially if databases are used, because they generally give data for a class of products. In most cases, a price range will give an idea of the uncertainty.
A_i, the amount bought by the studied sector from IO sector i	It is possible that this parameter does not correspond to reality, because the product studied is not representative of the IO sector in which it is included. A full description of the IO sector and a discussion of the representativeness of the IO sector in relation to the studied process is necessary.
ε_i the cumulative CO_2 emission for IO sector i	This value might not correspond to reality, if the data used are "wrong," or if the studied process or product does not have the same characteristics as that of the average of the IO sector. The first cannot be assessed for a particular product. The second implies to analyse the variety of products in the IO sector and the corresponding environmental impacts.
P_j the contribution from process j	This can be under- or overestimated, but that would imply that the amount of the process considered is incorrect.

α_j the emission of the process j	As above, this is possible if something is missing in ecoinvent. In addition, as different products can be grouped and described by an average ecoinvent process, there might be, in reality, a range of emissions. This could be the case, for example, if different chemicals with different levels of purity are grouped under e.g. organic or inorganic chemicals.

2.6.4 Explaining the difference for the case of the pc-si wafer

2.6.4.1 Price variability of the pc-si wafer

The first potential reason for difference is the price variability for the wafer. Table 2 gives the variability of the pc-si wafer price, \$20 +/- \$10. In terms of CO2 emissions, this leads to a factor of three between the lowest and the highest values. However, as shown in figure 18, this is not sufficient to explain the difference between PLCA and IOLCA. The ratio between IOLCA and PLCA can nevertheless be reduced to respectively 3.71, 7.52, and 7.44, compared to 7.4, 15.0, and 14.9 previously.

2.6.4.2 Contributions of specific first tier processes

To further investigate the results of the first tier processes and sectors, we used the Swiss custom database to find prices and the corresponding quantity of products imported in Switzerland. This enables us to determine the prices (\$/unit) for the ecoinvent processes. A simple calculation enables us to compare both the cumulative CO_2 emissions per \$ and the quantity used for both the PLCA and the IOLCA directly in monetary units. The following IO sectors are studied: electric services, plating and polishing, and industrial inorganic and organic chemicals, as they contribute the most to the impact.

Table 7: First tier contributions to the process pc-si wafer, at plant, transformed in monetary units using the Swiss custom database. Comparison with the Input-Output data. Comparison of the cumulative CO_2 emissions per \$ for both PLCA and IO LCA.

Ecoinvent processes used in the PLCA			**Input-Output LCA**		
Process	**Cumulative CO_2 emissions**	**Contribution**	**Sector**	**Cumulative CO_2 emissions**	**Contribution**
	[kg/\$]	**[\$/pc-si wafer]**		**[kg/\$]**	**[\$/pc-si wafer]**
electricity, hydropower, at run-of-river power plant	5.7e-02	2.2e-2			
electricity, natural gas, at combined cycle plant, best technology	7.4	7.5e-2	Electric services		
electricity, medium voltage, production UCTE, at grid	8.7	3.0-2			
Average/Total for electricity	**6.3**	**1.3e-1**		**9.8**	**1.56e-1**

hydrogen, liquid, at plant	3.8e-01	2.8e-03	Industrial inorganic and organic chemicals		
Sodium hydroxide, 50% in H2O, production mix, at plant	1.0e+01	4.6e-04			
Hydrocholoric acid, 30% in H2O, at plant	4.5e+00	2.5e-03			
argon, liquid, at plant	7.6e-01	4.0e-03			
alkylbenzene sulfonate, linear, petrochemical, at plant	7.9e-01	5.6e-03			
ethylene glycol, at plant	1.0e+00	2.4e-04			
tetrafluoroethylene, at plant	4.6e-01	7.4e-05			
Average chemicals	**1.6e00**	**1.6e-02**		**1.3e0**	**4.9-1**
chromium steel 18/8, at plant	6.9e+00	2.4E-3	Plating and polishing	9.6e-1	3.32-01
Average plating and polishing	**6.9e+00**	**2.4E-3**		**9.6e-1**	**3.32-01**

Table 7 shows that for the electricity, the cumulative CO_2 emissions of the IO process are 1.5 times the cumulative CO_2 emissions. This partly reflects the amount of electricity used in the IO, which is 1.2 times what is consumed in the PLCA. A deeper analysis of the cumulative CO_2 emissions will allow us to learn whether the difference comes from the electricity mix or from the fact that some contributions are neglected in the PLCA.

For the chemicals and the plating and polishing, the evaluation of the cumulative CO_2 emission per $ shows better correspondence than the amount used expressed in monetary terms: For the chemicals, the cumulative CO_2 emissions evaluated with the IO is 0.8 times those of the PLCA. The amount used in the IO is a factor of 30 higher than for the PLCA. For the plating and polishing, these two ratios are 0.14 and 138. As a consequence, there is a better agreement for both approaches on the emissions than on the amount used per functional unit. This will be developed further in sections 2.6.4.4 and 2.6.4.5.

2.6.4.3 Electricity

The good correspondence between the contributions evaluated with the IO and the PLCA and the fact that the IO sector does not include many different products lead us to a preliminary conclusion that the difference comes from the emissions. This parameter will, therefore, be studied more in detail.

The electricity price was determined using data from the United States Environmental Protection Agency (EPA). The cumulative CO_2 emissions linked to electricity consumption is 1.5 times higher with the IOLCA (9.8 kg CO2/$) than with the PLCA (6.3 kg CO2/$). The difference could come from the following causes:

a. The electricity mix: The electricity mix used for the PLCA process includes 18% of hydropower, which is not the case in the US mix. From Table 6, we can deduce that if we remove the hydropower, the cumulative CO_2 increases from 6.3 to about 8;
b. The cut-off processes: We expected the IO to be higher than the PLCA because more contributions are taken into account;
c. The price: There is an uncertainty on the electricity price;

In order to identify the valid causes, the developed methodology has been applied to the production of electricity. In a first step, the US electricity production mix has been built using EPA data and the ecoinvent database. We assume that for a given fuel, the technology used in the US for the production of electricity is the same as in Europe. Figure 19 shows the CO_2 emissions for different countries. The variations are very significant. As expected, the PLCA US mix leads to higher cumulative CO_2 emissions (factor of 1.45) than for the European mix. The US mix evaluated with the PLCA leads to CO2 emissions very close (87%) to those evaluated with IOLCA (figure 20).

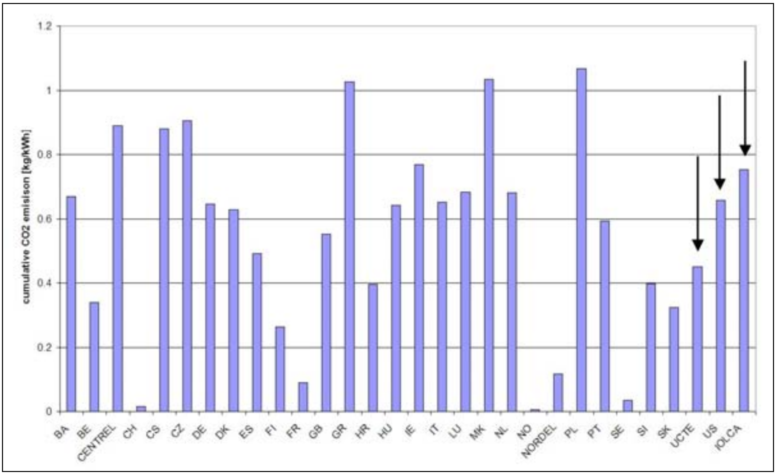


Figure 19: CO_2 emissions linked to the production of 1 kWh of electricity in various countries.

The US electricity production mix has been aggregated following the methodology described above. The results are presented in the figure 20.

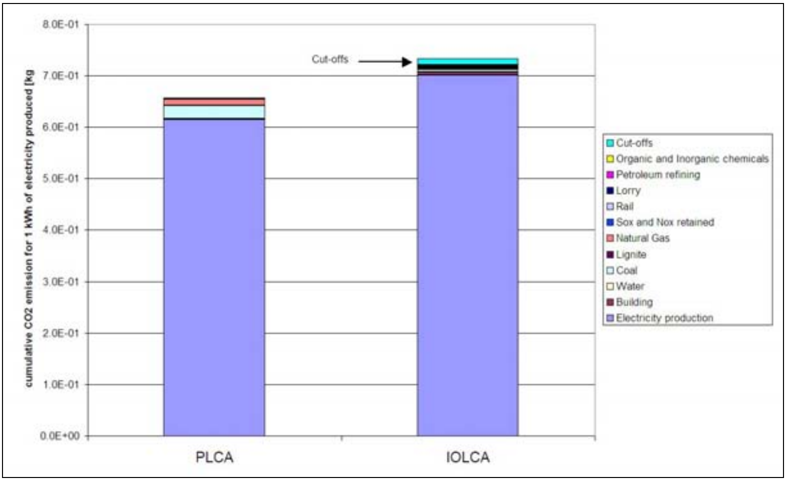


Figure 20: Cumulative CO_2 emissions for the US electricity production evaluated with a PLCA and an IOLCA.

The total CO_2 emissions linked to the production of 1 kWh of electricity in the US is very similar between the PLCA evaluation using the constructed US mix and IOLCA. The most important similarity is that the highest contribution for both evaluations comes from the direct CO_2 emitted when coal, petroleum, or gas is burned in power plants. In other words, the cut-off processes, or what has not been taken into account in the PLCA that we could consider with the IOLCA, is very small for electricity as it increases the CO_2 emitted by less than 2%. The 5 highest cut-offs are nevertheless presented in table 8.

Table 8: Contribution to the cumulative CO_2 emissions induced by the electricity production in the US by sector for the PLCA and the IOLCA and the five most important cut-offs.

Industrial sector/process	**Contribution to the CO2 emissions with PLCA**	**Contribution to the CO2 emissions with IOLCA**
Electricity (direct emissions)	93.6 %	97.3 %
Coal	4.0 %	0.8 %
Natural Gas	1.8 %	0.3 %
Sox and Nox retained	0.8 %	0.0 %
Building	0.1 %	0.7 %
Lignite	0.1 %	0.0 %
Rail	0.01%	0.4 %
Petroleum Refining	0.01 %	0.3 %
Organic and Inorganic chemicals	0.01 %	0.2 %
Lorry	0.0 %	0.05 %

Water	0.0 %	0.03 %
Cut-off processes to be considered		
Other repair and maintenance construction		0.5 %
Power, distribution, and specialty transformers		0.1 %
Turbines and turbine generator sets		0.1 %
Water transportation		0.1 %
Fabricated rubber products		0.05 %

In summary, depending on the state, the electricity average consumer price can vary from 4.4 to 14.5 ct/kWh. The 10% difference between the values for the CO_2 emissions found with PLCA and the IOLCA is a good result considering the price sensitivity. In addition Ecoinvent considered an average European plant, which can be different from the US average power plants.

In a hybrid perspective, we can correct the value in the IO data in the wafer case study. For that we replace the value for the direct emissions of the IO sector "electric services" by the value given by the US electricity mix calculated with ecoinvent. With this new data, the ratio between IOLCA and PLCA for the pc-si wafer becomes 1.95 instead of 2.40 (ratio of the IOLCA min and the PLCA: figure 21). On this graphic, only the IO results with the lowest value for the price of the pc-si wafer were used. Figure 21 also shows that the remaining difference mainly comes from the contribution of the chemical sector, of the plating and polishing sector, and of the direct emissions in the semi-conductor sector.

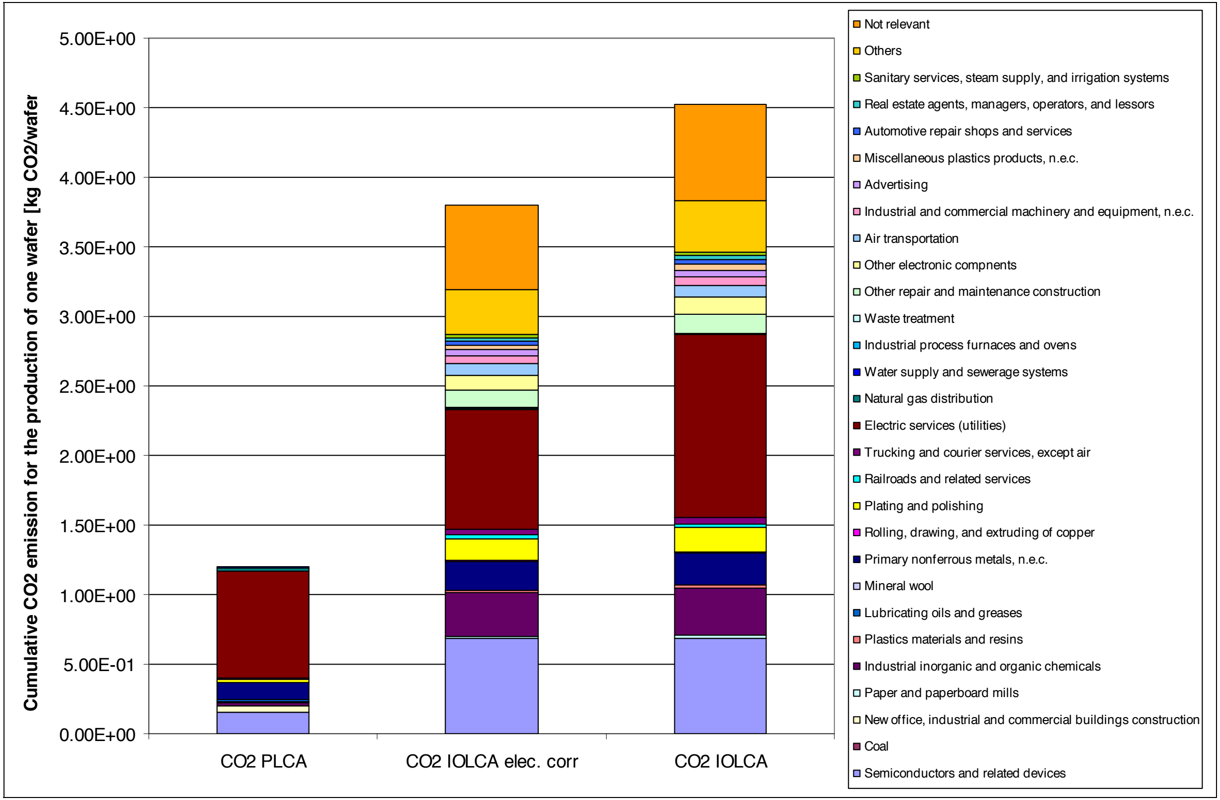


Figure 21: Comparison of the CO_2 emission with the PLCA and the IOLCA (min and average) with the electricity mix correction.

2.6.4.4 Chemicals

The CO_2 emissions for the chemicals evaluated with the IOLCA are much higher than for the PLCA. We start from table 6 to discuss this difference. The value given by the IOLCA can be overestimated if:

- ε_i is overestimated: That is, if the cumulative emissions linked to $1 of output of the industrial inorganic and organic chemical sector is overestimated;
- A_i is overestimated: That is, the amount of money from the chemical sector to the semiconductor and related devices sector is overestimated (for the production of the pc-si wafer), which could be true for one product like the pc-si wafer;
- p_i is overestimated: the price of the process (the price of the pc-si wafer, at plant) is overestimated.

It is impossible at this stage to say whether ε_i is overestimated or not. This could be done by studying other LCA data and comparing them with the direct IO emissions.

The "semiconductor and related devices" sector can be investigated by detailing all its components. Having the prices and existing PLCA for various components could give an idea of the variability (emissions per $) of the equipment composing the sector. This was not possible to achieve within the scope of this project, one of the reasons being that LCA on electronics are hard to find.

A sensitivity analysis for p_i has been performed and does not explain the difference. In addition, a variation of p_i would induce a change in all contributions. What we attempt to explain in this section is the fact that the contributions of some processes are much higher with the Input-Output than with the process and therefore the pc-si wafer price cannot explain the difference of the contributions of the chemicals.

The value given by the PLCA can be underestimated if:

- P_j is underestimated: That is, the amount of chemicals necessary for the production of the pc-si wafer is underestimated in ecoinvent;
- α_i is underestimated: That is, the amount of CO_2 emitted to produce the chemicals is underestimated.

Although it is unlikely, one source of uncertainty that we cannot judge here is the underestimation of P_i. This could be a point to check in ecoinvent, which will not be done within the scope of this project.

Like the IO table, ecoinvent also groups different products under the same process. In the case of chemicals, different products, with different levels of purity are grouped under the same process. This could lead to an underestimation of the emission α_i.

A further analysis of this process should be performed using the same methodology to learn more about the explanation of this difference.

2.6.4.5 Plating and polishing

We used the above methodology to compare the CO_2 emissions of the PLCA and the IOLCA. We basically have the same conclusion as for the chemicals and we will use the same methodology to analyse the difference.

- ε_i is overestimated: That is, if the cumulative emissions linked to $1 of output of the plating and polishing sector is overestimated;
- A_i is overestimated: That is, the amount of money from the plating and polishing sector to the semiconductor and related devices sector is overestimated (for the production of the pc-si wafer), which could be true for one product like the pc-si wafer;
- p_i is the price of the process (the price of the pc-si wafer, at plant) and is overestimated. This issue has already been discussed above.

Table 6 shows that the CO_2 emission per $ is higher with the PLCA than with the IOLCA. Therefore, it is unlikely that we have an overestimation of the value ε_i.

We have the same conclusion concerning the overestimation of the process.
The value given by the PLCA can be underestimated if:

- P_j is underestimated: That is, the amount of chromium steel necessary for the production of the pc-si wafer is underestimated in ecoinvent;
- α_i is underestimated: That is, the amount of CO_2 emitted to produce the chromium steel is underestimated.

The large variety of products within this IO sector means that the composition of the IO sector and the representativeness is the first track to follow to explain this very high difference.

A further analysis of this process should be performed using the same methodology to learn more about the explanation of this difference.

2.6.4.6 Direct impact of the semiconductors

One of the important differences in figure 17 is the direct emissions produced by the semiconductor industry. It is out of the scope of this study to assess the composition of the direct emissions of ecoinvent processes as well as an IO sector. However, we can note that there is a factor 10 between the CO2 emissions of the PLCA and the IOLCA.

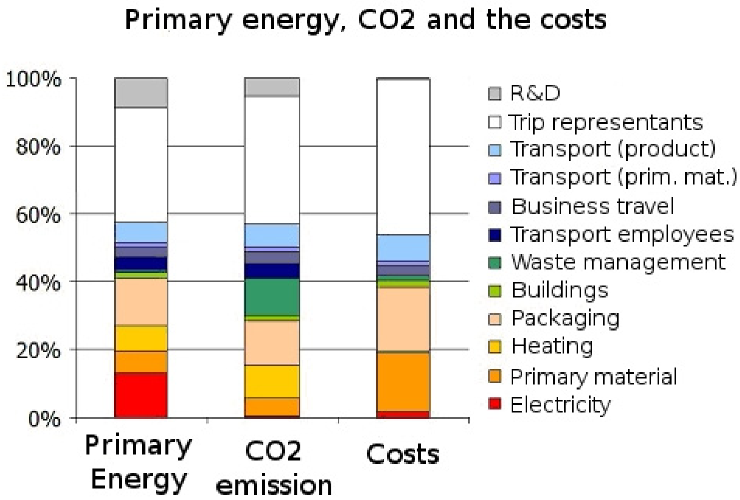


Figure 22: Estimation of the primary energy and the CO_2 emission of one company, performed by Margni, which shows that most of the emissions comes from travelling

The semiconductor and related devices sectors include: "Establishments primarily engaged in manufacturing semiconductors and related solid- state devices. Important products of this industry are semiconductor diodes and stacks, including rectifiers, integrated microcircuits (semiconductor networks), transistors, solar cells, and light sensing and emitting semi-conductor (solid-state) devices." As shown in the figure 22, the CO2 emissions produced by a chemical intensive company are various. It is likely that not all direct emissions of a company site are included in ecoinvent. For example some of the transportation linked to the marketing, or the different buildings heating etc.

2.6.5 Conclusion for the pc-si wafer

With this example we analysed how IOLCA and PLCA can be used together to enhance the quality of a study. In the first step, we found that for some processes, such as for the pc-si wafer, the cut-off processes, or contributions not taken into account in PLCA, are of importance, representing an increase between 32% and 36% and should be considered in the PLCA. An exception is the electricity sector where the cut off processes only represent 2%.

In the second phase, we tried to explain the other differences between the PLCA and the IOLCA. It has been shown that once the processes belonging to the same sector are carefully identified and combined, the structure of the contribution is rather similar between the IOLCA and the PLCA, at least for the two studied processes. On the other hand the absolute value can be very different. This is not the case with the electricity process, but the ratio between the total CO2 emitted for the production of the pc-si wafer is much higher with the IOLCA than the PLCA. The individual contributions to the production of the pc-si wafer have been compared between IOLCA and PLCA. The sources of this difference have been identifies as:

1) Part of this difference comes from the electricity mix. The hybrid methodology permitted us to take a new mix into account. This has been corrected here so that the electricity sector in the IO uses European CO_2 direct emission factors.
2) The amount of chemicals used in the production of the pc-si wafer needs to be checked in ecoinvent.
3) The level of purity and the price of these chemicals need to be looked at in ecoinvent. They could have an implication for the CO_2 emitted by kg of produced chemicals, given that it is an average value.
4). The amount of chromium steel used in the production of the pc-si wafer for ecoinvent.
5) The price and level of purity of the chromium steel.

If these four possibilities are not responsible for the difference, we can then estimate that the difference is due to the fact that the pc-si wafer is essentially not representative of the industrial sector and differs significantly from the mean of this sector. In that case, one of the solutions could be to use another hybrid methodology that disaggregates the IO table. One could, therefore, create a new IO sector called si wafer, for instance.

2.7 Generalisation to the whole Ecoinvent

Different levels of combination are feasible to merge an IOLCA and a PLCA.

2.7.1 Level 1: no merging

IOLCA and PLCA are not merged and no hybrid methodology is used. Data taken from the IOLCA is used:

1. to set priorities for the development of ecoinvent. Analysing the structure of the impacts of one country using IO permits to identify the main contributors and therefore give suggestions for the development of the ecoinvent datasets.
2. to identify potential data gaps in PLCA. This can be done by evaluating the impact of the processes of ecoinvent with IOLCA and by analysing more in detail those for which there is a big difference. It is then possible to identify what contributions are potentially missing for ecoinvent processes.

This level could be summarised as “learning from IOLCA to enhance the quality of PLCA”.

We learnt in this study that the evaluation of one process of ecoinvent could be very similar when evaluated with the IOLCA (that is the case for the electricity) or very different. If the

IOLCA is trusted, then the process pc-si wafer is underestimated and some of the PLCA contributions should be checked (chemicals, for instance). However, because of the aggregation of various products within one industrial sector, it is hard to determine whether the value given by the IO, that is, the average of the sectors, is representative of the process. In such a situation, the IO results can be used to determine what processes should be checked and give suggestions on what new processes should be added to the database (services, air transportation, etc.).

2.7.2 Level 2: tiered approach

The tiered hybrid would mean adding to the ecoinvent processes the cut-offs that were evaluated with the IOLCA (this includes all the cut-offs (see figure 16), excluding those considered to be not relevant for the process). This study shows that this could be done, but that the aggregation of the ecoinvent processes, using the developed methodology, has to be performed to allow for a correct comparison. The result of this study shows that the cut-offs added can be of importance (up to 30% of the impact) or negligible (a few percent in the case of the electricity sector). In addition, it has been shown that due to the limited number of sectors and the fact that sometimes many different products are included in one industrial sector, some of the cut-offs processes that should be added are not relevant for the studied process.

The update of the Input-Output data is not a problem as the structure of the IO table is not likely to change. On the other hand, the addition of new ecoinvent processes could necessitate complex updates. A potential problem here is that double counting could arise from the aggregation process described above.

2.7.3 Level 3: integrated approach

It is possible to think of a more integrated approach, with a disaggregated IO table using ecoinvent processes and ecoinvent processes using IO data.

This would mean to construct the matrices C and D of equation 3, which would lead to the development of a new tool that could be used to evaluate the cut-offs for any LCA performed using the ecoinvent database. This has not been done within this project. The development of such a tool would require one to reach level 2 as a first step. Then the IO matrix should be disaggregated, in particular to consider geographical differences and, for instance, electricity mixes. This last part is an important work and requires a large amount of information. The detailed comparison for both the electricity and the pc-Si wafer has shown that the source of uncertainties are presently too high and need to be analyzed and significantly reduced in both databases to enable a full integration.

2.8 Conclusion

2.8.1 Scientific conclusions

2.8.1.1 Lack of reliable economic and environmental IO data

In the first part of the report, we analysed the existing IO datasets (economic and environmental data) and compared the existing datasets on the basis of the following criteria: availability, age, level of detail of the economic data, exhaustiveness of the environmental data, representativeness, and reliability.

We came to the conclusion that the reliability of the datasets are similarly poor and that one of the most important parameters is the detail of the Input-Output sectors. In this regard, the US Input-Output datasets is the most adapted to further assess the possibility of merging an Input-Output database with ecoinvent. However, the results show that we lack reliable economic and environmental IO data. The US table describes a different economy than that of Switzerland, and the European countries' IO tables have a rather low level of detail.

2.8.1.2 Contributions of services and sectors out of the scope

The sectors traditionally considered as out of the scope of an LCA have been removed from the Input-Output table and their contributions to the CO_2 emissions evaluated to be in average 10% of the cumulative CO_2 emissions. The contribution of the service sectors to CO2 emissions has been calculated and amounts on average to be 10%, typically varying between 3% and 20%. The absolute values of these contributions have been found to be rather independent of the studied sectors. On average, the sectors considered out of the scope of LCA and the services have rather low contributions. The inclusion of these services would not explain a large difference between PLCA and IOLCA.

2.8.1.3 Methodology to compare PLCA and IOLCA

A methodology has been developed to enable an adequate comparison between PLCA and IOLCA. This is based on the fact that we need to have the same direct contributions for both and leads to the aggregation of various ecoinvent processes to find a similar structure to the IO table. The application of this methodology enables one to better understand the difference and similarities of the two approaches and therefore to better use IOLCA for enhamcing the PLCA quality.

2.8.1.4 High differences between IOLCA and PLCA

There can be high differences between IOLCA and PLCA, not only for emissions like the Nox or SO2, but also for the CO2. This implies that there is a **lack of consistency that makes the full combination of both approaches very difficult.** As mentioned in the introduction, taking advantage of both approaches is feasible, but should be done in an intelligent and skillful way (see recommendations for Ecoinvent).

In particular, three parameters have been found to be important: the prices, the reprensativeness of the IO sectors, and the representativeness of the PLCA processes for a specific process. These are linked to the level of detail of the IO table. The prices of the studied process, but also of its direct inputs, play a major role. In the case of the pc-si wafer, as well as for the electricity, the variability of these prices is very important, leading to high uncertainties. The level of detail of the IO table is directly linked to the extent to which an IO sector is representative of the process we are studying. In this case study, the IO sector electric services include mainly the distribution of electricity, and yet, the semiconductor and related device sector is composed of many products, some of them being very different from a pc-si wafer. However, evaluating if the product chosen is far from the average of the sector is a very difficult task. Similarly, the level of purity of chemicals and materials in the PLCA database can be problematic if average values are used for classes of chemicals or raw materials that significantly differ from the specific product considered.

2.8.2 Case study conclusions

2.8.2.1 LCI of monocristalline wafer

The first conclusion is that the cumulative CO_2 in IOLCA is much higher than in PLCA (+270%), although relative CO_2 contributions have a similar pattern.

The assessment shows that this large difference cannot be explained by the price of the wafer. But with a few contributions we see a large difference between the PLCA and the IOLCA, which partly explains the overall difference. Using one price's database we were able to show that this difference comes more from the quantity of the process "consumed" than the CO_2 emissions per unit. This assessment raises the question of the underestimation of the quantity of some processes in ecoinvent and the fact that ecoinvent also includes various products in one process (for instance, different levels of purity of one product), which might lead to an underestimation of the impact in some cases. This assessment confirmed the need for further assessment of chemicals for ICT in ecoinvent.

The determination of the cut-offs processes leads to a substantial increase of the CO_2 emissions (+ 40%, one third approximately being services). Some Input-Output sectors are of importance when considering the cut-offs (wholesale trade, air transportation, or advertising, in this case), which might constitute an indication of the new processes or contributions that should be considered in ecoinvent (this has already been shown in various paper such as (Norris et al., 2003). A lot of sectors contribute only a very small part to cut-offs (less than 1%). The total CO2 emissions induced by the production of one pc-si wafer is very different if evaluated with the PLCA or the IOLCA.

2.8.2.2 LCI of USA electricity mix

In the case of the US electricity mix, the cumulative CO_2 emissions in IOLCA and PLCA are rather similar (+ 10%). As in the case of the pc-si wafer, the structure of the contributions are similar. On the other hand, in this case, the contribution of cut-offs processes is neglected (1.5 %).

2.9 Recommendation

As a conclusion of the study, it is recommended to at least follow level 1 and use a tiered approach. That is, IOLCA should be used to set LCI investigation priorities and to identify potential data gaps in PLCA. This is motivated by the lack of consistency when merging both approaches and simply adding emissions obtained by both approaches. When significant differences are observed at level 1, it could be of interest to apply level 2 or above, at least to compare consistently PLCA and IO, and to better understand where weakness are coming from. We believe that following level 1 is an important point for the further development of ecoinvent.

2.10 Methodology used in chapters 3 to 5

In chapter 3, PLCA is used to evaluate the environmental impact of a desktop computer as well as of a notebook. Both PLCA and IOLCA are then used and compared to calculate the environmental impact of the EPFL computer network. The service-linked contributions included in the total cost of ownership of the computer network are evaluated using IOLCA. Finally, the cut-offs processes (all the contributions not considered in PLCA) are evaluated in the case of a personal computer using the methodology developed in this chapter.

Chapter 4 applies IOLCA to evaluate the environmental impact and benefits of the telemonitoring system of the city of Martigny. This application of ICT enables resource savings by better managing the urban networks. A tiered hybrid approach is applied where PLCA is used as a complement to the IOLCA. This enhance the quality of the evaluation, taking into account the geographical characteristics of the energy production and water consumption.

Chapter 5 uses PLCA to evaluate the environmental impact of an innovative service, the visiophonic station. The service-linked contribution as well as the communication infrastructure are included in the analysis using a tiered hybrid approach similar to that used in chapter 4. Finally both PLCA and IOLCA data are used for the development of the methodology that enables the quantification of the rebound effects linked to the use of the time and financial resources made available.

3 ENVIRONMENTAL EVALUATION OF A COMPUTER NETWORK USING PROCESS AND INPUT-OUTPUT LIFE CYCLE ASSESSMENT

3.1 Abstract

The environmental impact of a university computer network has been comprehensively assessed using two complementary LCA methods. A process-level study has been performed focusing on the direct, as well as indirect (“embodied”), energy and key pollutants (CO_2 and NO_x) attributable to the input requirements of the total physical infrastructure. It includes various scenarios for near-term technology changes in the computer network infrastructure. Results show the dominance of the PC's impact over the other equipment, though the server and the switches have a significant contribution due to their high electricity consumption. Shifting from cathode ray tube (CRT) monitors to liquid crystal display (LCD) flat screens and from desktops to notebooks enables significant reduction in environmental impacts. An Input-Output approach has been used to evaluate the impacts of both the material and the services associated with the total cost of ownership of the computer network infrastructure. It shows that the impacts of software, management, maintenance, and telecommunication services can be significant, and that an environmentally friendly computer is also a reliable one. Hybrid methodologies help us to enhance the quality of the evaluation of the environmental impact of a PC. In this sector, the Input-Output allows one to compensate for the lack of PLCA data and to include contributions generally not considered in the evaluation.

3.2 Introduction

ICT are increasingly applied throughout the economy as a tool for working, communicating, marketing, and training delivery, and as a substitute for traditional face-to-face meetings, and will thus have more and more environmental impacts (Berkhout and Hertin, 2001; Arnfalk, 2002; Herring and Roy, 2002). Nevertheless, the environmental impacts of a computer network and its infrastructure are not very well known.

LCA evaluates the environmental performance of a technology and is appropriate to identify key parameters related to the environmental impact of a product or a service. Process LCA (PLCA: (Heijungs et al., 1992; Frischknecht and Kolm, 1995; ISO, 1997; Nielse et al., 2001; Heijungs and Suh, 2002; Jolliet et al., 2005) commonly takes into account the material and energy inputs to an infrastructure such as a computer network. IOLCA is based on the Input-Output theory (Miller and Blair, 1985) that has been extended to perform LCA (Cobas et al., 1995; Cobas-Flores et al., 1996; Gaines and Stodolsky, 1997; Hendrickson et al., 1997; Joshi, 2000; Lenzen, 2001; Suh and Huppes, 2002; Suh and Huppes, 2005). IO-LCA is a method based on the monetary flows induced in the economy and through all the supply chain by a product, process, or activity. It allows quantifying energy consumption and pollutant releases that are linked to these monetary transactions according to the sectors (industries) to which these transactions are related.

Available LCA studies assessing the environmental impact of PC are rare ((MCC), 1993; Tekawa et al., 1997; Atlantic Consulting, 1998; Williams, 2004 (b); Williams, 2004 (c)), and almost unique for LCD monitors and notebooks (Tekawa et al., 1997; Leet Socolof et al., 2002). PLCA of PCs are all older than 1998, except the study performed by Williams (Williams, 2004 (b); Williams, 2004 (c)), and the technology and modes of production of PCs these days are very different. As shown in figure 23, there are high variations between different assessments of the Life Cycle Impact of a PC using PLCA. For instance, Leet (Leet Socolof et al., 2002) evaluates the PLCA of a desktop monitor and find results higher than for the evaluation of a complete computer by a factor of ten. PCs are difficult to assess using PLCA because of the high number of components and suppliers involved, and because of the confidentiality of most data. This renders a study time which is consuming and expensive to perform (Spielmann and Schischke, 2001). The available studies also mainly evaluate the environmental impact using indicators such as the primary non-renewable energy and the CO_2 emissions, and we miss information on the impact categories using a more comprehensive life cycle impact assessment method, such as Impact 2002+ (Jolliet et al., 2003). Information on the environmental impact of the end-of-life phase is generally missing. Scharnhorst (Scharnhorst et al., 2005) evaluated that, although the use and production phase dominate the impact over the entire life cycle of a GSM 900 mobile phone network, the end-of-life phase dominates the impacts on ecosystem quality.

The environmental impacts of the computer network infrastructure are generally not taken into account when comparing e-services with traditional services, as in comparisons of e-commerce and traditional commerce (Matthews et al., 2002; Williams and Tagami, 2002; Norris et al., 2003). In order to prioritize efforts to reduce the environmental impacts of the computer networks, we need to know what the key impacts are in the present system and in projections for future infrastructure configurations. In addition, although services such as maintenance, management, and training, as well as communication, are of importance in terms of expenses, their contributions to the environmental impact are rarely included (Rosenblum et al., 2000).

In this context, the IOLCA can be seen as a powerful tool to assess a complex technological system with related services. However, it has to face two main limitations: 1) it cannot discriminate between various products from the same industrial sector, and 2) Input-Output data are old and therefore IOLCA is not the best appropriate method to analyze fast changing technologies.

To answer the above-identified needs, the present paper addresses the following questions: What is the environmental impact of a computer, of CRT and LCD monitors as well as of notebooks? What are the key elements of a university computer network leading to the largest environmental impacts? How important is the production compared to the use phase? What are the consequences of near-term technology changes? What is the relative importance of software, management, maintenance, and telecommunication services compared to hardware-based emissions? How do IO results compare to PLCA results and complement them in the context of telecommunication systems?

This paper aims at evaluating the environmental impact of a PC and a notebook. It uses these results to calculate the environmental impacts of the computer network infrastructure in a university. It identifies, from an environmental point of view, the key elements of the computer network infrastructure and evaluates the potential of various short-term technological changes. The contributions of all the components to the total cost of ownership – all the associated costs necessary to run the system (Coleman, 1998) - are taken into account to capture the overall impact of the network use.

Following this introduction and the review of available literature, the paper successively describes the developed approaches to assess the environmental impact of: a) the manufacturing of personal computers, b) the impact of the network infrastructure, including the use phase, and c) the cost of ownership linked to network management and maintenance. It then presents and discusses results for each of these three parts.

3.3 METHODOLOGY

3.3.1 Assessment of computer manufacturing

The best available data sources were merged together with confidential data from the industry to obtain the most reliable results for primary non-renewable energy, CO_2 and the NO_x (table 1) as well as the damage factors of the Life Cycle Impact Assessment method Impact 2002+ (Jolliet et al., 2003) for a control unit, a CRT monitor, a LCD monitor and a notebook. Different references were used to determine the composition of a control unit (Atlantic Consulting, 1998; Williams, 2004 (b)), a CRT (Leet Socolof et al., 2002) and a LCD (Leet Socolof et al., 2002) monitor. We dismantled a notebook and weighted all of the components. The most reliable data on microchips (Williams et al., 2002; Williams, 2004 (a); Williams, 2004 (b)) and printed wiring boards (PWB) (confidential data) (Scharnhorst, 2003; Williams, 2004 (b)) are combined with the ecoinvent database (Swiss Centre for Life-Cycle Inventories, 2004) to perform the evaluation of the environmental impact of the production of the equipment.

3.3.2 Assessment of the University computer network

Two approaches to LCA, PLCA and IOLCA, have been used to evaluate the impact of the computer network infrastructure of the Swiss Institute of Technology (EPFL). The functional unit studied is one year of use of the network. In order to apply both the process and the IO LCA, an inventory of the necessary equipment has been performed within the school (EPFL). Calculation of the electricity consumed in one year by the network infrastructure is based on the following scenario: the PCs and monitors are on 8 hours a day, 230 days a year. Servers, switches and routers operate continuously. The calculation of the total time spent printing versus idling in stand-by mode for the printers is based on paper consumption, assuming an average time of 3.53 s per page printed. The printers are considered to be in the stand-by mode otherwise. For the production of the servers, the switches and routers, and the printers, we use the same per kg values as for the PCs. Data for paper and electricity (European and Swiss mixes) are obtained from the ecoinvent 2000 database (Swiss Centre for Life-Cycle Inventories, 2004). Optic fibers and copper cables have been dismantled and the different parts weighed. The ecoinvent (Swiss Centre for Life-Cycle Inventories, 2004)database was then used to calculate the primary energy and emissions. The lifetime of all equipment is assumed to be 5 years.

The IO LCA is based on the datasets chosen in chapter 2: the US 1998 IO table and environmental data by Suh (Suh, 2004 (b); Suh, 2005). The IO approach uses energy consumption and pollutant emissions per dollar of output. Thus, the energy consumption and the emissions have been estimated based on an average price per type of equipment (see table 9).

Table 9: List of the equipment, paper and electricity used annually to run the Swiss Federal Institute of Technology-Lausanne computer network and corresponding prices, non-renewable primary energy consumed, and main pollutants emitted. Data are from 2001.

Equipment	Amount	Average price [$/equipment]	Weight [kg/equipment]	Electricity cons. [W/equipment]	Primary energy [MJ/kg equipment]	CO_2 [kg/kg equipment]	NO_x [g/kg equipment]
Control unit	6’745	1'533	9.7	100	577	23.4	55.6
CRT screen	4’722	400	17.0	150	85	3.9	11.5
LCD screen	2’024	533	4.8	40	136	6.0	21.0
Notebook	355	2’333	4.0	40	928	36.8	81.9
Server	68	4800	36.0	500	577	23.4	55.6
Switch-router	116	7’470	50.0	700	577	23.4	55.6
Printer	400	1’667	20	420/20	577	23.4	55.6
Paper	50’600 kg/year	3.6 [$/kg]	-	-	29.7	1.34	5.16
Cable	121’225 m	3.1 [$/m]	-	-	4.4 [MJ/m]	0.2 [kg/m]	0.4 [g/m]
Electricity (EU mix)	$2.86\ 10^6$ kWh/year	0.1 [$/kWh]	-	-	11.8 [MJ/kWh]	0.51 [kg/kWh]	0.95 [g/kWh]
Electricity (CH mix)	$2.86\ 10^6$ kWh/year	0.1 [$/kWh]	-	-	6.0 [MJ/kWh]	0.021 [kg/kWh]	0.079 [g/kWh]
Electricity (US mix)[28]	$2.86\ 10^6$ kWh/year	0.1 [$/kWh]	-	-	11.4 [MJ/kWh]	0.65 [kg/kWh]	1.4 [g/kWh]
Building furniture and maintenance	303000 $/year	-	-	-	6.23 [MJ/$]	0.356 [kg/$]	1.27 [g/$]
Telecom	486000 $/year	-	-	-	5.17 [MJ/$]	0.315 [kg/$]	1.88 [g/$]

[28] The environmental impact of the US mix has been evaluated using the US electricity mix, but with European technologies.

Software	26740 $/year	-	-	-	4.12 [MJ/$]	0.245 [kg/$]	0.895 [g/$]
Management	9.3 10^6 $/year	-	-	-	2.06 [MJ/$]	0.179 [kg/$]	0.62 [g/$]

Two alternative scenarios have been investigated. In the first case flat LCD screens replace all CRT monitors. In the second scenario notebooks replace all desktops computers.

3.3.3 Total cost of ownership

The analysis further expands the boundaries by considering the environmental burdens of non-hardware input requirements associated with the network use such as software, training, management, trouble-shooting – the "Total cost of ownership" (TCO) for the personal computer portion of the system. This total cost of ownership and the related CO_2 emissions have been investigated by collecting the expenses linked to the use of the EPFL computer network in 2001: the physical data such as ICT value, space used, electricity consumption, and the fraction of the total EPFL expenses that was allocated to the computer network infrastructure. In addition, interviews were carried out to quantify some internal costs associated with the management of the computer network infrastructure. According to EPFL employment, 12 people are working full time for the maintenance of the University's network. In addition, 6 employees are necessary to maintain the local networks, advise the collaborators, test the software, and perform the everyday maintenance. Finally, based on interviews with professionals, we estimate that employees spend on average 1% of their time on the management of their individual computer. This includes solving problems connecting the computer to the network, with printing, with installing important software, etc. Emissions induced by different expenses have been evaluated using the IO approach by assigning them to the best corresponding IO industrial sector, both for the infrastructure and for its maintenance and management. To avoid double counting, we removed the already considered contributions, such as the equipment. The communication costs linked to Internet use and data exchange outside EPFL were evaluated to $486,000 per year.

Emissions are calculated for the CO_2 and the NO_x inventory results and the Life Cycle Impact Assessment carried out using the Impact 2002+ method (Jolliet et al., 2003).

3.4 RESULTS

3.4.1 Impact of personal computers manufacturing

Figure 23 presents the non-renewable primary energy for the production of three EPFL personal computers and compares it to other studies. The weight of the studied control units ranges from 6.8 to 11.6 kg and for the CRT monitors from 12.1 to 15.0 kg. Including the control unit, the energy consumed amounts to 7042 MJ with a CRT monitor and 6254 MJ with an LCD monitor. The notebook is less energy intensive, with 3710 MJ non-renewable energy consumed for its production. Chips and microchips dominate the non-renewable primary energy of the control unit and of the notebook with 67% of the impact from the control unit and 62% of the impact from the notebook. This is followed by the printed wiring board (PWB) with 25% of the impact from the control unit and 11% of the impact from the notebook. Finally the bulk materials contribute to 8% and 27% of the life cycle primary energy for manufacturing the control unit and the notebook. The packaging was not considered in our evaluation, as other studies have shown that it is negligible in the case of a PC. The impact of an LCD monitor is 2.2 times smaller than that of a CRT. For the CRT monitor, the PWB contributes the most (44%), but the shares of glass (9%) and steel (11%) are significant. The PWB is responsible for 42% of the impact of the LCD monitor and the contributions of the polycarbonate (9%) and the polymethyl methacrylate (9%) are significant. Figure 24 extends these results to other impact categories by applying the Impact 2002+ method (Jolliet et al., 2003). The human health impact is dominated by the PWB. For ecosystem quality, the contributions of the PWB and the chips are similar and together represent more than 80% of the impact. Finally, for the global warming potential and the resources, the highest share of the impact is due to the chips and microchips.

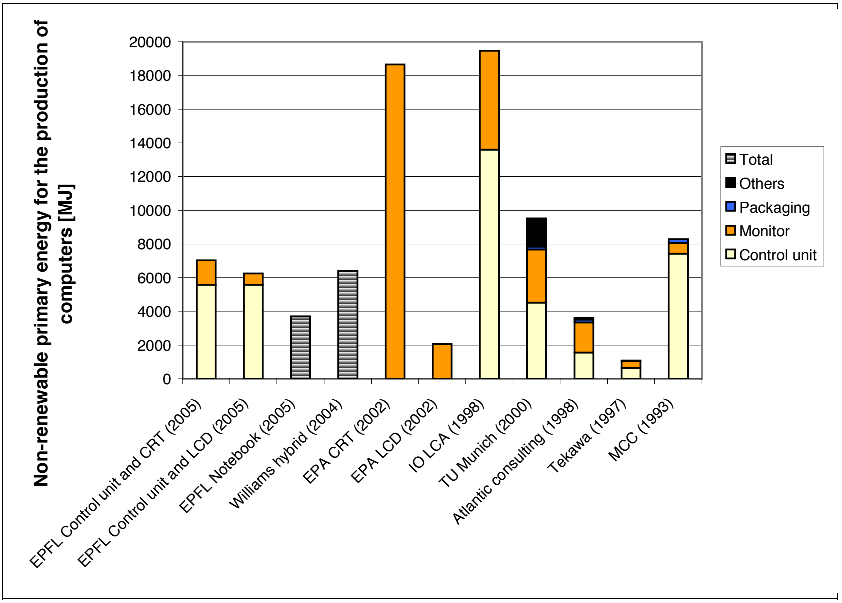


Figure 23: Non-renewable primary energy for the production of a personal computer and related peripheral equipments compared to literature sources, from cradle to gate.

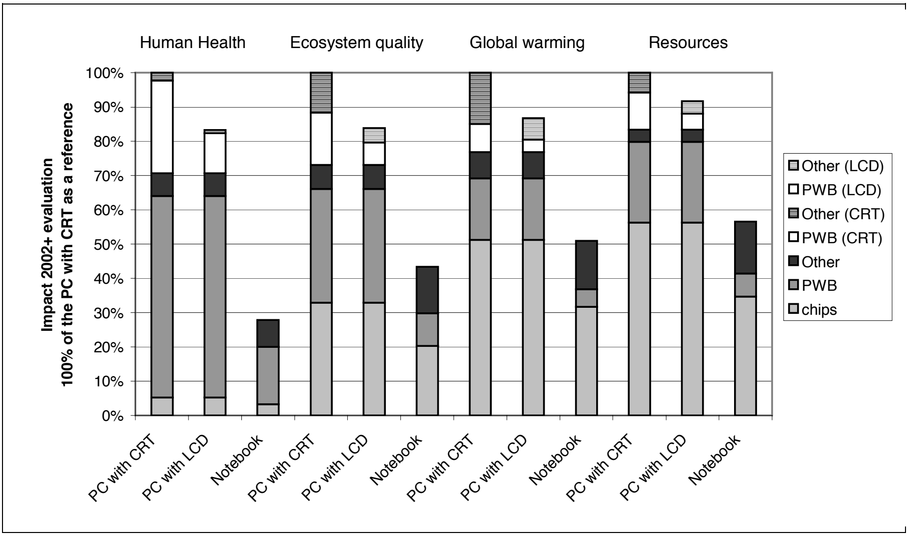


Figure 24: Evaluation of the environmental impacts of the personal computer with a CRT monitor, with an LCD monitor and the impacts of a notebook using Impact 2002+.

3.4.2 Assessment of the computer network

When considering the use phase and all network components, figure 25 show that the PCs (control units and screens) cause the largest share of environmental impact, while the 116 routers and switches also contribute significantly to non-renewable primary energy use and to CO_2 and NO_x emissions. The use phase plays a dominant role when the US or the EU electricity mixes are used, but the production phase is also of importance. For the desktop PC scenario, the use phase amounts to 71% to 82% of the impact, whereas it only amounts to 14% to 17 % when the Swiss electricity mix is used. Use phase impacts are almost exclusively caused by electricity use, thus the key role played by the electricity mix, as shown on figure 23 for the US, the European and the Swiss mixes given by the ecoinvent database[29] (Swiss Centre for Life-Cycle Inventories, 2004). Printer and paper production represent a rather small share of the environmental impact.

[29] The ecoinvent database does not give any value for the US electricity mix. It is nevertheless possible to build it using data from the US EPA for the electricity mix and data from European average technology from Ecoinvent for the emissions from electricity production.

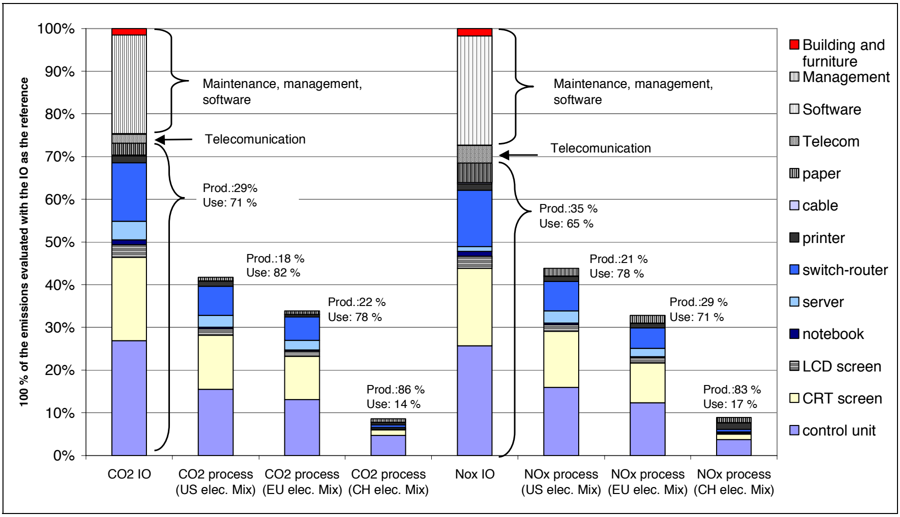


Figure 25: CO_2 and NO_x emissions over the entire network life cycle using IO with management and maintenance as well as PLCA with the European and Swiss electricity mixes. The TCO has not been taken into account with PLCA.

In the future, the foreseeable use of flat screens and the move from desktops to notebooks will reduce the energy consumption (figure 24): If all desktops are replaced by notebooks, the non-renewable primary energy requirements are reduced by 50%. The current replacement of CRT screens by LCD provides another way of decreasing the impacts, with a 20% reduction for a complete substitution.

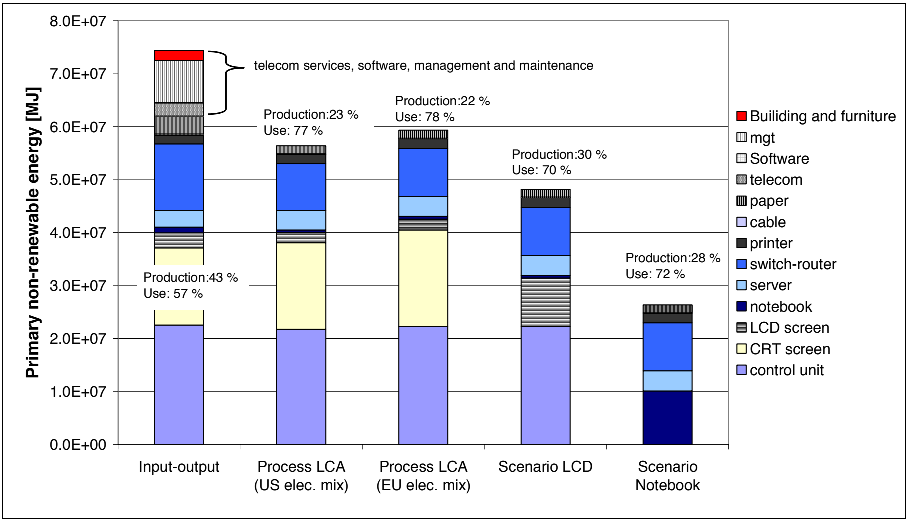
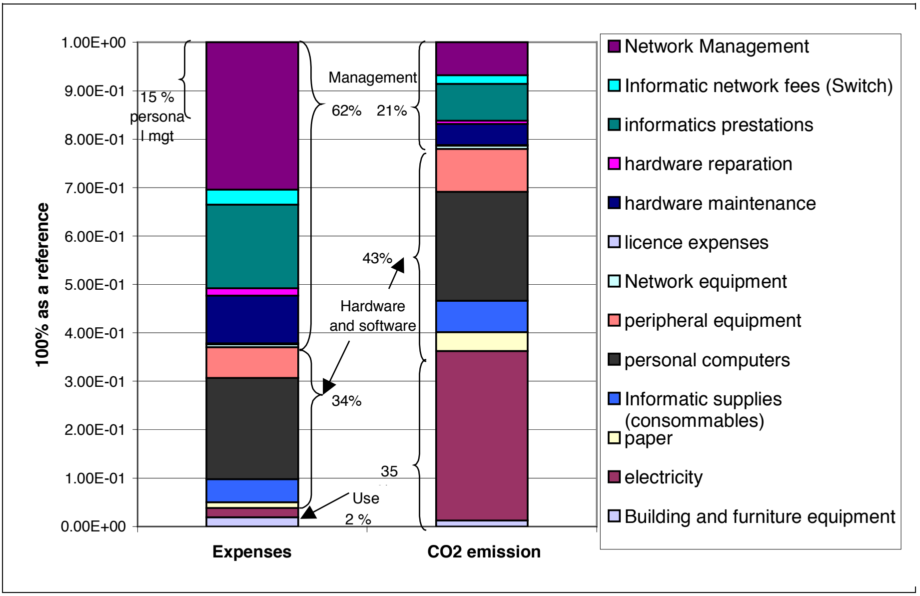


Figure 26: Primary non-renewable energy for one year of the use of the computer network of the EPFL and comparisons with scenarios in which all CRT monitors are replaced with LCD or all desktops are replaced with notebooks. TCO has not been considered with PLCA.

3.4.3 Total Cost of Ownership

Based on the expenses of the Swiss Institute of Technology (table 9), the IO approach enables calculating a first estimate of the emissions linked to the total cost of ownership, taking into account the service oriented tasks: software, management, maintenance and telecommunication services (figure 27). On the one hand, hardware costs are restricted, personal computers contributing to only 21% of the overall cost followed by peripheral equipment (6.4%) and informatics supplies (4.8%). On the other hand, services dominate with more than 55% of the overall costs. In accordance to the PLCA results, the personal computers and the electricity consumption dominate the impacts. Service contribution is smaller but still significant with 21% of the CO_2 emissions and of the primary non-renewable energy consumption (figures 24 and 25). The cost and environmental impact of the connection to the greater world, which can be seen as the use of the international network that constitutes the Internet are rather small with respectively 3% and 1.8% of the total. The low price of the electricity makes it significant for the cost (less than 2%) but the highest contributor in terms of CO_2 emissions (35%).



Figures 27: Repartition of the total cost of ownership (TCO) of the EPFL computer network and associated CO_2 emissions calculated using IO LCA.

3.4.4 Comparison between IO and Process LCA

Figures 23 and 24 show similar impacts with the IO LCA and with the PLCA for the primary non-renewable energy and higher values for the IO LCA for the other pollutants. The ratios between the IO LCA and the PLCA with the US electricity mix is 1.10 for the non-renewable primary energy, 1.75 for the CO_2 and 2.28 for the NO_x. The share of the contribution of each equipment is however, comparable, with IOLCA and PLCA. In both cases PCs are dominating.

The results for the non-renewable primary energy show higher values for the production phase with the IO LCA than the PLCA, but it gives lower values for the use phase. This is not the case for the CO_2 and the NO_x, where the IO LCA gives higher values for both the production and the use phase (figures 24).

3.5 Discussion

3.5.1 Impact of personal computers

LCD monitors and notebooks consume less energy than respectively CRT monitors and desktops and the impact of their production is also lower. The higher need for non-renewable primary energy for the production of a CRT monitor than an LCD is confirmed by the EPA study (Leet Socolof et al., 2002), although the absolute value found in this study is far higher than our results and unrealistic according to Williams (Williams, 2004 (c)). This difference comes from the reduction in PWB in the LCD compared to the CRT monitor and from the difference in weight between the two screens (the LCD is much lighter than the CRT). The decrease of the environmental impact when shifting from a desktop to a notebook occurs principally because the quantity of chips and of PWB is lower in the notebook. A smaller part of the difference also comes from the fact that the notebooks are lighter than desktops. These results need, however, to be taken with care as chips and PWB are supposed to be the same in both machines.

For the chips and microchips, the electricity, and more generally the energy consumed to produce the chips, is responsible for the major part of the primary non-rewewable energy use. The very high values for the SO_2 emissions for palladium and platinum explain the very high value of the human health damage factor (figures 24).

The rapid technological change and high level of confidentiality of the data makes it difficult to regularly perform assessments of the non-renewable primary energy demand for the production of electronic equipment. As PC production represents a significant share of the environmental impact, following closely its evolution is important and should be more intensively tackled in close collaboration with producers. The end-of-life phase should also be better considered and assessed in more details as its impact, especially on ecosystem quality, could be significant (Scharnhorst et al., 2005).

Figures 23 shows a large difference in the evaluation of the non-renewable primary energy for the production of a PC using PLCA and IOLCA. In order to explain this difference, the methodology developed in Chapter 2 has been applied to the case of one personal computer composed of one control unit and one CRT monitor. The aggregation scheme[30] is presented in Figures 27. The difference in the evaluation of the CO_2 emissions is explained partly by the higher impact of the cover and the motors and generators of the PCs, and by the inclusion of the CO_2 emissions linked to the PC assembly. The cut-off processes that were not considered in the PLCA contribute to 40% of the CO_2 emissions, and are dominated by the wholesale trade and the air transportation. Their important contribution in the IOLCA suggests that PLCA should include these processes in the analysis.

[30] Some processes are aggregated to enable a comparison between PLCA and IOLCA. Basically, all the sub-processes that are included in the same IO sector as the studied process (in this case, the personal computer) are aggregated with it. Detailed explanations of the aggregation process are presented in Chapter 2.

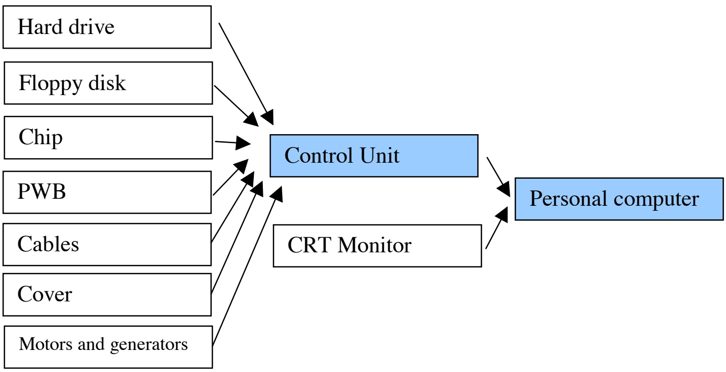
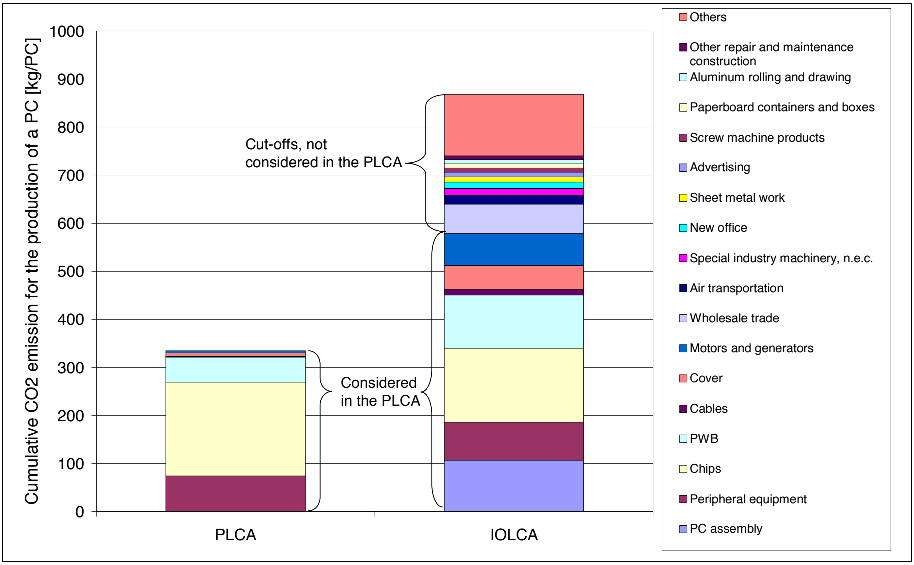


Figure 27: Aggregation scheme of the personal computer to perform a detailed comparison between the process and the Input-Output LCA. Processes in blue are aggregated.



Figures 28: Comparison of the cumulative CO_2 emission for the production of one personal computer with the PLCA and the IOLCA.

3.5.2 Impact of the computer network

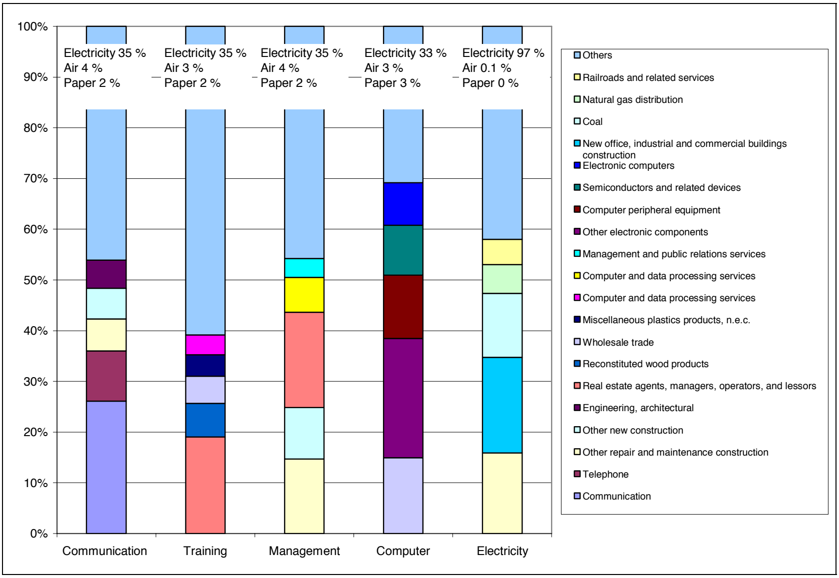
The domination of the PCs is not surprising due to the large number of machines necessary to run the network. Due to their high electricity consumption, the switches-routers contribute in significantly to the environmental impact. The other equipment, such as notebooks, servers, printers, cables and paper, each play a minor role. The use phase, mainly electricity consumption, contributes to approximately 70% of the impact. This share is relatively high compared to other studies. This can be explained by our scenario, which defined that the daily use time is 8 hours. Decreasing this value as well as using another electricity mix (such as the Swiss mix), would give more importance to the production phase of the equipment. Efforts should be put both toward the reduction of the electricity consumption of the machines and the reduction of the impact of the production phase. The former should be given a much higher priority for all PC manufacturing and not only for notebooks. The latter could be achieved by extending the lifetime of the machines. The choice of the system used (PC and Windows, Macintosh, Linux) can therefore have an indirect effect on the environmental impact, given that the lifetime of a computer can be significantly different depending on the system.

In the EPFL case, the total electricity consumption of the computer network infrastructure represents 7.5% of the total University consumption. The various scenarios presented show that an institutional purchasing policy that favors notebooks and flat screens has the potential to significantly reduce the burdens of the total computer network infrastructure. The shift to LCD monitor could decrease by 20% the impact of the use phase. Projection shows that the production of CRT monitors will probably (Coutance, 2005) drastically decrease in the following years. Excepted for some specific use, LCD monitors replaces advantageously CRT (Alzieu, 2004). They are thinner, less energy consuming and less tiring for the eye. The mobility of notebooks answers different needs from the consumer perspective and therefore the functional unit is likely not to be filled in the same way with notebooks instead of desktops. As a consequence the way people work with a notebook is not the same as with desktop computer and the boundary of the assessment should be further extended to take into account indirect effects. It is likely that some of the people working with notebooks would not need another computer at home. However, the machine must be transported between home and work and thus slightly increases the energy consumption of mode of transportation.

Communication to the outside world contribute to a small part of the total impact of the computer network (figures 23 and 24), which means that the use of the Internet network around the world does not contribute that much to the impact of one computer network.

3.5.3 Total Cost of Ownership

Traditionally impact assessments have concentrated on hardware, which only provides a partial view of the environmental impacts of a computer network for instance. The evaluation of the TCO using the expenses of the EPFL shows that the contribution of services is significant and should be taken into account. In particular, the management of the computer network, including the time spent by the collaborators managing their computer (fatal errors, installation of program, windows updates, viruses etc.), is responsible for a significant part of the impact. The improvement of total ownership costs, such as increased operating system stability, can therefore significantly reduce both the cost and the total environmental impact of the computer network. Figures 29 analyses the cradle to gate CO_2 emissions of these services as well as some others key Input-Output sectors for the evaluation of the computer network. The total share of three industrial sectors: the electricity production, the air transportation and the paper are given as well. It shows for instance that 35% of the CO_2 emissions induced by the communication sector is generated in the electric services sector. It is important to notice that only 50% of the CO_2 emissions are linked to the top five direct contributors. Overall, the electricity production is the sector responsible for most of the CO_2 emissions linked to the service sectors. As it also accounts for the highest share of the impact of the computer network, reducing the electricity consumption and producing electricity using renewable resources and polluting less should be the first priority in order to reduce efficiently the environmental impact of the computer network. Figures 27 shows that the cost associated with the electricity consumption is not dominant and therefore a small increase would only play a minor role in the overall costs and would lead to important savings for the environment. This could be achieved by using more efficient computers and by having a special electricity contract with green electricity ecolabel, provided that the additional payment in such labels are entirely invested in the development of new technologies and do not simply support existing green technologies.



Figures 29: CO_2 emissions linked to the direct contributors of some industrial sectors and overall importance of the following sectors: electricity production, air transportation and paper production. The graphics shows which industrial sectors are of importance for certain key sectors for the computer network. This evaluation has been performed by analysis industrial sectors of the IO table.

3.5.4 Comparison between IO and Process LCA

PLCA traditionally takes into account the environmental impacts of the production of physical inputs, but data on the delivery of services are not currently provided by PLCA databases. The use of the IO approach is very promising for the evaluation of the impacts of services when combined, as in this case, with data on service costs such as provided in the estimated components of total cost of ownership. Different options can be taken here:

- learning from IOLCA to enhance the quality of PLCA and extend it to the treatment of services for the computer network as well as for the evaluation of the environmental impact of the ICT equipment;
- to use a tiered hybrid approach, which would mean to evaluate the contributions not considered in a PLCA with the IOLCA and to sum them up. In particular, this would require a new evaluation of the production of ICT equipment using PLCA data and results presented in figures 27;

3.6 Conclusion and learning

The methodology described and developed in chapter 2 can be used to evaluate the environmental performances of ICT equipment and, in particular, of complex systems. In the case of a computer network, the PC and the screen dominate the impact, but the server and the switches have a significant contribution due to their high electricity consumption. In a professional context, characterized by a long use of the equipment, the impact of the use phase (electricity consumption) dominates, and yet the impact of the production phase is still significant. The PLCA shows us that near-term technology changes can have a very important effect on the environmental impact, evaluated here with the CO_2 emissions, and can decrease impacts by 20 to 50%. Extending further the system boundaries leads to the conclusion that services needed for the maintenance of the network, the management of the computer, etc. have a significant impact and that the total cost of ownership (TCO) should be considered when evaluating the environmental impact of an ICT system. Finally, hybrid methodologies help us to enhance the quality of the evaluation of the environmental impact of a PC. In this sector, the Input-Output allows one to compensate for the lack of data and to include contributions generally not considered in the evaluation.

4 ICT APPLICATION: EVALUATION OF THE ENVIRONMENTAL IMPACT OF THE TELEMONITORING SYSTEM IN THE CITY OF MARTIGNY

4.1 Abstract

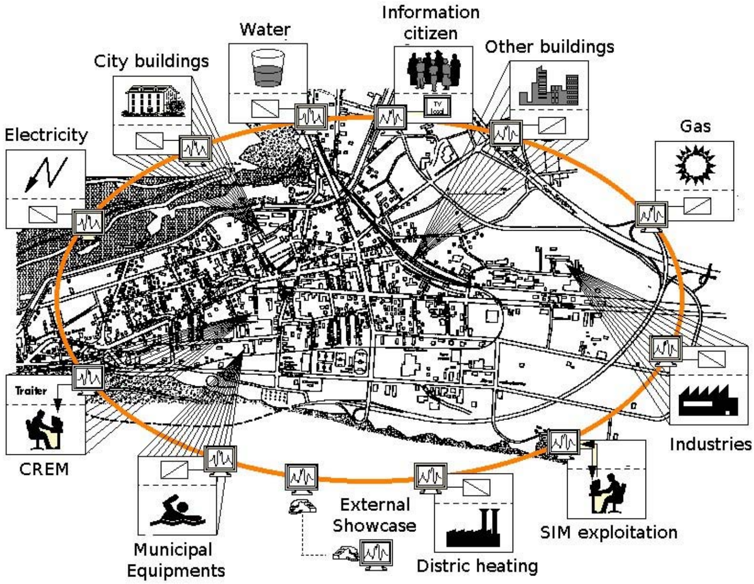
Nowadays, the urban utilities management is complex and often poorly coordinated, due to departmental compartmentalism. A systemic approach, defined as urbistics, gives the public managers better tools for sustainable city management. Using microcomputers and the cable TV network, the CREM (Urbistic Competence Center) monitors a real scale observation: Martigny, 15'000 inhabitants. Every hour, the electricity, natural gas, district heating, and drinking water flows are measured in 30 locations, centralised and visualized on a computer. The use of ICT permits the Industrial Utility Services to gain key information about the network's behaviour. This information enables the utility services to better understand consumption patterns and to improve the management of the network, which could lead to substantial savings of resources.

An LCA has been performed to evaluate the overall effect of the system and to balance the impacts of the additional monitoring infrastructure against its benefits. The first task was to make an inventory of the necessary infrastructure and to determine the direct and indirect effects of the use of the monitoring system. The direct impacts are negative and include the necessary infrastructure: computers, electricity consumption, maintenance, research, etc. The indirect impacts are mostly positive: increased efficiency of the network, the elimination of the need to build a reservoir, the possibility to dialogue with the customers and influence their consumption, etc. The benefits of its use have been evaluated using reports and interviews. Environmental impacts were first calculated using IOLCA. To strengthen the analysis, PLCA data were also used to take into account geographical particularities. The evaluation shows that the monitoring system is beneficial, both from economic and environmental points of view, with the environmental benefits being proportionally far higher than the financial savings. The telemonitoring system of the city of Martigny is an example of how and under which conditions ICT can contribute to sustainable development.

4.2 Introduction

Applications of ICT are numerous and may have positive or negative impacts. This paper develops an approach to evaluate the direct and indirect environmental impacts and benefits of ICT and apply it to the city of Martigny, Switzerland to illustrate how the information society can have effects on the management of urban networks.

Without a coordinated management with a systemic vision, a city remains a dynamic, chaotic system. A monitoring system allows one to capture the dynamic and complex nature of the whole system in order to better understand the interactions between users and the energy and water distribution networks in the urban area. From this information, actions and coordination to optimise the system efficiency can be taken. The Industrial Utility Services of Martigny (IS) supplies drinking water, electricity, district heating, natural gas, and cable TV for 15’000 inhabitants.



Figures 30: The behaviour of urban networks is very complex. The urbistic approach is based on the measurement of the flows to understand the behaviour of the networks (electricity, water, natural gas, district heating) and to better manage them.

In order to monitor the urban networks, the CREM, supported by the IS and the Swiss Federal Institute of Technology in Lausanne (EPFL), developed and installed a telemonitoring system using desktop computers and the cable TV network. This installation records every hour more than 300 measurements of consumption (electricity, district heating, water, and gas) taken from 30 sites. This system enables managers to effectively visualise the city in terms of energy consumption and resource utilization, and gives local authorities an effective tool for decision-making.

Figures 31: The industrial services of Martigny have equipped 30 sites with computers and data acquisition equipment. The data are then centralised on a server.

After fifteen years of experimentation in the field of urban network management using telemonitoring system, interesting results were found. Indeed, uninterrupted monitoring of the water supply and district heating networks made it possible to detect anomalies. Similarly, measurements of the electric power output carried out on selected subscribers made it possible to reduce their power consumption significantly.

However, a question was raised whether the environmental benefit outweighs the impact produced by the necessary telemonitoring infrastructure. This implies the quantification of the environmental impacts that were avoided due to resources and energy savings and those impacts generated due to the use and set up of the telemonitoring system.

The environmental impact of the infrastructure has been the subject of various LCA studies through the assessment of PCs ((MCC), 1993; Tekawa et al., 1997; Atlantic Consulting, 1998; Williams, 2004 (b); Williams, 2004 (c)), LCD monitors, and notebooks (Tekawa et al., 1997; Leet Socolof et al., 2002). Chapter 3 describes in detail the environmental impact of a computer network infrastructure.

The Japanese Ministry of Telecommunication evaluated in 1997 that the combination of possible ICT applications could reduce CO2 emissions in Japan by 7%. (Miura et al., 2002). E-banking and e-commerce for instance, allow the trading of goods, money, stocks, and shares at home, saving paper, time, and transport (Berkhout and Hertin, 2001; Faucheux et al., 2001; Loerincik and Jolliet, 2002; Loerincik and Jolliet, 2002; Palmin et al., 2002). Rome-based Merloni Eletrrodomestici, the fourth largest household-appliance vendor in Europe, has developed a line of digital refrigerators, washing machines, and dishwashers with remote Internet-control features that save energy by allowing homeowners and local utilities to monitor the power consumption of each appliance. Using web-based micro-management, individual appliances can be powered-down during peak loads and programmed to operate during off-peak periods when utilities have excess generating capacity.

These studies show that there is a potential for lowering the environmental impact with ICT and ICT applications, but that we lack detailed results and practical examples. Several studies have shown, for instance, that e-commerce and traditional commerce are fairly equivalent in terms of environmental impact (Matthews et al., 2002; Williams and Tagami, 2002; Norris et al., 2003). Arnfalk demonstrates that for telework, the total CO2 emissions are largely dependent on the effects of commuting. Depending on the telework arrangements, it can lead to a reduction or an increase of CO2 (Arnfalk, 2002).

Many studies do give lots of examples about the potential of ICT for reducing the environmental impact. But to give a clear message, we need to understand through various case studies in which circumstances the ICT can play an important role on the environmental impact and when it cannot. In addition, it is essential that impacts and benefits are compared in a consistent way, with a full life cycle analysis that includes the impact of created and avoided infrastructure and services.

This study aims to address this need by providing answers to the questions set forth by researchers of the CREM concerning the effectiveness of the urbistic concept they developed. It will also attempt to evaluate how far ICT can help to better manage industrial network in cities. This implies the quantification of the environmental impacts that were avoided due to resources and energy savings and those impacts generated due to the use and set up of the telemonitoring system.

In particular, the following questions are raised: Is the telemonitoring system of the city of Martigny a positive economic and environmental investment? What method can be used to assess such an infrastructure? What is the potential of ICT to enhance the efficiency of the management of urban networks?

More specifically this paper aims to:

- Evaluate the impact of the computer and monitoring infrastructure using Life Cyle Assessment of ICT;
- Develop a method to evaluate in a consistent way the indirect benefits induced by telemonitoring;
- Determine how far and under which conditions the application of ICT and the use of the collected information is beneficial from an economic and an environmental perspective in the case of the city of Martigny.

Following this introduction, the methodology used to assess the telemonitoring infrastructure and its benefits is described. Impacts versus benefits of the infrastructure are then compared. The results are further analyzed in the discussion and final recommendations are given in the conclusion.

4.3 Methodology

To achieve these goals, Life Cycle Analysis (LCA) has been chosen as an environmental assessment tool. In a first step, we will perform an LCA using an Input-Output table from 1998 and corresponding environmental data (Suh, 2004 (b); Suh, 2005). Input-Output analysis is a macroeconomic technique that uses sectarian monetary transaction data to account for the complex interdependencies of industries in modern economies (Miller and Blair, 1985; Cobas et al., 1995; Joshi, 2000; Nielse et al., 2001; Suh et al., 2004). The Input-Output approach links the economic output of one industrial sector to its impact on the environment. On the one hand, this approach has the advantage of including the whole economy in a comprehensive way and of being easy to perform. On the other hand, it has the disadvantage of high aggregation levels, because various products are included in the same industrial sector. This makes it impossible to perform an accurate analysis that takes into consideration the specificity of assessed projects.

In a second step we used PLCA data (ISO, 1997; Jolliet et al., 2005). Process analysis is a technique in which the resource requirements and pollutant releases of the main production processes are assessed in detail. The application of this technique aims to take into account the characteristics of the region and the avoided impacts that are unique to the city of Martigny. This approach was applied only for specific avoided impacts: the electricity production, the water consumption, and the district heating (natural gas consumption). Data are taken from the Swiss ecoinvent database (Swiss Centre for Life-Cycle Inventories, 2004). For the PCs, the results of the PLCA of chapter 3 are used.

The functional unit studied is the use of the telemonitoring system for one year. Before applying these two life cycle analysis approaches, it was necessary to perform an inventory of the infrastructure used to set up the telemonitoring system. This included the hardware (PC, modems, sensors, cables etc.), and the software developed specifically to make the system operational, as well as electricity and cable TV networks. Moreover research projects and work places required for the maintenance and use of the telemonitoring system were also included. Table 10 below summarizes the telemonitoring system inputs and the corresponding monetary funds for the period 1987 to 2002. The exchange rate is $1 = 1.5 CHF.

Table 10: Annual investments for all necessary equipments to support the telemonitoring system developed by the CREM researchers.

Expenses	**Quantity**	**Unit**	**Life time [year]**	**Price [$/device]**	**Cost [$/year]**
Hardware					
Computers	27	Device	5	1’666	9’000
Modems	31	Device	10	333	1’033
Sensors	100	Device	10	266	2’667
PC Cards	52	Device	5	400	4’160
Cables	52	Km	15	150 [$/km]	520
TV cable	1’200’000	$	15		80’000
Subtotal					**97’380**
Human resources					
Personal	72’992	$/year			72’992

Research	2’345’328	$	15		156’355
Subtotal					**229’347**
Use and maintenance					
Electricity	19’140	kWh_e/year		0.11 [$/kWh]	2’105
Software	64’666		15		4’310
Subtotal					**6’415**
Total					**333’142**

The software value is based on the price of all software used either by the CREM or the IS. The research costs add all full projects or parts of projects linked to the setting and the use of the telemonitoring system. The TV cable network is not only use for the telemonitoring system. 30% of the costs have been allocated to the telemonitoring system. This takes into account the fact that four channels have been installed for the bi-directional flow of information. A detailed review of available literature on the urbisitic approach (Saugy et al., 1986; Matas, 1994; Revaz et al., 1994; Revaz, 1997) allowed us to quantify some benefits. The remaining data were provided by interviews with researchers from the CREM and IS employees.

The telemonitoring system have enabled attractive benefits in terms of saved resources. For example, very high water flows were measured in the skating rink compressor’s cooling system. A reduction in the flow to the compressor’s cooling system allowed IS to reduce the water consumption by 388’800 m^3 per year. Proper management of the heating power station, using the telemonitoring system, made it possible to detect faulty operations in district heating network, particularly in the interseasonal period. The adjustments made to the system enabled to save 600’000 kWh/year of thermal energy. Table 11 below provides an estimate of the annual benefits by sector.

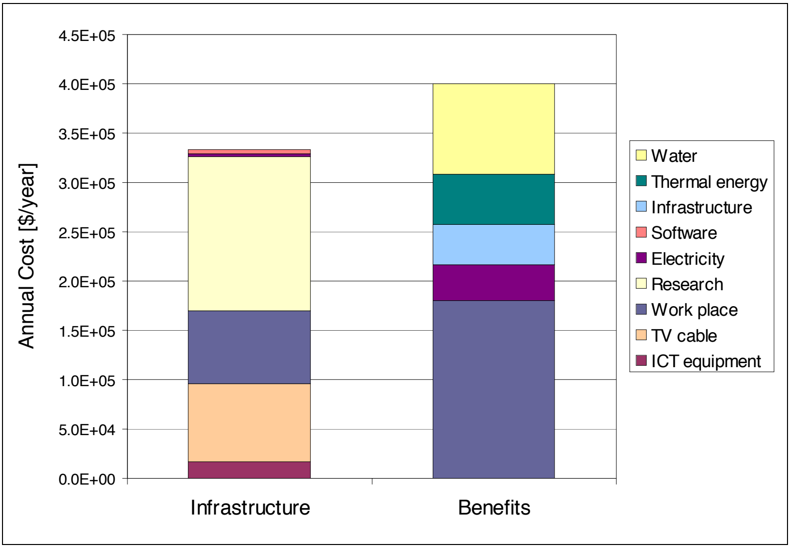
Table 11: Annual Inventory of all the savings induced by the use of the telemonitoring system within the city of Martigny.

	Quantity	Unit/year	Cost [$/year]
Human resources			
Work places	3	Men-year	180’000
Electricity			
Aluminium recycle SA	201’818	kWh_e	14’800
Hotel de la poste	20’000	kWh_e	1’466
Magnésium SA	43’636	kWh_e	3’200
Installation of variable-displacement Pump for the district heating	230’000	kWh_e	16’866
Stop of pumping at swimming pool	11’520	KWh_e	845
Subtotal			**37’177**
Others			
Water tank	2’000’000	$	40’000
District heating			
Network Temperature drop	600’000	KWh_{th}	30’400
Optimization of the regulation	418’000	KWh_{th}	21’180
Subtotal			**51’580**
Drinking water supply			
Skating / swiming pool	388’800	m^3 Water	77’760
Automatic watering	70’000	m^3 Water	14’000
Subtotal			**91’760**
Total			**422’517**

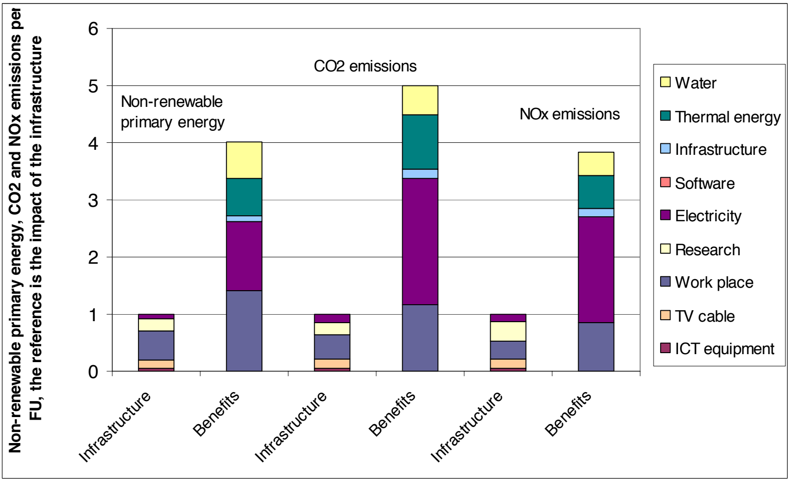
The Input-Output approach requires one to know the price of the resources in order to apply the methodology. In our case, the electricity price was set to 0.11 $/kWh, the water to 0.30 $/m3 and the district heating 0.076 $/kWh. Prices were given in $ to be consistent with the U.S. Input-Output data. The water tank was estimated to cost $2'000'000 and has a lifetime of 50 years.

4.4 Results

The economic comparison is in favor of the telemonitoring system. Figures 32 shows that the economic benefits induced by its use dominate the investment by a factor 1.3. The research projects and the installation of the TV cable dominate the impact of the infrastructure. It is interesting to note that the impact of the computers and their electricity consumption is not significant. The main benefits of the telemonitoring system are the elimination of work places and the water consumption.

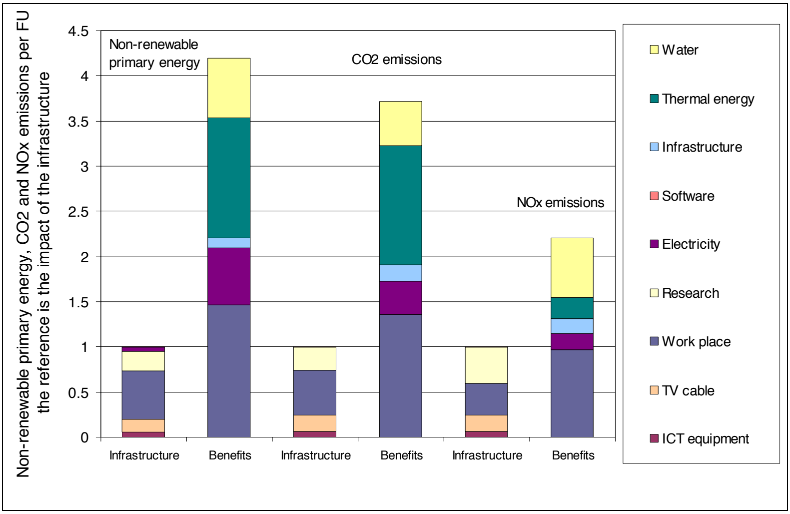


Figures 32: Economic balance of the investment to set up the telemonitoring system and the benefits induced by its use.



Figures 33: Evaluation of the non-renewable primary energy, the CO2 emissions as well as the NOx emissions, on the one hand for the infrastructure and on the other hand of the benefits.

From the environmental point of view, the savings induced by the use of the telemonitoring system are significantly higher than the impact of the infrastructure. This is at least true for the three indicators used: the non-renewable energy, the CO_2 emissions as well as the NOx. The ratios of benefits over impacts of the infrastructure are between 4 and 5.5.



Figures 34: Evaluation of the non-renewable primary energy, the CO2 emissions as well as the NOx emissions, on the one hand for the infrastructure, and on the other hand of the benefits. Electricity, water and thermal energy (district heating) have been evaluated with the ecoinvent database.

To improve precision and to take into account geographical specificities, PLCA data were used (ecoinvent) to evaluate the non-renewable primary energy, the CO2 and the NOx emissions of the thermal energy, the electricity, and the water consumption. The results are presented in figures 34. The PLCA leads to the same conclusion, which is that the use of the telemonitoring system is beneficial for the environment. However, as we used the Swiss electricity mix the benefits induced by the electricity savings play a minor role. This contrasts with our first evaluation. In contrast, the thermal energy (natural gas saved) plays a much more important role.

4.5 Discussion

The comparison of the investment required to set up the telemonitoring system and the benefits induced by its use is in favor of the benefits. The investments are dominated by the research projects, the TV cable installation, and the work places, all of which are basically human work. The cost of the physical infrastructure, such as computers, is not significant. In the case of the CREM the research costs are also very important because the city is used as a laboratory. However, a generalisation of the concept of urbistic, and for instance the installation of a telemonitoring system in other cities, would induce more synergies between of different users and less researchers working on this issue (per research institute). This would imply a rationalization of the research costs and a collaboration between interested schools.

Part of the electricity savings does not benefit directly the IS and the city of Martigny, but instead the companies where the actions have been taken. This represents 52% of the costs of electricity and almost $20’000. But these actions were made possible by the telemonitoring system and these savings have to be considered when comparing the environmental impact.

In terms of work place, the main savings come from the fact that the work is done more efficiently and therefore fewer workers are needed to perform the same task. One could argue whether or not this is good news for the employees. However, the amount of money invested in the research is as high as the savings and thus it is more a transfer of workers from the industrial services to the university or the high school than a loss of jobs. The evaluation of indirect jobs linked to both scenarios, like those induced by the construction of a reservoir, or the installation of the TV cable network, have not been considered here.

From the environmental point of view and when using only the Input-Output approach, the ratio between the savings and the impacts is between 4 and 5.5, and therefore the telemonitoring system and the urbistic approach are worth the investment. The main contributions are electricity, work place, thermal energy, and the water savings. Including PLCA data does not change the fact that the savings are much more important than the impacts of the infrastructure, excluding the NOx where the ratio between savings and impacts is now between 2 and 2.5. But the structure of the emissions is not the same. On the one hand, the use of the Swiss electricity mix evaluated with ecoinvent instead of the Input-Output sector that represents the US electricity generation decreases both the environmental impact and the savings linked to the electricity production. On the other hand, the burning of natural gas evaluated with ecoinvent shows much higher impacts than the Input-Output sectors chosen in the IO LCA. This is probably due to the fact that the IO LCA does not consider the direct emissions. This overcompensation leads to the fact that for the CO_2 emissions the IO LCA and the hybrid LCA show similar total results. The situation is different for the NO_x.

Using the Input-Output permits one to make a rapid evaluation of some impacts that would be very difficult to estimate with the PLCA (work place, TV cable, research, software, etc.) and this example shows the pertinence of using IOLCA and PLCA, not only in parallel, but also the merged approach. However, our study shows that users have to be very careful when performing an assessment because IOLCA can lead to high uncertainties.

When compared to other LCA, the results show that the application of ICT to the management of urban networks is a profitable investment, both financially and environmentally. It actually appears that such ICT applications that enable a reduction in fuel, water, or electricity consumption have a much higher positive impact than e-commerce or e-banking, for which environmental benefits are not always clear or significant. The saved water represents almost 70 liters per day per inhabitant, which is a significant 19% reduction. More than 500'000 kWh were also saved, representing an average of 33 kWh per person per year or 0.4% of the electricity consumption. Though significant when compared to the generated impact of the ICT infrastructure, this is a small reduction. This points to the necessity to take further measures, using ICT or other means, to further decrease the household and industrial electricity consumption (e.g. high efficiency equipments, systematic support to energy star or A+ labeled appliances).

4.6 Conclusion

The evaluation of the set up of and the use of the telemonitoring system for Martigny is positive using both the Input-Output and the hybrid approaches. The environmental benefits, as evaluated here, are 4 to 5 times higher than the impacts of the infrastructure and the necessary investment to set up, maintain, and exploit the telemonitoring system. This shows the pertinence of the approach of the CREM and the importance of the measurement and the information to understand the behavior of the networks. It also shows that the use of ICT is very important and can have very interesting applications. At the same time, these benefits are not automatic consequences of the ICT use: it is only through a thorough data analysis leading to actions and measures taken to reduce electricity and water consumption that ICT provides its full benefits.

Finally, the applied evaluation faces various limitations and points to the need for further research. The use of the IOLCA allowed us to perform a first comprehensive evaluation of an ICT service used for urban utility management, including all contributions and benefits. But the IOLCA should be followed by an iterative integration of PLCA to consider particular characteristics, such as geographical or processes specialties. In addition, the long-term effects of the telemonitoring system and its continuous effect on the network management need to be further evaluated. Similar analyses need be performed on other cities using the concept of urbistic and telemonitoring systems to confirm these results in different contexts.

5 THE ENVIRONMENTAL IMPACT OF INNOVATIVE SERVICES IN THE FIELD OF ICT, INCLUDING THE EVALUATION OF INDIRECT EFFECTS

5.1 Abstract

Innovative services in development within the research and development division of France Telecom have been comprehensively assessed using two complementary LCA methods, PLCA and IOLCA. This chapter evaluates the direct as well as the indirect non-renewable energy consumption, together with damage indicators, using the Impact 2002+ method. The National Agency for Unemployed People in France introduced, along with France Telecom, an innovative service named the visiophonic station. It helps to perform remote interviews. The environmental impact of this virtual desk has been assessed in detail. The transport of the users dominates the impacts of both the traditional service and the new service. The visiophonic station leads to important savings due to the reduction of the distance previously covered by car. The computer and related equipment have a rather low impact in their production as well as use phases. The potential savings of three other innovative services have been evaluated using an LCA method and compared to the visiophonic station, which shows the highest potential. A hybrid LCA approach has been used to further extend its system boundaries. Although the dominance of the transport impacts is confirmed, other service-linked impacts, such as research and development, or marketing, become significant. Finally, other indirect effects are included in the analysis such as modal transfer, presence rate, and the environmental impact of the saved time and saved money. Provided that the users of the visiophonic station were previously travelling with public transportation, a modal transfer could significantly decrease the environmental benefits of the virtual interviews if the car is used with the new service. Time and money use implications on the environment have been assessed using process as well as Input-Output data. The evaluation of these effects and their corresponding environmental impact shows that the final benefits of introducing new services depends on the type of activities of the consumer. The consumer can increase the environmental savings if the money is smartly reinvested or can generate a sufficient amount of negative impact to counterbalance the savings. Finally, recommendations are given to decrease the environmental impact of the service and increase the savings.

5.2 Introduction

This paper presents an evaluation of the overall environmental impacts of an innovative service offered by France Telecom – the visiophonic station. It aims to take into account all direct and indirect impacts of this technology that could potentially reduce the need for transportation by offering distance interviews.

5.2.1 Direct and indirect second and third order effects

ICT are seen by many as offering an important potential for the reduction of the impacts of the industrial ecosystem on the environment (Romm et al., 1999). However, the complexity of indirect impacts, as well as the high number of different applications, makes it difficult to get a global view of the impact of ICT. Existing overviews classify and give examples of the different types of impacts (Berkhout and Hertin, 2001; Faucheux et al., 2001). Yet they lack quantified and detailed results for one particular service and do not lead to practical recommendations.

Telecom providers, like France Telecom, are increasingly developing and proposing innovative services that could potentially help society on its way to sustainability. Analysing these services requires one to assess the direct impacts of the equipment, the indirect effects such as saved transportation or reduction in materials inputs, and, last but not least, the effects on lifestyles or rebound effects.

Table 12: Summary of some existing studies and the type of effects addressed.

Reference	Direct, qualitative	Direct, quantitative (LCA)	Indirect, 2nd order, qualitative	Indirect, 2nd order, quantitative (LCA)	Rebounds, qualitative	Rebounds, quantitative (LCA)
(Romm et al., 1999)	++	+	++	-	-	-
(Berkhout and Hertin, 2001)	++	-	++	-	++	-
(Faucheux et al., 2001)	++	-	++	-	++	-
(Williams, 2004 (b))	-	++	-	-	-	-
(Williams, 2004 (c))	-	++	-	-	-	-
(GESI, 2002)	+	-	+	-	-	-
(Matthews et al., 2002)	-	++	-	++	-	-
(Norris et al., 2003)	-	+	-	++	-	-
(Gard and Keoleian, 2002)	-	+	-	++	-	-
(Hischier and Reichart, 2003)	-	+	-	++	-	-
(Plepys, 2002)	-	-	-	-	++	+
(Arnfalk, 2002)	+	-	++	+	+	-
(Jalas, 2002)	-	-	-	-	+	++

5.2.1.1 a) Including second order indirect impacts

Direct effects have been presented in detail in chapters 1 and 3, as well as in other references (Williams, 2004 (a); Williams, 2004 (b); Williams, 2004 (c)). These studies give a rather good and consistent analysis of the direct impact of ICT, in particular of a personal computer. But PCs are always used to fulfil a given task. Most of the time this generates indirect positive and/or negative impacts. Assessing the production and use phase is essential to efficiently decrease the environmental impact of ICT, but considering indirect effects is also of great importance. Chapter 4 for instance, has shown that the benefits of the use of ICT in the field of urban network management can induce important resource savings. But this case study is limited as it concerns a specific application for professionals, and the problem turns out to be very different when ICT services are proposed and used by consumers.

As an example, ICT can permit one to control and to optimise the energy performance of buildings. Companies such as IBM and Johnson and Johnson have set up company policies in order to adopt these technologies. They decreased the energy use per dollar of output by 4% and 3% per year in the nineties (Faucheux et al., 2001). A study performed by Lexmark concludes that less and less paper is used to print photos, although the number of shots taken always increases. However, these analyses are very often limited to specific findings and for instance do not compare the environmental impact of the infrastructure (direct impact) with the savings (indirect impacts). A life cycle approach is necessary to ensure that all direct and indirect impacts are included in the analysis. LCA is therefore well suited to address these questions.

5.2.1.2 b) Considering service-linked contributions

Answering machines have been replaced by voice box. Telia evaluated that the energy consumed and the greenhouse gas by a classical answering machine are more than 200 times the similar services by network services (GESI, 2002). Matthews and Williams have shown that e-commerce and traditional commerce is fairly equivalent in terms of environmental impact (Matthews et al., 2002; Williams and Tagami, 2002; Norris et al., 2003). Digital media, for instance do not always imply less environmental impacts than printed media. It depends on various parameters, such as if information is printed or not, the power consumption, the number of people reading the same book or newspaper, etc. (Gard and Keoleian, 2002; Hischier and Reichart, 2003). Many studies address the environmental impact of ICT applications, using LCA. However, they generally do not consider the environmental impact of the services-linked contributions, such as, for instance, the marketing or the research and development, as well as the background infrastructure enabling the communication.

5.2.1.3 c) Including rebound effects

More and more studies do take into account all effects of ICT in the evaluation of the environmental impact. Plepys provides a very detailed description of effects on lifestyles, and in particular rebound effects (Plepys, 2002). He does not, however, quantify and compare these impacts to those of the infrastructure or the potential savings due to the use of the ICT equipment or service. Arnfalk lists and deeply analyses the rebound effects associated with virtual mobility and concludes that they might play a key role, in particular, the environmental impact of the time and money use (Arnfalk, 2002). Time use as well as budget use implications on consumption have been widely used to assess the sustainability of consumption (Heiskanen and Pantzar, 1997; Jalas, 2002; Hofstetter and Madjar, 2003). Goedkoop uses the E2 (Economy-Environment) vector to assess and illustrate the indirect impact on the environment of the saved money for two alternatives (Goedkoop et al., 1999). Jalas used Input-Output data, together with household expenditures and time budgets, to evaluate the environmental impact per minute for various leisure activities (Jalas, 2002). As mentioned in chapter 2, it is important to add PLCA data to consider as well the direct environmental impact of the activities, such as transportation, and to gain in precision. In addition, we believe that time and budget should be combined to grasp the real implication of indirect effects, as the value of time or money depends on the individuals.

5.2.2 Objectives and roadmap

To better characterize the advantages and disadvantages of new ICT systems, it is therefore necessary to address the following questions:
What is the impact on the environment and the potential savings induced by the new service, the visiophonic station? What is the respective impact share of services and of the communication to the global network? How can indirect effects be considered? What is their significance? How can we decrease the direct negative impacts and encourage such reductions? How do new e-services compare to each other?

This work aims at comparing in terms of environmental impacts the traditional service of interviewing and meeting in a fixed office with the innovative visiophonic station. In addition, it compares the potential savings of this service with those related to other services. It specifically aims

- to include in the evaluation the service-linked contributions, such as marketing or research and development, using IOLCA and PLCA,
- to take indirect effects into consideration, in particular the time and budget use impacts, using IOLCA and PLCA, as well as the E2 vector representation.

This chapter is divided into 4 sections: following this introduction, the second section presents the methodology used throughout the paper. The next section presents the results for the PLCA of the visiophonic station followed by the hybrid approach to include service-linked contributions and, finally, the inclusion of indirect effects. The potential savings for the studied service compared to other innovative services is presented. These results are then discussed in the last section, which also includes the conclusion and the recommendations.

5.3 Methodology

5.3.1 Environmental impact of the visiophonic station

5.3.1.1 Direct and indirect effects evaluation of the visiophonic station using Process Life Cycle Assessment

A process based PLCA has been used to evaluate the direct environmental impact of traditional interviews compared to the innovative service of the visiophonic station developed by France Telecom. The non-renewable primary energy as well as the four damage indicators of the method Impact 2002+ (Jolliet et al., 2003) are evaluated. The functional unit studied is one interview. The system boundary is presented in figures 34.

The innovative service called the visiophonic station is basically a virtual desk that permits one to connect, via visiophony, a service supplier (bank, shop, authorities administration, post office, etc.) with a customer. It is composed of two stations that transmit, in real time, sound and image, as well as written documents that can be printed. The customer's screen is sufficiently large to permit him to see the employee of the service provider in real scale.

The case study is a program of the ANPE (National Agency for Employment) of Figeac (Morbihan, France). The unemployed people have one interview every 6 months and traditionally go to Figeac, most of them by car. One visiophonic station has been installed in Biars-sur-Cère, a small city located 50 km from Figeac. The unemployed people from the three border counties may go to Biars-sur-Cère instead of to Figeac, shifting from physical to virtual meetings. One ANPE employee normally holds 50 interviews per week. Their duration is approximately 30 minutes. The average distance from employee's home to office is 5 km. The office is 20 m^2 and the employee works with a PC and the following peripheral equipment: mouse, modem/router, scanner and laser printer. It is assumed that the cyberbase, where the visiophonic station is located, is in average 10 km from the user's home. Users save, therefore, about 90 km per interview by shifting from the traditional to the virtual interview.

The visiophonic station is a PC equipped with a plasma monitor (30 inches), a camera, and a microphone. The device also includes a scanner, a printer, and a modem/router. It is situated in an Internet café or a similar location, where a technician can help the user to start using the device. The required time to introduce the user to the new service is 5 minutes per user. The station communicates with another PC equipped for visiophony via the ADSL network. The APNE employee uses another computer for the work related to the ANPE.

The PLCA is based on real case studies from France Telecom. For the evaluation of the environmental impact, all hardware equipments considered as a computer, using data from chapter 3. For the electricity mix used (French) as well as the infrastructure or the transportation, data come from the ecoinvent database (Swiss Centre for Life-Cycle Inventories, 2004). Simapro is used to for the calculations and to perform the analysis.

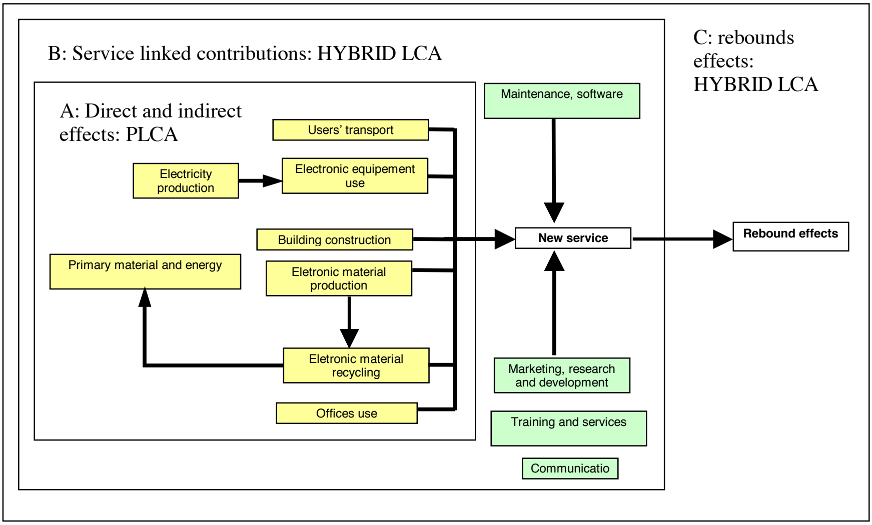


Figure 34: description of the system and its boundary with the methodology used for the assessment.

5.3.1.2 Impact of services: hybrid methodology to extend the system boundaries

As proposed in chapter 2, the IOLCA is used to further extend the system boundaries to consider the service-linked contributions, such as R&D, marketing, maintenance, or telecommunication. The following hypotheses have been made to evaluate these contributions. We suppose that the price of the traditional equipment corresponds to 50% of the overall cost, the maintenance 30%, the software 10%, and the training 10%. In the case of the visiophonic station, the hardware material is supposed to represent 50% of the overall costs, maintenance 10%, software 5%, R&D 15%, and marketing and advertising 20%. Finally, the IOLCA permits us to consider the use of the telecommunication network. It has been estimated to 75 euro per month, among which 50% is for the infrastructure and management, 30% for the research and development, and 20% for the marketing and advertisement. The environmental impact of all contributions is evaluated with the Input-Output approach, except for the transportation for which ecoinvent is used.

5.3.1.3 Rebound effects

The following rebound effects are assessed in more detail

- modal transfer: This can be, for instance, the transfer from rail to road if the users of the new services have to travel less.
- time and money saved: These are the environmental impacts of the activities done or the goods purchased with the saved time and money. These are then used to assess third order indirect effects.

Modal transfer: To analyse the modal transfer, two additional scenarios are analysed: instead of traveling by car to the traditional interviews, the unemployed people are traveling by bus or by train. The cyberbase where they can find the visiophonic station is located such that they have to use their car for virtual interviews. This evaluation has been performed using PLCA and the ecoinvent database.

Saving time and money: The users save around 127 minutes and $26.4 per interview[31]. On the one hand, shifting from the traditional interviews performed in the ANPE offices to the virtual interview permits the users to save a trip, which means saving money and time. On the other hand, the user can take advantage of the saved time and money to purchase additional goods, use additional transportation, or invest this saved time and money in environmental friendly measures. A methodology is developed to evaluate this rebound effect.

We distinguish between two different situations:

- the user is a rather low or middle class citizen that is limited in his or her activities by the parameter "money" rather than by the saved time. This is in particular the case for the unemployed people who have enough time but a rather limited amount of money.
- the user is a high middle or high class citizen who is very busy and has enough money to spend when he wants to. The time rather than the money is the limiting factor.

The next step is to analyse how people use their money and time and to assess the corresponding environmental impacts. National statistics are used to determine the typical schedule and budget of consumers (1999; Glorieux and Vandeweyer, 1999). As an example, citizens spend an average 203 minutes per week in reading periodicals or books. All activities are grouped in a given number r of categories (table 13).

To assess the variations linked to the type of activity that the user will perform, five scenarios are studied:

- reinvestment: in that case, the money saved is reinvested in a product good for the environment, for instance to buy low energy bulbs, or to buy a class A washing machine, etc.
- best case activity: the user chooses the less polluting activity within those available;

[31] To evaluate the spared time, the saved distance d is divided by the average velocity of travelling by car v [km/h]. The cost of this trip can be found by multiplying d by the average km price p [$/km]. In our case d is 66 km. The average velocitiy v is 31.1 km/hour (1998/1999) and the average price per km p is 0.4 $/km (Defeyt 2005)

- societal average scenario: the money and the time saved are reinvested like the consumer average schedule;
- worst case activity: the money and time is reinvested in the most polluting activities among the r presented.
- worst case scenario: the money and time is reinvested in flying with a low cost plane company.

The scenario reinvestment is based, for the money, on buying electricity from wind power instead of the traditional Swiss electricity mix. This permits the saving of 30.6 MJ/\$. For the time, reinvestment is based on walking instead of driving a car, typically for short trips. The worst-case scenario is based on a one-day trip to one of the major European cities with a low cost airline. The cost is about \$ 0.20 per km (\$ 200 for 1000 km) and we assume that the people live early in the morning at 7.00, spend one day in another European city and come back late in the evening 23.00, the required time is 16 hours, thus an equivalent speed of 62.5 km/h.

Evaluation of the third order indirect effects: The methodology to evaluate these indirect effects begins with the definition of a matrix of activities, L. It is constructed using the Input-Output table and the ecoinvent data. The columns of L represent the activities and the rows represent the necessary resources to perform these activities. In our case, the lines can be seen as the industrial sectors of the Input-Output table or processes of the ecoinvent database. The matrix L summaries the intermediary flows used for the realisation of the various activities.

$$L = \begin{matrix} IO_1 \\ \cdots \\ IO_n \\ eco_1 \\ \cdots \\ eco_m \end{matrix} \begin{pmatrix} L_{11} & \cdots & L_{1r} \\ \cdots & & \cdots \\ L_{n1} & \cdots & L_{nr} \\ L_{(n+1)1} & \cdots & L_{(n+1)r} \\ \cdots & & \cdots \\ L_{(n+m)1} & \cdots & L_{(n+m)r} \end{pmatrix}$$

L_{ij} = contribution of the intermediary flow i (which can correspond to an Input-Output sector or an ecoinvent process) to the activity j [monetary unit/monetary unit] or [physical unit/monetary unit]. In the case of the activity “reading,” the resources are: newspaper and periodicals (\$210), books (\$157), a place to read (apartment), the trip to go and buy the books, as well as electricity to light the room.

To measure the environmental impact of an activity or a group of activities (for instance one hour of activity A + 5 hours of activity C) we define two activity vectors:

$\vec{a}_t$ is a r vector and $\vec{a}_t(j)$ = time invested by the person in the activity j ;

$\vec{a}_a$ is a r vector and $\vec{a}_a(j)$ = money invested by the person in the activity j;

In our case the vector $\vec{a}_t$ describes how the user is allocating his saved time T to the different activities and $\vec{a}_a$ how he allocates his money G saved in shifting from the traditional to the virtual service. We therefore have:

$$\sum_j \vec{a}_t(j) = \text{T and } \sum_j \vec{a}_a(j) = \text{G}$$

To measure the environmental impact of these activities, we use the environmental matrix *H*. The rows of *H* represent the emissions and resource extractions pollutants and the columns the intermediary flows used in *L* (the rows of *L*).

H_{ij} = cumulative emission i (or resource or land use, etc...) to produce the intermediary flow j.

The total impact induced by the time saved T or the money spared G can thus be written:

$$\vec{b}_a = H \cdot L \cdot \vec{a}_a \text{ and } \vec{b}_t = H \cdot L \cdot \vec{a}_t$$

Table 13: Activities describing how the average consumer spends his money and time. Time and money are given on a yearly basis.

Activities	**Time [minutes/year]**	**Time [%]**	**Money [$/year]**	**Money [%]**
Hobby and games	2945	2.0	3555	11.5
Sports	1198	0.8	247	0.8
Going out (bal, dancing,...)	471	0.3	1701	5.5
Cultural and sport event	1119	0.8	538	1.7
TV and video	19005	12.9	2828	9.1
Listening to music	825	0.6	212	0.7
Reading	3985	2.7	923	3.0
Internet, e-mail, computer	569	0.4	250	0.8
Communication (tel,...)	9404	6.4	1845	6.0
Spending time with family	3259	2.2	1128	3.6
Travelling	11525	7.8	3329	10.7
Sleeping and resting	74742	50.9	9669	31.2
Training	510	0.3	393	1.3
Associative life	1296	0.9	169	0.5
Housework	16119	11.0	4185	13.5

Average consumer data are used to determine the costs associated with each activity. Scenarios were used to evaluate the transportation and electricity consumption. The corresponding environmental impacts are evaluated using, respectively, the Input-Output data and the ecoinvent

To take into consideration the transportation, Belgium statistics (1998/1999) were used to evaluate the number of km for each activity. The environmental impacts of the consumer's living place have been evenly allocated among the different activities performed at home. Similarly, scenarios have been set up to evaluate the electricity consumption of the different activities, based on the device power and the time used. Only the direct electricity consumption has been considered.

5.3.2 Comparison with other services

The potential benefits of the use of the visiophonic station have been compared to the following services, all provided by France Telecom:

- the teleechography is a service of distant echography with the reproduction of the sensation of touch. It enables specialists to perform an echography while being in another institution. Visophony helps them to communicate.
- Gluconet facilitates the recording of the tests a diabetic has to perform everyday and sends them regularly to the doctor who can thus adapt the patient's treatment.
- Visadom permits home convalescence. Using visiophony, a medical team can have permanent contact with their patient and therefore ensure the recovery of the patient at home instead of in the hospital, with the help of home healthcare.

The comparison is carried out on a yearly basis, taking into account the predicted number of devices that will be in use in France in a time frame of a couple of years:

- Gluconet for pregnant women : 15'000 used devices ;
- Teleechography : 100 devices in place ;
- Visadom : 5'000 used installation ;
- Visiophonic station : 10'000 « Visiophonic stations » installed in France.

5.4 Results and discussion

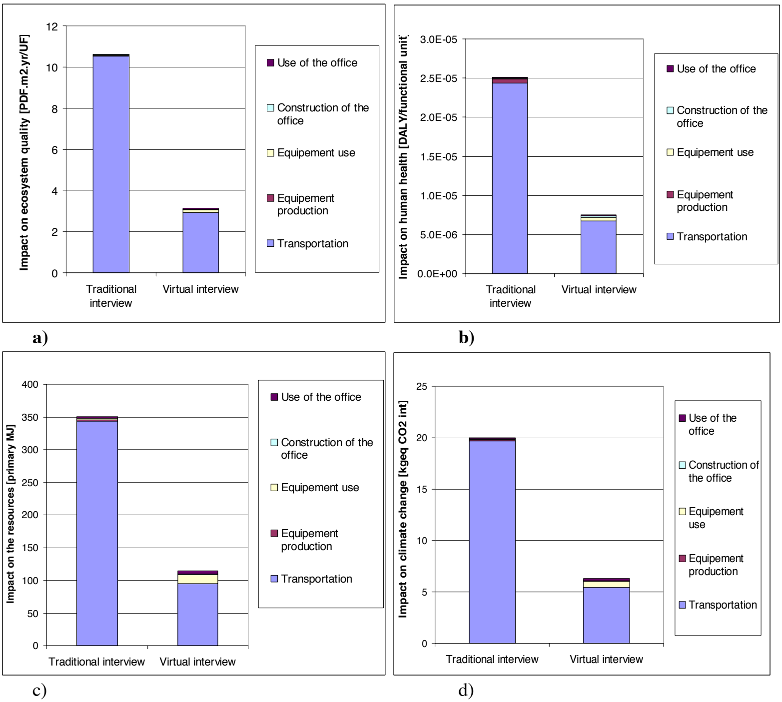
5.4.1 Environmental impact of the visiophonic station

5.4.1.1 Life Cycle Assessment of the direct and 2nd order indirect impact of the visiophonic station

The traditional service shows around 3 times higher impacts than the visiophonic station (figures 35) for the impact on human health, on ecosystem quality, on climate change and on resources of the Impact 2002+ method (Jolliet et al., 2003)

The reduction in the distance driven by car counterbalances largely the increased impact due to the office construction and its use, as well as the production and use of the equipment. In both alternatives, building use has low but distinguishable impacts. For the virtual interview, the ICT equipment gains in importance and represent respectively 6% and 12% of the impact.

The monitor of the visiophonic station is by far the most significant impact of the equipment, due to the fact that it is a large size display with high electricity consumption (on average 390 W) and that it is on permanently. If there are no interviews, the screen is used to display advertisements and information for the public. The corresponding environmental impact has been allocated to the interview.

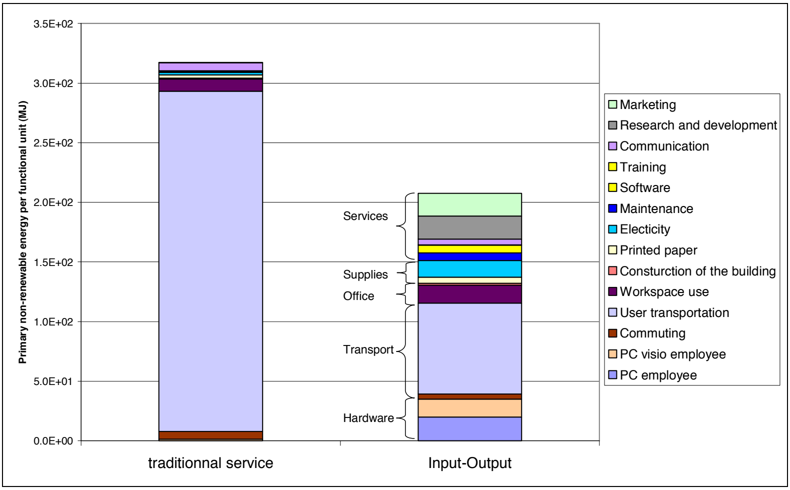


Figures 35: Environmental impact of one interview carried out traditionally and with the "visiphonic station." a) Impacts on human health and b) on ecosystem quality, c) on climate change and d) on resources for the Impact 2002+ method.

Transportation by far dominates the environmental impact of the traditional service. The impact on human health of car transportation arises mainly through emissions of primary and secondary particles. Fuel consumption generates high impacts on global warming (CO_2) and the resources. The visiophonic station necessitates a significant amount of resources for its production and even more for the use phase of the electronic material. Nevertheless, these values remain low compared to transportation.

5.4.1.2 Extending the system boundaries with hybrid methodologies: evaluating the impact of services

A hybrid LCA was used to further extend the system boundaries for the visiophonic station. The advantage of the virtual meeting is significantly reduced (figures 36). Transportation still dominates for both the traditional meeting and the visiophonic station. But now the environmental impact of the production, as well as the use phases of the equipment for the virtual meeting, is much higher. Maintenance, research, and telecommunication are all significant.



Figures 36: Comparison of the traditional service and the visiophonic station for one interview using an hybrid approaches combining IOLCA and PLCA.

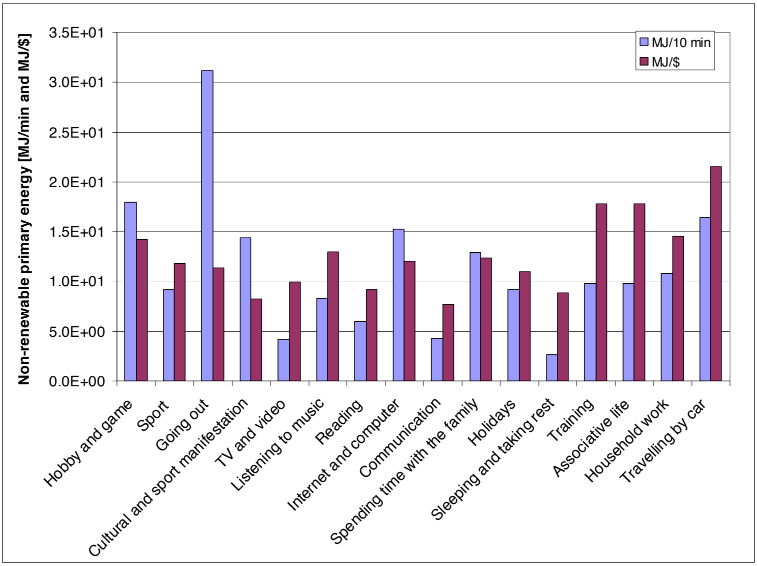
The aim of this evaluation was to include service-linked contribution to the analysis. This proved to be important, as the marketing, the research and development, the communication, and the maintenance represent 30% of the environmental impact in the case of the visiophonic station and 7% for the traditional service. The important difference between the traditional and the new service is related to the fact that the service-linked contributions were evaluated to be directly proportional to hardware price, which is much higher for the visiophonic station.

5.4.1.3 Taking into account rebound effects

5.4.1.3.1 What do people do with their spared time and money?

Using the above described methodology and data, the primary non-renewable energy consumption is evaluated for all the selected activities. It has been calculated considering both time and money limitations (figures 37).

The non-renewable primary energy per unit of money is relatively stable across the different activities compared to the non-renewable primary energy per unit of time. Going out (restaurant, night activities, etc.) is the most polluting activity per minute, followed by a group of activities: hobby and games, travelling by car, cultural and sport event, Internet and computer, and spending time with family.



Figures 37: non-renewable primary energy per unit of time and unit of money of all considered activities.

Figures 38 and 39 show that depending on the type of activities, the new service can have a higher impact on the environment than the traditional service and offset the initial advantage. This is the case if the user chooses going out, the activity with the highest non-renewable primary consumption.

In the case that the time or money saved is reinvested in a positive action for the environment, then the new service is very interesting on an environmental perspective.

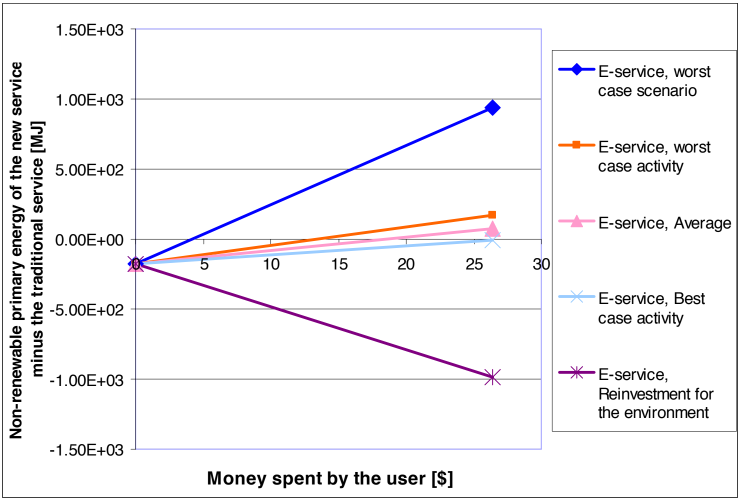


Figure 38: Difference in the non-renewable primary energy between the traditional and the new service (visiophonic station) versus the spared money spent by the user. Different ways of spending the money have been studies: in the "worst case" scenario the consumer flies to one of the major Europeau cities (London, Madrid, etc.) and spends the day there. In the "worst case activity" scenario the consumer spends all the saved money in the most polluting activity, "hobby and game" (in MJ/$). The "average scenario" shows the impact of the rebound effect if we assume that the consumer spends the saved money like the average citizen. In the "best case" activity scenario, the consumer spends his money in the activity consuming the less energy per $ and finally the scenario "reinvestment for the environment" assume that the consumer uses its money to buy environmentally friendly produced electricity (hydro).

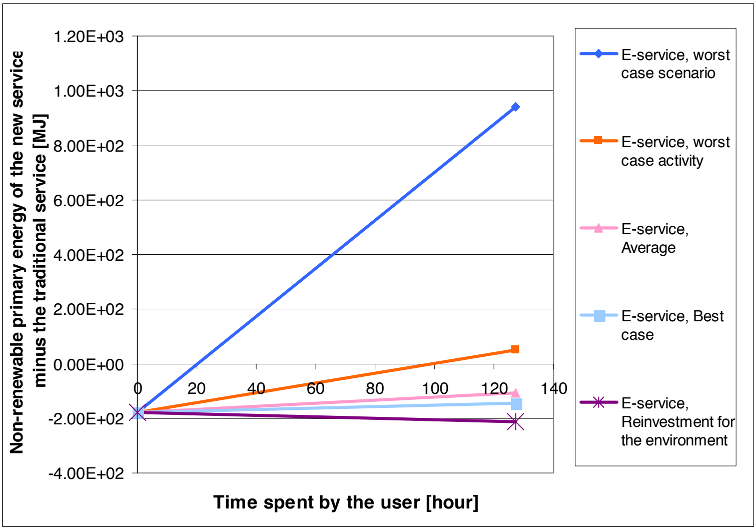


Figure 39: Difference in the non-renewable primary energy between the traditional and the new service (visiophonic station) versus the saved time spent by the user. Different ways of spending the time have been studies: in the "worst case" scenario the consumer flies to one of the major Europeau cities (London, Madrid, etc.) and spends the day there (16 hours). In the "worst case activity" scenario the consumer spends all the saved time in the most polluting activity, "going out" (in MJ/minute). The "average scenario" shows the impact of the rebound effect if we assume that the user spends the saved time like the average. In the "best case" activity scenario, the consumer spends his money in the activity consuming the less energy per minute and finally the scenario "reinvestment for the environment" assume that the consumer uses its to replace a trip by car by walking.

If the average schedule is used, the new service is still more interesting on an environmental perspective if time is the key parameter. If money is the limiting factor, which is likely to be the case for unemployed people, the results for the non-renewable primary energy are pretty similar.

The environmental impact per minute of the different activities presented in figure 37 shows important variations. In particular, "going out" has a high environmental impact compared to the other activities. This is due to the expenses in restaurants and cafés. Table 14 gives the main contributors to the environmental impact of the activities per minute and per $ of the activity.

Table 14: Description of the main contributor to the environmental impact of the various activities

Activities	**Main contributors on the env. impact**
Hobby and games	Flower and plants, pets, paper products
Sport	Sport supplies, restaurants, and café
Going out (bal, dancing, etc.)	Restaurants and Café, transportation
Cultural and sport event	Restaurants and Café, museum
TV and video	Electricity, paying TV
Listening to music	Equipment
Reading	Book, newspaper
Internet, e-mail, computer	Equipment, electricity
Communication (tel,etc.)	Apartment, equipment fixed telephony
Spending time with family	Apartment, café, and restaurant
Travelling	Airplane, hotels
Sleeping and resting	Apartment
Training	Transport, restaurant and café
Associative life	Transport, restaurant and café
Housework	Household

Depending on the activity that the consumer chooses to perform, the environmental impact of the indirect effects can counterbalance the benefits linked to the saved km. The global evaluation depends on what the user will do with the saved time and money. If the average behaviour of consumers is used, the new innovative service is still positive and permits some savings for the environment only if time is the limiting factor. If the consumers decide to reinvest the money or the time for the environment, then the global impact is extremely positive. But if he or she uses this money to travel by plane with a low cost company, then the final impact is very negative.

5.4.1.3.2 Modal transfer

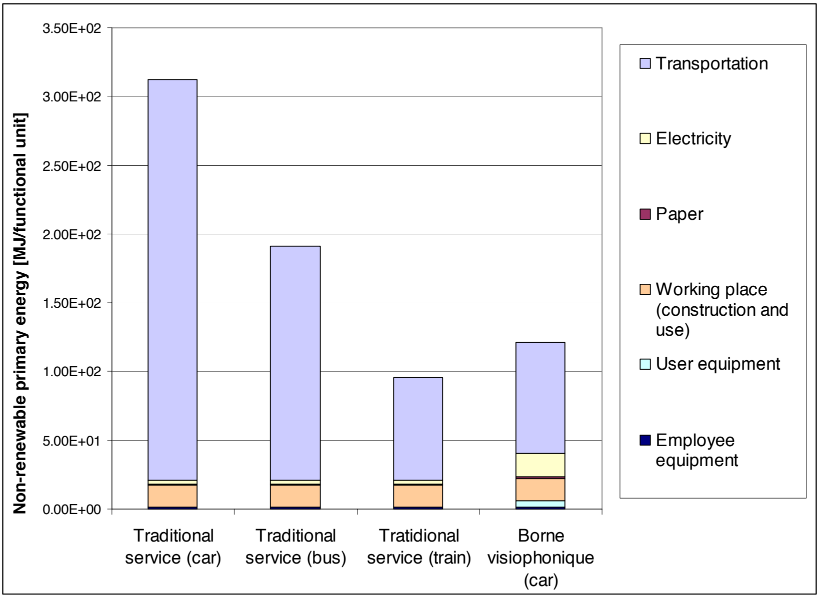


Figure 40: Evaluation of the non-renewable primary energy for the traditional service if the unemployed people go to their interviews by car, bus or train compared to the new service if they use their car.

Figure 40 shows that a modal transfer from car to rail would offset the advantage of the new service and lead to comparable environmental impacts. This confirms the importance of studying the mobility habits of the potential users of a visiophonic station before installing it. Is it also possible that the users go to the more distant city because they had to buy something there anyway? This would mean that we only have additional impact with the virtual service, as the user would go to the place where the traditional service occurs anyway. And finally, rebound effects can also occur from the traffic reduction: less people driving may incite others to increase the use of their car. These effects have already been assessed in the literature (Plepys, 2002) and should be studied when a new device is to be installed.

5.4.2 Generalisation Potential for environmental savings of different services

The potential savings of the various innovative services described have been evaluated and multiplied by the number of devices that are planned to be in use in France within a time frame of a couple of years. The savings in primary non-renewable energy is plotted against the saved km induced by the shift from the traditional to the new services (figure 41).

Without reduction in transportation, the visadom (home health care facilities) is the only service that is environmentally positive. This is induced by the non-utilisation of a hospital room. It is also the service that has the greatest potential per device to reduce environmental impacts. When considering the forecasted number of devices in France, the visiophonic station has the highest potential, followed by the visadom, the Gluconet, and the teleechography.

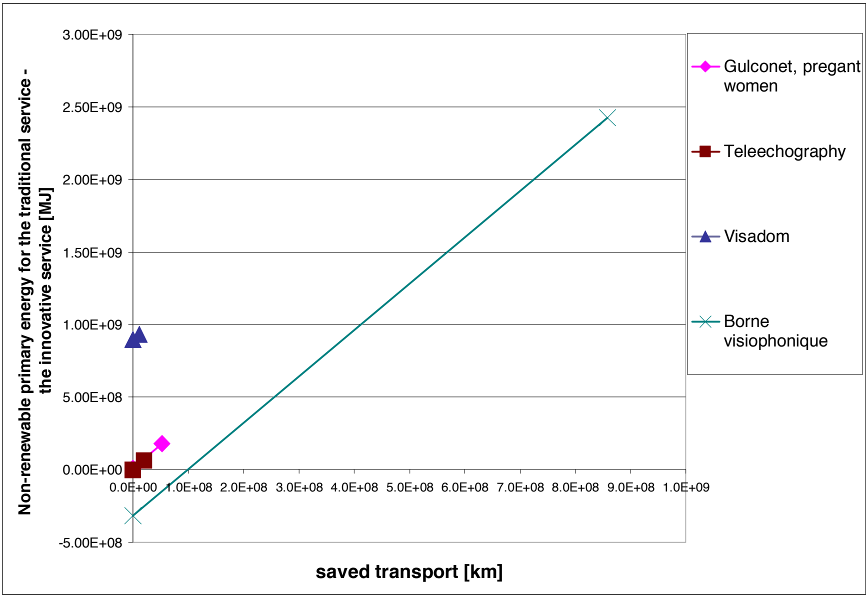


Figure 41: Evaluation of the non-renewable primary energy for the traditional services minus the non-rewewable primary energy for the innovative services versus the saved transport. The evaluation considers one year of use of the services for the forecasted number of devices that will be in use in France in a couple of years. That explains the high values of both the non-renewable primary energy and saved km.

When considering reduction in transportation, the visiophonic station is the service that has by far the highest reduction potential, due to the large amount of km saved, 450 km per day of use for one device. The other services permit avoiding 6 km for the visadom, 10 for the Gluconet, and 800 for the teleechography. In addition, the visiophonic station will be widely distributed with 10’000 devices in use in a couple of years, as compared to 100 for the teleechography. The visadom is also very interesting because it saves the construction and the use of a hospital room. It, therefore, can reduce the environmental impact even if no km is saved.

5.5 Discussion and conclusion

5.5.1 Including second order indirect impact

The environmental impact of one interview of an unemployed person is dominated by transport. The shift from a traditional meeting to a virtual interview, using the visiophonic station can lead to the reduction of these impacts, however, the transportation impacts are still dominant. It is, therefore, important to take into account this parameter when the place where the station will be located is chosen. In particular, it should be easy to reach with public transportation or car sharing.

On the equipment side, the potential for impact reduction is less important. Nevertheless, the use rate should be maximumized to decrease the environmental impact of the production phase per interview. The stations are always on in order to show advertisements and, therefore, consume electricity continuously, making the use rate even more significant. An LCD screen could be used instead of plasma. The first consumes less electricity and has a longer lifespan. In addition, the service provider should push its suppliers to provide environmental information about their products and to decrease their environmental impact.

5.5.2 Considering service-linked contributions

Further extending the limit of the system using the Input-Output approach leads to a significant 30% increase of the environmental impact of the visiophonic station. The reasons for this difference are:

1. the extension of the system boundary;
2. the price of the equipment linked to the visiophonic station;
3. the Input-Output characteristics.

The kg of equipment is much more expensive for the visiophonic station, 150 $/kg, than for a traditional PC, 60$/kg. This price difference can be “real” and arise from an important change in the technology or it can be due to the long optimisation of the industrial processes used in the production of the traditional PC and the very large production quantity that permits very low prices for the components as well as the very high market competition. The difference in price might be partially due to the use of a plasma screen for the visiophonic station, which still is much more expensive than a traditional LCD. However, the structure and the components of the visiophonic station is very similar to commonly used equipment, which is in favour of a similar environmental impact per kg and per $. Confidentiality of data made it impossible to further deepen the analysis.

As the service-linked contributions are directly deduced from the price of the materials, their environmental impact is more important in the case of the new service than the traditional service.

As seen in chapter 3, the environmental impact of electronic material is higher when evaluated with the Input-Output approach than with a PLCA. This is due to the inclusion of the environmental impact of the assembly as well as the service-linked contributions. This might also explain part of the difference between the traditional and the new service.

The extension of the system boundaries shows that the service-linked contributions are significant. Activities such as marketing or research and development should implement environmental management systems in order to decrease their impacts.

5.5.3 Including indirect effects

Finally, some indirect effects have been evaluated and turn out to be important. As a consequence, a green attitude should be promoted and implemented in all type of activities and this is the only way new services will really result in decreased environmental impacts.

These impacts can be taken into account by extending the system boundaries. However, a systemic approach to analysing these applications is missing. In particular, extending the system boundaries by considering the service linked inputs should be done systematically. In addition, third order indirect effects, also called rebound effects, should be considered and evaluated for all ICT applications. The evaluation of these indirect effects needs to be discussed as it opens the debate of consumer and corporate responsibilities. A private company has no or little influence on how people live and consume. But should it be allowed to sell a product as green when the seller is aware of its global effect? It could nevertheless be possible to make the consumer aware of the environmental consequences of his or her choices. In the case of the visiophonic station, messages to promote public transportation could be, for example, displayed on screen as well as advertisement for green products, such as economic light bulbs.

6 CONCLUSION AND FUTURE OUTLOOK

The conclusions are structured according to the scientific objectives that were proposed in the introduction. For each objective, the main findings of this thesis are summarized and the need for future work is discussed.

6.1 Combining Process LCA (PLCA) and Input-Output LCA (IOLCA)

This work explored the possibility of combining PLCA and IOLCA to take profit of the advantages of the two approaches, with a particular focus on their application to ICT.

Reliability of Input-output datasets: The first part of chapter 2 describes the Input-Output data available and a method to select the most appropriate dataset for performing IOLCA. In particular, the reliability of these datasets has been tested. Chapter 2, as well as the case studies in chapters 3 to 5, shows that one of the key parameters leading to reliable results is a detailed description of the economy including a high number of sectors. For instance, the US IO table permits us to choose among at least twice as many industrial sectors for ICT than the datasets of other countries. We have seen that the results found with various Input-Output datasets can lead to important differences, even of a factor higher than 10 when evaluating the CO_2 emission of some industrial sectors. In particular, Switzerland was found to be very poor in terms of both Input-Output and environmental data, with only 37 sectors and no corresponding environmental data. The US Input-Output dataset was found to be the most suitable set with its almost 500 sectors as a starting basis for combining PLCA and IOLCA, the sets from other countries being used for sensitivity studies.

This illustrates the need for a more detailed Input-Output table, especially in Europe. It is also important to identify the adequate level of detail and number of industrial sectors needed to make a more integrated merging of IOLCA and PLCA possible. Another need is the elaboration of exhaustive and consistent environmental data. Chapter 2 shows very high differences in the direct environmental emissions between different datasets. To measure the difference induced by the structure of the economy, the same environmental emissions could be used with different Input-Output tables (US, Germany, the Netherlands, etc.) to understand which variations are linked to the economic structure.

Environmental impacts caused by services and cut-offs processes usually not considered in PLCA: The IOLCA has been used to evaluate two specific contributions to the total environmental impact: the processes classified as out of the scope of LCA because they are linked to private consumption and the processes classified as services. Removing the contributions of processes considered as out of the scope of LCA leads to a decrease of 8.9% on average. But it shows large variations within the sectors. In the case of services, a standard deviation of about 0.05 to 0.07 kg cumulative CO_2 emission per $ has been observed, which corresponds to an average of 7.3 % of the total cumulative CO_2 emission. Although these contributions are restricted on average, once combined they can explain specific significant differences between PLCA and IOLCA. In general, industrial sectors have a rather fixed share of their costs linked to services (banking services, insurance, etc.). In the case of ICT applications, the case studies show services contributing to a higher share of the environmental impact. This can be explained by the very fast evolution of ICT. In this highly competitive industrial sector, the time to market is an important criterion for success, which could explain the importance, in terms of cost, of the research and development, the marketing and the advertising.

The methodological development proposed in chapter 2 allows us to evaluate the cut-offs processes, which are the contributions that PLCA does not, for some reason, include. Within the cut-offs, some Input-Output sectors have a greater importance than the others: wholesale trade, air transportation, or advertising in the case studies of this work. We then have lots of sectors contributing individually to a very small part of the cut-offs (less than 1%) but to a rather large part together. In the case studies of ICT devices, the cumulative CO_2 emissions linked to the cut-offs processes is rather important (40%). The main contributions to the cut-offs processes are wholesale trade and air transportation, which should be more systematically considered when evaluating ICT with LCA.

Comparing PLCA and IOLCA consistently and understanding sources of difference: A methodology was developed to compare PLCA and IOLCA in order to explore the possibility of merging both approaches as well as determining the appropriate level of combination. PLCA databases and IO tables have a very different structure because many processes of the PLCA database are sometimes included in the activities of the same company, without any economic flow corresponding to physical flows. The proposed solution is to aggregate the PLCA to reach a structure comparable to the IOLCA. The application of the aggregation methodology to two case studies of the ecoinvent database, "pc silicon wafer, at plant" and "electricity production, UCTE mix," point to different sources of variation:
a) The *prices* of the studied process are very important, both in the case of the pc-si wafer and of electricity production, and can lead to high uncertainties. When evaluating the environmental impact of LCD screens and notebooks, significant differences are observed compared with traditional PCs, due to their price. This shows the influence of the market on the IOLCA and a problem that must be taken into consideration when discussing ICT. The price of a new PC sent on the market is much higher than the price of the same PC a few months after, although it is sold in the same shop. However, the environmental impact of the sold PC does not change.
b) The *representativeness* of the IO table for the considered process is directly linked to the above discussed level of detail of the IO table. In the present case study, the IO sector electric services includes mainly the distribution of electricity, but the semiconductor and related device sector is composed of many products, some of them being very different from a pc-si wafer. However, evaluating whether or not the product chosen is far from the average of the sector is a challenging task and further research is needed to quantify the uncertainty linked to the inclusion of very different products in an IO sector. The rapidity of the ICT development also raises the question of whether or not available data are still representative of this

industry. This is a strong limitation of the ICT evaluation that we have with both the PLCA and the IOLCA.
c) The *quantity of direct inputs* necessary to manufacture a product can also play a major role.
d) Finally, the *level of purity* of the considered chemicals and materials in the PLCA database could introduce a bias if average values are used for classes of chemicals or raw materials that significantly differ from the specific product considered.

The Role of IOLCA and possible levels of combination: IOLCA can play two complementary roles: a) The first is to identify what the significant processes are that one has to concentrate the data searching on. The IO shows that the electricity supply, the printed wiring board (PWB), the chips and microchips, the cover, and the motors and generators of the PC, as well as the assembly processes, contribute significantly to environmental impacts. Future work should collect more precise data on these contributions to enhance the quality of the LCA. More generally, LCA data about products and the ICT products we are buying should be collected at all steps, from the consumer level to large companies.
b) The second role is to model complex devices, even if little data on physical flows are available. LCA of ICT indeed faces an important challenge of data acquisition as ICT devices have many components coming from many different suppliers and as the corresponding data to perform PLCA are difficult to obtain. The quality of the assessment will depend in a large part on this issue.

The conclusion of chapter 2 proposed different levels of aggregation for PLCA and IOLCA:

level 1 - identification of significant impacts: Data taken from the IOLCA is used to identify and set priorities for the development of the PLCA and the PLCA databases. Analysing the structure of the impacts of one country using IO permits one to identify the main contributors and therefore give suggestion for the development of PLCA databases. It can also be used to identify potential data gaps in PLCA. This level could be summarised by "learning from IOLCA to enhance the quality of PLCA." In chapter 3, PLCA and IOLCA were performed in parallel to assess the environmental impact of the computer network of a university. Both approaches lead to similar conclusions on the type of devices that have the largest impact. However, the IOLCA permits one to show that the production phase of a computer is more important, which could be explained by a more detailed assessment.

Level 2 - tiered approach: The cut-offs evaluated with the IOLCA are added to the PLCA. The aggregation of the PLCA, using the developed methodology, has to be performed to enable a correct comparison. The tiered approach can also be used to include other contributions in the study, such as the marketing, the management, the research, and development, or other cut-offs that are traditionally considered in the PLCA. Chapter 3 shows the case study of a computer network and chapter 5 of an innovative Internet service. In these two examples, these services have a very significant impact, which implies that they should be systematically considered. Further work could test the pertinence of applying both the IOLCA and the PLCA for the evaluation of service type contributions themselves.

6.2 The direct impacts of a computer network and the consequences for policy making

One main result of this thesis is the identification of the key elements of the computer network of the Swiss Institute of Technology that affect the environment. First, the impact of various short-term technological changes has been assessed. Finally, the impacts of the services included in the total cost of ownership have been included in the assessment.

The PLCA performed to assess the environmental impact of the production of *computers* shows that more non-renewable primary energy is necessary to produce a desktop computer than a notebook, with the major impacts coming from the production of chips and the PWB. Other direct emissions are linked to the assembly of the computer, its cover, and to the electricity supply. Among the not-considered contributions in PLCA, one finds the wholesale trade and the air transportation. But a large part is due to the many other Input-Output sectors that contribute to a very small part of the total impact. These “hidden” contributions can be an important part of the described cut-offs.

The evaluation of the environmental impact of a *computer network* shows that the PC and the screens are dominant. The server and the switches have a significant contribution due to their high electricity consumption. In a professional context, characterized by a long use time per day of the equipment, the impact of the use phase (electricity consumption) dominates, and yet the impact of the production phase is still significant. The PLCA shows that near-term technology changes can have a very important effect on the environmental impact, evaluated here with the CO_2 emissions, and can decrease the impacts by 20 to 50% by shifting from CRT to LCD screens and from desktops to notebooks. One of the easiest and most efficient ways to decrease the environmental impact is to set up a buying policy that promotes notebooks, requires one to have LCD screens, and to prefer to buy low consumption devices. In addition, there is a need to further assess the environmental impact of notebooks as their function differs from a traditional desktop. They can be moved easily and can therefore have an impact due to the fact that people might decide to travel less with their bicycle, as well as the fact that they might decide that they don’t need another computer at home.

To decrease further the impact of the production phase will probably require a technology breakthrough to shift from ICT based on silicon to alternative solutions.

Extending the system boundaries further leads to the conclusion that services needed for the maintenance of the network, the management of the computer, etc. have a significant impact and that the total cost of ownership (TCO) should be considered when evaluating the environmental impact of an ICT system. In particular, the time lost by all of us in managing our computer is very important. An environmental friendly computer is therefore a reliable computer. Further work could compare different exploitation systems, such as Windows, Mac, or Linux to study whether one implies less time to manage the computer and the computer network due to less viruses, less breakdown, an easy or more difficult installation, etc. When evaluating ICT with an LCA approach, the TCO should always be considered. In chapter 5, the evaluation of the services linked to the production and commercialisation of new Internet services shows that they are important, especially the research and development and the marketing.

6.3 Assessing not only the negative impacts, but also the benefits of ICT.

Two case studies, the city of Martigny and the visiophonic station, have been assessed using both the PLCA and the IOLCA. Indirect effects linked to the applications of these services were included in the analysis.

6.3.1 ICT benefits in utility management

The combination of PLCA and IOLCA enables the inclusion of the indirect effects and allows one to quantify the benefits of some ICT applications. They also permit one to confirm that some ICT applications induce more benefits for the environment when compared to the traditional service.

In the case of the city of Martigny, the environmental benefits are 4 to 5 times higher than the impacts of the infrastructure and the necessary investment to set up, maintain, and exploit the telemonitoring system. This shows the pertinence of the approach of the CREM and the importance of the monitoring of the networks to understand their “behavior”. It also shows that the use of ICT is very important and can have very interesting applications. At the same time, these benefits are not automatic consequences of the use of ICT: it is only through a thorough data analysis leading to actions and measures taken to reduce electricity and water consumption that ICT provides its full benefits. The potential for improvement in the management of urban network is very promising and should be intelligently expanded to other cities. Further work should include a more detailed monitoring of the use of the system to better identify the benefits and problems produced by the use of the telemonitoring system.

6.3.2 Benefits of ICT innovative services

In chapter 5 various innovative services are presented, among which some are responsible for large benefits for the environment while others do not. Including the service linked contributions of the TCO, such as the marketing, the research or the communication, is of great importance. The IOLCA shows us that this traditionally not considered impact could be significant and could reserve some surprises. However, extensive research is needed to have a better idea of these impacts and this should be carried out using both PLCA and IOLCA.

In both case studies, the environmental impact of the ICT devices is very low compared to the other costs, such as the cable TV network for Martigny (although only part of the cable TV network has been allocated to the studied application), or the benefits. Two types of substitution turn out to be very beneficial for the environment: 1. when ICT replace the construction and occupation of a building for living or for working, 2. when the need for transportation is eliminated, the more kilometres substituted, the better. Two parameters should be used to characterise a “good” ICT application in respect to the environmental benefits it can produce: the first is the importance of the benefits induced by one device and the second is the number of devices that can be installed and the penetration factor of the technology among consumers. The penetration and diffusion of new technologies, especially of green technologies, should be taken into account when the global potential for environmental benefits of a new service or technology is evaluated.

In the development of new ICT services, LCA should be included more systematically to point out the key parameters that the developers must take into account. It has to be included from the beginning of the development process of a new device or service. This case study shows that it is much more important to work on the service development and to consider the potential benefits of ICT service as well as the indirect effects rather than “wasting” lots of resources on the eco-design of the device itself.

6.3.3 A method to address indirect and rebound effects and its application for the assessment of the impacts and benefits of innovative ICT services

The system boundaries were further extended to consider rebound effects. As shown in chapter 5, this could have a very significant effect on the evaluation of the environmental impact of ICT applications.

The methodology developed enables one to consider either the use of financial resources or of time as the critical parameter and to include the indirect effects in the LCA. Significant improvement, however, are needed on the methodological side. We could consider different types of statistics depending on the type of consumers that are generally thought to use the service. The time and budget use might be very different depending on the social class of the users of a service and that should be considered. Moreover, how people spend additional spared time or money is likely to be different from how they behave normally. In addition, better data could be used to evaluate the environmental impact of the activities.

The results show that ultimately, it is the consumer that “chooses” whether the innovative service induced benefits or not. The service providers can promise a potential for environmental load reduction, but it is the consumer that has the final choice. In our case, the consumer that chooses to buy an environmentally friendly product will capitalise the first positive effect of the use of the service and induce a clear positive effect. On the contrary, if the money is used to fly to Rome or any other European capital, then the final balance is negative. The role of consumers is therefore very important. In this example, it is difficult to determine where are the responsibilities. Is it the company or the consumer, or both? But even if companies argue that it is not their responsibility, having identified the impacts give them some information on where they should act to decrease the environmental impact more efficiently. Sometime they have the possibility to influence the consumer choices. More generally an impact is the results of many decisions and both the producer and the user share responsibilities.

These discussion on rebounds effects leads to a discussion on system boundaries and especially the boundary of the cause-effect chain. Where do we have to stop? Should we include rebound effects in the analysis? Are they a direct consequence of the use of ICT? In the case of the visiophonic station, the fact that the users will save money and time can be seen as a direct consequence of the use of the ICT device. But what they are doing with this money and time depends of many other parameters. The fact is that society evolves as a result of complex interactions between the system components, and it is very often difficult to state and understand what is caused by what when we are considering broader social changes and corresponding costs and benefits. One answer is that system boundaries should be set in relation to the objectives of the study, the data we have and where it is possible to act and to have an influence.

Finally, the indirect effects on the environment are so broad, that we carried out a sensitivity study based on a few realistic scenarios. The general effect of ICTs on our culture, social values, and lifestyle, as well as their effects on the environment, are even more difficult to evaluate. One of the greatest benefits of the Internet could be a change in the perception of everyone’s personal freedom. Instead of being linked to the car and other means of transportation that enable us to move freely, individual freedom might become increasingly associated with access to the Internet and information (Allenby).

Another very interesting question is whether information and ICTs can raise greater environmental awareness among the population. The Internet is a way to access and distribute information that many people can not do without. In raising awareness about environmental problems there are not only possibilities for Non-Government Organizations (NGOs) to address a large audience, but also extraordinary possibilities for those interested in environmental protection to become informed. However, as everyone knows, the problem is not a lack of information, but rather an offer-in-excess of information on the Internet, and it is often difficult to judge whether the information sources are trustworthy.

"We have the choice about whether the digital revolution will work for or against the environment".

Commissioner Wallström

let us make the right one....

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8 ABBREVIATIONS

IOLCA Input-Output Life Cycle Assessment.

PLCA Process Life Cycle Assessment.

LCA Life Cycle Assessment.

ICT Information and Communication Technology

$\vec{b}_{IOLCA}$ m vector of the total impacts, m is the number of pollutants assessed.

B_{IOLCA} the environmental matrix, it is a m by n matrix representing the emissions per $ for all industrial sectors, n is the number of industrial sectors.

$\vec{x}_{IOLCA}$ n vector that represents the total output, that is, everything needed to produce the studied final demand.

A_{IOLCA} matrix of the technology coefficient, a_{ij} = input of sector i to sector j in order to produce $1 of sector j.

$\vec{y}_{IOLCA}$ n vector that represents what we want to buy in all sectors (the final demand or the reference flows).

$\vec{b}_{PLCA}$ p vector of the total impacts, p is the number of pollutants assessed.

B_{PLCA} ecoinvent environmental matrix, it is a q by p matrix representing the direction emissions per process, q is the number of processes considered.

A_{PLCA} ecoinvent technology matrix. $A_{PLCA,\,ij}$ = input or quantity of process i to produce one unit of process j.

$\vec{y}_{PLCA}$ reference flows (amount consume by each process to produce a functional unit).

C (n x 2630 matrix) represents the upstream cut-off flow to the PLCA system, that is the contributions of the Input-Output to the processes, $C,_{i,j}$ = inputs from Input-Output sector i to process j (monetary value/physical unit). n is the size of the chosen IO table.

D (2630 x n matrix in our case) represents the downstream cut-off flows to the IO system, that is, the contributions of the PLCA to the Input-Output, $D_{i,j}$ = inputs from Input-Output sector i to process j (physical unit/monetary value).

$A_{IOLCA\text{-}NTIA}$ represents the Input-Output matrix, where where $a_{ij} = 0$ when i is a line corresponding to a sector that we do not want taken into account in PLCA.

$A_{IOLCA\text{-}S}$ represents the Input-Output matrix, where $a_{ij} = 0$ when i is a line corresponding to a sector that is considered as a service in this work (see page 15 for more details).

9 GLOSSARY

Dematerialisation: The provision of equal units of function (or, more broadly, quality of life) using less material. Dematerialisation is a process that over time offers an obvious path to achieve greater environmental and economic efficiency.

Environmental Impact: “Any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization’s activities, products or services that can interact with the environment “ (ISO 14’001:2004)

Environment: “Surroundings in which an organisation operates, including air, water, and , natural resources, flora, fauna, humans, an their interrelation” (ISO 14’001:2004)

Environmental Managements System: A corporate management system including an environmental policy and goals for the activities of the company. ISO 14’001 and EMAS commits the company to continuous improvements of the environmental performance.

Functional Unit: “Quantifies performance of a Product System for sue as a reference unit in a life cycle assessment study” (ISO 14040: 1997)

Information Society: The concept of “information society” is referring to a society in which the information and communication technologies (ICT) play a key role

Input-Output Life Cycle Assessment (IOLCA): A life cycle assessment that is based and use the Input-Output theory and data.

Input-Output theory: A macro-economic theory, developed by Vassily Leontief, that divides the economy in sectors and modelises the monetary flows between these sectors.

Knowledge based society: The concept of “knowledge-based society” is strongly linked to the concept of “information society”. But the knowledge-based society does not focus on the flows of information, but on knowledge and creativity, and interest itself on the impacts of the diffusion of knowledge on the economical development, culture,

Life Cycle Assessment: “Compilation and evaluation of the inputs, outputs and the potential Environmental Impcats of a Product System throughout its life cycle (ISO 14040:1997)

Process Life Cycle Assessment (PLCA): It it a detailed LCA that complies to the ISO standards without specific modifications or adaptations.

Product System: “Collection of materially and energetically connected unit processes which performs one or more defined functions” (ISO 14’040:1997). The product system is the system in reality.

Sustainable Development: Development that “meets the needs of the present without compromising the ability for future generations to meet their own needs” (WCED 1987). Sustainable development addresses economic, environmental and social aspects.

System Boundary: “Interface between a product and the environment or other product system” (ISO 14’040:1997)

10 LIST OF FIGURES

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12 CURRICULUM VITAE

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Swiss
30 ans
Married
2 children

Education

2002-2006 Ecole Polytechnique Fédérale de Lausanne (EPFL), PhD ès science, "Environmental Impacts and Benefits of Information and Communication Technology Infrastructure and Services, using Process and Input-Output Life Cycle Assessment".

1994-2000 Ecole Polytechnique Fédérale de Lausanne (EPFL), diploma, physics; *I had the opportunity to study one year in England at the University of Nottingham.*

Professional experience

2006-today **Ecointesys – Life Cycle Systems sàrl**, co-founder of the company and executive director.
Environmental management system, Life cycle assessment, continuing education, risk management.

2001-today **Ecole Polytechnique fédérale de Lausanne**, Insitute for Environmental Science and Technology, Laboratory of ecosystem management, group for industrial ecology and life cycle systems, PhD, forum and international conferences organisation, courses.
I'm a member of the program committee of the Swiss Discussion Forum on LCA and I coordinate its activities. Three forums are organised per year, one in Lausanne, under our responsibility, and two in Zürich.

2001-today RDS technique et conseils en environnement SA, **bureau d'investigation sur le recyclage et la durabilité.**
Project management in the field of waste management, eco-construction, health waste management and expert for asbestos detection.

2001 Institute for the communnication and the analysis of sciences and technologies (ICAST).
Practice in the field of **Industrial Ecology.**

2000 Indian Institute of Science Bangalore, department of environmental sciences, Bangalore and Indian Institute of Technology, New Delhi, department of rural engineering, **India**.
Research projects (2 times three months) in the field of energy efficiency and waste management.
Participating in these two research projects gave me the opportunity to discover the country through on the one hand a professional activity and on the other hand in traveling.

Languages

French : Mothertongue
English : Good knowledge – *one year in England and seven months in India*
German : Average knowledge – *continuing education*
Spanish : Basics

Leisure

Activities with family : discovering the beauty of nature, traveling
Reading : scientific magazines and books, comics
Sports : Scuba diving (level 3 CMAS), bicycle, walking

Publications

Loerincik, Y. and O. Jolliet, 2002, La société de l'information: quels impacts sur l'environnement?, *Infosociety.ch newsletter*, (19), 2-4.

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13 APPENDIX A: BASICS OF INPUT-OUTPUT AND HYBRID LIFE CYCLE ASSESSMENT (IOLCA)

The IO table of direct requirement coefficients is needed to estimate the monetary flows induced throughout the economy by the "ripple effect" emanating from a given sector output. For each sector, average emissions and the energy consumption per economic unit of output are required to assess the total environmental burdens.

"An IO-table gives an overview of the trade in a national economy. It shows how products are being sold from producers to either be used by final consumers or to contribute to further production in other industry sectors....The number of sectors and their definition vary from country to country." (Nielse et al., 2001)

The Input-Output theory (Miller and Blair, 1985) divided the economy in sectors and/or commodities. As it is not possible to have one sector for each product that exists, some sectors include many different products, sometimes quite different in terms of environmental impact. The more sectors we consider the more data (and therefore work and time) we need, but at the same time, the more precise we are. In the United States, for example, the economy is divided in 500 sectors.

The final demand and the corresponding total output are linked through the following equation:

$$\vec{x} = (I - A)^{-1} \cdot \vec{y}$$

$\vec{y}$ [$] is an n vector that represents what we want to buy, or to assess (the final demand). n is the number of industrial sectors.

$\vec{x}$ [$] is also an n vector that represents everything needed to produce y (the corresponding total output).

A is the matrix of the technology coefficient. a_{ij} = input of sector i to sector j in order to produce 1 $ of sector j [$/$].

The final demand is what is taken out of the economy that we want to assess, that is our functional unit (for instance one bottle of orange juice, if we want to assess the orange juice bottle). The corresponding total output is what needs to be produce in the economy to enable the manufacturing of this final demand (in our example, the glass, the orange juice and so on, that needs to be produce to enable the sell of one bottle of orange juice).

13.1 Environmental impacts

In environmental science, the goal is to link the output of one sector with the emissions of pollutants or the energy consumption of this same sector.

Total impact of one sector = impact per $ of output [emissions per $] · final output [$]

Total impact associated to the final demand = sum on all the sectors of: impact per $ output of sector i · final output sector i

In matrix form, this is written:

$$\vec{b} = B \cdot \vec{x} = B \cdot (I - A)^{-1} \cdot \vec{y}$$

$\vec{b}$ [Physical flows = kg, etc.] is the m vector of the total impacts; m is the number of pollutants assessed.
B is the environmental matrix, it is a m by n matrix representing the emissions per $ for all industrial sectors [Physical flows/$]

13.2 Derivation of the IO equation

The IO methodology is based on two matrices, *A* the economic matrix and *B* the environmental matrix.

$$A = \begin{pmatrix} a_{11} & \dots & a_{1i} \\ \dots & \dots & \dots \\ a_{i1} & \dots & a_{ij} \end{pmatrix} \qquad B = \begin{pmatrix} b_{11} & \dots & b_{1i} \\ \dots & \dots & \dots \\ b_{i1} & \dots & b_{ij} \end{pmatrix}$$

where a_{ij} is the amount of money spent in the sector i in order to produce one $ in the sector j. b_{kl} is the elementary flow for the emission of pollutant or the consumption of resource k associate with the production of 1 $ by the sector j.

We can traduce the references flows in expenses in the different economic sectors. This is called the final demand and it is represented by an n vector $\vec{y}$ (y_i = the expenses in the sector i per functional unit). It is possible to determine the total flows spent in the different economic sectors to reach this final demand. To take into account all the direct and indirect contributions, we can use the following formula:

$$\vec{x} = \left(I + A + A^2 + A^3 + A^4 + \dots\right) \cdot \vec{y} = (I - A)^{-1} \cdot \vec{y}$$

The term $A^i \cdot \vec{y}$ represents the contribution of the tier i. When i = 0 it is the direct emissions. When i = 1, we take into account the emissions linked to the direct contributions to the functional unit. When i = 2 we take into account the emissions linked to the contributions to the direct contributions, etc...

13.3 Advantages and limitation of Input-Output Life Cycle Assessment

13.3.1 Advantages

- Full direct and indirect implications (the whole economy is taking into account); “LCA based on Input-Output analysis inherently cover all upstream production stages, and thus remove the limitations imposed by conventional system boundary selection” (Lenzen, 2001);
- Low cost of the anaylsis.

13.3.2 Limitation

- An Input-Output table and an environmental matrix are required. Specialists must work on the task if one wants to have reliable data;
- Environmental data are not available for all industry sectors;
- Sectors include many type of equipment and therefore the value we have is an average;
- It is assumed that the relationship between price and environmental impact is linear, which is not always true;
- The Input-Output does not permit to compare two very similar products;
- Activities associated with final consumers, such as energy for product use or wastes of product disposal (Lave et al., 1995)are not included.

13.4 Truncation errors in Process Life Cycle Assessment

Lenzen (Lenzen, 2001) has evaluated the truncation errors resulting from the omission of resources requirements or pollutant emissions of higher-order upstream contributions. According to his study, this error can be on the order of magnitude of 50%. He concludes by assessing that uncertainties of Input-Output based life-cycle assessments are often lower than truncation errors in even extensive third-order process analysis. He states that the error induced by the system boundaries limitations are often important.

13.5 Hybrid methodologies

Various Input-Output hybrid approaches have been developed in the last 15 years. See (Suh et al., 2004) in ES&T for a summary of the existing studies and a good bibliography. Suh classified the approaches in three main categories:

13.5.1 Tiered hybrid analysis

A tiered hybrid analysis uses the Input-Output methodology to evaluate the contributions that were not taken into account by a PLCA. Direct requirements as well as some important lower order upstream requirements are examined using a traditional PLCA. The other contributions are covered by Input-Output. Various tools are available to perform tiered hybrid analyse:

- MIET 2.0 (Missing Inventory Estimation Tool) 2.0, developed by Sangwon Suh is freely available (Suh and Huppes, 2002). This software is however limited to 90 economic sectors and based on past/old data http://www.leidenuniv.nl/cml/ssp/software/miet/;
- CEDA 3.0 is the new version of MIET 2.0. More accurate data and more sectors (500) are available. The software and the data have to be bought http://www.enviroinformatica.com/;
- EIOLCA has been developed by Carnegie Mellon University. It is an Internet tool (www.eiolca.net) that permits to perform Input-Output estimation;
- Open-LC is a tool developed by Greg Norris. See www.sylvatica.com for more information.

13.5.2 Input-Output based analysis

In an Input-Output hybrid based analysis, new sectors are created and/or important sectors are disaggregated in more detailed sectors. This has been applied by Joshi (Joshi, 2000), who defined different models depending on the situation and the aim of the LCA. To perform the LCA of a product, Joshi proposed to allocate the product to one economic sector or to define a new artificial sector that represents it. In addition, he described the possibility to disaggregate existing Input-Output sectors to better take into account the specificities of a product. Finally the use and the end-of-life stage of a product, which is generally not taken into account when using an Input-Output approach, can be included as a new IO economic sector.

13.5.3 Integrated hybrid analysis

An integrated hybrid analysis has been developed by Suh and Huppes (Suh and Huppes, 2005). In this model, the process-based system is represented by a technology matrix[32] and the Input-Output system is represented by monetary units. The flows crossing the boundaries from one model to the other (monetary unit per physical unit for Input-Output data

[32] A process technology matrix is a square matrix describing the flows from one process to the other. Typically a_{ij}= amount of process i to produce one unit of process j.

contributing to a process and physical unit per monetary unit for process data used in the Input-Output) are determined and the process technology matrix is integrated into the Input-Output framework. This approach has the advantages of avoiding double counting by subtracting the commodity flows in the process-based system from the Input-Output framework.

14 APPENDIX B: INPUT-OUTPUT ECONOMIC AND ENVIRONMENTAL DATA AVAILABILITY

Although the economic data are in general available, the environmental data are more difficult to find and aggregate. One problem that also arises is the fact that economic sectors and environmental sectors do not always match.

The following table describe only the most recent and detailed data (per country).

Table 15: Description of the available Input-Output and environmental data per country.

Country	**Number of sectors**	**Base year**	**Environmental data**
Australia	135	1994-95	27 energy types, emissions of CO_2, CH_4, N_2O, CO, NO_x, Non-methane volatile organic compounds, CF_4, C_2F_6, HFC134a, SO_2, SF_6, water use (mains and self-supplied), land disturbance (6 land types)
Austria	57		SO2, Nox, NMVOC, CH4, CO, CO2, N2O, NH3,
Denmark	130	1997	35 energy types, water, 8 types of emissions to air
Germany	71	1997, 2000	30 energy carriers, water, 3 types of waste, emissions of CO_2, CH_4, N_2O, CO, NO_x, Non-methane volatile organic compounds, SO_2, particles
Japan	349 ('75,'80) 406 ('85) 405 ('90) 397 ('95)	1975, 1980, 1985, 1990, 1995	Energy, emissions of CO_2, CH_4, N_2O, NO_x, SO_x, SPM
Netherlands	105	1996, 1997, 1998, 1999	Land use, N and P (in soil and water), CO, CO2, CH4, NOx, SOx, NH3, N2O, VOC, PM10, water, resources depletion, benzene, wood, fish
US	94 - 491	1992 1996 1998	Toxic pollutants from manufacturing industry, greenhouse gas emissions, pesticide use, nutrient emission, conventional pollutant emission, energy requirements
Switzerland	37	1990 (based on 1985) 2004[33]	Energy

[33] A new Input-Output table has been worked out on the basis of the old table and updated data. This was presented September the 1st in Zürich. The matrix will be available within a few months, energy data will be available.

OCDE[34]	36	1995 (in revision)	None
GTAP[35]	57	2001 (last revision)	None
Eurostat[36]		from 1992 to 2002 depending on the countries	CO2, biomass as fuel, NO2, CH4, HFCs, PFCs, SF6, NOx, SOx, NH3, NMVOC, CO, PM10, CFCs, HCFCs, As, Hg, Pb, Zn, Cd, Cr, Se, Cu, Ni, depending on the countries

[34] The Input-Output tables from the OECD were published in 1995. The tables exist for 10 OCDE countries: Australia, Canada, Denmark, France, Germany, Italy, Japan, Netherlands, United Kingdom and the USA. The classification used is the CITI (second revision) that divide the economy in 36 sectors. The common industrial classification chosen by the OECD for the collection of the input-output tables was designed to identify technology-intensive and/or trade-sensitive sectors -- pharmaceuticals, computers, communication equipment, automobiles, aircraft, etc. -- which are the focus of much of the 10 analysis conducted within the Directorate of Science, Technology and Industry (DSTI). Consequently, the manufacturing sector is disaggregated more finely than the agriculture, mining or service sectors. To ensure compatibility with other OECD databases, countries were asked to supply data which adhered to the second revision of the International Standard Industrial Classification (ISIC, Rev.2). All the matrices should therefore present a square industry-by-industry configuration. To achieve this, most countries formed industry-by-industry matrices using the Use matrix (which shows purchases of commodities by industries) and the Make matrix (which shows the principal and secondary production of commodities by industries). A few countries, such as Japan, compiled this matrix by simply converting commodity-based input-output tables using the commodity (activity) and industry correspondence.

[35] GTAP (Global Trade Analysis Project): the centerpiece of the GTAP project is a global data base describing bilateral trade patterns, production, consumption and intermediate use of commodities and services. The number of users of this data base exceeds 400 individuals in 40 countries. The Global Trade Analysis Project, with headquarters at Purdue University, has organized a consortium of national and international agencies which provide guidance and base-level support for the Project. The GTAP staff work closely with representatives of these member institutions in order to ensure continuity in the data base, modeling framework, training activities, and research network that comprise this Project. The last version of the database is the GTAP 6 Data Package. It is a global data base consisting of regional input-output data, macroeconomic data, bilateral trade flows, protection and energy data. This updated data base corresponds to the global economy in 2001. It includes 87 regions that are divided in 57 sectors. For more information:
http://www.gtap.agecon.purdue.edu/default.asp

[36] Eurostat publishes data for each member state of the European Union and for Acceding and Candidate Countries as far as available. Regarding products Eurostat applies the CPA P60 classification that delineates sixty products. For the classification of industries Eurostat uses NACE rev.1 A60 as reference which distinguishes 60 industries. Figures are given for most of the variables of the tables 1500 "Supply Table", 1600 "Use Table", 1700 "Symmetric Input-Output Table", 1800 "Input-output Table for Domestic Output" and 1900 "Input-Output Table for Imports". The tables 1500 and 1600 are provided annually whereas the tables 1700 to 1900 are delivered for intervals of five years.
http://europa.eu.int/comm/eurostat/newcronos/reference/sdds/en/iot_sut/iot_sut_base.htm
http://europa.eu.int/comm/eurostat

15 APPENDIX C: FABRICATION ET RECYCLAGE DU MATÉRIEL ÉLECTRONIQUE

15.1 Unité centrale PC

15.1.1 Introduction

L'unité centrale du PC se compose des éléments suivants[5] :
- processeurs et microprocesseurs.
- circuits imprimés
- moniteur : CRT (Cathodic Ray Tube) ou LCD (Liquid Cristal Display).
- fils électriques, boîtier et structure interne du boîtier (yc alimentation)

Afin de compléter ce bilan, les composants suivants sont également pris en compte :
- lecteur de disquette.
- disque dur.
- alimentation (dans boîtier)

15.2 Bilan matériel des divers composants

15.2.1 Processeurs et microprocesseurs

L'élément central dans la fabrication des semiconducteurs est le silicone. Celui-ci est utilisé sous forme de galette (wafer) préalablement préparée. D'après (Williams et al., 2002), 0.16 [gr] de galette de silicone donneront 1 cm^2 de chip utilisable. Un chip entier nécessite 0.25 [gr] de galette de silicone et un ordinateur moyen nécessite 25 [gr] de galette de silicone (Williams, 2004 (b)) : un ordinateur moyen contient donc une centaine de chips. A noter qu'1 cm^2 de galette de silicone correspondra à un chip d'une capacité de 20 mb de DRAM et qu'un chip, dans ce contexte, correspond à un chip fonctionnel de 32 mb de DRAM. Dans (Williams, 2004 (b)), l'électricité nécessaire pour un chip de 1,6 cm^2 est de 2.9 kWh, soit 1,8 kWh par cm^2 de galette de silicone ; dans (Williams et al., 2002), l'électricité est de 1.5 kWh par cm^2 de galette de silicone. La première valeur est retenue. Pour l'eau, 32 litres sont nécessaires pour la fabrication d'un chip. L'auteur donne alors la valeur de 310 litres pour les chips nécessaires à un ordinateur : peut-être s'agit-il d'une faute d'impression (facteur dix au lieu de facteur 100). Dans un autre article du même auteur (Williams, 2004 (a)), la valeur de 32000 l est donnée pour la fabrication de l'ensemble des chips d'un ordinateur.

Table 1 : composition des chips et des microchips

The 1.7 kg Microchip : Energy and Material Use in the Production of Semiconductor Devices				
		g/cm^2 de galette de silicium	g/chip	g/ordinateur
Elements				
Silicon wafer		1.60E-01	2.50E-01	2.50E+01
Gaz élémentaires	He	1.70E-01	2.66E-01	2.66E+01

	N_2	4.40E+02	6.88E+02	6.88E+04
	O_2	3.00E+00	4.69E+00	4.69E+02
	Ar	1.70E+00	2.66E+00	2.66E+02
	H_2	4.60E-02	7.19E-02	7.19E+00
		4.50E+02		
Autres gaz	silane (SiH_4)	7.80E-03	1.22E-02	1.22E+00
	phosphine (PH_3)	1.70E-05	2.66E-05	2.66E-03
	Arsine (AsH_3)	4.30E-06	6.72E-06	6.72E-04
	diborane (B_2H_6)	4.30E-06	6.72E-06	6.72E-04
	dichlorosilane (SiH_2Cl_2)	1.40E-03	2.19E-03	2.19E-01
total		9.23E-03	1.44E-02	1.44E+00
etchants	N_2O	7.20E-02	1.13E-01	1.13E+01
	Cl_2	4.80E-03	7.50E-03	7.50E-01
	BCl_3	8.70E-03	1.36E-02	1.36E+00
	BF_3	3.50E-05	5.47E-05	5.47E-03
	HBr	2.20E-03	3.44E-03	3.44E-01
	HCl	5.00E-03	7.81E-03	7.81E-01
	HF	9.50E-04	1.48E-03	1.48E-01
	NF_3	2.30E-03	3.59E-03	3.59E-01
	WF_6	4.30E-04	6.72E-04	6.72E-02
	SF_6	6.50E-03	1.02E-02	1.02E+00
	C_2F_6	5.00E-02	7.81E-02	7.81E+00
	CHF_3	3.10E-02	4.84E-02	4.84E+00
	CF_4	3.00E-02	4.69E-02	4.69E+00
total		2.14E-01	3.34E-01	3.34E+01
acides/bases	HF 1 vol + NH_4 30 vol mixture	2.84E+00	4.44E+00	4.44E+02
	acide phosphorique H_3PO_4 86%	2.41E+00	3.77E+00	3.77E+02
	acide fluorhydrique 0.5%	3.42E+00	5.34E+00	5.34E+02
	acide fluorhydrique 5%	4.55E-01	7.11E-01	7.11E+01
	acide fluorhydrique 50%	2.52E-01	3.94E-01	3.94E+01
	acide nitrique 70%	1.19E+00	1.86E+00	1.86E+02
	acide sulfurique 96%	7.85E+00	1.23E+01	1.23E+03
	HCl 30%	2.52E+00	3.94E+00	3.94E+02
	Ammoniac 28%	7.76E-01	1.21E+00	1.21E+02
	slurry	2.86E-01	4.47E-01	4.47E+01
	HCl 30%	5.06E-01	7.91E-01	7.91E+01
	NaOH 50%	6.51E-01	1.02E+00	1.02E+02
total		2.32E+01	3.62E+01	3.62E+03

agents photolithographiques	peroxyde d'hydrogène 30%	4.43E+00	6.92E+00	6.92E+02
	alcool isopropylique	2.02E+00	3.16E+00	3.16E+02
	hydroxide de tetramethylammonium	4.31E+00	6.73E+00	6.73E+02
	methyl-3-methoxypropionate	1.48E+00	2.31E+00	2.31E+02
	acetone	5.54E-01	8.66E-01	8.66E+01
	hexamethyldisilazane	2.20E-02	3.44E-02	3.44E+00
	hydroxyl monoethanolamine	1.42E+00	2.22E+00	2.22E+02
total		1.42E+01	2.22E+01	2.22E+03
agent de neutralisation	NaOH	7.60E+00	1.19E+01	1.19E+03
électricité	kWh	1.50E+00	2.34E+00	2.34E+02
combustibles fossiles utilisés de façon directe	MJ	1.00E+00	1.56E+00	1.56E+02
eau	litres	2.00E+01	3.13E+01	3.13E+03

15.3 Circuits imprimés (PWB = Printed Wired Board)

Les circuits imprimés sont les supports des semiconducteurs et autres composants électroniques (diodes, résistances…) faisant partie de l'ordinateur. Il faut distinguer les circuits imprimés sans composants (uniquement le circuit avec les trous et les lignes de cuivre) et ceux avec composants. Des données concernant la composition des circuits imprimés avec leurs composants ont été obtenues d'une étude en cours de réalisation (les données sont confidentielles): ces données concernent 1 kg de PWB d'un ordinateur. D'après (Williams, 2004 (b)) ,il y a 1.85 kg de circuits imprimés dans un PC . A cela est ajouté l'utilisation d'électricté, de combustibles fossiles (utilisation directe uniquement) et d'eau.

15.4 Moniteur (CRT et LCD)

De nombreuses tentatives ont été menées pour déterminer la composition matérielle des moniteurs, mais pour le moment sans résultat probant. Pour le moment, seules les valeurs d'énergie totale liée à la fabrication des moniteurs selon les différentes études sont présentées ici.

Figure 2 : énergie primaire non-renouvelable pour la fabrication d'un écran, comparaison entre plusieurs études.

Etude	Moniteur	MJ pour la fabrication d'1 unité
EPA	17" CRT	18666
EPA	15" LCD	2073
Atlantic	15" CRT	1780
MCC	CRT	650
Miyamoto	CRT	411
TU Munich	CRT	3144

15.5 Boîtier et câbles

La composition d'un boîtier et de l'alimentation a été déterminée par (Atlantic Consulting, 1998). Quant un élément est composés de plusieurs matériaux, le poids total est réparti de manière égale entre ces différents matériaux (ex. : câbles et prises 210 gr, composés de cuivre, PVC et PS => 70 gr de cuivre, 70 gr de PVC, 70 gr de PS).

Table 3 : composition du boîtier, de l'alimentation et des câbles.

Elément		Composition	g/PC
Boîtier desktop	Structure interne	acier	2680
	Support du disque dur	acier	250
	Recouvrement	feuille d'acier	2180
	Cache avant	PPO	210
Alimentation	Structure	feuille d'acier	505
	Ventilateurs	PS	100
	Composants électriques	PWB avec composants	100
	Condensateurs	Al, Cu, résine phénolique, PS	45
	Bobines	PVC, cuivre laqué, ferrite	110
	Refroidissement	aluminium	30
	Câbles et prises	cuivre, PVC et PS	210

Table 4 : Composition des câbles

Câbles dans 1 PC	Quantité [gr]
ABS	30
PVC	190
Cu	190

15.6 Lecteur de disquette et disque dur

La composition des lecteurs a été déterminée par (Atlantic Consulting, 1998).

Table 5 : composition d'un disque dur et d'un lecteur de disquette

Elément		Composition	g/PC
Disque dur IDE 340 mb	Recouvrement	feuille d'aluminium	60
	Structure	aluminium	205
	Plateaux	alliage d'aluminium	85
	Composants électriques	PWB avec composants	60
Lecteur de disquette	Partie mécanique	acier galvanisé	110
	Partie mécanique	PS	130
	Recouvrement	feuille d'aluminium	70
	Composants électriques	PWB avec composants	30

15.7 Résultats pour l'énergie primaire

15.7.1 Unité centrale

Table 6 : calcul de l'énergie primaire non-renouvelable pour le PC

1 unité centrale PC (MJ-Eq)				
Impact category	processeurs et microprocesseurs	circuits imprimés et composants	cables divers	boîtier
Non renewable, fossil	2310	991	25.8	112
Non-renewable, nuclear	1790	395	7.62	34.5
Renewable, biomass	1.21	5.28	0.0263	0.453
Renewable, wind, solar, geothe	0.635	5.68	x	0.597
Renewable, water	217	57.4	0.888	4.84
Impact category	lecteur de disquette	disque dur	alimentation	Total
Non renewable, fossil	36.6	77	103	
Non-renewable, nuclear	10.2	28.4	30.1	
Renewable, biomass	0.087	0.171	0.304	
Renewable, wind, solar, geothe	0.0921	0.184	0.309	
Renewable, water	3.59	14.8	5.44	6270