University of Southern Queensland

Faculty of Engineering & Surveying

Life Cycle Assessment in Semiconductor Foundry

A dissertation submitted by

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ABSTRACT

The environmental impact related to the use and manufacturing phases of the semiconductor chips could be potentially very strong due to the high technological level of process, the amount of energy and the special materials used for their realization. As society becomes more affluent, the demand for ubiquitous devices such as cell phone, laptops, digital cameras and other accessories becomes an integral part of modern life. Semiconductors are the essential component of these products but are often overlook in terms of their environmental impacts.

LCA is a useful tool to quantify the environmental impact. LCA is made up of four key components; goal and scope definition, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation.

This project will identify the scale of environmental impacts in the semiconductor manufacturing of a CMOS wafer during its manufacturing phase based on the Life Cycle Assessment methodology.

The functional unit of the device under study is a CMOS wafer. The data collected is a gate to gate inventory that has been obtained from detailed technological analysis, from information obtained directly from company database and material suppliers. Simapro7 is used to carry out the impact assessment.

The impact assessment will identify the environmental hotspots. With this, suggestions and recommendations are made on the manufacturing process and materials used for environmental sustainability.

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Limitations of Use

CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Signature

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Date

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Abdul Hamid Bin Ahmad
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ABBREVIATIONS

APCVD	Atmospheric Pressure Chemical Vapor Deposition
CMOS	Complementary Metal Oxide
CMP	Chemical Mechanical Planarization
CVD	Chemical Vapor Deposition
DALY	Disability-Adjusted Life Years
DIW	Deionised Water
EPA	Environmental Protection Agency
EOL	End of Line
EPROM	Erasable and Programmable Read Only Memory
FAMU	Fresh Make Up Unit
FFU	Fan Filter Units
FOL	Front of Line
HVAC	Heating, Ventilation, Air-Conditioning
ISO	International Organization of Standardization

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PECVD	Plasma Enhanced Chemical Vapor Deposition
PVD	Physical Vapor Deposition
POUA	Point-of-Use Abatement Equipment
REPA	Resource and Environmental Profile Analysis
SCCM	Standard Cubic Centimetre Per Minute
SETAC	Society of Environmental Toxicology and Chemistry
SimaPro7	System for Integrated Environmental Assessment Products version 7
UNEP	United Nations Environmental Programme
USG	Undoped Silicate Glass

Chapter 1 Introduction

1.1 Project Background

As society becomes more affluent, the demand for ubiquitous devices such as cell phones, computers, digital cameras, and other accessories becomes an integral part of modern life. The past decade has also seen the growing importance of emerging technologies in telecommunication resulting in the enormous growth in all parts of economy particularly in the electronic sector. Unfortunately the required hardware for the application of these technologies is characterized by severe environmental impacts in manufacturing and end of life.

Semiconductors are the essential component of electronic products, but are often overlooked in terms of their environmental impacts. Semiconductor devices are very small in size and have wide variety of applications. The environmental implications of this new industry are a matter of concern given its substantial high rate of growth and economic of scale. A large part of environmental impact of semiconductor chips occurs during semiconductor process manufacturing. (William, Ayers & Hellers, 2002) estimate that to produce a 2 gram 32 megabytes dynamic random access memory, the total weight of secondary fossil fuel and chemical inputs requires 1600 gram and 72 gram respectively.

Wafer fabrication, as part of semiconductor manufacturing process, involves complex process technology. Wafer fabrication process, whose activity is in the clean room area, is very resource intensive, using substantial amount of chemical, gas, energy, and water.

This research project will identify the scale of environmental impacts in the semiconductor manufacturing of a CMOS chip by adopting the life cycle assessment methodology.

Silicon wafer processing is predominantly based on CMOS process. CMOS technology is advantageous for its portability and high performance applications. As demand for electronics increased, it is expected that CMOS technology will remain the dominant technology.

Chapter 2 Literature Review

2.1 Introduction

This chapter reviews the past and present published literatures on Life Cycle Assessment topics. It starts with the brief introduction to LCA, its origin and international developments and standards on LCA. The LCA methodology and techniques are discussed followed by the limitations, benefit and uses of LCA. The methodologies for this research project are from the concepts developed from this review.

2.2 Introduction to Life Cycle Assessment

LCA is a powerful evaluative tool with the potential to assist industry in their environmental assessment strategy. It involves cradle-to-grave analysis of production systems and provides comprehensive evaluations of all upstream and downstream energy inputs and multimedia environmental emissions. The cradle-to-grave or life-cycle impacts include the extraction of raw materials; the processing, manufacturing, and fabrication of the product; the distribution or transportation of the product to the consumer; consumer usage of the product and the disposal or recovery of the product after its useful life. Figure 2.1 illustrates the different stages in the life cycle of a product.

LCA has become more important with the recognition that the production and consumption of manufactured products have environmental impacts. Thus, it is essential to consider the final overall state when designing a product.

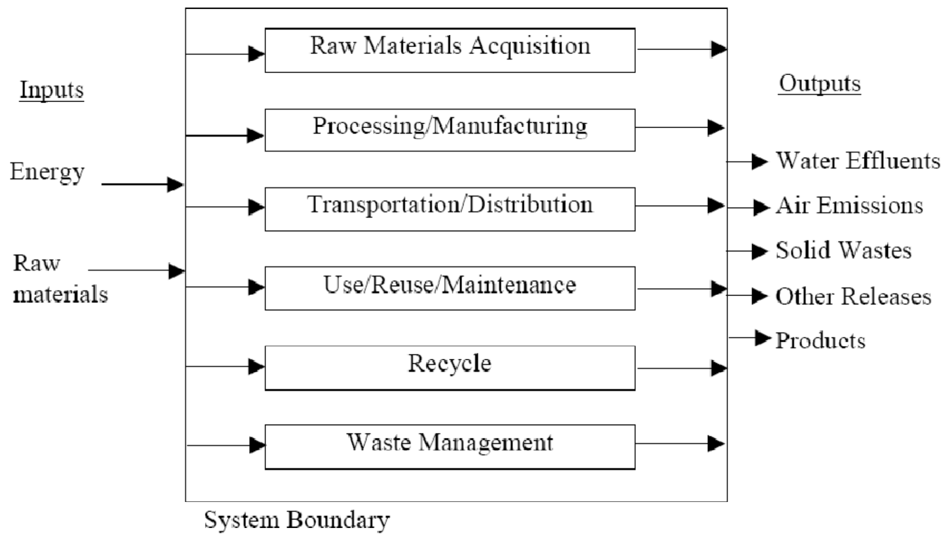


Figure 2.1 LCA – Stages in Life Cycle of a Product (SETAC 1991)

2.3 Origins of Life Cycle Assessment

There is increasing awareness that society is responsible for the need of the sustainable development concept and the environmental impacts caused by amount of pollution and waste released. In the 1960s due to the rapid depletion of fossil fuels, scientists develop LCA as an approach to understand the impact of energy consumption. A few years later, the global modeling predicted this rapid depletion of fossil fuels resulting in climatological changes.

In the 1970s, the U.S. Environmental Protection Agency (EPA) created an approach known as Resource and Environmental Profile Analysis (REPA). REPA is a methodology to determine the material that has the fewest demands for raw materials and energy and the lowest release to the environment upon disposal. Driven by the oil crisis in 1973, about 15 REPAs were performed between 1970 and 1975(Svoboda 1995).

Hazardous waste management became the main environmental issues from the late 1970s to early 1980s. This resulted in the emergence of risk management in association with the life cycle activity.

The late 1980s witness the global issue of solid waste. The life cycle analysis method developed in the REPA studies became an analytical tool. The Council for Solid Waste Solutions conducted two studies in 1990. Initial study involved the comparison of the energy and environmental impacts of paper to that of plastic grocery bags and an identical study comparing disposable diapers to washable cloth diapers.

Besides the public sector, there has been a steady increase on the number of private corporations and non-profit organizations adopting LCA as an aid to understand the environmental impacts of their actions (Svoboda 1995).

2.4 International Organizations and Standards On LCA

There are 3 international bodies that are concerned with the application and development of LCA; namely SETAC (the Society of Environmental Toxicology and Chemistry), ISO (International Organization of Standardization) and UNEP (the United Nations Environmental Programme). Each of them is discussed here.

2.4.1 SETAC

In 1989, SETAC set up its first workshop in Smugglers Notch, Vermont. Being the first international organization responsible for the development of LCA as a tool, it has its roots in academia, industry and government. SETAC sets its aim in scientific development specifically in areas of research and application in the field of environmental management. There are two different schools of LCA development in North America and Europe. However in 1991, SETAC published a "Code of Practice", which was generally accepted and presented the first internationally accepted technical framework for LCA.

2.4.2 ISO

LCA became a worldwide environmental management tool with the advent of the ISO14040 international standards. In the late 1990's, ISO 14040 series on LCA was released as a development of the ISO 14000 Environmental Management Standards. The series includes standards for goal and scope definition and inventory assessment (ISO 14041, 1998), impact assessment (ISO 14042, 2000a), and interpretation (ISO 14043, 2000b), as well as a general introductory framework (ISO 14040, 1997). The LCA methodology is defined in the ISO documents ISO14040 to ISO14043 (ISO 14040 Series). The current version of this standard is ISO 14040:2006 Environmental Management – Life Cycle Assessment – Principles and Framework and ISO 14044:2006 Environmental Management - Life Cycle Assessment - Requirements and Guidelines.

ISO remains the best code of practice for conducting an LCA. As a result, this project research follows the ISO 14040 series at all times. Any reference to 'standards' in this report refers to ISO standards unless otherwise stated.

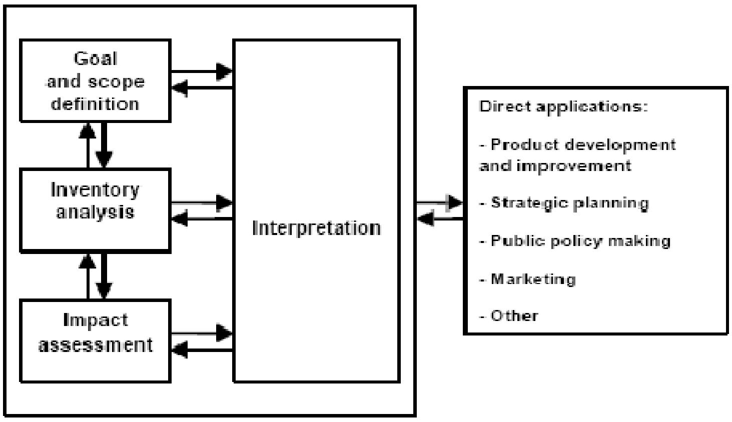


Figure 2-2 Phases of an LCA according to ISO 14040:1997(E)

2.4.3 UNEP

UNEP (the United Nations Environmental Programme), focus mainly on the application of LCA especially in developing countries. UNEP first published a guide to LCA titled "Life Cycle Assessment: What it is, and what to do about it", in 1996. This was followed by another publication in 1999, "Towards Global Use of Life Cycle Assessment" (Guinee et al 2001). A series of international workshops dealing with various aspects of LCA was organized by the Environmental Protection Agency of the US (US-EPA) and CML in the Netherlands, under the auspices of UNEP.

2.5 Life Cycle Assessment Methodology

An LCA study must consider all environmental effects throughout the entire life cycle of the product, from raw material acquisition to manufacture, use, and final disposal. It takes on a holistic view or sometimes referred to as cradle-to-grave approach. An LCA methodology is structured along a framework base on a number of ISO standards. The framework has four key components. They are goal and scope definition (ISO 14041:1998), life cycle inventory assessment (ISO 14041:1998), life cycle impact assessment (ISO 14042:2000) and life cycle interpretation (ISO 14043:2000). Each of these components will be further discussed and summarized below.

2.5.1 Goal & Scope Definition

The goal definition process establishes the breadth, depth and scope of the system and the proper types of data needed for the assessment. LCA study is designed to include all information that is relevant to the decision or activity and omit information that is irrelevant. The scope describes the boundaries defining the system being studied. It should be well defined to ensure that the breadth and depth of the study are compatible with the stated goal. The goal and scope definition for this LCA study are described further in sections 4.5 and 4.6.

Goal and scope definition process links the goal of the LCA and establish the boundary conditions, the product of study, that is, functional unit and the quality criteria of the inventory data. This involves an iterative process.

2.5.2 Life Cycle Inventory

LCI development is the data based process of quantifying inputs and outputs throughout the life cycle of a product, process or activity. The inputs refer to raw materials and energy whereas the outputs are products and solid, liquid and gaseous emissions. In the life cycle inventory phase of an LCA, all relevant data is collected and compiled. The data are used to evaluate comparative environmental impacts or potential improvements. Since LCI methodology evolved for more than 20 years, it is the only component of the LCA that is well developed. The data collection for certain company is a sensitive issue which must be treated with strictest confidence as they are corporate information.

2.5.3 Life Cycle Impact Assessment

Life cycle impact assessment is defined as the phase in the LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system (Goedkoop, Schryver & Oele 2006). The LCIA evaluates the effects of actual and potential environmental effects of the environmental loadings or resource requirements due the inputs and outputs of the inventory components. Thus it should address human health impacts, resource depletion, pollution and habitat modification. This is an establishment that seeks the linkage between the process or product life cycle and their potential impacts.

2.5.4 Life Cycle Interpretation

This component evaluates the necessities and opportunities to reduce the environmental burden associated with inputs use and outputs throughout the life cycle of a product or process.

The two objectives of life cycle interpretation as defined by ISO are:

- Analyze results, reach conclusions, explain limitations and provide recommendations based on the findings of the proceedings phases of the LCA and to report the results of the life cycle interpretation in a transparent manner.

- Provide a readily understandable, complete, and consistent presentation of the results of an LCA study, in accordance with the goal and scope of the study.

2.6 Limitations of Life Cycle Assessments

Conducting an LCA requires huge amounts of data collection for the life cycle inventory. Some companies notably from the semiconductor industry, the life cycle data on manufacturing materials and production chemicals supplied are strictly confidential. Even if data obtained from life cycle inventory and impact are available, they might be subjective. There are difficulties to standardize the data. Unfortunately standardization of data collection process allows a good starting point to conduct LCAs. Thus LCA can be expensive, time consuming and labour intensive. Also, our ability to compare product and process alternatives using life cycle assessment remains limited due to the complexities of our interactions with the environment, and the nature of inventory data collected. LCA can be regarded to be largely confined to existing products and lacking in techniques that is use to analyze the environmental impact of new products (Poole and Simon, 1997). An LCA study relates to one specific product at a particular time. A study of current systems might not necessarily indicate a better option in future since a separate study is required using different data.

LCA does not offer a total solution. It is just another tool for environmental management. It cannot assess human and environmental safety and does not address comprehensive environmental management. Hence LCA by itself is insufficient for decision-making.

Social or economic factors must be considered for any decision-making process in sustainable development. However the social and economic factors are areas outside the system boundary of an environmental LCA since LCA does not address both of these factors. The decision-making process may not be conclusive.

2.7 Benefits and Uses of Life Cycle Assessment

Despite of all the limitations, life cycle studies have many uses and benefits. They are applied both in public and private sectors for improving, developing and comparing products.

Public sector uses life cycle studies as a tool for making purchasing decisions and developing regulations. Its main importance is to develop long-term policy in reducing environmental impacts and risks posed by materials and processes throughout the product life cycle and evaluating resource effects associated with source reduction and alternative waste management techniques. Some applications include environmental or eco-labeling programs, thus providing information to the public about the resource characteristics of products or materials (Ryding, 1994).

Results of life cycle studies are use for product improvement. One such study was conducted on components of a computer workstation to find out the main contributor of raw material usage, wastes, emissions and energy consumption. Findings from the study point to the display monitor. Thus all efforts are made to reduce the level of energy consumed by the display monitor.

Life cycle studies are being use to make product comparison. (Rosselot and Allen 1999) conducted a study comparing cloth and disposable diapers; plastic and paper cups; and polystyrene clamshells and paper wrappings for sandwiches. This comparison helps to identify which product having lesser resource consumptions and emissions.

2.8 Life Cycle Assessment of Semiconductor

There are very few LCA studies done in the semiconductor industry. The primary reason is the refusal of companies to reveal life cycle data on manufacturing materials and production chemicals supplied. Other reasons include the difficulties in LCI data collection for actual process manufacturing and the way LCA is structured. The case studies available were reviewed thoroughly and results are summarized below.

The LCA of a CMOS chip was conducted by UC Berkeley and Applied Materials Inc. (Boyd et al. 2006). A gate-to-gate approach was adopted for this LCA. The functional unit is a 130 nanometer(nm) 6 layer copper CMOS chip manufactured using 300mm (12 inch) wafers. A life cycle inventory for comparative assessment of a 6 and 8 layer CMOS devices were made. The consumption of energy use, material inputs and emissions data at the process equipment level and facilities scale, normalized per wafer were presented.

The data for a single process step of plasma chemical vapor deposition undoped silicate glass (USG) were collected. Exhaust of deposition and etch process which contain perfluorinated gases and other pollutants were treated using point-of-use abatement equipment. Post POUA emissions data were also presented. To accurately quantify the energy and material usage, the idle time, production time, machine down time and production yield were taken into consideration.

The results of the emission inventory of post-POA emissions in gram/wafer excluding water and nitrogen were tabulated as in Table 2.1. The largest three components in the emission inventory excluding water and nitrogen are hydrogen peroxide, utility nitrogen and alumina slurry A. This inventory only represents the energy and material flows for device processing. They do not include the facility infrastructure and energy required for chemical production and purification.

Emissions per wafer	Percentage
H3PO4	35
Utility N2	30
Alumina Slurry A	12.2
NH3	5.4
CO2	4.9
IPA	3
O2	2.7
H2SO4	2.2
Process N2	1.2
H2O2	0.8
Other	2.7

Table 2-1 Largest nine components in emissions inventory excluding water and nitrogen (Boyd et al 2006)

Another study was conducted by ST Microelectronics and Telecom Italia (Taiariol et al. 2001) titled LCA of an Integrated Circuit Product. There are two functional units; a single EPROM device in a ceramic dual in line package for back-end and a single silicon wafer for front-end. Front-end involve wafer fabrication process and back-end is the assembly and encapsulation of the integrated device. A gate-to-gate approach was adopted.

LCI was obtained from detailed technological analysis, where information obtained directly from material suppliers and from commercial database. Several database were used for impact assessment such as Boustead, TEAM, EIME and Model. A subset of more than 400 materials was used.

As shown in Table 2.2, water consumption contributes about 29 litres of deionised water for a single EPROM device. The highest environmental impact related to materials is in the End of Line (EOL) production phase. About 81% of the total energy usage related to the chip came from the use phase of the EPROM chip followed by EOL (14.2%) and FOL production processes (3.4%).

Material	Quantity
DI water	29 litres
Oxygen	140 mg
Nitrogen	122 g
Hydrogen	2.9 mg
Ceramic	7 g
PVC	0.4 g
HDPE	0.1 g
Lead	0.03 mg
Copper	1.2 mg
Tin	0.15 g
Boron	2.9 mg
Arsenic	6.9 mg

Table 2-2 Material used manufacturing a 1 Mbit EPROM memory in Italy, 2001

The last case study involved a life cycle inventory analysis of an Integrated Circuit by Motorola and Fraunhofer IZM (Schischke et al. 2001). The aim was to generate a complete mass and energy data set so as to identify the environmentally significant areas in IC manufacturing. The used clusters were divided by the facilities and wafer fabrication process modules. The functional unit was the wafer area multiply average number of mask layers. Consumption of energy, raw water, chemicals, and gases and the origin of water, wastewater, and emissions were considered. Wafer geometry, yields and other technical data were collected through questionnaires. Data for certain categories of process, and material and energy flow data for certain process module were collected by detailed questionnaires. Educated assumptions were made by experts for data that are not available.

The software package for impact assessment was done using ProTox and GaBi 3.2. Sulfuric acid was identified as the most critical chemical followed by hydrofluoric acid. The most environmentally significant aspect in terms of toxicity potential was identified in the wafer cleaning/wet bench process. About two-thirds of electricity use was related to facility modules. High electricity use was the main contributor to the environmental impacts. This was followed by nitrogen and processes water.

All the three case studies had shown difficulty in collecting LCI data in the semiconductor manufacturing. It involves many exhaustive processes and will be the most challenging part of the project research.

Chapter 3 CMOS Technology

3.1 Introduction

The functional unit of the LCA, which is the CMOS wafer, and its process manufacture is explained in this chapter. This chapter includes the application of CMOS chip, the main sections that made up the infrastructure of a semiconductor foundry and the manufacturing process flow of CMOS technology.

A lot of effort and time was spent to understand the manufacturing process flow through process engineers and circuit integration staffs. Discussions and meetings were conducted on this process aspect of this LCA study. To maintain a manageable scope, only the wafer fabrication process within the manufacturing phase of a CMOS wafer is included.

3.2 Definition and Application

Complementary Metal Oxide (CMOS) used the semiconductor technology building transistors that are manufactured into most of today's computer microchips. Semiconductor consists of silicon and germanium conducting or restricting electrical flow depending on its application. CMOS chip is the most widely used integrated circuit found in almost every electronic product from handheld devices like cell phones to mainframes.

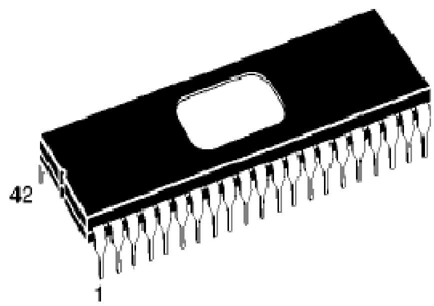


Figure 3-1 CMOS Chip

Figure 3.1 illustrates a typical CMOS manufactured in the semiconductor foundry.

CMOS chips have both NMOS (negative polarity) and PMOS (positive polarity) circuits. Areas of silicon or germanium that are "doped" by adding impurities become full-scale conductors of either extra electrons with a negative charge (N-type transistors) or of positive charge carriers (P-type transistors). In CMOS technology, both kinds of transistors are used in a complementary way to form a current gate that forms an effective means of electrical control. At any point in time, only one circuit is active, resulting in lesser power consumption when compared to a transistor. CMOS transistors use almost no power when not needed. It is for this reason that they are widely used in battery-powered devices such as cameras, laptop, etc.

However the transistors become hot when the current direction changes rapidly. This characteristic tends to limit the speed at which microprocessors operate. The real challenge today is to enhance existing silicon technology to speed computing performance.

3.3 Semiconductor Plant Infrastructure

The infrastructure of a semiconductor plant consists of many components due to the complex production requirements. However there are two main areas as summarized below are:

- Wafer Fabrication – refers to wafer processing performed in the front end manufacturing line.

- Facilities – supporting production tool and processes requirements by supplying, maintaining and delivering materials essential for manufacturing.

3.3.1 Wafer Fabrication

The Wafer Fabrication area is as shown in Figure 3.2. The block arrows indicate direction of the process flow. There are 3 sections that made up the wafer fabrication. They are Front End manufacturing consisting mainly of 5 modules (Photoresist/Photolithography, Etch & Strip, Diffusion, CVD/PVD and CMP), another section made up of 3 modules namely; Materials Management, System Automation and Computer Integration Management (CIM) and third section being Measurement and Inspection section.

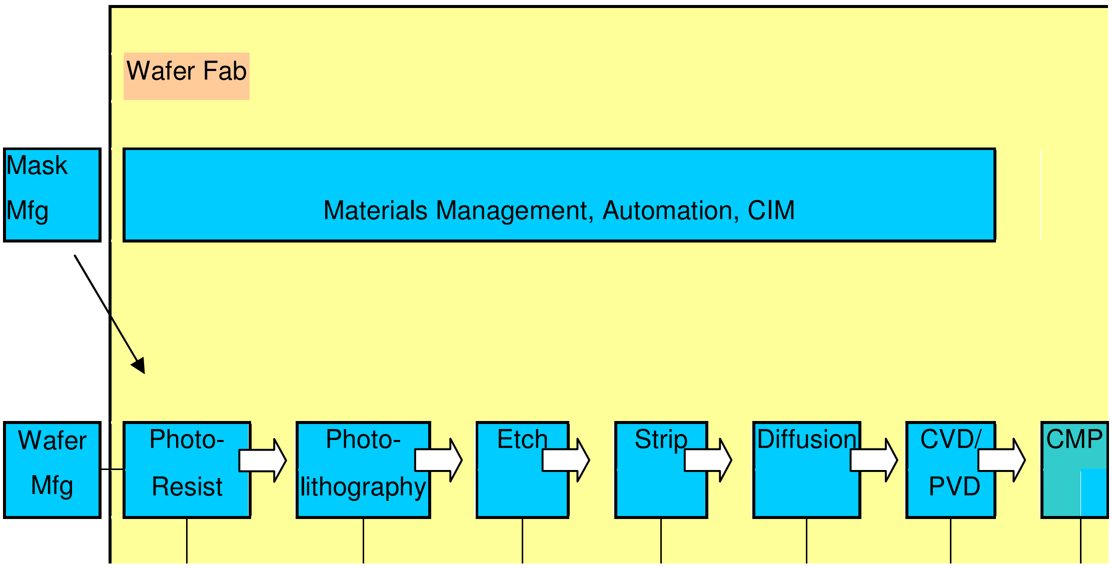


Figure 3-2 Wafer Fabrication

"Wafer manufacturing", outside the wafer fabrication boundary on Figure 3.2, refers to the wafers before being processed, also known as bare silicon wafers.

The production of CMOS wafer consists of two different main manufacturing steps, the Front End and the Back End. The Front End manufacturing is a clean room area, consisting of different processes related equipments for wafer manufacturing. Clean room is required for production process because any particle as small as a fraction thickness of a hair may destroy a circuit. The Back End is related to the packaging and device testing. The Back End is out source to other vendors and not done in this company. In this LCA study, only the Front

End is considered. Thus any reference to manufacturing process in this report refers to Front End unless otherwise stated. The Front End and Measurement and Inspection sections will be further discussed in the next section as they are related to the production process flow.

3.3.2 Facilities

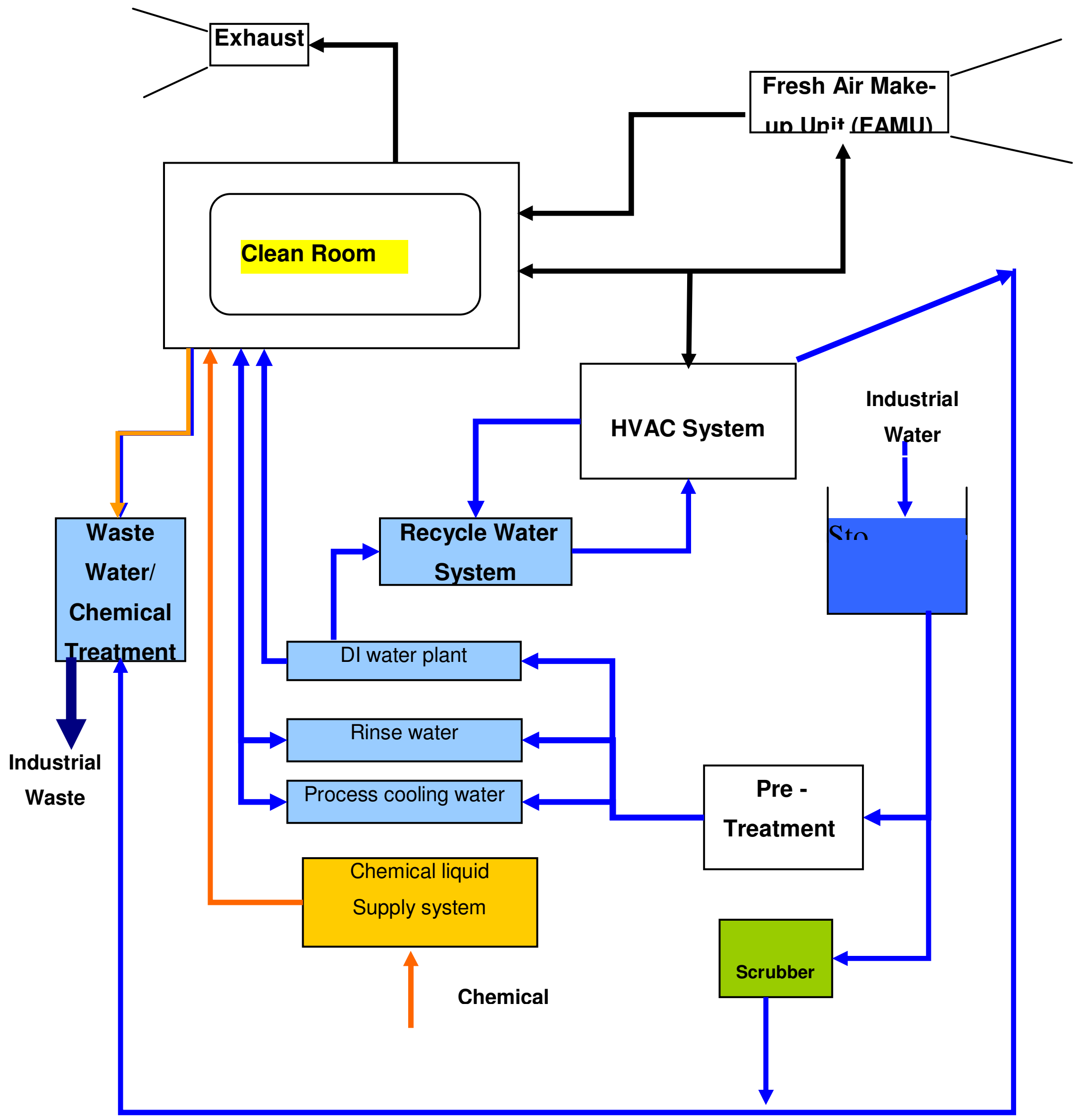


Figure 3-3 Major Facilities Systems

Figure 3.3 shows the major facilities systems. The facilities systems consists of many operational units but the main systems are highlighted as:

- Water recycling system (light blue box) – its main function is to received deionised water (DIW) and condensed water from HVAC system, recycle the reject osmosis water, and supply this recycled water for the cooling towers, mechanical systems and wet scrubbers for air emissions.

- Waste water and chemical treatment system (light blue box) – post production water and chemical are treated with chemical agent to neutralize before release as industrial waste material.

- HVAC (Heating, Ventilation, Air Conditioning) system – is the central environmental control for both clean room and non clean room area. Regulates exhaust air flow using fan motors, control chilled water flow rates in cooling towers, heat recovery system through heat exchangers, chillers, fresh make-up units (FAMU) and fan filter units (FFU).

- Pre-Treatment system – received industrial water for treatment by filtration and softening process to obtain high purity.

- Utilities system – the infrastructure components that deliver materials from the facilities to manufacturing equipment. They include chemicals, gases, vacuum, dry air, exhaust and energy requirements.

- Scrubber – the facility abatement system that neutralize the acid and chemical by-product after process manufacturing from exhaust line. The scrubbed water is fed into waste water treatment tank for neutralization before draining.

3.4 Process Flow

The complete manufacturing process required 16 masking steps and more than 100 process steps using 90 nanometer technology. Each process step went through some or all of the major steps of photolithography, etch, strip, diffusion, chemical/physical vapor deposition and chemical mechanical planarization. The process time of a single wafer takes about 4 weeks and is dependent mainly on semiconductor equipment performance. There are many factors affecting the cycle time. For example, process optimization, equipment failure, waiting time for spare parts, trouble-shooting, etc. Most importantly, a larger sample was taken of one month output of 45000 wafers for better data accuracy.

3.4.1 Photolithography/Photoresist

Photolithography is the process of transferring an image from a photographic mask to a pattern on an oxidized wafer. It is the most crucial step in semiconductor manufacturing because it sets a device's dimensions. Incorrect patterns alignments ruin or distort the electrical functions of the semiconductor. The image comes from the reticle and then projected through a complex quartz glass lens system onto the wafer were coated or spun on with an ultra thin layer of photoresist material. The reticle was printed on a 1:1 in size. The photoresist must be applied uniformly to the entire wafer. This uniformity is ensured by a class of chemical compounds called ethylene glycol ethers used to thin the photoresist.

After the pattern on the photoresist were exposed, the photoresist is then developed to leave the pattern onto the wafer. The exposure time is dependent on many variable including the sensitivity of the resist, lens aperture, etc.

The machine used for exposure is called the "stepper" because it literally does one die at a time, then steps to the next die until it has exposed the entire wafer. The semiconductor equipment manufacturer for this process is ASM Lithography. The developer is manufactured by TEL. The coater for photoresist material, stepper and developer are situated next to each other respectively in accordance with the process flow in the photolithography stage.

3.4.2 Etch & Strip

The wafer with patterned photoresist was placed into an oxide etch process to remove the oxide where there was no pattern. This transfers the pattern to the oxide creating barriers of oxide preventing subsequent processes from impacting the silicon underneath. Thus the etch process remove the oxide where the photoresist material is absent. The equipment used for this process is manufactured by Lam Research.

The photoresist removal process is called “strip”. The photoresist is stripped completely off the wafer as it has done its purpose. Any remaining photoresist not removed would cause defects. Mattson Technology is the equipment vendor for this process.

3.4.3 Diffusion

The dopant chemical, Boron, was deposited onto the surface of the wafer then diffuse or drive it into the surface of the silicon by exposing it to high temperature of 900 °C. The vertical furnace was used for this diffusion process manufactured by Aviza Technology (formerly Silicon Valley Group). The regions doped with Boron created n-type source and drain regions of the transistor in a p-type silicon base. Thus these regions are the source and drain of the CMOS transistor.

3.4.4 Chemical & Physical Vapor Deposition

By using the same oxidation and photolithography, etch and strip process, with a different mask, an opening is made in the oxide to build the transistor's gate region. The gate is a conductive layer, separated from the bulk silicon by a thin gate oxide. A positive electrical charge on the gate will create an opposite negative field in the surface of the silicon. This negative field essentially creates a conductive channel between the source and the drain, letting current flow between them. The gate oxide is typically about 3-5 nm since electric field must be transferred across this insulator. This is made possible by depositing silicon nitride film via a Chemical Vapor Deposition process (CVD).

The gate itself is either made of polysilicon or a metal. Polysilicon is deposited by a Physical Vapor Deposition (PVD) process, often known as "sputtering". The CVD and PVD process use equipment are supplied by Novellus and Applied Materials respectively. This module is normally referred to as thin film deposition and is the area of focus for this project research.

3.4.5 Chemical Mechanical Planarization

Chemical Mechanical Planarization (CMP) is an abrasive process used for polishing the surface of the wafer flat. It is performed on both metals and oxides. It involves the use of chemical slurries and a circular (sanding) action to polish the surface of the wafer smooth. The smooth surface is necessary to maintain photolithographic depth of focus for subsequent steps. The semiconductor equipment manufacturer for this process is Novellus.

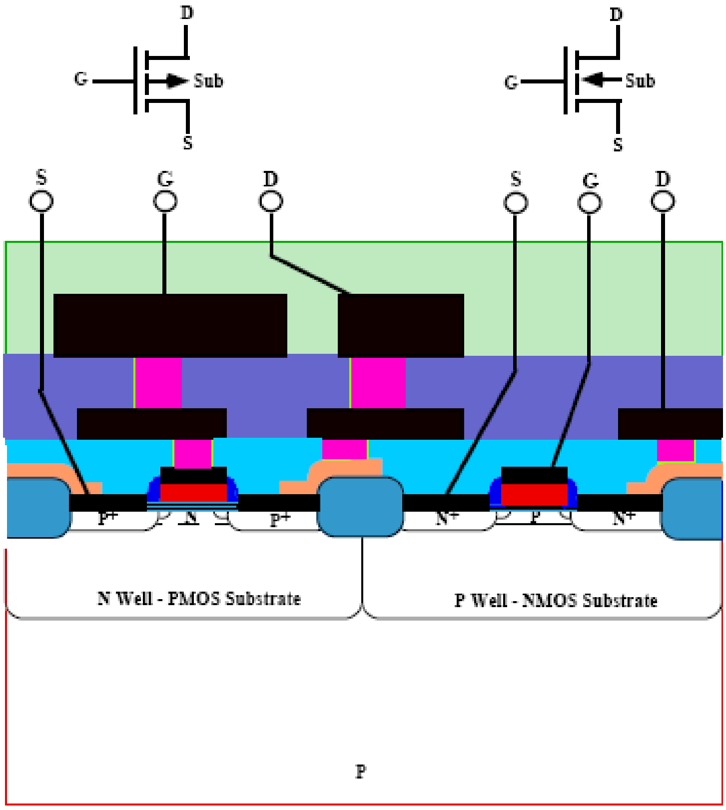


Figure 3-4 Final Result of Process Flow

3.4.6 Measurement & Inspection

Measurement and inspection is a vital area in semiconductor manufacturing. Wafer manufacturing deals with so many materials, of small features and precision that the ability to measure and monitor the process is critical.

Measurement is defined as the ability to quantify the physical, dimensional, or electrical properties of materials. Measurement tools used to monitor the quality of the process relative to its design specifications include KLA-Tencor and Hitachi SEM. Generally, if all materials and processes are within specification, the chip will operate as designed. Measurement applies to wafer flatness, film thickness, electrical properties, critical dimensions (CDs), etc.

Inspection is defined as the ability to observe and quantify defects. These tools include optical instruments and, with shrinking features down at the sub-micron level, scanning electron microscopes (SEM) must be used. As fine geometries get down to sub-micron level, the ability to observe these defects becomes challenging and expensive. Inspection typically applies to such items as reticles (masks), wafers, etc.

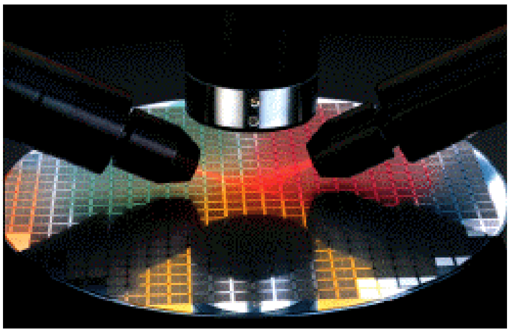


Figure 3-5 Measurement & Inspection of Wafer

Chapter 4 Goal and Scope

4.1 Introduction

The conclusions of the SETAC document on impact assessment support this view – "The study goal and scope are crucial to managing and coordinating a life-cycle study by bringing together the LCA information needed to make an identified decision and an understanding of the reliability and representatives of the LCA". Thus this chapter highlights the methodology used for the goal and scope definition of the LCA study. The goal of the LCA study was formulated such that the ultimate results of the LCA are suited for use in the framework of the process goal. This means that before starting the LCA study, there were measured reflection on the potential significance of the LCA results within the established framework of system boundaries and assumptions of the product system. Also the LCA study was carried out as an iterative process, with ongoing reflection throughout.

Modeling is the main technique used in LCA. A model is a simplified representation of a system. Due to the simplification, results obtained may be distorted. Thus the challenge of a LCA practitioner is to develop a model that minimizes the distortions influencing the result. However the ultimate aim of this research project is to develop a high quality model yielding a consistently valid and reliable outcome.

4.2 Methodology

The goal and scope definition is a critical phase of an LCA study. It should be meticulously defined, otherwise other stages of the LCA may run into problems affecting the final results. As an LCA study is an iterative process, various aspects of the goal and scope definition need to be flexible to meet the original goal of study. The justification and changes should be documented.

4.3 Goal Definition

The most important pitfall in the implementation of LCA turns out to be the lack of a clear definition of the purpose and application of LCA (Goedkoop, Schryver & Oele 2006). Thus the goal definition of the LCA should describe the reasons for carrying out the study, specify the intended use of the results (application) and for whom the study results are intended (target audience). The reasons for carrying out the study should be clearly described. During the initial phase of an LCA study, it is vital that the use for which the study results are intended is clearly identified. The intended application refers to the decision made on the basis of the LCA, the extent of impacts these decisions could make and what the LCA can and cannot be use for.

If the results are intended for private company internal decision-making purpose, then the required level of data need not be of high accuracy. However if the intended audience are for public forum, then estimated data or best engineering judgement may not justify the final results.

4.4 Scope Definition

In the scope definition, the main characteristics of an intended LCA study are established. Scoping also defines the assumptions and limitations during the course of LCA study. It determines, justify and report the overall level of sophistication of the study. Scoping requires the establishment of a multi organization group and a formal procedure for reviewing the functional unit, system boundaries, and data quality requirements. It is here where the system boundaries are determined and the strategies for data collection are chosen.

4.4.1 Functional Unit and Reference Flow

The functional unit is a measure of the performance of the functional outputs of the product system. It describes the primary functions fulfilled by a product system, and indicates how much is to be considered for the LCA study. Based on the functional unit, a number of alternative product systems can be declared functionally equivalent and reference flows can be determined for these systems. System performance is quantified by means of reference flow, that is;"a measure of the needed outputs from processes in a given product system required to fulfill the function expressed by the functional unit" (ISO14041, 1998). Reference flow is then used to calculate the input and outputs of the system.

4.4.2 System Boundaries

System boundaries define the unit processes or activities that are included in the system under study. Decisions are made on which processes or activities are to be included. Thus data collection may be reduced significantly. System boundaries also determine the breadth and depth of the study and ensure they are compatible with the stated goal.

Justification of the system boundaries is important in establishing the LCA. Sometimes initial system boundaries cannot be followed due to the limitations in the later stages of the LCA. Any modifications must be documented as the features are affected. Figure 4.1 shows the life cycle of a generic product and its system boundaries.

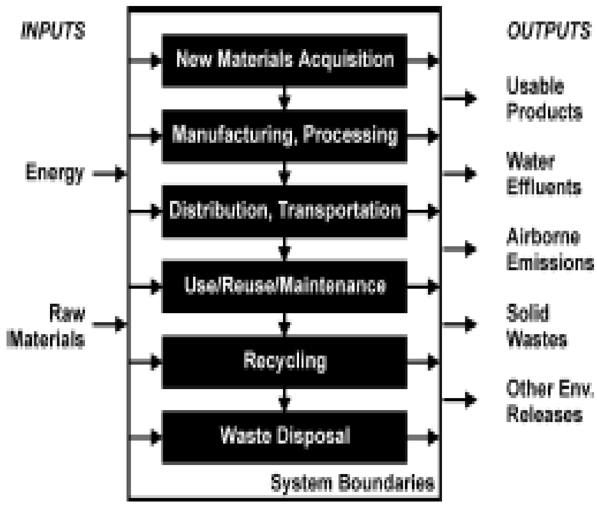


Figure 4-1 Life Cycle of a Product

4.4.3 Criteria for Inputs and Outputs

Besides the criteria for system boundaries, levels below a certain threshold level deem useless to collect data for an inflow or outflow. ISO 14041 recommends the following benchmark for threshold levels :

- If the economic value of an inflow is lower than a certain percentage of the total value of the product system

- If the mass of the inflow is lower than a certain percentage.

- If the contribution from an inflow to the environment load is below a certain percentage.

Lately, the use of input output data has been suggested to estimate the “missing” environmental load.

4.4.4 Allocation

Usually, there are more than one functions or output for most processes. Hence the necessity to allocate the various functions and outputs. ISO 14041 recommends the following procedure to deal with allocation issues:

- Avoid allocation either by extending system boundaries to include processes needed to achieve a similar output or by splitting the process making two separate processes each having a single output.
- If unavoidable, use mass or energy content to allocate the environmental load.
- If this procedure is not applicable, use socio-economic indicators as a basis for allocation.

The allocation is in percentage so that the total allocation is 100%. The allocation percentage for using mass or economic allocation basis must be documented.

4.5 Goal Definition of this LCA Study

The goal definition of this LCA study is to evaluate the environmental impact of a CMOS wafer during its production and use phase base on the LCA methodology. The results of this study are used to minimize the environmental impacts associated to the production process.

This project research was done for purely an educational purpose.

4.6 Scope Definition of this LCA Study

4.6.1 Functional Unit

The functional unit is a CMOS wafer as shown in Figure 5.2. The wafer is made up of many integrated chips each weighing approximately 675 milligram measuring 29 x 9.3 x 4.1 mm. The manufacturer is a semiconductor foundry located in Singapore.

4.6.2 System Boundaries

Figure 2.1, illustrates the stages of the life cycle of a CMOS wafer, which is broken down into the following stages:

Raw Material Acquisition – All activities necessary to extract raw material and energy inputs from the environment including the transportation prior to processing.

Processing/Manufacturing – Activities needed to convert the raw material and energy inputs into the desired product. This is the manufacturing of bare silicon wafers done by external company, the actual process manufacturing in the semiconductor plant and finally the test and assembly of the end product done by an external company. All companies are located in Singapore.

Distribution and Transportation – Delivery of the final product to the end users all around the world.

Use, Reuse, and Maintenance – Utilization of the finished product over its service life.

Recycle – Begins after the product has served its initial intended function and is subsequently recycled within the same product system.

Waste Management – Begins after the product has served its intended function and is returned to the environment as waste.

For this project research, the 'gate to gate' product life cycle of a CMOS wafer was conducted. In the 'gate to gate' approach, only the raw material and energy flows entering and exiting the manufacturing facility are considered.

The 'gate to gate' LCA approach was conducted involving only the process/manufacturing stage of the CMOS wafer. However due the mammoth task of data collections and limited resource, only the thin film part of process manufacturing was considered. This defines the system boundary of this LCA study. The remaining stages were excluded. The system boundaries developed is further illustrated as in Figure 4.2.

The system boundaries as illustrated consist of two main components of the semiconductor plant:

- Thin film deposition of wafer fabrication (CVD/PVD) where wafer process manufacturing in clean room is performed

- Facilities (bounded by whole area except “process manufacturing”) where raw materials are provided.

The blue arrows indicate the flow of energy, water and air. The inputs for chemical, gases and unprocessed wafer are indicated by brown arrows.

The system boundary shown is in accordance with the ‘gate to gate’ approach as mentioned. This research project takes a process-based approach to LCI. The inventory developed does not focus on products and their entire life cycle. Instead the inventory developed focus on the manufacturing process of the CMOS chip. Thus the manufacturing processes become the product.

The inventory was organized into process operations. There are two advantages. Firstly since process operations are process-centered, it serves the goal of developing a process-based LCI. Secondly, it is easily understood by the industry.

In compliance with the goal definition, a full scale LCA study is preferred. However, a streamlined LCA was conducted due to several limitations.

They are;

- Insufficient Time – It would be practically impossible to complete a full scale LCA within the allocated period of two semesters.

- Lack of Resource - The data obtained are from the facilities and manufacturing engineers. Other data required for the detailed LCA are not available within the company.

Due to the limitations, it is only possible to conduct a streamlined LCA approach.

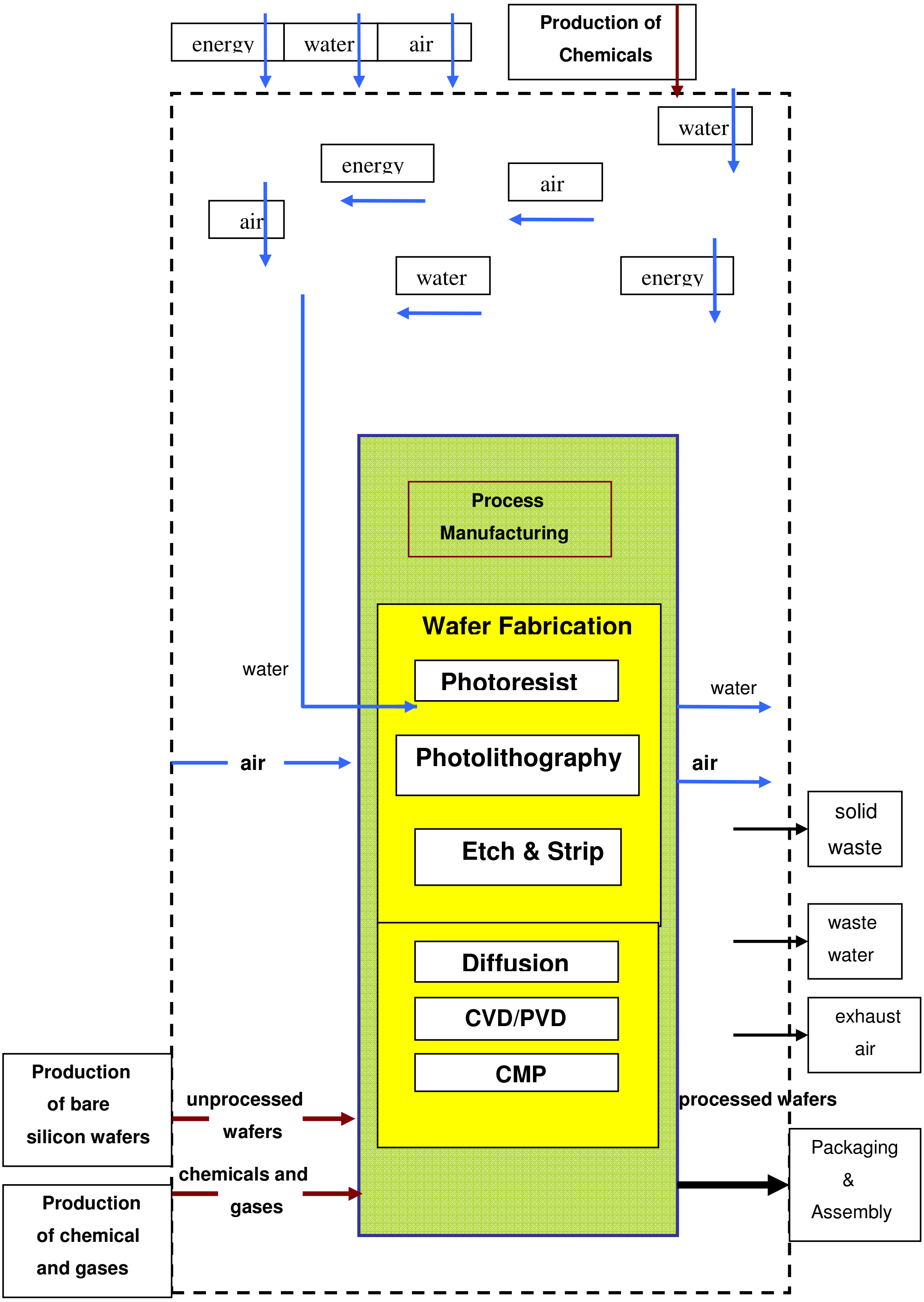


Figure 4-2 System Boundaries

Chapter 5 Life Cycle Inventory

5.1 Introduction

This is the second phase of the LCA. This phase is associated with data collection and the goal was revisited periodically as data collection progressed to ensure the goal was met. The process data provided by the company were organized around unit processes and they are in terms of inputs and outputs per unit time with relation to some physical (reference) flow.

The method of approach, techniques used and the results obtained are discussed in the subsequent sections. The LCI was carried out carefully, bearing in mind that its accuracy had a major influence on the final results. Thus, considerable time and effort were spent in this phase of the LCA.

5.2 Methodology

According to ISO 14041, LCI is concerned with "the collection of the data necessary to meet the goals of the defined study" and with the associated "data collection and calculation procedures" and "is essentially an inventory of input/output data with respect to the system being studied". Thus LCI seeks to provide the necessary qualitative and quantitative data about inputs and outputs of a product throughout its life cycle by either collection and/or calculation.

In 1993, the Environmental Protection Agency (EPA) published a guidance document entitled "Life Cycle Assessment: Inventory Guidelines and Principles" and in 1995, "Guidelines for Assessing the Quality of Life Cycle Inventory Analysis" (LCA101 2001).

The LCI was executed meticulously, using the guidelines from the combinations of the two guided documents, by the following steps as listed below:

- Flow diagram development
- Data collection plan
- Collection of data
- Data evaluation and reporting

Each of the four steps is briefly described in the following sub-sections.

5.2.1 Flow Diagram Development

A flow diagram is a tool to map the inputs and outputs to a process or system (LCA101 2001). It consists of systematic arrangements of main process making up the product system. Essentially the system boundary for each individual process and the environmental needs were determined. A process flow diagram shows the main constituent unit process and their relationships. With this, the whole LCA process could be less complicated, providing a methodological approach to data collection. Increased complexity of flow diagram gives better accuracy and utility to the results, however more time and resources are needed. The flow diagram was drawn out after discussions with process engineers.

5.2.2 Data Collection Plan

Ideally, the data collection plan consists of four different tasks namely; definition of *data quality goal*, identification of *data sources and types*, identification of *data quality indicators* and development of *data collection inventory checklist*.

Definition of *data quality goal* is to provide guidance for the quality of data required for collection. Data quality here refers to the reliability and validity of the process data. It is imperative that the data quality requirements are defined and met to satisfy the goal and scope of this study.

Before the actual data collection, it is necessary to identify *the data sources and its types*. This could lead to substantial savings on both time and resources required for this LCA study. There are 3 *data sources* type*; primary*, *secondary* and *other resources*. *Primary data,* being the most reliable and accurate data obtained from company database that include information from production sites associated with the unit processes within system boundaries, direct measurements and calculations based on real processes and equipment. A majority of the data sources for this research project originate from the company database.

The other sources, *Secondary data* are from published sources of other LCI studies. *Other resources* of data include journals, textbooks, and patents and engineering estimation methods. Data quality assessments are done so that accuracies are not being compromised. The *data types* could be described either by generic or product specific. Generic data are appropriate for studies done for public use where inventory results are to be used for broad application across the industry. Product specific data are used where the purpose of the inventory is to find ways to improve internal operations.

Data quality indicators are measurements of data goodness and applicability use to determine if the data quality requirements are met. It is the qualitative or quantitative characteristics of data. This plan was not carried out due to insufficient time.

The next task after identifying data quality indicators is to devise the *data collection inventory checklist.* The inventory checklist is an effective guidance tool that covers most decision areas in the performance of an inventory. It is used as a preparation to guide data collection and validation as well as computational data modeling. Checklist help to clarify issues, boundaries and conditions to be dealt with in the LCA study. Checklists ensure consistency, accuracy, completeness and soundness of a particular life cycle inventory. The data collection inventory checklists were developed as shown in Appendix B.

There are two methods recommended for data collection; ‘top-down’ and ‘bottom-up’ approach for semiconductor manufacturing. The ‘top-down’ involves collection of data at a factory level and then disaggregating it into process levels. This method is unsuitable for a production line that produced many different products. The main advantage is the rapid and accurate measurement of mass and energy flows. In the ‘bottom-down’ approach, the inventory is quantified at equipment level on a process basis and aggregated at factory or product level. This method is very time consuming. However, it has the potential to be more accurate as data are directly related to the equipment or process. A combination of both methods was adopted in this LCA study.

Data collection plan is important since it ensures that the accuracy and quality of the LCI studies satisfy the goal and scope definition stage.

5.2.3 Collection of Data

Collections of data involve direct contact with experts and professionals, site-visits and research on the related product of study. This may not be an easy task. Some data may be impossible or difficult to obtain. Even if they are available, they may be difficult to quantify into the functional unit level. Thus an educated and calculated guess by experts are alternatives. Therefore, the system boundaries or data quality goals may have to be refined iteratively.

5.2.4 Data Evaluation and Reporting

This is the final step where results of the LCI are evaluated and documented. The methodological approach, boundaries that were set, and assumptions made must be clearly reported. This step set the stage for life cycle impact assessment.

5.3 Life Cycle Inventory of a CMOS Wafer

The LCI of the CMOS wafer was conducted by the methodologies as described in previous sections. The data was collected in accordance to the processes and activities as in chapter 3 and 4. These data are associated with the process manufacture of the CMOS wafer within the system boundary as outlined in Figure 4.2. There are two clusters namely the process manufacturing and the facilities area. For process manufacturing area, the data for each individual process were broken into functional unit level. For the facilities area, the data were quantified at factory level and allocated to unit level accordingly. Thus, 'bottom-up' and 'top-down' approaches were both used. The process manufacturing and facilities area were defined by the types and availability of data and the ease of data collection.

The process manufacturing, located in clean-room and facilities area were frequently visited to understand the process flow. Educational visits were made to the two areas and any queries were directed to the respective engineers or other technical experts. With the knowledge attained, the data in the thin film deposition stage of the process manufacturing were collected. Flow diagrams, such as Figure 5.1, were drawn to assist in the inventory collection. Based on the flow diagrams, checklists were prepared for data collection.

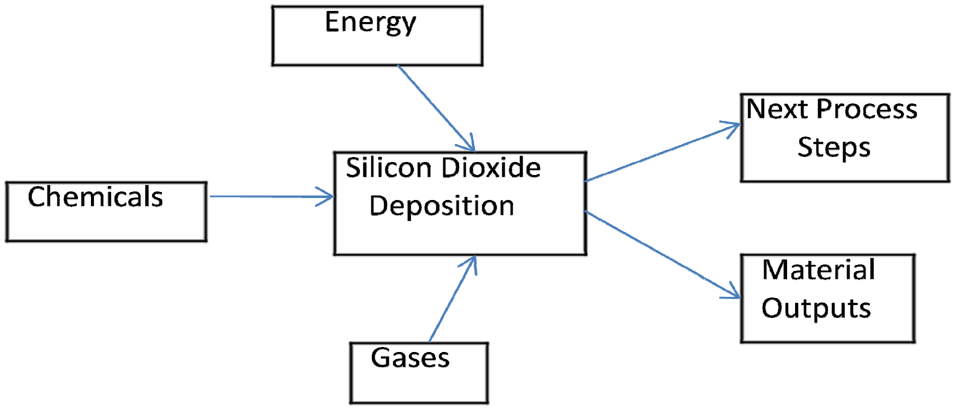


Figure 5-1 Flow Diagram of Silicon Dioxide Process Step

In wafer fabrication manufacturing process, semiconductor equipments are not operational all the time. They could be down for preventive maintenance or equipment failure. Preventive maintenance includes periodic and unscheduled maintenance. Equipment failure includes troubleshooting and recovery time. Those equipments awaiting incoming wafers are referred to be in idle or standby state. As shown in Figure 5.2, the wafer is a full circle of 200mm (8 inch) diameter and the unused area is very small. Therefore the surface area of the wafer that was not fabricated but went through the process manufacturing steps are ignored for simplification.

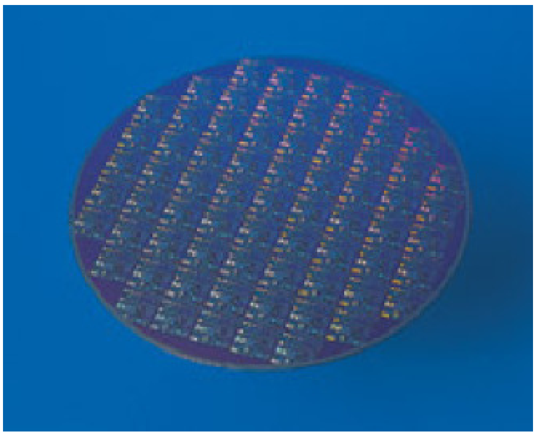


Figure 5-2 A 200mm Wafer

The production yield varies but on the average, it is 83% for most of the processes. Production yield refers to the part of the wafer that met the quality and specification requirements.

Identifying the reference unit is the next task before data collection. The 200 mm CMOS wafer was decided to be the functional unit. The frontal surface area of the die as shown in figure 3.1 measured 29 x 9.3 x 4.1 mm and has an actual die size of 19.6 x 6.1 x 0.8 mm weighing approximately 85 milligram.

With this information, the frontal surface area of the CMOS chip may be calculated as follows:

Frontal surface area = 19.6 x 6.1 = 1.1956 squared centimetre

This data, if applicable, was quantified purely based on the consumption.

5.3.1 Process Manufacturing

The life cycle inventory of thin film process manufacturing was quantified by using the "bottom up" approach. For the chemical, gas and other raw material consumption, they were obtained from the company's database while others from the process recipes. If they are not available, data were obtained from process manual or facilities engineers, process engineers and other experts. For better accuracy, the data was averaged out onto daily basis. The calculation methods were documented in the following pages. There are 2 special gas commonly used in thin film deposition. They are silane and Teos. Silane is a chemical compound with chemical formula SiH_4. Above 420°C, silane decomposes into silicon and hydrogen. Teos is the acronym of Tetraethylorthosilicate. TEOS has many remarkable properties, but perhaps the most useful is its easy conversion into silicon dioxide.

Checklists were created for data collections on the chemical and gas, energy and water consumption during the process manufacturing for a period of four weeks. Similarly, with the information from the checklist, the life cycle inventory data quantified for the CMOS chip.

Chemical and Gas Consumption

The chemical and gas consumption for thin film semiconductor equipments were obtained from company database and process recipes. This data were use to quantify the chemical and gas requirements associated with individual process. The process chemical and gas flow in semiconductor equipments are normally measured in sccm(standard cubic centimetre per minute). In order to be able to compare the data for various chemicals and gas consumption, the units are normalized in seconds and then multiplied by the chemical density to give the total chemical and gas flow. For this purpose, units of grams were used. Therefore the generic equation for total chemical flow is equivalent to:

$$\frac{chemical\ flow(sccm)}{60\ secs} \times\ time(secs)\ \times chemical\ density\left(\frac{gram}{sccm}\right).$$

To illustrate the method used, an example is shown below. Table 5.1 shows the process recipe for Silane USG silicon dioxide deposition.

Step	Silane(sccm)	Nitrogen Oxide(sccm)	Time(sec)
1	260	3900	5
2	260	3900	10
3	260	3900	100
4	-2	-2	10

Table 5-1 Silane USG Deposition

Total Silane flow = $(\frac{260}{60} \times 5 + \frac{260}{60} \times 10 + \frac{260}{60} \times 100) \times 0.001342$

$= 0.6688$ g

Similarly,

Total Nitrogen Oxide flow = $(\frac{3900}{60} \times 5 + \frac{3900}{60} \times 10 + \frac{3900}{60} \times 100) \times 0.0018$

$= 13.455$ g

where 0.001342 and 0.0018 are the chemical density for silane and nitrogen oxide respectively. A full listing of density for various chemical and gases are listed in the Appendix D.

This calculation represents just one of the many process recipes in thin film manufacturing. The results are summarised and tabulated in Table 5.2.

Chemical/Gas Consumption Per Wafer(Process Manufacturing)			
	Process	**Chemical and Gas Consumed**	**Mass(gram)**
THIN FILM DEPOSITION	PECVD USG		
		Oxygen	4.287
		Helium	0.5358
		Teos	2.652
	PECVD USG Chamber Clean		
		NF3	3.8575
		Argon	4.8465
		Oxygen	0.7145
		Helium	0.0893
		Teos	0.312
	Silane USG Deposition		
		Silane	0.6688
		N2O	13.455
	Silane USG Chamber Clean		
		NF3	50
		Argon	6.2143
		Silane	0.08723
		N2O	1.755
	PE Silane Nitride		
		Silane	0.3344
		N2O	2.925
	Silicon Dioxide BPSG		
		N2	22.4723
		Boron	0.1597
		Phosphane	0.1245
		Teos	0.2912

Table 5-2 Chemical and Gas consumption for Process Manufacturing

Energy Consumption

Data filled in from the checklist were used to quantify the energy requirements of the semiconductor equipments and other process manufacturing utilities. A power factor of 0.88 was used for all semiconductor equipments during production and in idle state. The peak currents were mostly obtained from equipment installation report, otherwise through maintenance manual under "power supply requirements". Daily machine utilization time was noted and an average was taken. Since the semiconductor foundry produced 45,000 wafers per month, the average wafer produced per day is 1500. With this information, the effective electric power, P was calculated by the generic formula of:

$P = VI \cos \emptyset$ where V is the voltage, I is current and $\emptyset$ is the power factor.

However to properly account for energy consumption on a per wafer basis, it is necessary to consider both the active and idle load condition. The above formula was expanded for energy consumption calculation by including variables like peak current at peak load and idle current during idle load, rated voltage and equipment utilization. The total energy consumed is the summation of energy consumed at active and idle load condition. Thus effective electric power can be rewritten as:

$$P = V\ (I_{active} \times Time_{active} + I_{idle} \times Time_{idle}) \cos \emptyset$$

The processing energy per wafer, E in kWhr/wafer is calculated as follows;

$$E = \frac{P}{1000 \times daily\ average\ number\ of\ wafers\ produced}$$

The above formula applies for a 100% production yield.

For process yield of 83%, therefore the total energy consumption of the process per wafer is:

Energy Consumption per wafer = $\frac{E}{0.83}$ kWhr/wafer

The following example will illustrate the methodology described. Table 5.3 shows the energy requirements for the plasma enhanced chemical vapor deposition equipment.

Process Equipment	Quantity	Rated Voltage(V)	Active Load Current(A)	Idle Load Current(A)	Uptime (hrs)	Downtime (hrs)
PECVD USG	14	415	240	215	18.37	5.63

Table 5-3 PECVD USG energy data collected

P, effective electric power = 415(240 x 18.37 + 215 x 5.63) 0.88 = 2052150.1 W

E, processing energy per wafer = $\frac{2052150.1}{1000 \times 1500}$ = 1.3681 kWhr/wafer

Net Energy Consumption per wafer = $\frac{1.3681}{0.83}$ = 1.6483 kWhr/wafer

The rest of the energy consumption for other semiconductor equipments were calculated by the same method. The results are tabulated as shown in Table 5.4.

Energy Consumption kWhr Per Wafer(Process Manufacturing)				
	Process	**P, Effective Power (W)**	**E, Processing Energy (kWhr/wafer)**	**Net Energy Consumption (kWhr/wafer)**
T	PECVD USG	2,052,150.10	1.3681	1.6483
H I	Chamber Clean (PECVD USG)	1,970,604.97	1.3137	1.5828
N	Silane USG	2,191,293.58	1.4609	1.7601
F	Chamber Clean (Silane USG)	2,020,174.66	1.3468	1.6226
I L	PE Silane Nitride	1,459,859.29	0.9732	1.1726
M	Silicon Dioxide (BPSG)	217,983.74	0.1453	0.1751

Table 5-4 Energy consumption for Process Manufacturing

Water Consumption

There are two types of flow for water. They are continuous and discontinuous. Most semiconductor equipments, even during idle mode, require water to be purge continuously. This ensures the chamber environmental temperatures are maintained at constant temperature. This is an example of continuous flow. An example of discontinuous flow is the requirement to replace ultrasonic water tank once every 24 hours as per daily scheduled preventive maintenance. This ensures the conveyor belt of the APCVD tool is not contaminated.

The equations for both continuous and discontinuous are as described:

Continuous flow for wafer fabrication modules given by,

$$daily\ usage\ in\ litres = flow\ per\ minute\left(\frac{litres}{minute}\right) \times 24 hours\ \times 60\ minutes$$

Whereas discontinuous flow for wafer fabrication modules,

$$daily\ usage\ in\ litres = flow\ per\ minute\left(\frac{litres}{minute}\right) \times number\ of\ machine \times number\ of\ runs\ per\ day$$

From the checklist, the data obtained were calculated using the above formulas. The next task is to quantify the data into wafer level. Therefore

$$Consumption\ per\ wafer = \frac{daily\ usage\ in\ litres}{average\ number\ of\ wafers\ produced\ per\ day\ \times yield}$$

The calculated values were converted to mass. Table 5.5 illustrates the mass of water consumption in the thin film module.

Water Consumption Per Wafer (Process Manufacturing)				
T	**Process**	**Process Cooling Water PCW (grams)**	**Deionised Water DIW (grams)**	**Rinse Water (grams)**
H	PE CVD	2.3507	-	-
I N	Chamber Clean(PECVD)	2.8961	-	-
	Silane USG	-	5.5092	-
F I	Chamber Clean(Si USG)	-	6.4385	-
L M	PE Silane Nitride	-	3.7258	-
	Silicon Dioxide BPSG	8.0896	-	1.4305

Table 5-5 Water consumption for Process Manufacturing

5.3.2 Facilities

Collecting data in the facilities operations and determining process-specific emissions factors is a complex task in the semiconductor industry. Considerable amount of time and effort were invested to ensure the data collected are as accurate as possible. For example, with the assistance from facilities engineer, when determining gas usage, the residual gas left in the "empty" cylinders were returned to the supplier and accounted for accurately. The volume of water supplied was recorded by subtracting final value from initial gauge flowmeter reading.

As illustrated in Figure 3.3 and mentioned earlier, there are six primary systems making up the facility operations.

They are:

- Water recycling system
- Waste water/chemical treatment system
- HVAC(Heating, Ventilation, Air Conditioning) system
- Pre Treatment system
- Utilities system
- Scrubber POU Abatement system

For each system, checklists were created based on their flow diagrams. A 'top-down' approach was used since data collected were quantified at factory level resulting in a manageable database. The number of wafers produced per day represents the factor for disaggregating the factory data accurately. The methodologies in process manufacturing are similarly adopted for disaggregating the factory level data into a wafer level.

Chemical and Gas Consumption

There are dozens of chemicals used in the facilities for purification process. They are required for removing the organic and inorganic contamination impurities effectively and safely so that the waste water and waste chemical liquids be reused as ultra pure water.

Table 5.6 shows the daily chemical and gas consumption of the six primary systems. The daily consumption was divided by the numbers of wafers produced per day so as to disaggregate into wafer level.

Chemical/Gas Consumption Per Wafer(Facilities)				
	Process	**Chemical/Gas**	**Daily(kg)**	**Mass/wafer (grams)**
THIN FILM	Recycling Water	Chemical Organic	87.9	58.6
	Waste Water	Hydrochloric Acid	1361.19	907.46
		Sodium Chloride	232.8	155.2
		Sodium Hydroxide	3739.74	2493.16
		Ammonium Hydroxide	100.5	67
	HVAC	Lubricant	0.42	0.28
		Corrosion Inhibitor	134.7	89.8
		Glutaraldehyde	158.8	105.87
	Pre Treatment	Chemical Inorganic	91.3	60.87
		Glycerin	62.36	41.57
	Utilities	Nitrogen	192240	128160
	Scrubber	Ammonium Hydroxide	56.43	37.62

Table 5-6 Chemical and Gas consumption for Facilities

Energy Consumption

The life cycle inventory energy data collected for facilities are sub divided into six primary systems for the ease of collection. They are tabulated as shown in Table 5.7.

Energy Consumption kWhr Per Wafer(Facilities)				
	System	**Description**	**Total (kWhr)**	**Per Wafer (kWhr)**
THIN FILM DEPOSITION	Recycle Water	Water Recycling	2610	1.74
		Total		1.74
	Waste Water	Waste Water Treatment	1733	1.1553
		Total		1.1553
	HVAC	FAMU	11250	7.5
		FFU	3047	2.0313
		Exhaust	2305	1.5367
		Chiller	15388	10.2587
		Chiller sub-systems	5621	3.7473
		Total		25.074
	Pre Treatment	Process Cooling Water	3750	2.5
		Deionised Water	5440	3.6267
		Total		6.1267
	Utilities	Dryer	1911	1.274
		Vacuum	3373	2.2487
		Air Compressor	7008	4.672
		Total		8.1947
	Scrubber	Electric Oxidation	620	0.372
		Total		0.372

Table 5-7 Energy consumption for Facilities

The total energy consumed divided by 1500 wafers produced per day gives the energy consumed per wafer pass as indicated on the last column of the table.

Water Consumption

The total volume of water usage per day is about 4,007,143 kg. However about 70% was used for wafer processing, the rest being for office use, building maintenance, etc. Therefore total mass for wafer processing is about 2,805,000 kg of water. This value divided by 1500 wafers produced per day give 1870 kg/$wafer$. Table 5.8 shows the estimated water consumption.

Water Consumption Per Wafer(Facilities)		
Purpose of Water Usage	**Total Mass (kg)**	**Mass Per Wafer (kg)**
Plant	2805000	1870
Recycling	1437000	958
Net Usage		912

Table 5-8 Water consumption for Facilities

Since $958 kg/wafer$ of water recycled to the main plant water supply, the different between them give the daily net usage of 912 kg/$wafer$.

Chapter 6 Life Cycle Impact Assessment

6.1 Introduction

The Life Cycle Impact Assessment phase aims at evaluating the significance of potential environmental impacts using the results of LCI analysis. It should address both ecological and human health impacts, including social and economic impacts. This chapter includes the LCIA methodology and the introduction of the preferred software package, SimaPro7 covered in section 6.3. The application of SimaPro7 is used to model the semiconductor foundry life cycle and explore the selected impact assessment method for this study, the Eco-indicator 99. LCIA results are shown in section 6.5. This chapter ends with the conclusions based on the LCIA results.

6.2 Methodology

LCIA evaluates the impacts caused by the proposed products, processes or activities. It provides a link between the product or process and its potential environmental impacts. Thus the final result is an environmental profile of the system. According to ISO 14042, there are 7 key steps as listed below. The first three are mandatory while the rest are optional.

Select and Define Impact Categories – This step is to select the categories considered as part of the overall LCA. The selected categories should form a comprehensive set of environmental issue that are consistent with the goal and scope of the LCA study. Prior to the selection of impact categories, identification of end-points or damage indicators is recommended. Mid point is the point in the environmental mechanism at which the category indicators defined is close to the intervention. Alternatively they may be defined at the level of category endpoints.

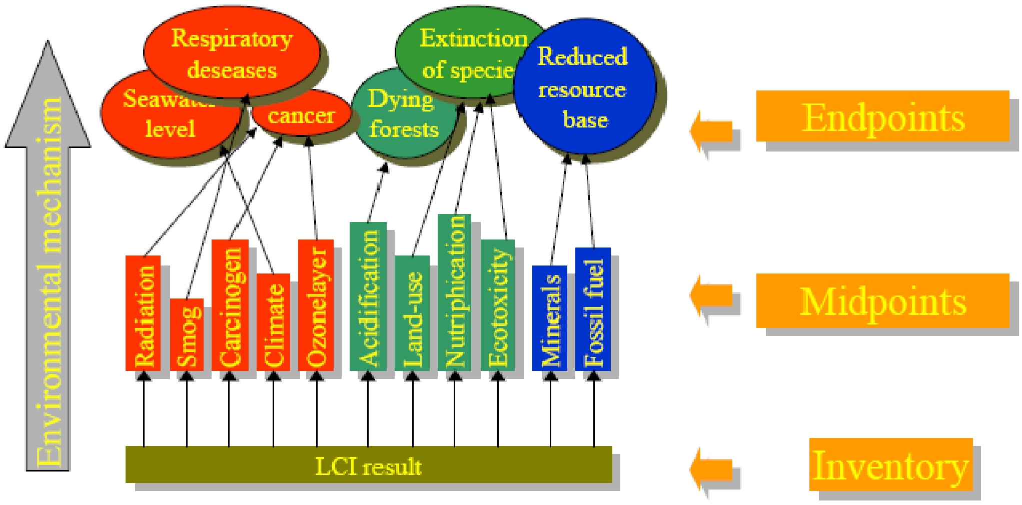


Figure 6-1 General Overview of the Structure of an LCA (Goedkoop, Schryver & Oele 2006, p.21)

Endpoints are issues of environmental concern, like human health, extinction of species, availability of resources for future generation, etc.

Classification – In this step, the LCI results are compiled and organized into impact categories. The procedure is straightforward for LCI items that contribute one impact category. For two or more impact category, rules must be set and the allocation procedure must be clearly documented.

Characterisation – For every impact category, the LCI results are converted into category indicator scores and aggregated into one indicator result. Scientific based conversion factors, known as characterization factors, are used to convert and combine the LCI results into representative indicators of impacts to human and ecological health. Multiplication of the characterization factors to the LCI results gives the impact category indicator result.

Normalisation – Normalisation is used to express impact indicator data for comparison amongst impact categories. This is by having the indicator results divided to a selected reference value. Normalised data can only be compared within an impact category.

Grouping – Impact categories are grouped by ranking indicators to better facilitate the interpretation of the results into specific areas of concern. The LCIA data may be rank by characteristics such as emissions or by a ranking system, such as high, medium or low priority. It is not used for this LCA study.

Weighting – Weighing is an important step since the impact categories must reflect the study goal. It is vital that the methodology be clearly explained and explicitly documented. In this step, the impact categories are assign weights or relative values based on their relevance or importance. Weighting proves to be a challenge since its procedure is subjective. There is no clear answer in proving that one impact category is more important that another. Thus weighting were not used for this LCA study.

Evaluation and Documentation of the LCIA Results – The final step of LCIA is to document the methodology used in the analysis, boundaries that were set and discussion of the assumptions and limitations made. There are two impact assessment methods. They can be classified as problem-oriented or damage-oriented. Problem-oriented approach, such as EDIP and CML 92, are driven by environmental issues where the quantitative results are grouped at mid-point categories to reduce the uncertainties. Calculations of the impact assessment results at the end-points categories such as Eco-indicator99, Eco-indicator95 and EPS 2000 (Environmental Priority Strategy) are known as damage-oriented method.

Thus the LCIA phase is a mammoth task to perform. However, it can be simplified with the aid of software tools. Since most practitioners are only interested in actual results of the study for product and process improvements, by keying in the appropriate inventory data, the software packages gives immediate calculation of results such as characterization, normalization and weighing. The various software packages available are further discussed in the following sections.

6.3 Software Packages

6.3.1 Types of Software

The three main software packages used by the semiconductor industry are GaBi, SimaPro7 and TEAM (LCA White Paper 2002).

GaBi gives simple and quick modeling for analysis of complex and data-intensive problems. Besides being able to generate ISO-conformable LCAs, it provides a consistent and detailed cost evaluation of assessed system.

TEAM has a comprehensive database and is ISO 14040 compliant. It is designed to describe and model complex industrial systems and to calculate the associated life cycle inventories, life cycle potential environmental impacts, and process-oriented life cycle cost.

SimaPro7 is a full featured LCA professional software tool. Being the worlds' most widely used LCA software, it was chosen for the analysis for this LCA.

6.3.2 Introduction to Simapro7

SimaPro7 is the acronym for "System for Integrated Environmental Assessment Products" and is developed by Pre consultants, a Dutch based company. SimaPro7, first released in 1990, can handle very advanced inventory techniques, but is at the same time very easy to use and understand. SimaPro7 comes with very large and up to date datasets. It is widely used worldwide mostly in industries, consultancies and universities. The software allows easy modeling with a proven track record amongst LCA practitioners worldwide. In house LCA consultants and software development ensure a high standard of software, support, and data availability.

The four stages of the LCA and an optional category are the five main components for modeling an LCA using SimaPro7. The fifth component does not influence the results of a LCA, consists of minor details such as images, literature references and information. Although SimaPro7 is unofficially accredited with ISO standards, it has been developed to suit the existing ISO set of LCA standards.

6.3.3 Using Simapro7

The demonstration version of the SimaPro7 software is freely available from its website. Since the cost of the single user license is expensive, a demo version is used for this project research.

SimaPro7 recommends two tutorials, 'Guide tour with coffee' and 'Tutorial with wood' to familiarize with the software. The demo version can only use the save command 16 times. Doing both tutorials by itself took up all the 16 saves. The laptop and desktop were reformatted many times to overcome this limitation.

SimaPro7 treats every LCA as a project. Upon creation of a project, the goal and scope section of the software begin with the documentation of goal and scope of the study. The next subsection, which is the 'libraries', gives the choice of database available. The chosen database is used to build assemblies, life cycle and waste scenarios for a project. The database was developed by various research organizations. There are ten assemblies available. The last subsection allows the user to choose data quality indicators. The assemblies, sub-assemblies, disposal scenarios and the full life cycle of a product are modeled in the product subsection by using the data from the libraries. The process sub-section of the LCI phase consisted of various information on raw materials, processes, energy usage, transportation, waste scenarios and waste treatments. The user can create a new item or edit item from the database if the data for the inventory is insufficient or inappropriate. Any altered data will not affect the default software database.

After the completion of building the life cycle of a product, the assessment method was chosen in the method subsection. The SimaPro7 demo version has 16 assessment methods. Most LCA assessment require only one method unless for comparative analysis. For calculating the LCIA results, the user select between characterization, grouping, normalization, weighing or single score. The results are displayed almost immediately on the screen. Selecting either 'tree' or 'network' display, a complete view of the life cycle of the product is obtained. The interpretation phase is accomplished by using network and tree displays, single score and process contribution graphs.

6.4 Modeling a CMOS Chip Using Simapro7

The CMOS chip life cycle was modeled applying the methodologies as described in section 6.2. Using an existing tutorial project, the LCA has been modified since the demo version does not allow us to create a new project. The first step was the selection of libraries and the data quality indicator requirements such as geography and time. The three chosen libraries were:

- BUWAL 250 – focus mainly on packaging materials, energy, transport and waste treatments. Developed by EMPA St. Gallen in Switzerland for a study commissioned by Swiss Ministry of Environment.

- ETH – ESU 96 – includes about 1200 processes such as energy, electricity generation, waste treatment, transport, etc. The database covers mainly Swiss and Western Europe situations.

- IDEMAT 2001 – main focus of this database is very much on production of materials. Developed at the Delft University of technology, Netherlands, the data is original and not taken from other LCA databases.

6.4.1 Eco Indicator 99

The Eco Indicator 99 is a damage oriented impact assessment that has been adopted in which only three number of damage categories are weighted. It is a much improve version of Eco Indicator 95 developed by the Dutch. It was developed in a top-down approach. The top-down approach starts by defining the required result of the assessment. This involves the definition of the term "environment" and the way different environmental problems are to be weighted.

The main advantage of the Eco Indicator 99 is that category indicators are defined at the end point level, giving them greater environmental relevance. The three damage categories can be compared to grouping of different end points. The end points are linked to the inventory results by the damage models.

The Eco Indicator 99 methodology consists of two parts:

- scientific calculation of the three forms of damage due to the life cycle of the product under study

- procedure evaluation to establish the significance of these damages.

Basically the three damage categories mentioned are the damages to:

- Human Health – the ideology that all human beings should be free from environmentally transmitted illnesses, disabilities or premature deaths.

- Ecosystem Quality – the ideology that non-human species should not suffer from disruptive changes of their populations and geographical distribution.

- Resources – the ideology that nature's supply of non-living goods should be available for future generations.

Damages to Human Health – human health is the absence of sickness, disease, irritations or premature death caused by emissions from agricultural and industrial processes to air, water and soil. A single health indicator was developed to quantify the damage category of Human Health. It is expressed as the number of Disability-Adjusted Life Years (DALYs) that measures the total amount of ill health due to disability and premature death, attributable to specific injuries and diseases. DALY is a tool for comparative weighing. The damages to human health are caused by the following impact categories listed below:

- Carcinogenic substances – emissions to air caused through inhalation and emissions to water caused through food intake.

- Respiratory effects - emissions causing exposure to particulate matter, nitrate and sulphate and carbon monoxide.

- Climate change – may lead to infectious diseases and death.

- Ionising radiation – exposure to radiation.

- Ozone layer depletion – caused by emission of ozone depleting substances such as halons and CFCs (chlorofluorocarbons).

Damages to Ecosystem Quality – is expressed as Potentially Disappeared Fraction (PDF) multiply by area multiply by time (PDF*m2*yr). This expression refers to the percentage of the species that have disappeared or are threatened of their natural habitat due to environmental load. Since the damage categories are not homogenous, the damage indicator is more complex to define. The damages to ecosystem quality are caused by the following impact categories listed below:

- Ecotoxicity – substances that are toxic to the environment. Emission released through air, water, agricultural soil and industrial soil and concentrations in water, and pores water of agricultural, industrial and natural soil.

- Acidification & Eutrophication – caused by deposition of inorganic substances such as nitrates, sulphates and phosphates changing the nutrient level and acidity in the soil.

- Land Use – the area of land used for an activity and the damage caused by preventing the occupied area returning into its natural condition.

Damages to Resources – expressed in MJ surplus energy per extracted materials, models minerals and fossil fuels only.

- Minerals – refers to the decrease of resource quality resulting in increase of the effort to extract the remaining resources.

- Fossil Fuels – refers to constant effort required to extract the resources until it reach depletion state, which in this case, increase the effort to extract the remaining resources.

Three versions of the damage models were developed to deal with the uncertainties for the LCA study of a product. The modeling was based on a wide range of basic attitudes and assumptions in predicting the perspectives to provide a basis for important modeling of the three chosen version. The three choices are the individualist, hierarchical and egalitarian version. The three versions are briefly described as follows:

Individualist – only considers substances which have demonstrable short-term adverse effects but does not consider the consumption of fossil fuels. It further assumes that the adoption of technological measures and economic development can solve all environmental problems.

Hierarchical – considers all substances for which a consensus has been reached on medium term adverse effects. It further assumes that environmental problems can be solved through political choices.

Egalitarian – considers all substances that may have long term adverse effects. Even no consensus has been reached about these effects, it is a very conservative perspective, based on the assumption that environmental problems are difficult to solve and may result in catastrophes.

In view of the long term effects of future generations and resource depletion, an egalitarian perspective was chosen for this LCA study.

The following table summarized the basic attitudes related to the value system used in Eco Indicator 99.

Version / Predictions	Egalitarian	Individualist	Hierarchist
Criteria	Argument	Experience	Evidence
Management	Preventative	Adaptive	Control
Time	Long Term	Short Term	Between long & short term
View of Resources	Depleting	Abundant	Scarce
Attitude Towards Risk	Risk-aversive	Risk-seeking	Risk-accepting

Table 6-1 Typical values in the three perspectives

The Eco Indicator 99 methodology is based on the best available data and scientific understanding of the environmental mechanisms. Therefore the methodology is not perfect. The Eco-indicator values are not an absolute truth. The indicator aimed at showing the approximately correct direction for designers who want to analyze and minimize the environmental load of product systems. Decisions made base on this methodology must raise the awareness of those limitations.

6.5 LCIA Results

The inventory data collected from previous section were entered into the Simapro7 software and this chapter highlighted the environmental impacts caused by the production of the CMOS chip in thin film deposition process manufacturing and the facilities of the semiconductor plant. The impact assessment method chosen, Eco Indicator 99, however normalizes the impact results with the environmental effects caused by an average European during a year.

As this project research seeks to identify the environmental impacts caused in the manufacturing of the CMOS chip, the following methodology was adopted. Firstly, the LCIA analysis was carried out on the thin film process manufacturing. Further analysis was then carried out on the facilities. Mostly network, tree diagrams and some characterization results were used for analysis. The cut-off values for each network were set accordingly so that important information can be documented.

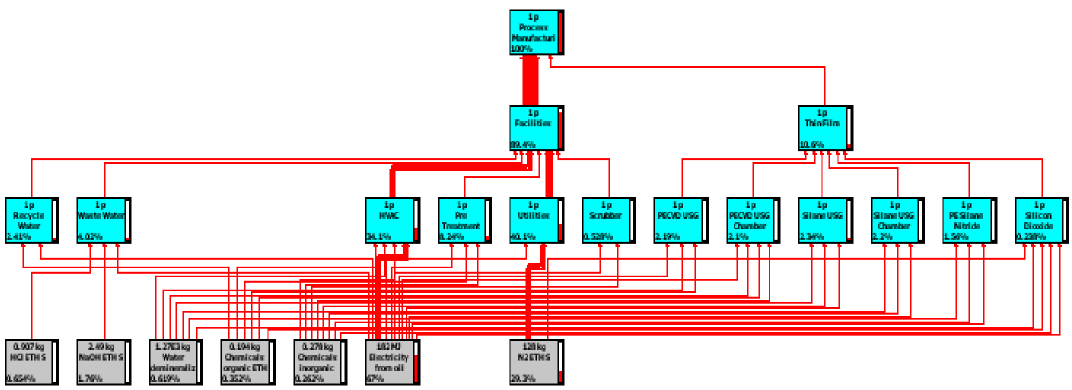


Figure 6-2 Network Analysis of CMOS chip in process manufacturing

With respect to figure 6.2 and other network diagrams, the red line indicates the "environmental hotspots". The thicker the line that link different processes, the greater contribution it has to the total environmental loads. The thermometer indicators on the right of each box show the process results with respect to the final result. Thus all results shown are cumulative. The blue boxes include the major components. The grey boxes are the items from the database comprising of the processes in the software. It can be seen the poor quality of the network analysis diagram presented. This is a major drawback. Better resolution of the network analysis diagrams are shown in Appendix C.

Figure 6.2 shows the network analysis which includes thin film process manufacturing and facilities in the production of CMOS chip. The figure shows the facilities department has a greater environmental load and HVAC module has the greatest impact within the facilities. On closer observation, the energy used (electricity) is the main attribute. It can be seen that processes having insignificant environmental load are omitted. To overcome this, further analysis was carried out on the thin film and facilities.

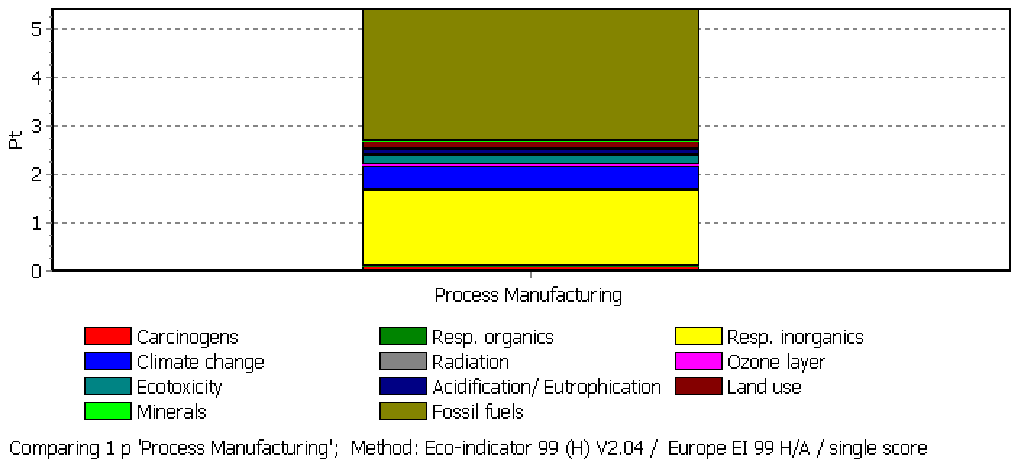


Figure 6-3 Comparison of environmental impact assessments

Figure 6.3 illustrates the various impact assessments summarized in a single bar chart hence it is called single score. Each image assessments are normalized for easy comparison. The results of the analysis are expressed in points(Pt), the unit of measure which the software uses to assign a numeric value to environmental impact. The higher the "score" in Pt, the higher the damage done to the environment. The top eight environmental impacts in descending order are damaged caused by fossil fuel, respiratory inorganics, climate change, ecotoxicity, acidification/eutrophication, land use, carcinogens and minerals.

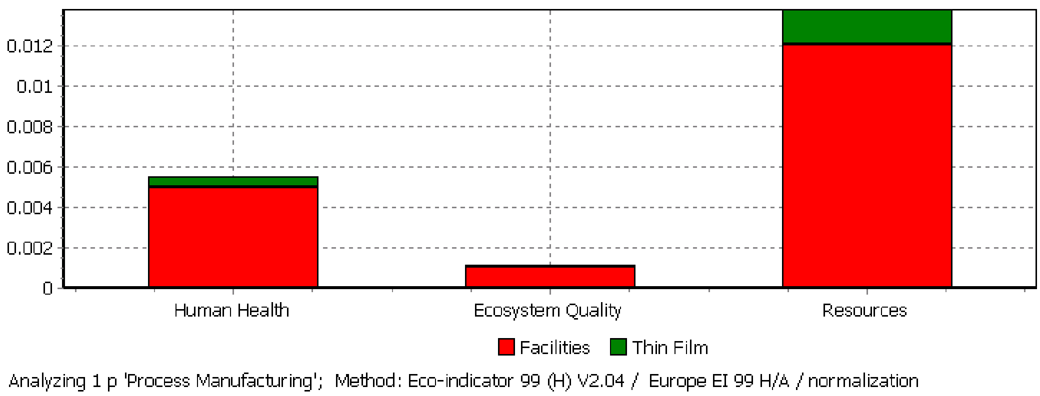


Figure 6-4 Normalization of environmental damage assessments

From the above figures, it may be concluded that

- Damage to resources by fossil fuel caused the worst environmental damage. Fossil fuels being a non-renewable resource, each time it is utilized, there is a certain amount of environmental impacts caused.

- Damage to human health caused by respiratory inorganics and climate change is the second most affected damage category. Contributions from the rest impact categories are insignificant.

- Damage to ecosystem quality is the least affected. This was due to the small contributions made by ecotoxicity, acidification/eutrophication and land use impact categories.

- The facilities module is the primary contributor to each impact category.

The following sections give comprehensive analysis for only the top impact category for each damage category level. The rest of the results are ignored since they do not contribute significantly to the overall results. Thus, only fossil fuel depletion cause due to damage to resources, respiratory inorganics due to damage to human health and ecotoxicity due to damage to ecosystem quality results were discussed in the following sections.

6.5.1 Damages to Resources and Impact Categories

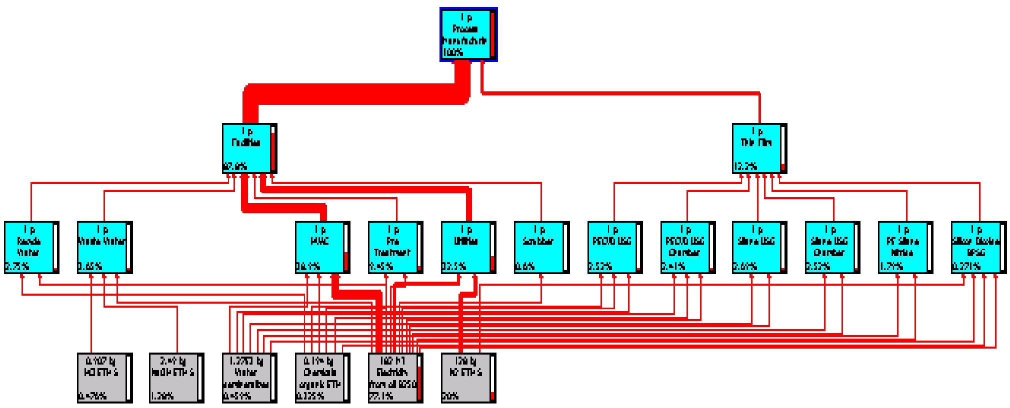


Figure 6-5 Network analysis of damage to resources due to process manufacturing

Figure 6.5 illustrate the network analysis of the environmental impact results for damage to resources in process manufacturing. The actual damage score is 115MJ surplus energy. The results shown on the network analysis are expressed in percentage. Facilities module is the main contributor to resource damage at 87.8%. The remainder 12.2% comes from thin film. Closer observation indicate about 77.1% of the total contributions to resource damage come from energy consumption (electricity) followed by nitrogen at 20%.

Facilities – Damage to Resources

Figure 6.6 gives the detail of the above 87.8% damage to resources due to facilities module. On closer observation, there are two main contributors to the resource damage linked to the facilities. About 63.2% of the total energy consumption comes from supporting tools in facilities module and 32.7% from nitrogen usage. Supporting tools include ozone analyzer for ozone production, chemical refill system for specialized chemical delivery, various vacuum pumps to generate different vacuum level, etc. HVAC and utilities each contributing 38.1% and 44.9% respectively, make up 83% of the damage to resources. Nitrogen is used for all byproduct process flow because it does not react readily.

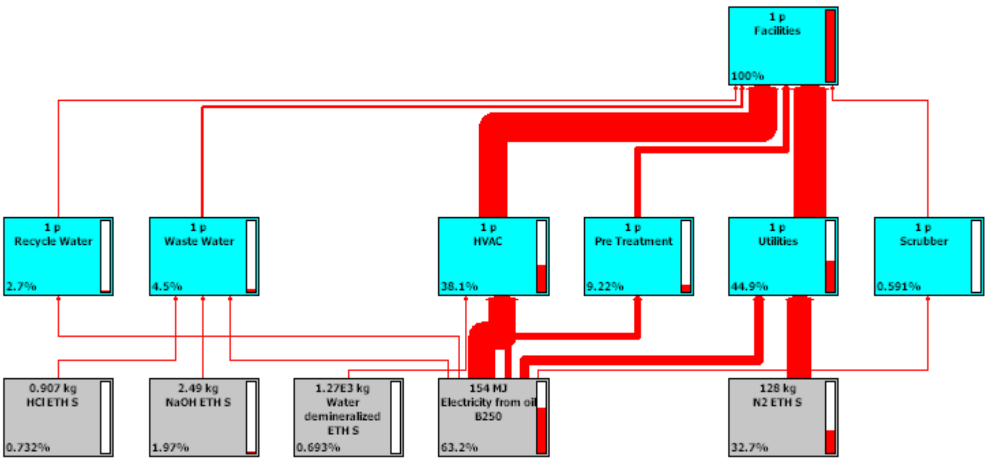


Figure 6-6 Network analysis damage to resource due to facilities

Thin Film – Damage to Resources

Figure 6.7 gives the detail of the 12.2% of the total damage to resources due to thin film module.

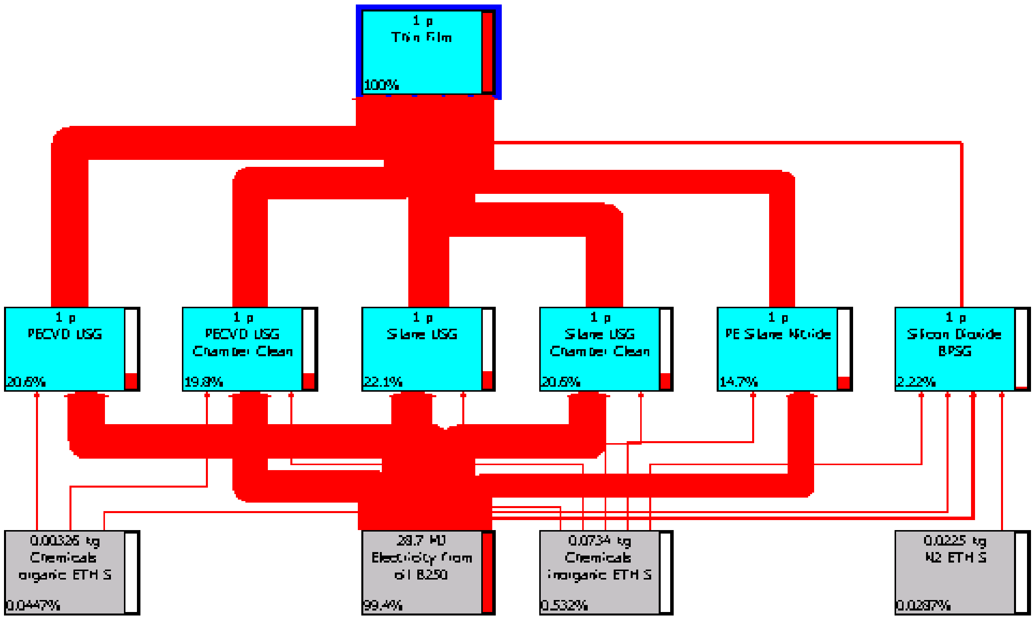


Figure 6-7 Network analysis damage to resource due to thin film

Within the thin film process manufacturing stage, again the total energy for electrical usage is the main contributor for the damage to resources. Silicon Dioxide BPSG stage contributes only 2.22% to the damage, a small percentage compared to the other 5 processes. This equipment being an APCVD (atmospheric pressure chemical vapor deposition) process had a conventional chamber. The rest are cluster tools having four vacuum chambers for each process. This explains the high demand of electricity needed for the cluster tools.

Depletion of fossil fuel is the major impact category contributing to the damage to resource. The only other impact category; minerals, are ignored due to its insignificant contribution.

Impact Category – Fossil Fuel Depletion

Fossil fuel is a non renewable source of energy. They are found in deposits beneath the earth and are burned to release the chemical energy that is stored within this resource. The byproducts formed from the burning of fossil fuels are very dangerous. These small particles that exist in the air can travel and reach deep within the lungs. A high percentage of our energy demands are met by combustion of fossil fuels. Figure 6.8 below is the characterization results for one of the impact categories; fossil fuel depletion, contributing to the damage to resources.

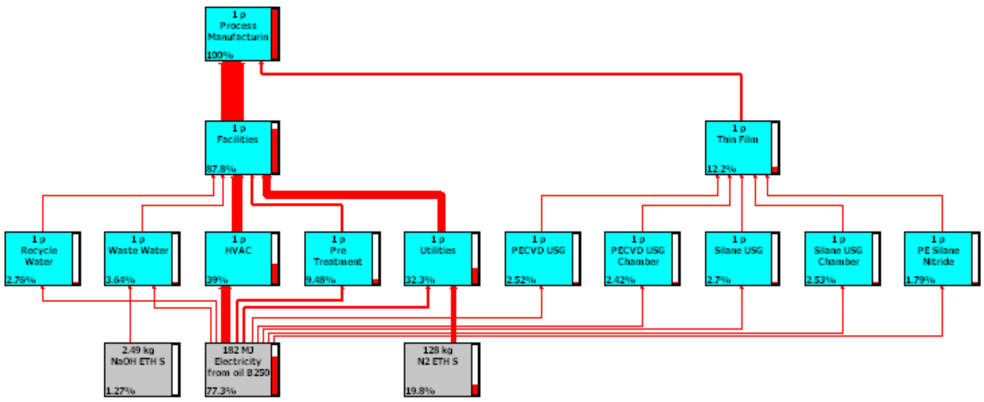


Figure 6-8 Network analysis impact category – fossil fuel depletion

A very high percentage about 77.3% of fossil fuel depletion is contributed by the energy consumption. The other major contribution is the usage of nitrogen at 19.8%. Due to the supporting equipments, 87.8% of the fossil fuel depletion comes from facilities, the rest about 12.2% from thin film.

Facilities – Fossil fuel depletion

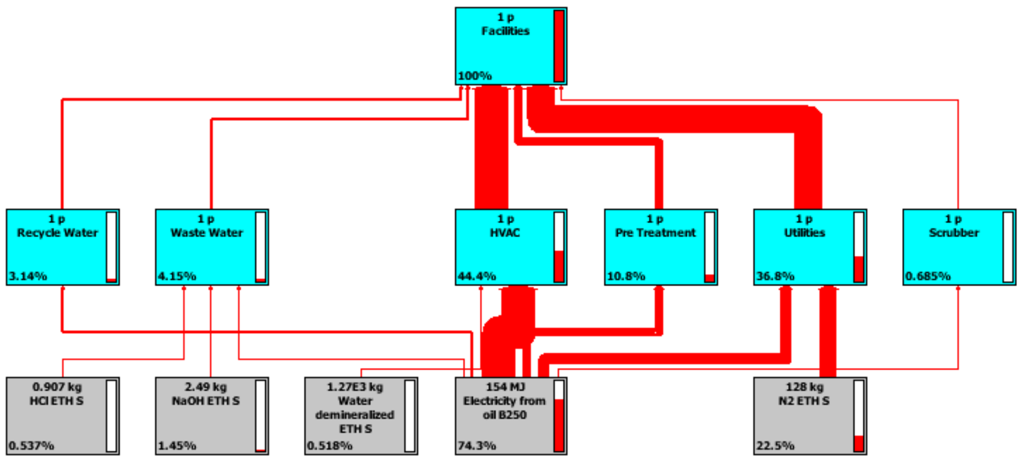


Figure 6-9 Network analysis impact assessment due to facilities

Shown in figure 6.9 is the characterized network showing environmental impact results for damage to resources in facilities. The results shown on the network are in percentage to the actual score of 101MJ surplus energy. Almost three quarter from facilities module towards fossil fuel depletion comes from energy consumption for the supporting machinery. The next highest contributor (22.5%) is nitrogen since they are used extensively in the cleanroom.

Gas line purging when equipments are in idle or standby mode requires continuous flow of nitrogen. This is to prevent any form of contamination and build up of moisture due to condensation. The consequence of contamination on the gas line will be costly to the end user of the process tool. Used of nitrogen include as a carrier gas for delivery when chemicals are converted from liquid to gaseous form. Some specialized chemicals are stored in liquid form for safety reasons. They are converted to gaseous form by thermal jackets or heaters for deposition. Nitrogen is also required on wafer foup/cassette cabinets for storing wafers while waiting for the downstream process. Most chamber cleaning recipes require nitrogen. Being an inert gas, it is does not react easily with other chemicals.

Thin Film – Fossil fuel depletion

Figure 6.10 is the characterized network showing environmental impact results for damage to resources in thin film process manufacturing.

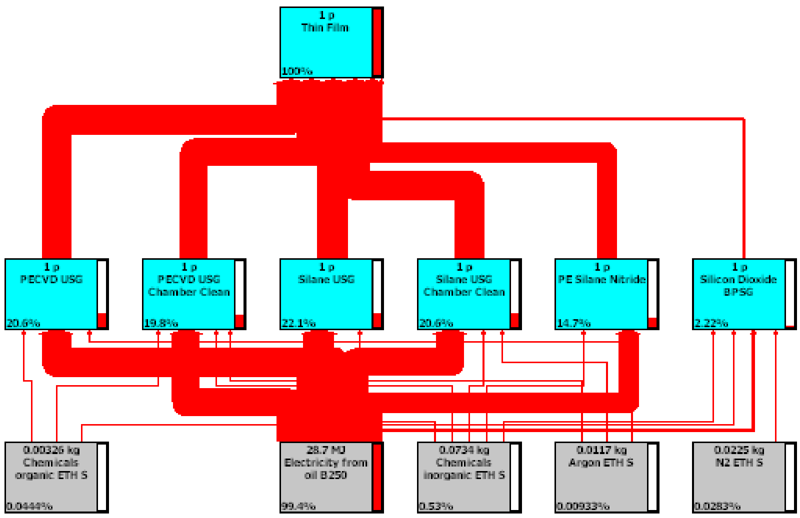


Figure 6-10 Network analysis impact assessment due to thin film

From Figure 6.10, almost all contributions (99.4%) in thin film towards fossil fuel depletion come from energy consumption for semiconductor equipments. All the process recipes, with the exception of Silicon Dioxide BPSG process, generally contribute equally towards fossil fuel depletion. As mentioned earlier, the energy requirements for Silicon Dioxide BPSG deposition is much lesser.

6.5.2 Damages to Human Health and Impact Categories

Figure 6.11 is the network analysis of the environmental impact results for damage to human health in process manufacturing.

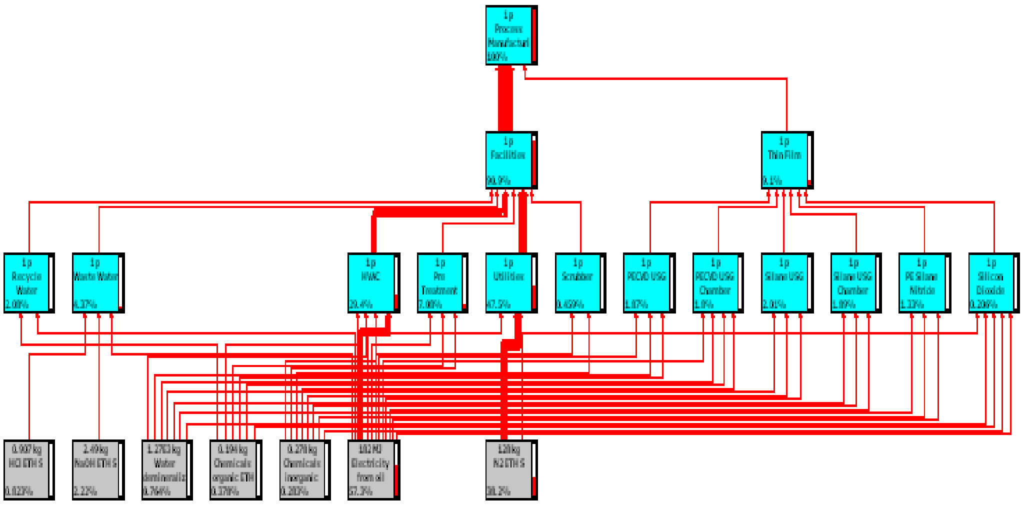


Figure 6-11 Network analysis of damage to human health due to process manufacturing

As can be seen from the above figure, a high percentage of 90.9% of damages to human health contribution comes from facilities particularly from utilities and HVAC modules. About 57.3% of impacts are associated with electricity consumption and 38.2% usage of nitrogen. The results shown on the network are in percentage term to the actual damage score of 8.4E-5 DALY.

Facilities – Damage to Human Health

The figure 6.12 is the network analysis showing the human health damage assessment due to the facilities modules.

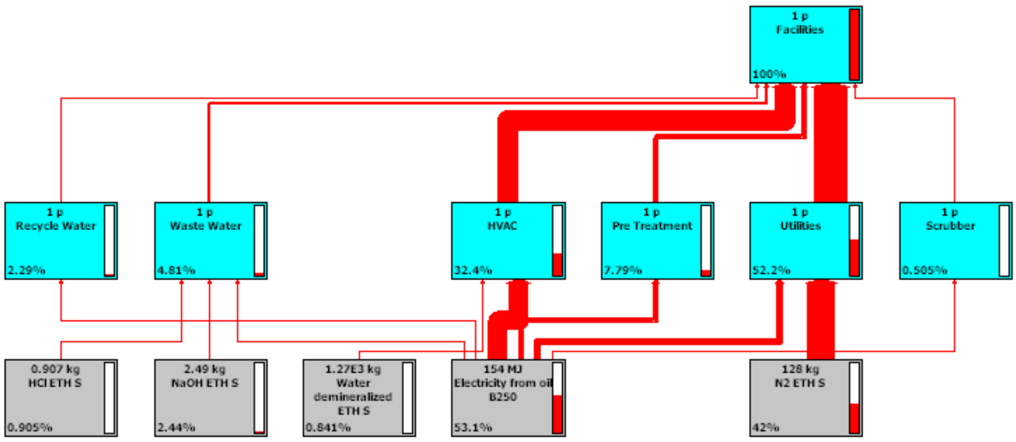


Figure 6-12 Network analysis damage to human health due to facilities

As observed from Figure 6.12, the contribution from facilities to human health damage mainly comes from utilities(52.2%) and HVAC(32.4%). The results shown on the network are in percentage term to the actual damage score of 7.64E-5 DALY. Electricity is the main contributor with 53.1% at 154MJ associated for the environmental burdens followed by nitrogen consumption at 42%. The other notable contribution is sodium hydroxide(2.44%), hydrochloric acid(0.905%) and demineralized water(0.841%).

Thin Film – Damage to Human Health

The figure below is the network analysis of human health damage assessment due to thin film process manufacturing.

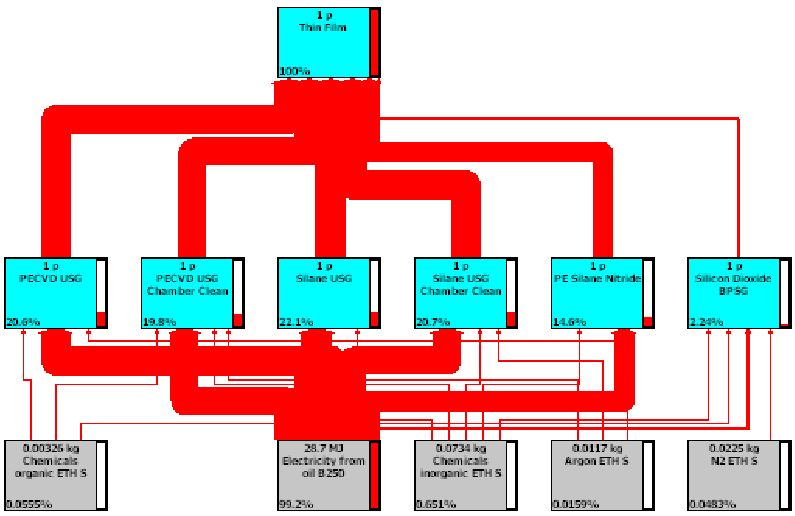


Figure 6-13 Network analysis damage to human health due to thin film

In thin film, almost all of the contribution comes from electricity consumption at 99.2%. The five process except Silicon Dioxide BPSG amount to a contribution of 97.8% of the environmental loads. Other contributions are from chemical inorganic(0.651), chemical organic(0.055%), nitrogen(0.0483%) and argon(0.0159%). The results shown on the network are in percentage term to the actual damage score of 7.65E-6 DALY.

Respiratory inorganics is the major impact category contributing to the damage to human health. The other impact categories are ignored due to their insignificant contribution.

Impact Category – Respiratory Inorganics

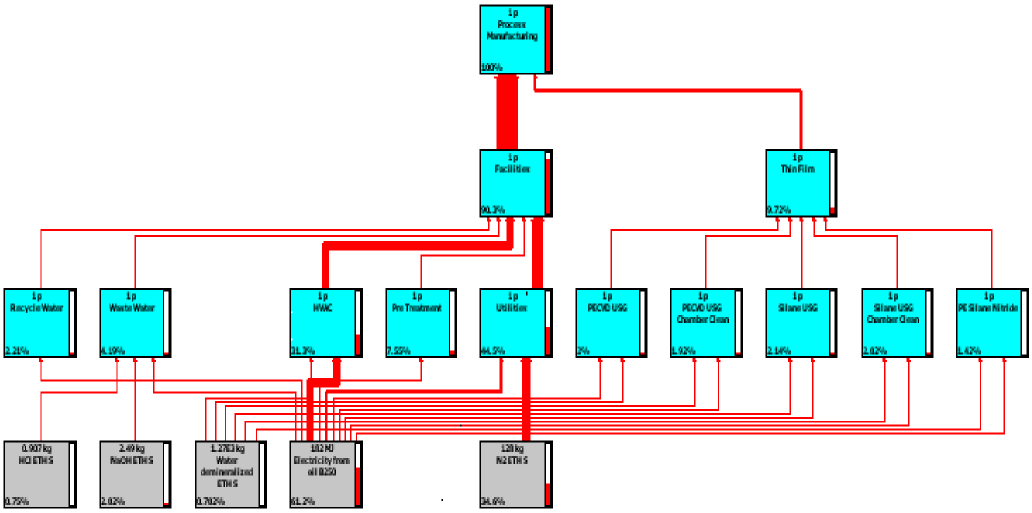


Figure 6-14 Network analysis of impact category – respiratory inorganics

Of the 5.98E-5 DALY for damage category respiratory inorganic associated with process manufacturing, about 90.7% comes from facilities. Damage category respiratory inorganics is the cause of various respiratory problems due to the airborne microscopic inorganic particles that travel into human lungs. For example, combustion sources like burning of fossil fuels are the biggest source of particulates in the air. This explains the high contributions related to electricity from oil at 61.2% and nitrogen at 34.6%.

Facilities – Respiratory Inorganics

Figure 6.15 gives the detail of the 90.2% of the total damage to human health due to facilities modules.

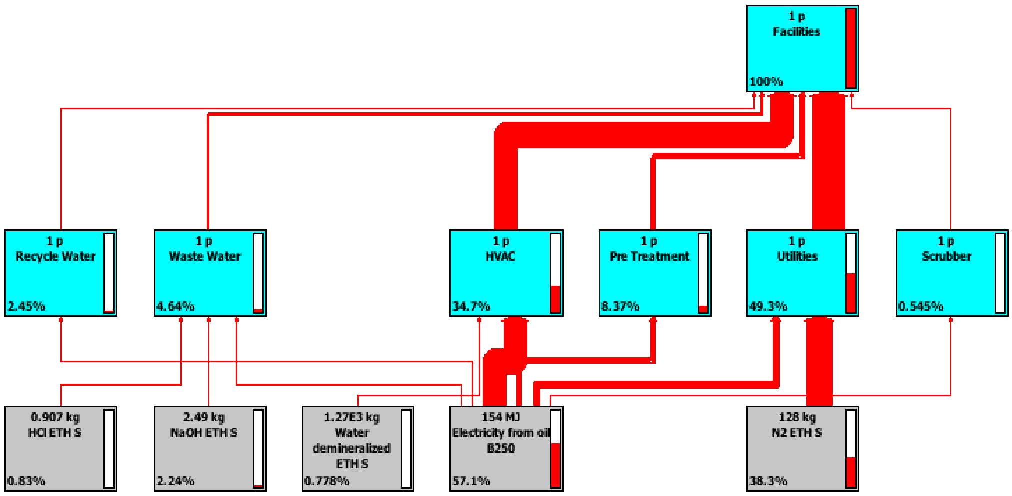


Figure 6-15 Network analysis of impact assessment due to facilities

Electrical consumption of the semiconductor equipment is the highest contributor at 57.1% followed by nitrogen consumption about 38.3%. Other notable contributions include sodium hydroxide(2.24%), hydrochloric acid(0.83%) and demineralized water(0.778%). The results shown on the network are in percentage term to the actual damage score of 5.4E-6 DALY.

Thin Film – Respiratory Inorganics

Figure 6.16 shows the characterized results of thin film and are in percentage term to the actual damage score of 5.82E-6 DALY. The major contribution is almost entirely from electrical consumption at 99%. The remaining percentage point comes from other chemicals and gas. The main contributions to Ecosystem damage in thin film comes from Silicon USG(22%) process followed closely by Silicon USG Chamber Clean(20.8%), PECVD USG(20%), PECVD Chamber Clean(19.7%), PE Silane Nitride(14.6%) and small contribution of Silicon Dioxide BPSG at 2.25%.

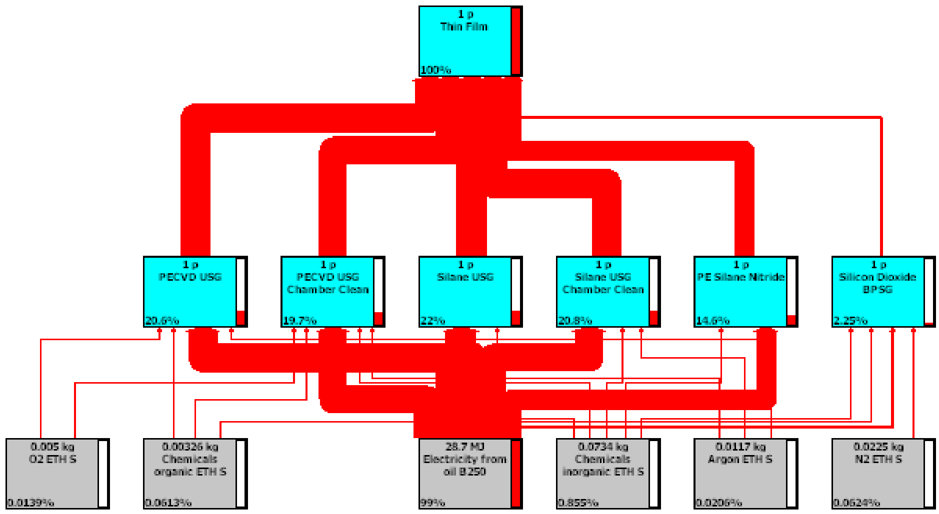


Figure 6-16 Network analysis of impact assessment due to thin film

6.5.3 Damage to Ecosystem Quality and Impact Categories

Figure 6.17 is the ecosystem damage assessment network analysis diagram.

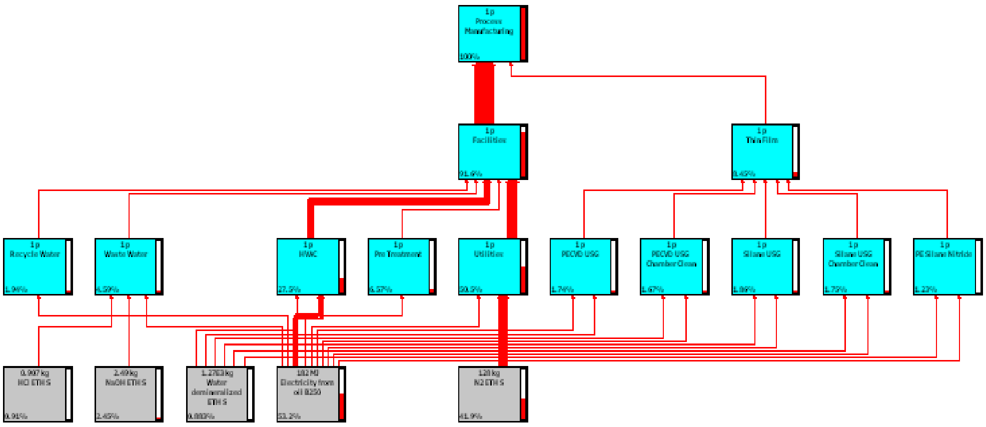


Figure 6-17 Network analysis of damage to ecosystem quality due to process manufacturing

The total score for ecosystem quality is calculated to be 5.99 $PDF * m^2 * yr$. Out of this, 5.48 $PDF * m^2 * yr$ calculated for facilities and only 0.506 $PDF * m^2 * yr$ for thin film. On closer observation of figure 6.17, the main contributions to ecosystem damage comes from facilities at 91.6% and the remainder, 8.4% comes from thin film module.

Facilities – Damage to Ecosystem Quality

The figure below gives the detail of the figure 6.17 where 91.6% damage to ecosystem quality due to facilities module.

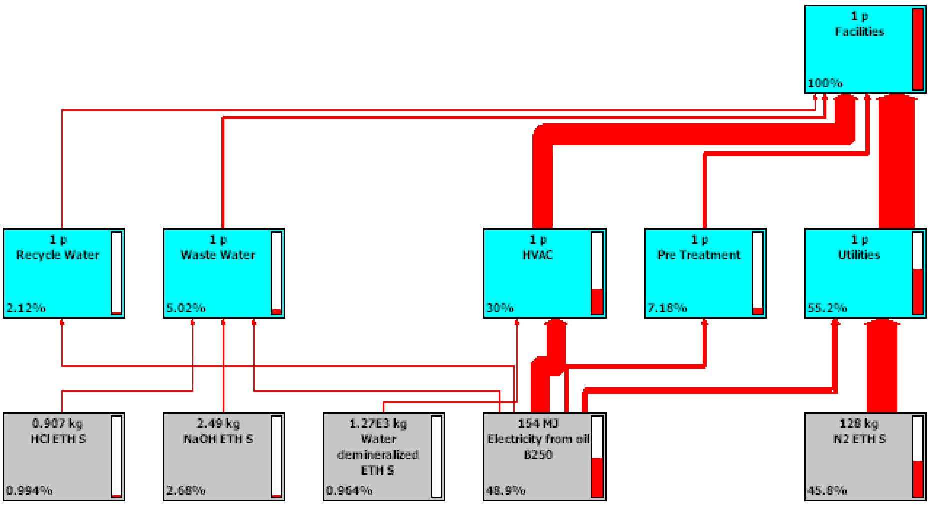


Figure 6-18 Network analysis damage to ecosystem quality due to facilities

Of the impacts associated with facilities, more than half; about 55.2% is linked to the utilities. The remaining contributors are HVAC(30%), pre treatment(7.18%), waste water(5.02%) and recycle water(2.12%). Again the highest contributor to ecosystem quality is electricity consumption. Next comes from nitrogen consumption as they are widely used during wafer processing.

Thin Film – Damage to Ecosystem Quality

Figure 6.19 is the network analysis diagram showing the damage to ecosystem quality due to thin film process manufacturing.

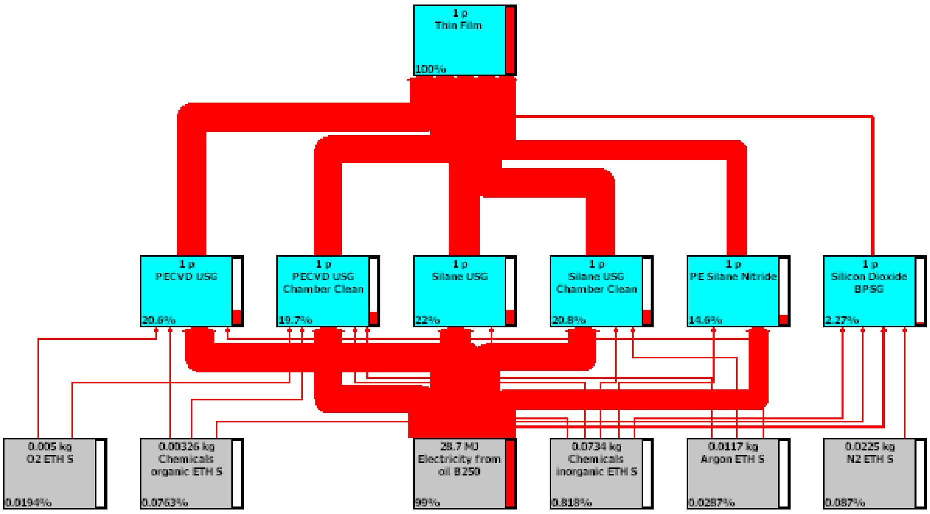


Figure 6-19 Network analysis damage to ecosystem quality due to thin film

From thin film deposition module, almost all of the contribution originates from energy consumption. About 28.7MJ surplus is energy required to power up the semiconductor process equipments. Heater elements, heater jackets, RF generators, ultrasonic generators,etc demands high current to operate.

Ecotoxicity is the major impact category contributing to the damage to ecosystem quality. The only other impact categories; land use and acidification/eutrophication, are ignored due to their insignificant contribution.

Impact Category – Ecotoxicity

Ecotoxicity is the study to understand the concentration of chemicals at which the environment and the organism living in it are affected. When an organism is affected, other organisms in the ecosystem may suffer since all organisms depend on each other. Major cause of concern for ecotoxicity include emission of oil during oil extraction, release of organic pollutants with waste water, release of metals and atmospheric disposition of metals and dioxins. Figure 6.20 shows the network analysis impact category of ecotoxicity due to the process manufacturing of a CMOS wafer.

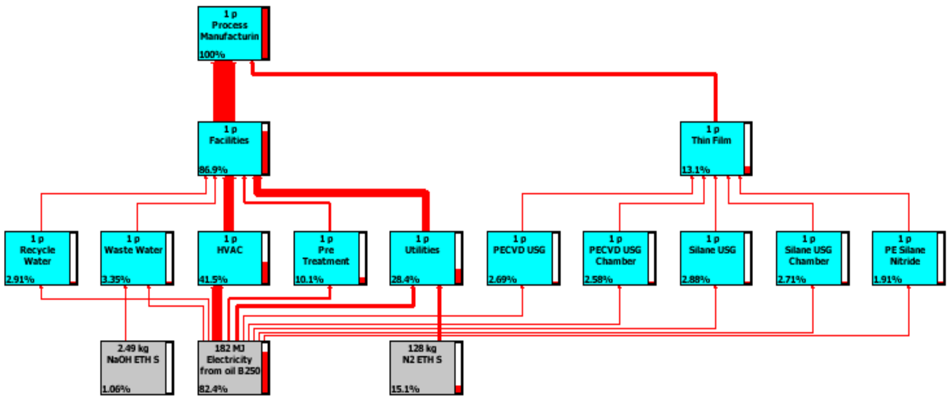


Figure 6-20 Network analysis impact category - ecotoxicity

As seen on figure 6.20, facilities account for 86.9% of the ecotoxicity impacts related to CMOS wafer production. The other module, thin film contributed about 13.1%. Electricity consumption accounts for 82.4% of the ecotoxicity impact category. The next major contributions are nitrogen consumption at 15.1% and a small contribution about 1% from sodium hydroxide.

Facilities - Ecotoxicity

The network analysis impact category of ecotoxicity due to facilities modules is shown below.

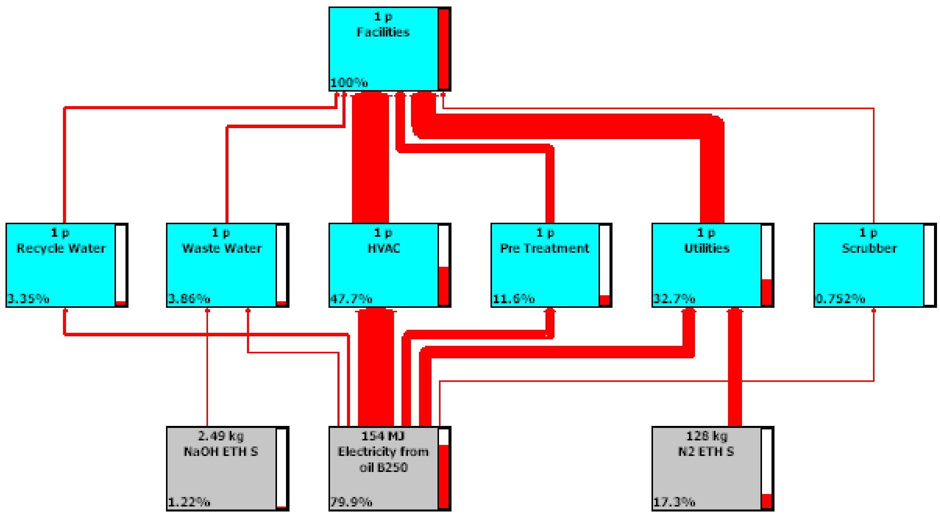


Figure 6-21 Network analysis impact assessment due to facilities

Within the facilities module, HVAC accounts for roughly half of the ecotoxicity impacts related to CMOS wafer manufacturing. The next highest contribution are utilities(32.7%), pre treatment(11.6%), waste water(3.86%), recycle water(3.35%) and scrubber(0.752%). On the whole, electricity consumption for supporting equipments is the highest contributor at 79.9%, nitrogen usage at 17.3% and sodium hydroxide at 1.22%.

Thin Film - Ecotoxicity

Figure 6.22 is the network analysis impact category of ecotoxicity due to thin film process manufacturing.

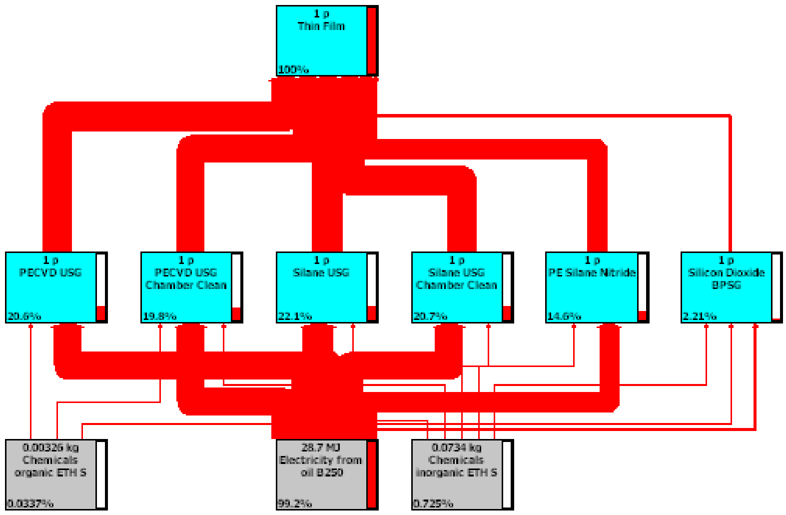


Figure 6-22 Network analysis impact assessment due to thin film

For thin film process manufacturing, the four process of PECVD USG, PECVD USG chamber clean, Silane USG and Silane USG chamber clean are roughly equally responsible for the ecotoxicity impacts. Again as can be seen, electricity consumption is the major contributor at 99.2%. The other contributor are chemical inorganic(0.725%) and chemical organic(0.0337%).

6.6 Analysis and Conclusions of LCIA Results

This section analyses the results obtained from the previous section for accuracy and reliability and draws conclusion from it. The single score and process contribution charts are used to substantiate the analysis and findings. Results from previous sections had shown consistently that energy consumption of process manufacturing equipments and supporting tools in facilities are the highest contributors to the environmental burden associated with the CMOS wafer. Figure 6.23 which is the process contribution results comprising of facilities modules and thin film process manufacturing prove this point.

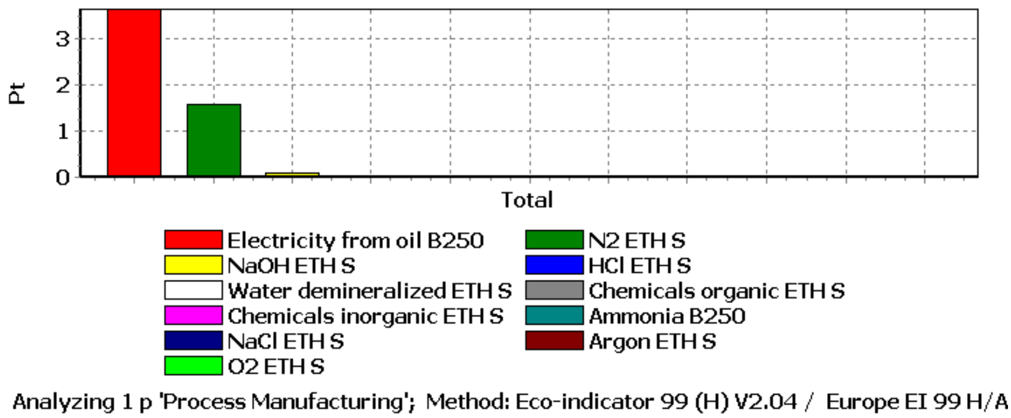


Figure 6-23 Process contribution results for CMOS wafer manufacturing

From above figure it can be seen that approximately 75% of electricity usage contribute to the environmental burden associated with CMOS wafer manufacturing. About one quarter is due to the nitrogen supply.

Facilities

Figure 6.24 shows the single score result for the facilities module. It was seen that most of the environmental impacts from facilities are linked to the energy consumption of the supporting tools.

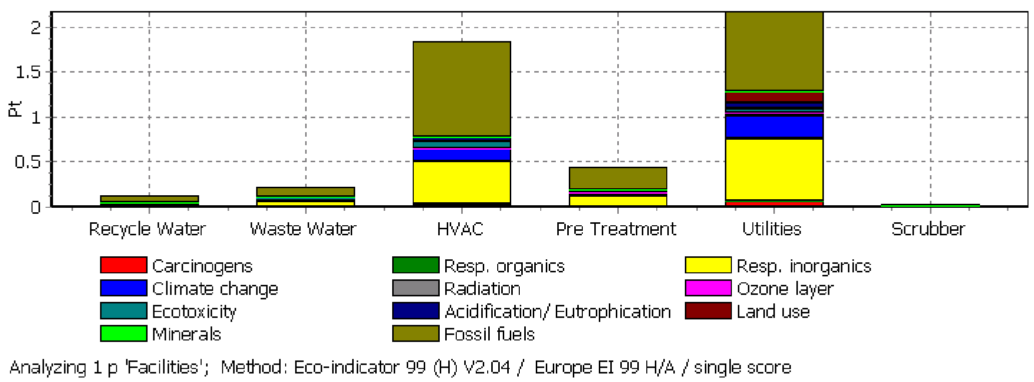


Figure 6-24 Single score results for facilities module

The single score, which is the aggregation of weighted impacted category scores, charts does not provide an accurate result. However they are used to substantiate the findings and analysis from the previous section.

Majority of the contribution is related to utilities and HVAC module. This is due to the high energy demand required to power heavy industrial tools such as air compressors, fresh air make-up units, chillers, etc. The least contribution is related to the scrubber. An interesting point was that the water and chemicals are insignificant to the overall results. The reason being the environmental impacts associated with the energy requirements far outweigh the impacts from other inputs.

Thin Film Deposition

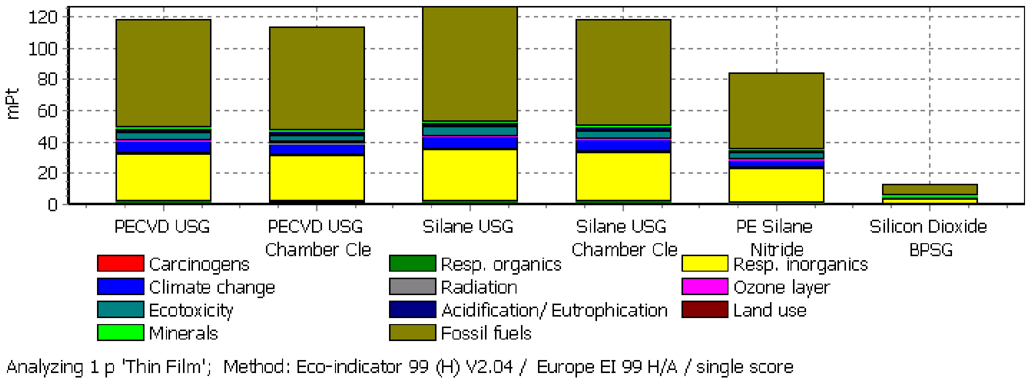


Figure 6-25 Single score results for thin film

It can be seen from figure 6.25 that most of the environmental impacts from thin film deposition are approximately linked equally to the 5 modules namely PECVD USG, PECVD chamber clean, silane USG, silane USG chamber clean and PE silane nitride. As mentioned in previous section, this was due to the high energy demand needed for operating the four process chambers.

Chapter 7 Life Cycle Interpretation

7.1 Introduction

Life cycle interpretation is the last phase of the LCA process. Interpretation stage analyses the results obtained from past LCA stages and check their validity. This was because of the complex nature during data collections due to assumptions made, technical estimates and other choices. This chapter documents the final phase of this life cycle assessment study including the methodologies used. Key steps of life cycle interpretation were discussed. Section two evaluated the LCIA results for completeness, sensitivity and consistency. This chapter ends with the recommendations and conclusions for this LCA study.

7.2 Methodology

ISO 14043 (2000E) defines life cycle interpretation as " a systematic procedure to identify, qualify, check, and evaluate information from the results of the LCI and/or LCIA of a product system, and present them in order to meet the requirements of the application as described in the goal and scope of the study. Also, Life Cycle Interpretation includes communication to give credibility to the results of other LCA phases (namely the LCI and LCIA) in a form that is both comprehensible and useful to the decision maker". Thus its main aim is to check the results of the Inventory analysis and of the Impact assessment against the Goal and Scope definition of the study.

The interpretation phase, within the ISO draft standard, consists of 3 key steps, they are:

- Identify significant issues.
- Evaluate the completeness, sensitivity and consistency of the data.
- Draw conclusions and recommendations.

Figure 7.1 illustrate the three key steps of the interpretation phase in relation to other phases of the LCA.

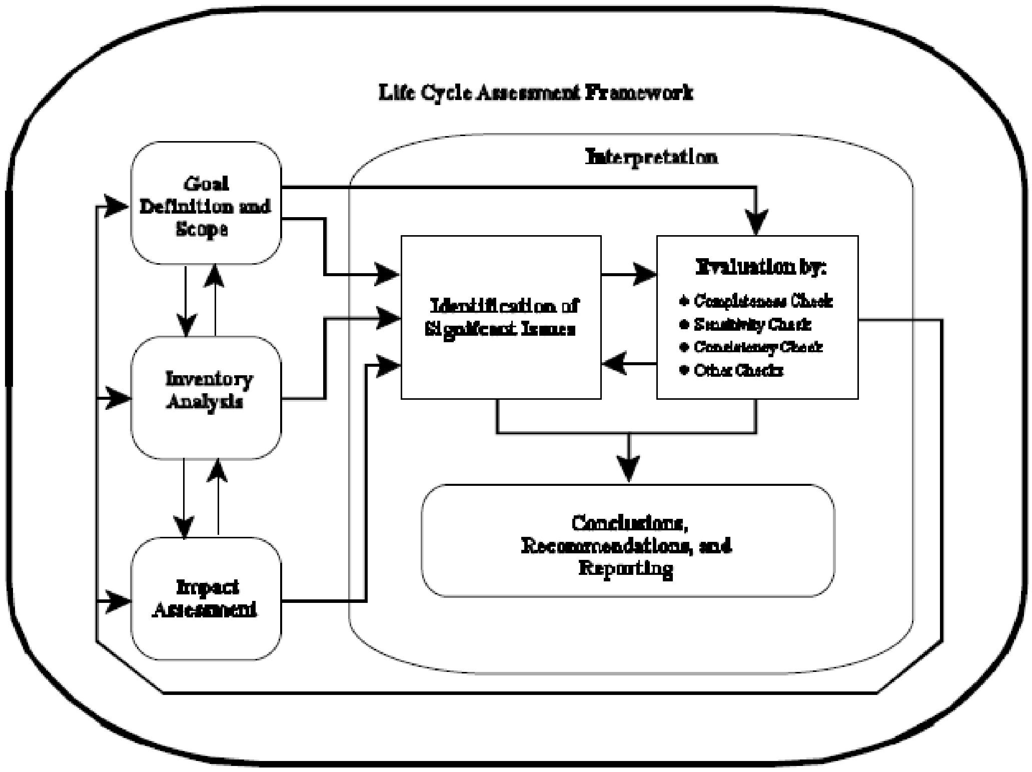


Figure 7-1 Relationship of Interpretation Steps with other Phases of LCA (Source: ISO, 1998b)

7.2.1 Identify Significant Issues

This is the first step of the LCI phase. The first three phase of the LCA process (Goal & Scope Definition, LCI and LCIA) were reviewed to identify "significant issues". "Significant issues" are data elements that contribute significantly to the outcome of the results of both LCI and LCIA for each product. The results must meet the goal and scope of the LCA study. Examples of "significant issues" include inventory parameters (raw material, chemical, energy, etc), the impact indicators used (waste, emissions, acidification, etc) and life cycle stages essentials (generation of energy, delivery, etc). Due to the complexities involved in an LCA study, the significant issues are identified mainly based on the impact assessment scores. Thus the process or products having the greatest effect on the impact assessment results are identified for further analysis.

The next recommended approaches are:

- Contribution Analysis – comparison between the magnitudes of environmental impacts associated with life cycle stages or groups of process to the total impacts associated with the product of study.

- Dominance Analysis – identification of significant contributions using statistical tools or other methods such as qualitative or quantitative ratings.

- Anomaly Assessment – abnormal or surprising trend of results based from past history are evaluated and compared from studies conducted on similar product.

It is common in a LCA study that some inventory items although are quantitatively insignificant, but contributed significantly towards the final results. These data should be as detailed as possible. However those uncertainties data of large inventory items but contributed minimally to the environmental impacts may be ignored.

7.2.2 Evaluate the Completeness, Sensitivity and Completeness of the Data

The second step of the LCI phase is the evaluation step to establish the correctness, validity and credibility of the results of the LCA. For this accomplishment, three tasks are required:

- Completeness check
- Consistency check
- Sensitivity check

The main reason for the *completeness check* is to ensure that all relevant information and data needed for interpretation are available and complete. This should be done with the aid of a checklist, indicating for each process/product of study that the results are complete meeting the stated goal and scope of the LCA. Alternatively, an independent LCA expert may examine issues such as methodological approached, software modeling used, assumptions made, process flows and other relevant issues.

The *consistency check* ensures that the assumptions, data and methods used throughout the LCA process are in tandem with the goal and scope of the study. Differences in issues such as data quality indicators, data sources, etc had to be taken into consideration to achieve a highly accurate result.

The purpose of the *sensitivity check* is to evaluate uncertainties and other expected deviations in identified "significant issues" so as to determine their sensitivity towards the final results of the LCA. They are performed by the following techniques for data quality analysis:

- Gravity analysis – identification of the data having the most contribution to the impact indicator results.

- Uncertainty analysis – LCA data variables are described to determine the significance of the impact indicator results.

- Sensitivity analysis – determines the effects of these variations on the impact indicator results of the study.

7.2.3 Conclusions and Recommendations

This is the final step of the interpretation stage. ISO 14043 defines this stage as, "to draw conclusions and make recommendations for the intended audience of the LCA study". The major results of the study should be discussed regarding its reliability and validity. Any errors, inconsistencies and incompleteness should be highlighted. At the end of this LCA study, conclusions and recommendations are to be made so as to increase the confidence of the audience on the results of the study.

7.3 Identification of Significant Issues of this LCA study

Two recommended steps, contribution analysis and anomaly analysis, as discussed in the previous section, were carried out to identify the significant issues for this LCA study. The significant issues were identified mainly based on the magnitude of the impact assessment results from the section 6.5.

7.3.1 Contribution Analysis

To understand the origin of the impact and its magnitude, a contribution analysis was carried out. The result is presented with the aid of a pie-chart of Figure 7.2, which complements the results from the previous chapter in section 6.5.

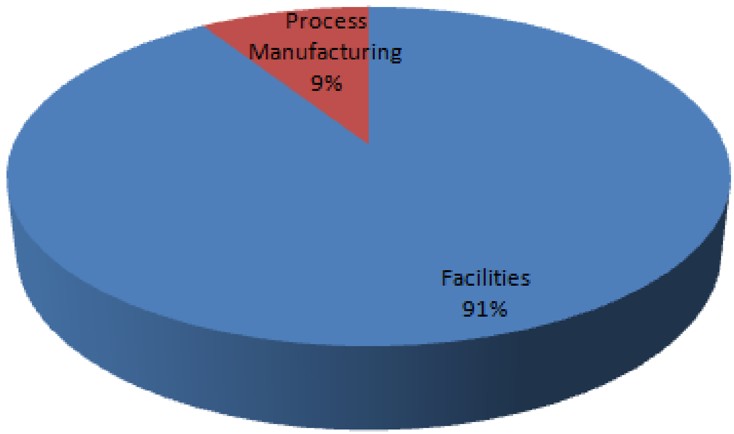


Figure 7-2 Pie chart of single score result for CMOS wafer

The figure 7.2 shows that 91% of the total impacts are related to facilities. The remainder, about 9% is related to thin film deposition which is part of wafer process manufacturing. This figure was from the network diagram of a single score results and the data obtained was manually keyed in to produce the excel spreadsheet.

Figure 6.23 from the last chapter is the process contribution analysis diagram of the inventory data. It can be seen that only a few items from the inventory list actually contribute significantly to the final environmental impact score. The results confirm that the highest contribution to total environmental score comes from energy consumption.

The next highest contributor is nitrogen. The remaining inventory items comprising mostly of water and specialized chemicals and gases contribute insignificantly and may be ignored for further evaluation.

7.3.2 Anomaly Assessment

The simplest way to conduct an anomaly analysis is to make comparison on results obtained on other LCA studies conducted on similar process or products. There are three such studies and notably, the LCA study titled, "Life Cycle Inventory of a CMOS Chip" was reviewed in chapter 2. These literatures are used for comparison.

The anomaly assessment was carried out to determine the accuracy and reliability of the life cycle inventory data collected. The Life Cycle Inventory of a CMOS Chip data was chosen for comparison because of its detailed approach in documenting its LCI data.

Table 7.1 shows the comparison of the undoped silica gate(USG) CVD process recipe for a 200mm wafer in thin film deposition and those provided by Boyd et al(2006) for a 300 mm CMOS chip.

Chemicals (gram/wafer)	LCI of CMOS chip	
	300mm	200mm
CH4	69.41	-
NF3	31.06	50
SiH4	0.95	0.756
O2	0.49	-
Ar	0.34	6.2143
Utility N2	196.9	-

Table 7-1 Comparison between process recipe for 300mm and 200mm CMOS chip

It should be noted that utility N2 is used in almost all semiconductor equipments. Nitrogen is used to purge equipments and its gas line to remove toxic vapors and gases. This is to maintain an inert and protective atmosphere on the gas line. The LCI data for utility N2 for the 200mm wafer was clustered under facilities inventory found in Table 5.6, hence not included on table 7.1.

As can be seen from table 7.1, the main components for this process; utility N2, NF3, SiH4 and Ar are basically similar. The high composition of Argon and the missing chemicals, CH4 and O2, were due to the process recipes from a different equipment vendor.

The next area for anomaly assessment focused the electricity usage for this process step. The total electricity consisted of the process and equipment facility inputs. Since it is not feasible to get the facility input specifically on this process, a hypothetical method was adopted.

To substantiate this and check the accuracy of data collected, a hypothetical energy consumption on facility input was calculated for this process. As seen from table 5.7, the total energy consumption for the facilities module was 42.6627 kWhr per wafer. Dividing this value by the number of modules in the process manufacturing and the number of main process steps give the facility input for this process step. The calculation for electrical energy facility input shown is below

$$\frac{42.6627}{6\times6} = 1.1851\ kWhr/wafers$$

The total energy for this process is made up of the process equipment input and the facility input. Since the facility input was calculated from the hypothetical method above, Table 7.2 was obtained.

<table>
<tr><th rowspan="2">LCI data of CMOS Chip</th><th colspan="3">CVD Electricity Usage (kWhr/wafer)</th></tr>
<tr><th>300 mm</th><th>USG</th><th>Chamber Clean</th></tr>
<tr><td>Process</td><td rowspan="2">5.83</td><td>1.7601</td><td>1.6226</td></tr>
<tr><td>Facility</td><td>1.1851</td><td>1.1851</td></tr>
<tr><td>Total</td><td>5.83</td><td colspan="2">5.7529</td></tr>
</table>

Table 7-2 Comparison between electrical energy for 300mm and 200mm CMOS chip

The third and fourth columns were added because for every USG deposition, it was followed by the chamber clean recipe. From the results calculated and shown in Table 7.2, it can be seen that the electrical energy consumption inventory data for a hypothetical 200mm wafer is very similar to calculations made by Boyd et al for a typical CMOS wafer.

7.4 Evaluation of Significant Issues of this LCA study

To better understand the impact on the final results caused by the significant items as identified in the previous section, they are further evaluated here. A completeness consistency check was carried out so as to ensure the data used throughout this LCA study was in accordance with the goal and scope.

7.4.1 Completeness Check

Although this LCA study was carried primarily for educational purpose, every effort was made to ensure the accuracy and reliability of the inventory data. The completeness check was performed with the assistance from facilities, equipment and process engineers plus technical experts. The process flow diagrams used for data inventory collection were inspected for any anomalies.

Process recipes and data consumption inventory checklists of Table 5.1 to 5.8 were thoroughly verified for any deficiencies and inaccuracy. Assumptions and estimations made to complete the inventory data were consulted and verified by the technical experts.

7.4.2 Sensitivity Check

A number of significant issues were identified from the contribution analysis and anomaly assessment done for this LCA. Of particular concern was the energy consumption from the life cycle inventory collection.

Uncertainty Analysis

This is the first step in conducting an uncertainty analysis check. The identified data were examined in detail for any possible irregularities or variance that could influence the results of the LCIA.

Since energy consumption is the highest contributor to the environmental impacts, its data was checked for accuracy. A sensitivity analysis on the electricity model was done to check for any influence on the overall LCIA results.

All other inventory items identified were analyzed and found that there are no irregularities found. This was due to their insignificant contribution to the environmental impacts.

Sensitivity Analysis

The sensitivity analysis seeks out to find any variation in the impact assessments results when different models were used. The methodology was to change the electricity models and analyze the single score environmental impacts contribution data for any changes.

In Singapore, it was assumed that electricity was entirely generated from oil. This was the electricity model used from the BUWAL250 library database. The same allocation was used to develop the electricity models from three different databases in SimaPro7. However due to the modeling restriction and limitation of being able to save the data only sixteen times, it is not possible to carry out this sensitivity analysis.

7.5 Conclusions and Recommendations of this LCA study

Results from the anomaly studies showed the similarity of the life cycle inventory data collected as from other LCAs done on the semiconductor industry. Unfortunately, the sensitivity analysis was not possible due to the limitations as mentioned on the previous sub-section.

Generally, it may be concluded that the interpretation stage has proved that the results obtained from other stages of the LCA are largely valid and in accordance with the goal and scope of this LCA study.

Chapter 8 Conclusions and Discussions

8.1 Introduction

This chapter basically summarized all the work that has been done for this research project. All major results are discussed for its reliability and validation. Major assumptions and limitations are presented. Conclusions and recommendations are made. Propose plans for future work are presented.

8.2 Major Accomplishment

The aim of my research project was to evaluate the severity of the environmental impact of a CMOS wafer through a Life Cycle Assessment. The results will be used to identify the potential avenues for any improvement.

The research begins with conducting a literature review from past and published literatures. From here, a better understanding of LCA origins, international standards, methodologies, techniques, limitations, benefits and uses were grasped. This was followed with understanding the whole process in the production phase of a CMOS wafer as outlined in Chapter 3. Chapter 4 defined the goal and scope, system boundaries were outlined and identification of the functional unit.

The next tasks involve data collections as part of the Life Cycle Inventory process and they are documented in Chapter 5. Much time and effort was spent filling up the checklist and discussing to process equipment engineers, respective management to obtain company database and to certain extent, semiconductor equipment engineer. Clusters were used for the ease of data collection. Simapro7 demo version was used to analyze the collected inventory data under Chapter 6. Finally the life cycle interpretation, highlighted on Chapter 7, was conducted to establish accuracy and reliability of the LCI and its result.

8.3 Major Outcomes

Major outcomes of this LCA study are summarized below:

- Almost three quarter of the impacts are linked to the facilities. The rest of the impacts are linked to the thin film process manufacturing.

- Majority of the environmental impacts from facilities are linked to the utilities and HVAC due to the high energy demand for supporting tools such as air-compressors, fresh air make up units, chillers, etc.

- For thin film process manufacturing, the major contribution comes from silane USG process.

- Environmental impacts associated with water and chemicals paled in comparison to the impacts caused by energy requirements.

- The total energy consumption for facilities modules was three times more than for thin film process manufacturing.

- The LCIA results in section 6.5 proved that the highest contributing factors to the environmental burdens associated with a CMOS wafer can be linked to the high energy consumption of semiconductor equipments and facilities supporting tools.

- The special chemicals used such as boron, phospane, silane, Teos contribute insignificantly to the environmental impacts as shown in figure 6.23.

- It was found by normalization chart that damage to resources (fossil fuels and minerals) is the worst affected damage category as seen in figure 6.4.

- As analyzed in section 6.5, ecosystem quality is the least affected damage category. This was due to the small contributions made by ecotoxicity, acidification/eutrophication and land use impact categories.

- Respiratory inorganics and climate change are the main contributors to human health damage category. The burning of fossil fuels for electricity generation was the major cause of respiratory inorganics.

- Only the highest impact category for each damage indicators were considered for further analysis. The rest were ignored due to their insignificant contribution.

8.4 Assumptions and Limitations

There are many limitations that surfaced during the work for this research project. The major limitation is the unavailability to get data inventories for the other process modules of the wafer fabrication plant. This was due to the reluctance from the respective modules management to release sensitive information. Even if this is possible, the amount of work required could not accommodate at such a short timeframe.

Another major limitation involved the usage of the demonstration version of Simapro7 software. Only sixteen saves are allowed. The computer was formatted numerous times to overcome this problem so that the modeling is as accurate as possible. Almost all of the inventory database used for modeling the CMOS wafer and impact assessment methods used for LCIA are based on an average European personnel. Exceptions to this are damages created by climate change, radiation, air emission of persistent carcinogenic substances, ozone layer depletion and damages to resources.

The SimaPro7 inventory databases did not contain many of the specialized chemicals and other raw materials that are commonly used in the semiconductor industry. There was lack of clarity on data associated with the production of special chemicals used extensively for wafer processing. Thus most of the special chemicals were substituted as either organic or inorganic compounds.

8.5 Plans for Future Work

The initial plan was to conduct the gate-to-gate life cycle assessment that includes all the modules involve in wafer processing. However due to time and resource constraint, only the thin film deposition of wafer processing was done. Hence, future plans are to conduct life cycle assessment that includes all the modules involve in process manufacturing namely; photolithography, photoresist, etch and strip, diffusion and CMP.

As mentioned, there are many limitations of using SimaPro7. Many of the inventory data were unavailable in the demonstration version of the SimaPro7 libraries. For those available, many of them were ambiguous. It is recommended to use the full licensed version of SimaPro7 as better quality and accurate data for impact assessment LCIA results would be obtained. However this is at the expense of higher cost. Also the geographical and temporal datasets of the data quality indicators (DQI) used were ignored for this LCA study because of limited resources. Future impact assessment carried out should address these differences.

Semiconductor industry used specialized ultra high purity chemicals for wafer processing. Many of the LCA databases do not specify the grade of chemicals used. This give less clarity of the chemical data used for impacts analysis. Generally there is a lack of publicly available data on manufacturing of these specialized chemicals. Future researches should also address this problem.

8.6 Recommendations

Electrical energy consumption to power up and maintain semiconductor equipments was found to be the major contributor as done in the sensitivity analysis in section 7.4. This research project had identified the importance of energy conservation to reduce damage to the environment. The company's management acknowledged this and has plans to minimize energy consumption by implementing measures like shutting down power on equipments that have low utilization rate. Equipment low utilization rate normally occurs at the end of the year due to manufacturing ramp down.

The next major contributor is nitrogen. Nitrogen is used in almost all process steps because of its property. It is an inert gas and does not react in the controlled environment and atmosphere. Reducing the amount of waste associated with nitrogen may reduce the environmental impacts. One way of achieving this would be to use it efficiently during manufacturing.

The recommendations are based on the results of this LCA study. The final decision and implementation plans will be at the sole discretion of the company.

8.7 Final Conclusions

This research project basically was able to achieve most of the objectives set. The environmental impact associated with a typical semiconductor product was established with a certain degree of confidence. The LCA study was conducted mostly in accordance with existing international standards. The literature review from past and published literatures ensures this.

The life cycle inventory data was collected as accurately as possible. Anomaly assessments conducted ensure the reliability and validity of the life cycle inventory data.

The research project was successful in accessing the environmental performance of CMOS wafer although only the thin film deposition was considered. This was through the analysis of the impact assessments done in chapter 6. This could be useful information for researchers who wish to do LCA studies on similar products.

The demonstration version of SimaPro7 again is a major drawback. The analysis was conducted using the most appropriate the option available. It is expected that with the major results obtained, the identification of the environmentally product/process is accurate and reliable. The life cycle interpretation stage proved this.

However, it should be reminded that this LCA study is done purely for educational purpose. LCA results presented in this dissertation are not solutions to environmental impacts associated with a CMOS wafer. They are to raise environmental awareness and merely a guide to improve the environmental performance. They should never be use as an aid for decision making since LCA is an evaluative tool that helps decision making but it does not replace it.

APPENDIX A – Project Specifications

A.1 Project Specification A

A.2 Project Specification B

University of Southern Queensland
Faculty of Engineering and Surveying

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

FOR: Abdul Hamid Ahmad
TOPIC: Life Cycle Assessment of Semiconductor Foundry
SUPERVISOR: David Parsons
SPONSORSHIP: Own

PROJECT AIM: The project seeks to evaluate the environmental impacts caused by semiconductor foundry using the life cycle assessment methodology.

PROGRAMME: **Issue A, 24 March 2007**

1. Do research on pass and present published literatures on LCA techniques to assess environmental impacts, origins of LCA, international developments & standards, LCA methodology, limitations, benefits and uses.

2. Investigate CMOS process manufacturing, equipment used and its commercial application. Research on past publish literatures done on similar LCA study.

3. Life Cycle Assessment; goal and scope definition.

4. Life Cycle Inventory; data collection on thin film deposition stage of the process manufacturing.

5. Life Cycle Impact Assessment; analyze inputs and outputs data for its impact on environment using Simapro.

6. Life Cycle Interpretation; check and quantify results. Make comparison to published results and evaluate own work including problems and limitations.

7. Make recommendations on materials used and processes involved and their environmental impact.

8. Write and submit a dissertation.

Agreed:_

Date: / / 2007 Date: / /2007

Co-examiner: ___________________

University of Southern Queensland
Faculty of Engineering and Surveying

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

FOR: Abdul Hamid Ahmad
TOPIC: Life Cycle Assessment of Semiconductor Foundry
SUPERVISOR: David Parsons
SPONSORSHIP: Own

PROJECT AIM: The project seeks to evaluate the environmental impacts caused by thin film module of a semiconductor foundry using the life cycle assessment methodology.

PROGRAMME: **Issue B, 9 August 2007**

1. Do research on pass and present published literatures on LCA techniques to assess environmental impacts, origins of LCA, international developments & standards, LCA methodology, limitations, benefits and uses.

2. Investigate CMOS process manufacturing, equipment used and its commercial application. Research on past publish literatures done on similar LCA study.

3. Life Cycle Assessment; goal and scope definition.

4. Life Cycle Inventory; data collection on thin film deposition stage of the process manufacturing.

5. Life Cycle Impact Assessment; analyze inputs and outputs data for its impact on environment using Simapro.

6. Life Cycle Interpretation; check and quantify results. Make comparison to published results and evaluate own work including problems and limitations.

7. Make recommendations on materials used and processes involved and their environmental impact.

8. Write and submit a dissertation.

Agreed:_

Date: / / 2007 Date: / /2007

Co-examiner: ___________________

APPENDIX B – Inventory Checklists

B.1 Checklist for Chemical and Gas Consumption

B.2 Checklist for Energy and Water Consumption

B.1 Checklist for Process Manufacturing

Process Equipment:

Process Name:

Tool Quantity:

Chemical & Gas Consumption

Process Step								Time
	(sccm)	(sccm)	(sccm)	(sccm)	(sccm)	(sccm)	(sccm)	(sec)
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								

B.2 Checklist for Process Manufacturing

Process Equipment:

Process Name:

Tool Quantity:

Energy & Water Consumption

Equipment Utilization				
	Week 1	Week 2	Week 3	Week 4
Manufacturing Time (%)				
Downtime (%)				

Equipment Electrical Energy Requirements		
Rated Voltage	Current at Active Load (A)	Current at Idle Load (A)

Water Consumption			
Consumption Mode Flow Rate	Process Cooling Water	Deionized Water	Rinse Water
Continous			
Discontinous			

APPENDIX C – Network Analysis

C1 Damage to Resources

C.2 Damage to Resources – Facilities.

C.3 Damage to Resources – Thin Film

C.4 Impact Category – Fossil Fuel Depletion

C.5 Fossil Fuel Depletion – Facilities

C.6 Fossil Fuel Depletion – Thin Film

C.7 Damage to Human Health

C.8 Damage to Human Health – Facilities

C.9 Damage to Human Health – Thin Film

C.10 Impact Category – Respiratory Inorganics

C.11 Respiratory Inorganics – Facilities

C.12 Respiratory Inorganics – Thin Film

C.13 Damage to Ecosystem Quality

C.14 Ecosystem Quality – Facilities

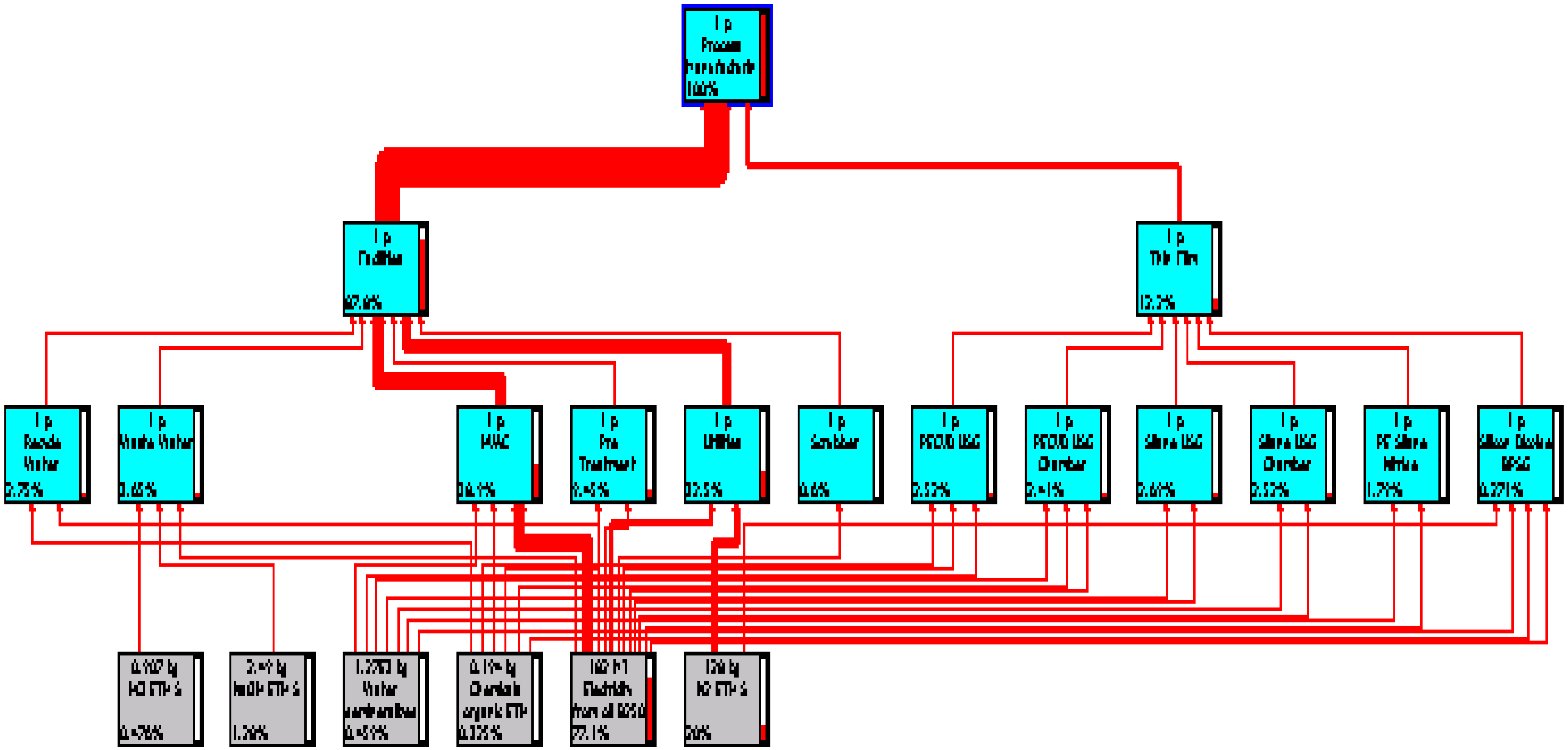
C.15 Ecosystem Quality – Thin Film

C.16 Impact Category – Ecotoxicity

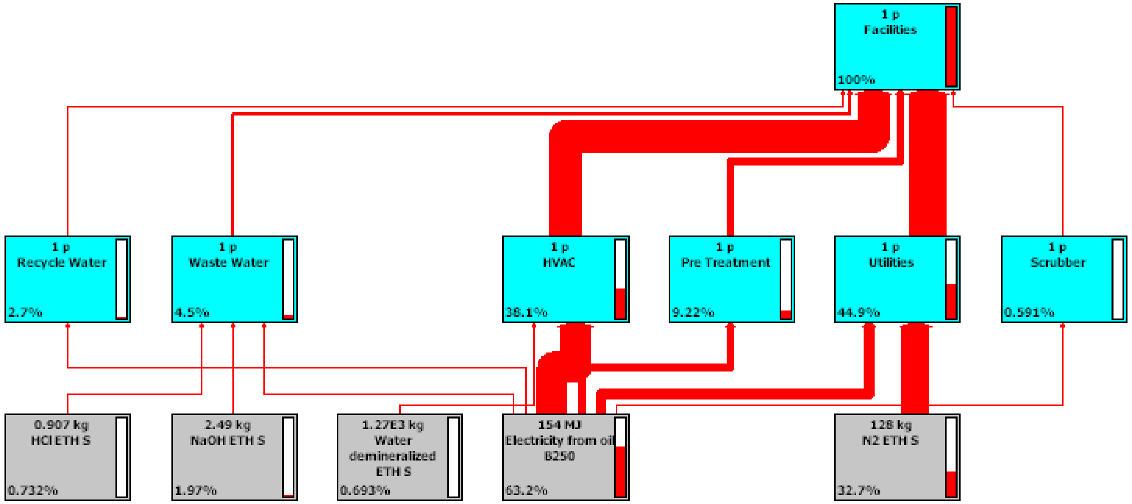
C.17 Ecotoxicity – Facilities

C.18 Ecotoxicity – Thin Film

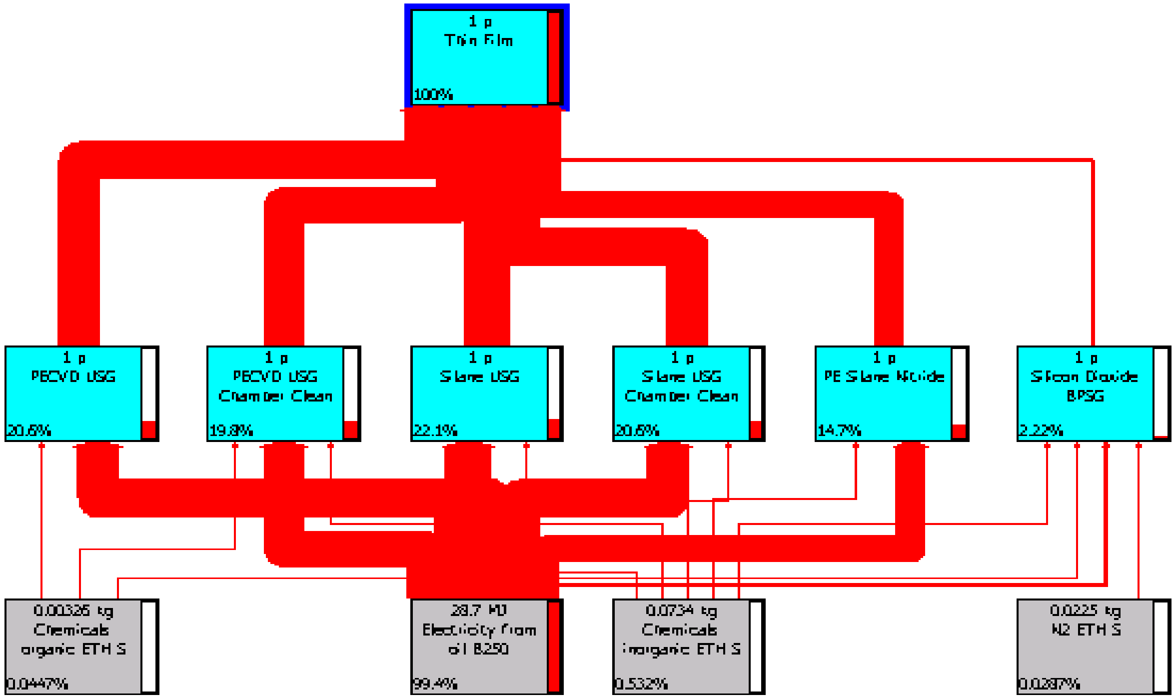
C.1 Damage to Resources



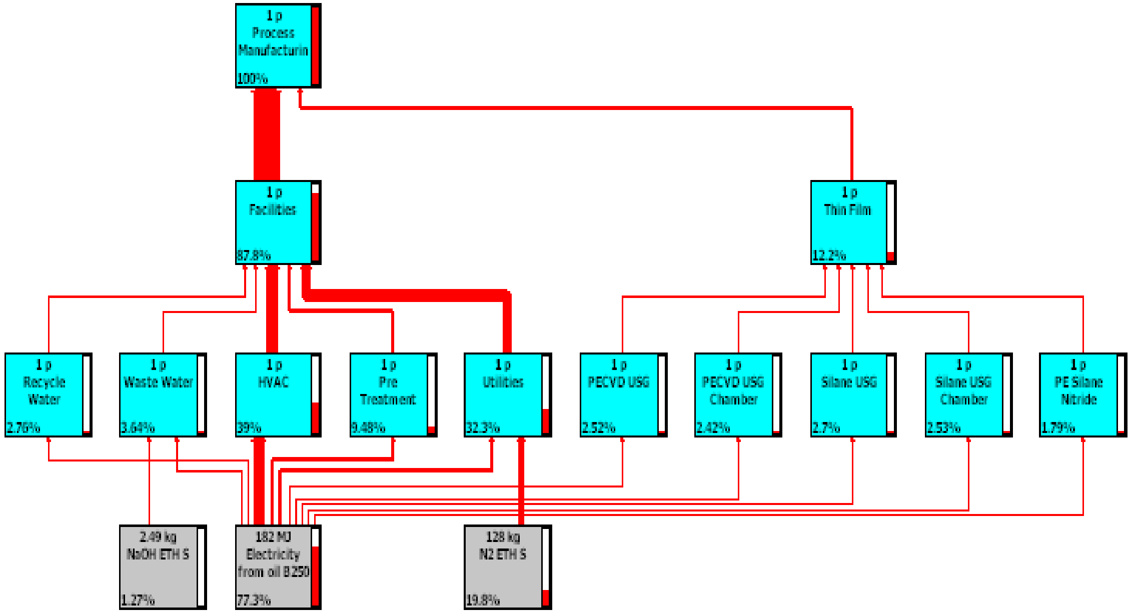
C.2 Damage to Resources – Facilities



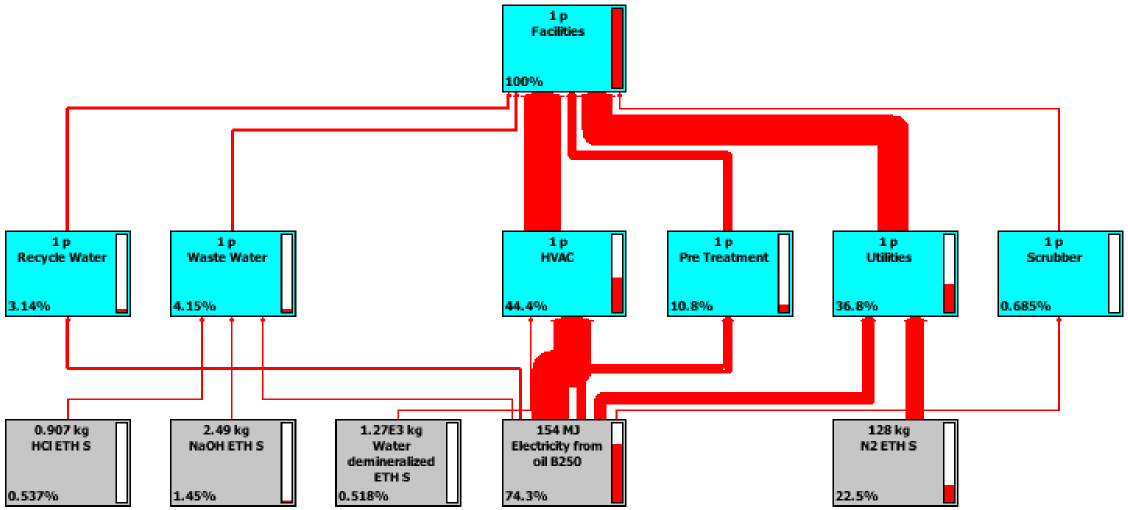
C.3 Damage to Resources – Thin Film



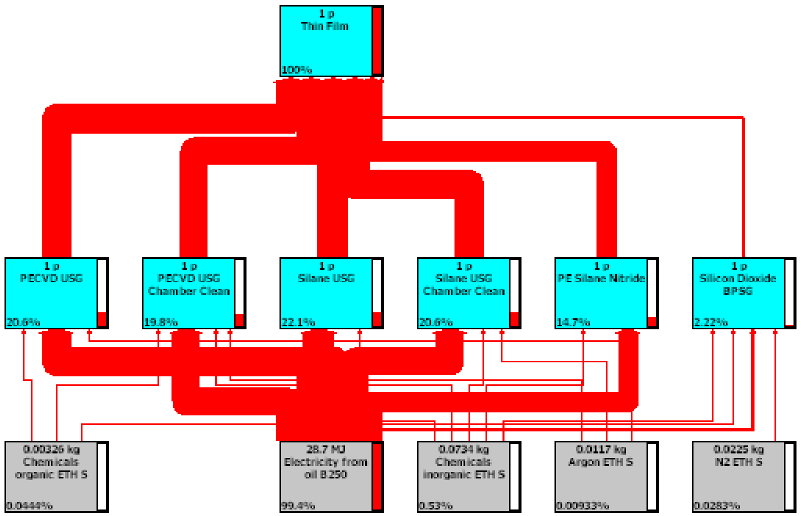
C.4 Impact Category – Fossil Fuel Depletion



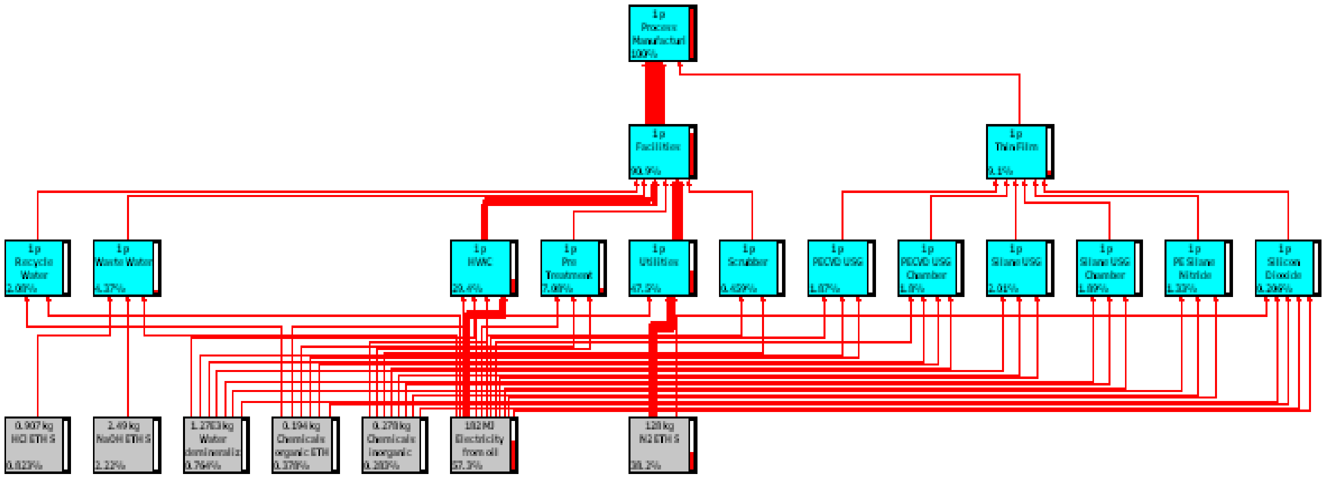
C.5 Fossil Fuel Depletion – Facilities



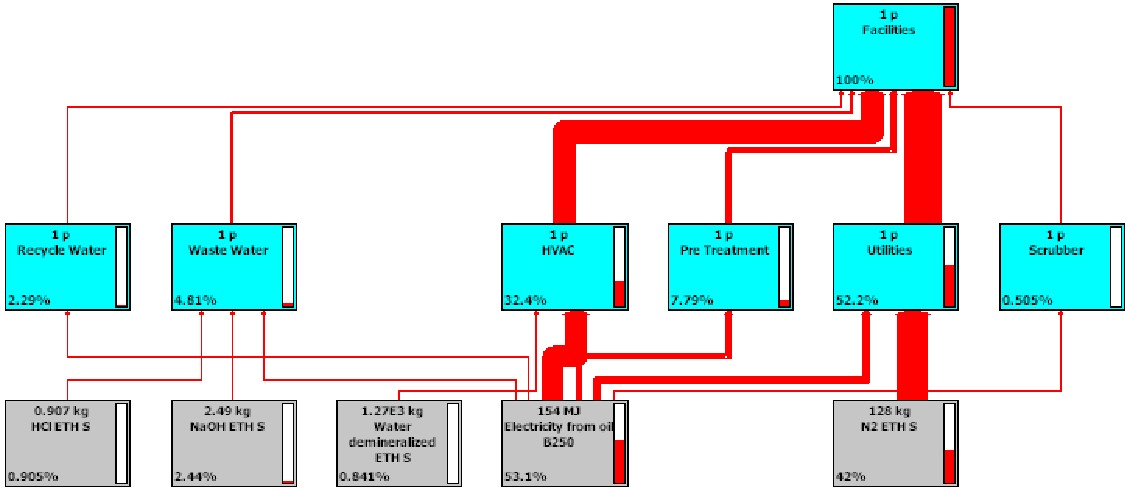
C.6 Fossil Fuel Depletion – Thin Film



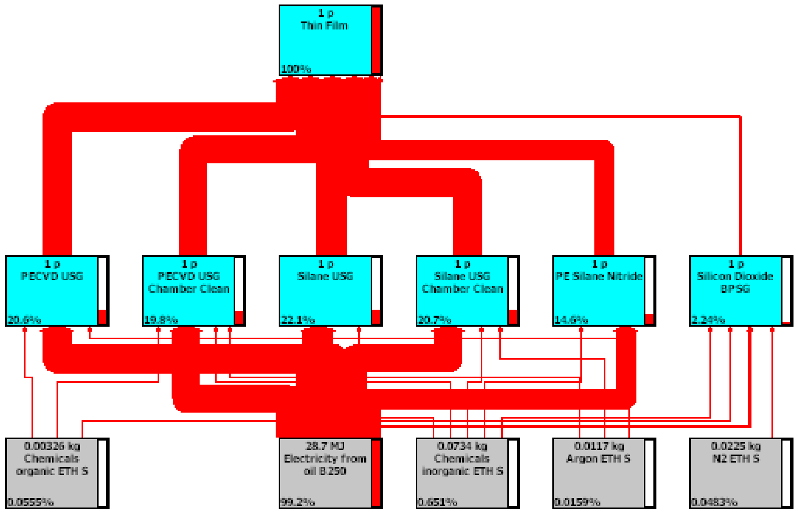
C.7 Damage to Human Health



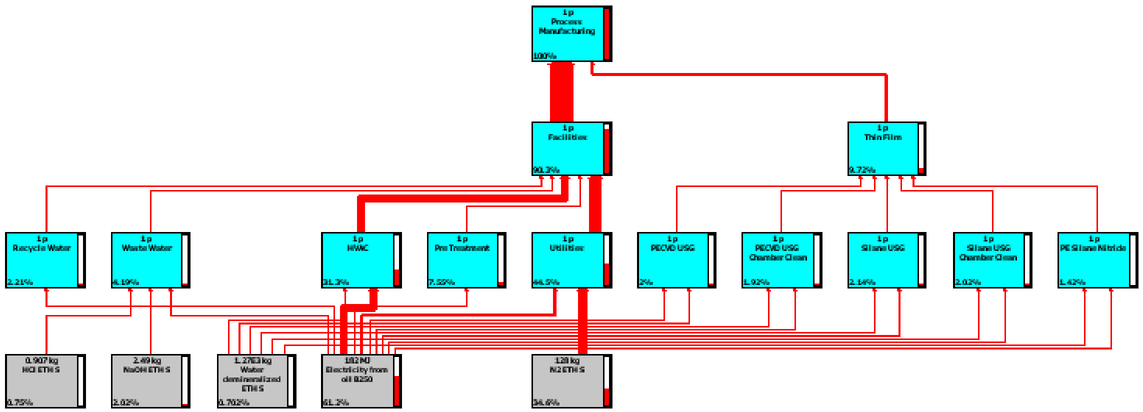
C.8 Damage to Human Health – Facilities



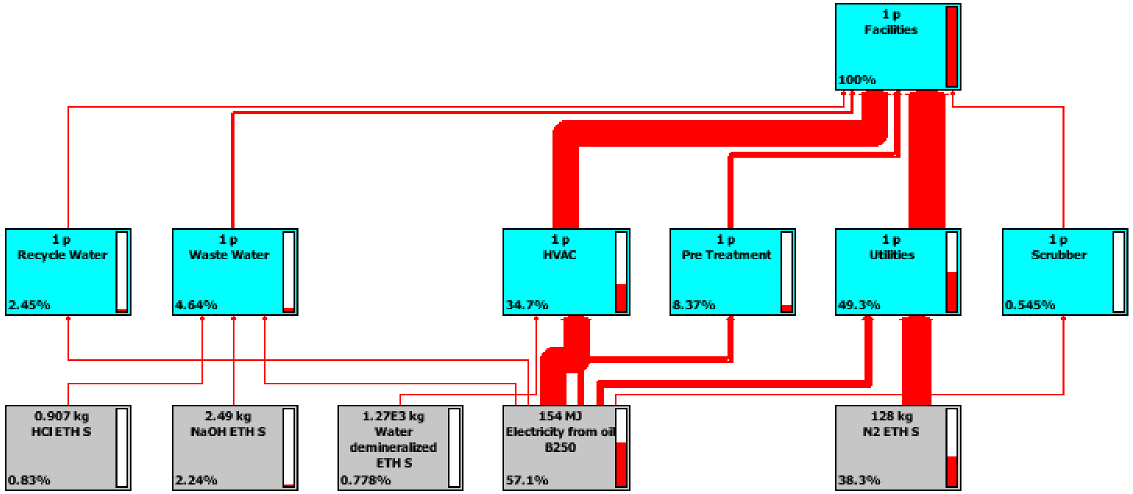
C.9 Damage to Human Health – Thin Film



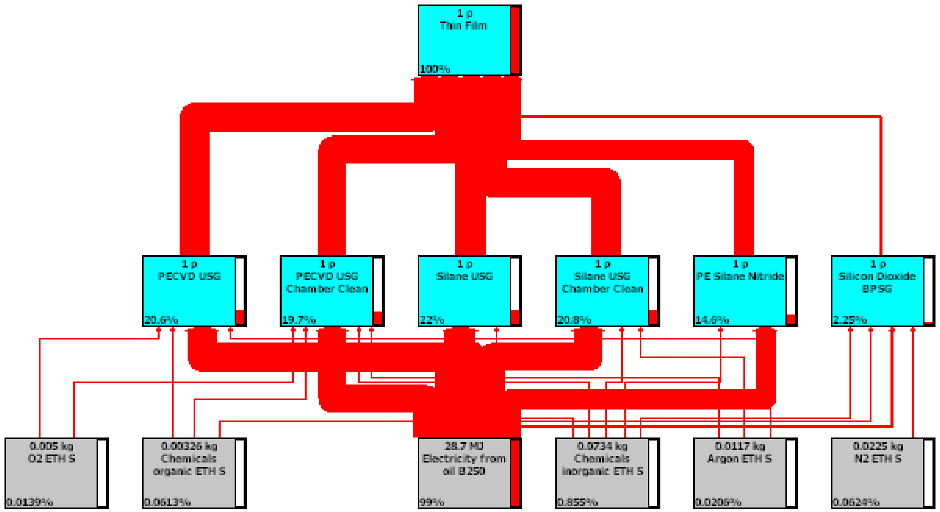
C.10 Impact Category – Respiratory Inorganics



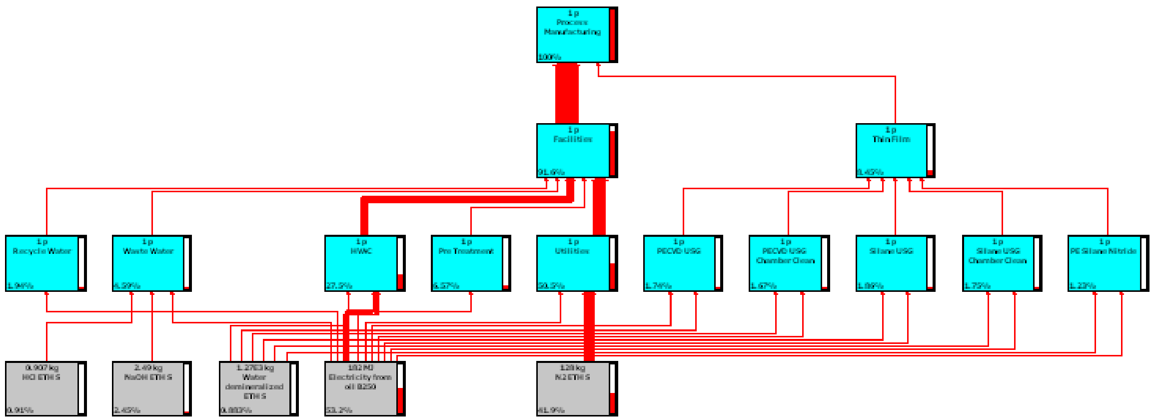
C.11 Respiratory Inorganics – Facilities



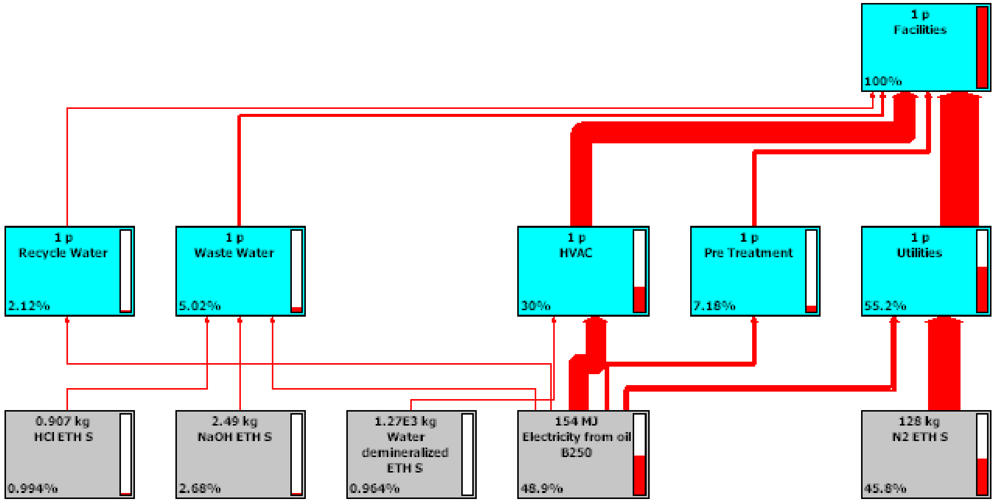
C.12 Respiratory Inorganics – Thin Film



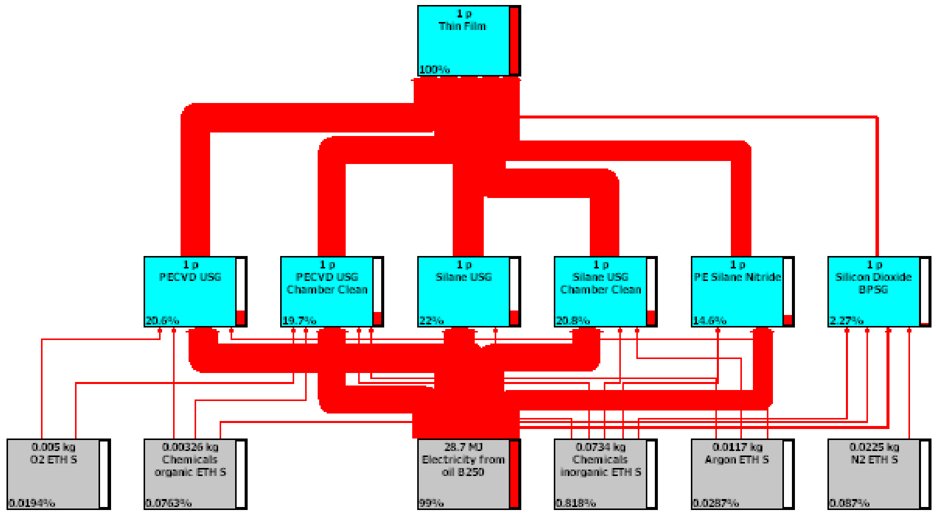
C.13 Damage to Ecosystem Quality



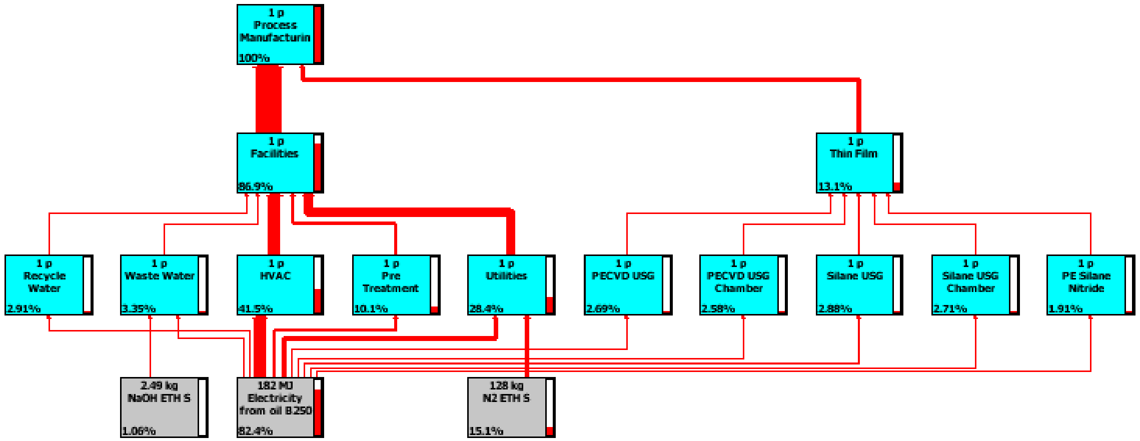
C.14 Ecosystem Quality – Facilities



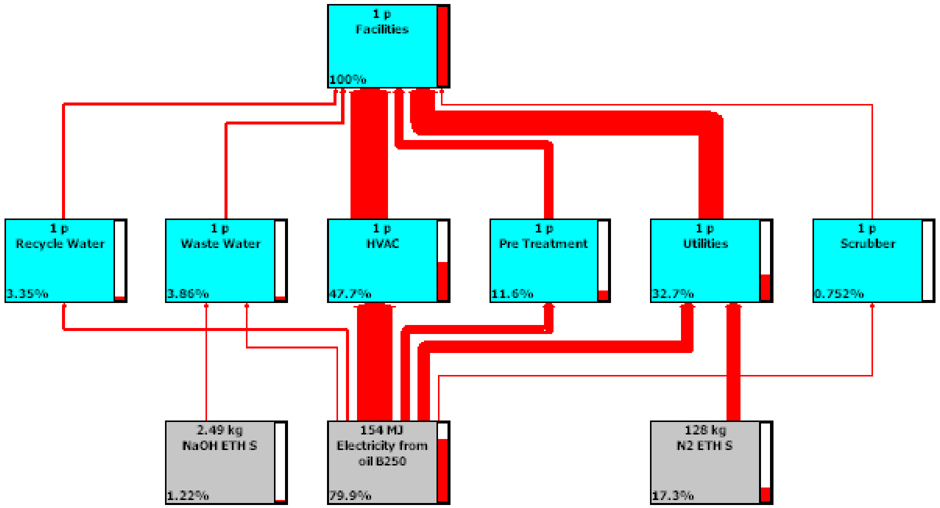
C.15 Ecosystem Quality – Thin Film



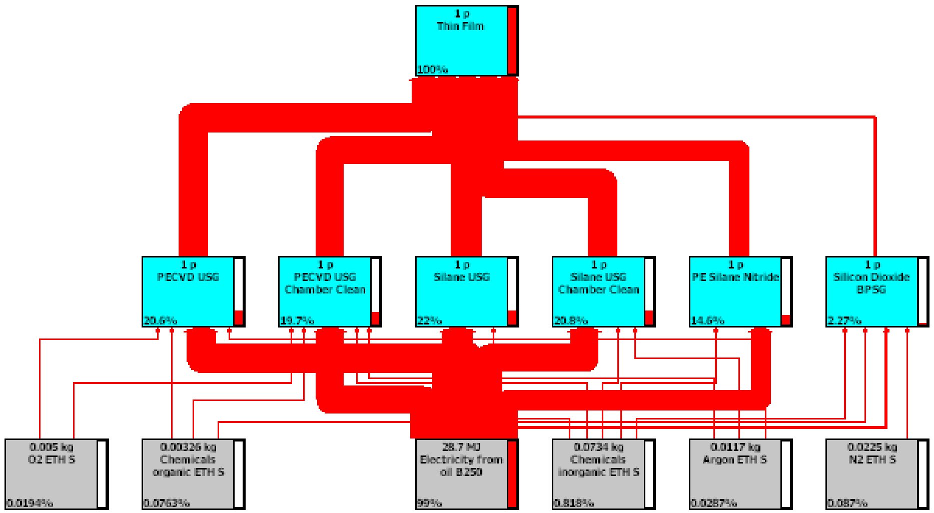
C.16 Impact Category – Ecotoxicity



C.17 Ecotoxicity – Facilities



C.18 Ecotoxicity – Thin Film



APPENDIX D – Chemical and Gas Density

Densities of Common Chemical and Gas	
Chemical/Gas	Density (sccm) grams per cubic centimeter
Oxygen	0.001429
Helium	0.0001786
Teos	0.936
NF3	0.003
Argon	0.001784
Silane	0.001342
N2O	0.0018
Boron	2.08
Phosphane	0.001379
Nitrogen	0.001251

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