Life-cycle Assessment of Semiconductors

by

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Abstract

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This thesis is the first complete and transparent study of the life-cycle environmental impacts of semiconductor chips using process-level data, as well as the first analysis of the changes in these impacts over time. LCA of complementary metal oxide semiconductor (CMOS) logic, flash memory and dynamic random access memory (DRAM) are presented. CMOS logic is the most common form of digital logic used today. This thesis provides a life cycle assessment for CMOS chips over 7 technology generations with the purpose of comparing impacts by life cycle stage, examining their trends over time and evaluating their sensitivity to data uncertainty and changes in production metrics such as yield. A hybrid life cycle assessment (LCA) model is used; Wafer production, electricity generation, water supply and certain materials are represented by process LCA data, while the remaining materials are described using economic input-output (EIO) LCA methods. It is determined that, in the case of CMOS logic, life-cycle impacts in all but one category are dominated by the use phase, and impacts are most sensitive to those variables which define use phase energy demand (chip power demand, usage patterns, power supply efficiency and chip lifetime). Using the same methodology, LCA of flash memory over 5 technology generations is presented. The most recent generation of flash memory is compared with magnetic storage, using a laptop hard-drive as a functional unit, and it is determined that in most impact categories, a flash-based drive will result in fewer impacts. Life-cycle impacts of DRAM, over 6 technology generations, are presented using as the functional unit, the memory requirements a popular operating system in each year of production. The influence of the choice of functional unit on results in semiconductor LCA is examined, and it is argued that functional unit is best defined as a computational power or memory capacity required for a given function, within a set time period. The LCA impact and inventory results for these three types of semiconductor products allow more accurate assessment of the environmental benefit or costs of information technology relative to traditional products and services.

Professor David A. Dornfeld
Dissertation Committee Chair

This work is dedicated to Jean G. Boyd.

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Chapter 1

Introduction

1.1 Objectives

The purpose of this thesis is to quantify the environmental impacts of semiconductor manufacturing with a life-cycle perspective. This will allow better management and understanding of these impacts by policy-makers and the public and by enabling more accurate life-cycle assessment (LCA) of electronic products and services. In order to effectively govern the production and use of electronics public policy must be informed by models which accurately reflect the total life-cycle environmental and human health impacts of semiconductor devices.

1.2 Overview

1.2.1 Semiconductor Life-cycle Environmental Impacts

Semiconductor production is highly resource intensive and generates a wide variety of emissions, some of which have global effects. The processes used to manufacture semiconductors emit several major classes of pollutants, including global warming gases (e.g. CF_4, NF_3, C_4F_8), ground level ozone-forming volatile organics (e.g. isopropyl alcohol, formaldehyde), hazardous pollutants (e.g. arsenic, fluorine) and flammable materials (e.g. silane, phosphine). Semiconductor fabrication facilities also consume large volumes of water and energy, and the high purity chemicals used in production are highly refined and thus have high "embodied energy". The upstream environmental effects due to chemicals manufacturing, as well as fabrication facility (fab) infrastructure and equipment, represent significant components of the environmental impact profile of semiconductor manufacturing. The use phase of semiconductor devices results in indirect environmental and human health impacts resulting from energy-related emissions which, in the case of logic devices, has been shown to dominate impacts over the product life-cycle. The end of life of a semiconductor chip results in lead emissions if there is lead present in the chip's leadframe solder. After 2006, the EU's Restriction on Hazardous Substances, commonly known as RoHS, banned the use of lead in electronics and most manufacturers switched to lead-free solders worldwide to comply with this regulation. While other effects from end-of-life disposal of semiconductor devices may exist, they are not included in this analysis because they have never been specifically measured.

1.2.2 LCA of Electronics and Information Technology

The use of electronics as a replacement for traditional media is a promising strategy for environmental impact reduction of various products, services and human activities. Consumer electronics can convey reading materials without printed media, improved telecommunication may be used to reduce individual travel and electronic controls can enhance the efficiency of existing technologies in a variety of applications. Current, detailed and technically specific models of the impacts of semiconductor products are a requirement for an accurate comparison between the life-cycle impacts of existing practices or technologies and their electronic replacements or enhancements. In nearly every study on the environmental benefit or damage of IT, there is an express or implied need for more detailed LCA data for semiconductor devices.

The products of this thesis, complete and transparent life-cycle assessments for commonly used logic and memory components, will enable more effective environmental management related to electronic products or the use of information technology (IT) to replace traditional services.

1.3 Literature Review

The earliest publicly available, published work relating to life-cycle assessment of semiconductors can be found in a 1997 conference paper from NEC Corporation on comparative LCA of two personal computers (PCs): a laptop and a desktop [100]. The paper provides significant detail into the quantities and types of environmental impacts from the PC life-cycle but limited insight into the methodology behind the analysis. Although the authors of the paper were within a semiconductor manufacturing company, they seem to have taken a crude approach to compiling the inventory: they break apart each computer and weigh the pieces. The life-cycle inventory (LCI) data for the electronic components, including the semiconductor chip, liquid crystal display and cables, were apparently based on economic input-output data for Japan, which implies that direct emissions from semiconductor fabrication are not included in the model. This is surprising given that NEC produced semiconductors and should have access to more accurate data. The paper reports quantitative life-cycle impacts for global warming potential, acidification, eutrophication and resource consumption, as well as the proportional impact of each component in the production stage. While the results are enticingly detailed, there are many important parts of the inventory that are left out, notably resource consumption and emissions from semiconductor fabrication.

The following year, researchers involved in the development of the Ganzheitliche Bilanzierung (GaBi) LCA software at University of Stuttgart presented a methodology paper on green design for electronics making the case for LCA as the best tool for the job [10]. The paper described some important aspects of semiconductor and electronics LCA, stating that feedback concerning the environmental consequences of production and use were necessary in the research and development stages in order to influence design, rather than after production ramp-up. Also, the paper pointed out that because of the complexity of electronic products, their dense supply chains and the distributed decision-making process behind their production, the development of an electronics LCA database would require intra-industry collaboration and information sharing and that the task was onerous, involving an ”immense demand of information.” The paper also pointed to the fact that the environmental impacts of production were not evident in the products themselves, as the toxic chemicals used in manufacturing do not end up in the final product. In the concluding statements, the author prioritizes future work, asserting that database development for generic chip production was the highest priority. However, eleven years later, GaBi does not offer LCA data for generic semiconductor chips in their electronics LCA data package.

A researcher in Japan used economic input-output techniques to estimate LCI data for several electronics components (including semiconductors, passive componentsand liquid crystal displays) [104] and came to some interesting conclusions. Industry-wide emissions data were taken from government sources in Japanese, and thus the accuracy and representativeness of the data are difficult to determine. The author notes that the data sets are missing some component materials and emissions data, and that direct greenhouse emissions from manufacturing sites are not included in the inventory. Ueno finds that impacts associated with chemical usage are large but difficult to estimate and concludes that LCI data is similar among all electronic components industries, which is a surprising assertation. The study was, in the words of the author ”insufficient but still useful.”

In 2001, a conference paper describing a life-cycle inventory (LCI) model for a semiconductor wafer was written by an academic with support of industry members at Motorola [83]. The purpose of the study was to investigate the most important environmental impacts of a fab, rather than to perform a life-cycle analysis of a product or process. Schischke describes an equipment-centric inventory method whereby mass and energy flows are accounted for in modules specific to process types and facility infrastructure. However, the inventory inputs are collected by questionnaire from unidentified industry members and outputs are estimated as fractions of the input flows. Concerning data quality, Schischke writes:

"For production and infrastructure processes, few data are known exactly, but estimations of experts concerning a suitable allocation of mass flows leads to sensible and high quality results."

At the time, these expert opinions and input-output estimations were the best semiconductor LCI data that had been compiled and reported publicly. Unfortunately, only a limited summary of inventory and impact results were given. No absolute impact results were shown by process, rather only the proportional contribution of each process module to each impact type.

At the same 2001 conference, another paper from ST Microelectronics reports a "gate-to-gate" life-cycle inventory (LCI) analysis for an 8Mbit EPROM chip [99]. The methodology is explained in greater detail than the previous NEC study: data for the chemicals, facilities resources (e.g., ultra-pure water) and electricity demands for each process step were collected, and summed to represent the entire process flow for the EPROM device. The inventory of the masses of materials is reported, making the study more transparent than the Motorola study, and transportation from the front-end to the back-end facility was included, making the analysis more inclusive than the previous papers. Process and facility emissions, were not included in the LCI, however.

At UC Berkeley, research has been done for a number of years on integrating human health and environmental concerns with economic cost in decision-support systems for the semiconductor equipment supplier Applied Materials. This work was a form of enhanced life-cycle inventory modeling specifically designed to inform semiconductor manufacturing equipment producers of human health and environmental risks, and was not directed towards the life-cycle of a semiconductor product. In 2000, Sara Thurwachter developed an environmental cost of ownership model dubbed EnV (environmental value), which assessed operating costs and emissions and included a novel multi-criteria health hazard scoring system [102, 101]. Nikhil Krishnan, in 2003, extended this model by accounting for the uncertainty in model parameters and running Monte Carlo simulations to estimate cost and impact values and used the updated model, named EnV-S (environmental value systems), to determine environmental cost of CMP process tools, as well as fluorine and per-fluoro-compound abatement systems [56, 54].

Descriptions of internal green design efforts by semiconductor industry members arose in trade magazines and conference proceedings [35, 96, 56] but there had been no significant peer-reviewed journal articles concerning LCA of semiconductor devices until 2002 when Eric Williams published an estimate of the energy and materials demands for a 32 MB DRAM chip in a paper entitled "the 1.7 Kilogram Microchip" [109]. The paper provided an abbreviated list of material inputs to semiconductor fabrication from an anonymous industry source, compared this with previous estimates and called for more accurate process-level LCI data for semiconductor chips. One of his main contentions was that the "upstream" energy used to make process chemicals would be very large due to the extremely high purity of semiconductor process chemicals and because the use of byproduct or "secondary" materials is much higher for semiconductors than for traditional products.

In 2003, Cynthia Murphy at the University of Texas at Austin described a plan to create parametric process models for semiconductor LCI [62]. Murphy measured power consumption and gas flows for several types of furnace-based thermal processes and provided an equation to estimate power and gas consumption based on oxide film thickness. The paper also provided power consumption data for photolithography. These LCI process data and the concept of parametric LCI models were useful and innovative, but there was no further work by Murphy on semiconductor LCI and without LCI models for all of the semiconductors processes (i.e., ion implant, chemical vapor deposition, etc.) it would not be possible to model a complete device. Although the idea of parametric LCI modeling is attractive, in practice these models cannot predict resource consumption outside of the range of measured data. For example, the equation presented by Murphy in the paper for thermal processes does not give a good prediction of process gas and power consumption for oxide films thinner than the thinnest film in her model.

Other researchers besides Murphy have studied the environmental effects of specific semiconductor manufacturing processes. For example, Paul Blowers measured LCI data for supercritical CO_2 as a replacement for ultra-pure water [12]. There has been a particular focus on solder and packaging technologies, due to the exceptional hazard of lead, a potent neurotoxin, in solder [63, 5, 25, 36].

In 2004, a life-cycle inventory for two generations of processor chips developed at Intel was presented in a conference paper [111]. In this study, the emissions and energy associated with each chip were based on facility-level data, i.e., the power, water, emissions and materials consumption for an entire fab were divided by production output to determine the impacts of a single device. The comparison of a 60 nm Pentium Pro processor with a 130 nm Pentium 4 revealed that the switch from 200 to 300 mm wafers resulted in significant reductions in emissions per chip. Comparison of life-cycle stages also showed that use phase dominates life-cycle energy use. While these results were useful, the study was not transparent or reproducible, the methodology was opaque and there were several other weaknesses. The life-cycle analysis apparently included only wafer production and chip use, and not back end operations, transportation, end of life or any upstream impacts. It is not clear how emissions were measured or estimated and emissions were presented by category rather than by chemical, which suggests that they are estimated from permits rather than measurements. The study reported ultra-pure water rather than actual water consumption, which is not a useful proxy for actual water use and may be misleading to some audiences.

Xiaoying Zhou , in 2007, completed a thesis at UC Davis entitled "Life-cycle thinking and assessment tools on environmentally benign electronics." The work includes the development of an integrated impact assessment and weighting methodology and two case studies of green electronics: the introduction of lead-free solder and remanufacturing of a cellular phone [114].

There are many challenges in application of LCA to integrated circuits. The relatively short development cycle and rapid technology change in design and manufacturing make assessment of existing chips obsolete in just a few years. (The Intel development timeline is illustrated in Figure 1.1 [38].) IC manufacturing is also highly complex, involving hundreds of chemicals and dozens of different process steps, combined in a process flow which includes hundreds of steps. Intellectual property issues also plague data collection, as semiconductor manufacturers consider process recipes to be their most valuable intellectual assets, and chemical suppliers often keep the formulations of process chemicals trade secrets.

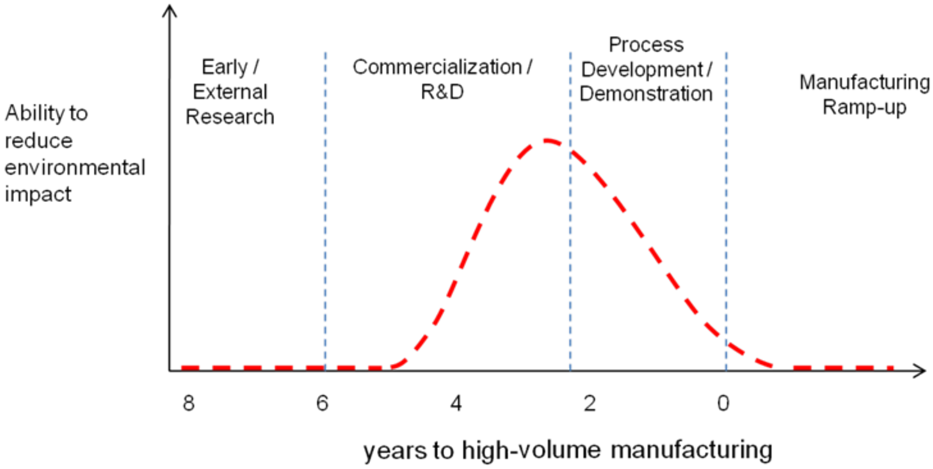


Figure 1.1. Development timeline [38]

1.4 Original Contributions

This thesis is the first complete and transparent study of the life-cycle environmental impacts of a semiconductor logic chip using process-level data, as well as the first analysis of the changes in these impacts over time.

The fact that the LCA performed within this thesis are based on equipment or process-level, rather than facility-level, data has allowed me to address the problem of LCA obsolescence. Process-level LCA of semiconductor manufacturing allows anticipative models of manufacturing production because if the process flow is known, a new device can be modeled pre-production using previously measured process data. Process-specific analysis also allows better accounting of the considerable upstream impacts associated with high-purity materials. While facility models can use data on chemical purchases, a process-based model can determine the volume of chemicals used per finished wafer with greater precision and certainty.

The transparency and completeness of the LCA methodology of this thesis are also a major contribution. Although some industry members have published conference papers which present LCA results for their products, the analysis is often not well described and the validity of the results are difficult to confirm. By presenting the sources and uncertainty of data transparently, this analysis is reproducible and adaptable, and thus more useful to other LCA practitioners. In all precious studies, significant portions of the analysis, such as the upstream impacts related to chemicals, have been neglected. By developing a more complete LCA, many of the lingering questions concerning the possible contribution of omitted aspects of the life-cycle (e.g., transportation and the upstream life-cycle impacts of chemicals and water) have been resolved.

1.5 Thesis Framework

The second chapter of this thesis will provide an overview of the semiconductor industry with the purpose of identifying environmentally-relevant trends in product types, semiconductor technology and geographic concentration of manufacturing. The third chapter is a life-cycle analysis of CMOS over several technology generations, with a focus on energy consumption and sensitivity of impacts to production metrics and product performance. The fourth chapter will provide a life-cycle analysis for CMOS, including all environmental emissions. LCA of flash memory is presented in Chapter 5. The topic of functional unit choice in semiconductor LCA and its impact on LCA results is explored in Chapter 6, in which LCA of DRAM is presented. The final chapter provides a summary of the research comprising this thesis and its main conclusions.

Chapter 2

Semiconductor Manufacturing Trends in Product Type and Geography

2.1 Introduction

This chapter provides an overview of the semiconductor industry, in order to establish the dominant device types, and to identify environmentally relevant trends in semiconductor product types and geographic concentration of manufacturing capacity.

The complementary metal oxide semiconductor (CMOS) configuration is the prevailing transistor structure in production today. CMOS is the standard structure for digital logic and CMOS transistors, integrated in various forms with capacitors, form DRAM and Flash memory. Although an exact accounting of the share of worldwide semiconductor capacity dedicated to CMOS logic, in particular, is difficult to ascertain, by extrapolating from market data concerning product types, it seems that more than half of the semiconductor market is CMOS logic. CMOS logic is therefore the primary subject of analysis in this thesis.

There is a significant expansion in semiconductor capacity in Singapore, Taiwan, Malaysia and China, which can be expected to result in an increased carbon intensity of ICs. Neither Singapore, Malaysia nor China are signatories to the Kyoto Protocol and while industry consortia in Japan, Europe and the US have announced GHG emissions reduction goals, industry in China, Taiwan, Singapore and Malaysia have been silent on the issue. Based on anecdotal evidence, the abatement of per-fluoro-compounds (PFCs, potent global warming gases used in production) is not common in Singapore or China. As production capacity shifts from Europe and the US to non-Kyoto-bound East Asian countries, more and more production could be conducted without controls on PFC emissions. Relocation of wafer fabrication capacity to China in particular has the potential to drastically increase the environmental impact profile of production as a result of the high global warming intensity of electricity in China. Finally, while often overlooked in LCA, transportation plays an important role in life-cycle impacts for semiconductors, as will be illustrated in Chapter 3. The lengthy transportation necessary to take products from the fabrication site to the US and Europe (the largest end markets) also worsens the profile of ICs produced in East Asia.

The growing popularity of Flash memory is significant from an environmental perspective due to the unique materials used in its production and their consequential emissions. The use of Flash in mp3 players, memory sticks and other portable storage has expanded the Flash market dramatically over the last several years. As the storage density of Flash memory increases and its cost falls, Flash has become competitive with hard disk storage. In the coming years, as solid-state storage replaces hard disks in portable computers, the Flash market can be expected to grow further. For this reason, the environmental analysis of Flash memory is also chosen as a topic for this thesis.

2.2 The Semiconductor Industry: Size, Growth and Trends

In 2008, worldwide semiconductor industry revenue amounted to $260 billion, with production averaging 1.9 million wafer starts per week in terms of 8 inch wafer equivalents [92, 95]. This amounts to over 5 billion square inches, or 800 acres, of silicon area produced in that year.

Growth in the global semiconductor market has occurred with vitality and volatility throughout the history of the industry, with year-over-year revenue growth ranging between -32 and 42% since 1993 [93]. The industry has generally sustained a high rate of growth overall, with a compound annual growth rate (CAGR) of 8% over the 1998-2007 period (in then-current US dollars). This represents a slowing from 12% for 1998-2004, and 17.5% for 1962-1995. The variable but strong expansion of the industry is illustrated by global annual revenues from 1952 to 2007 in Figure 2.1 [93].

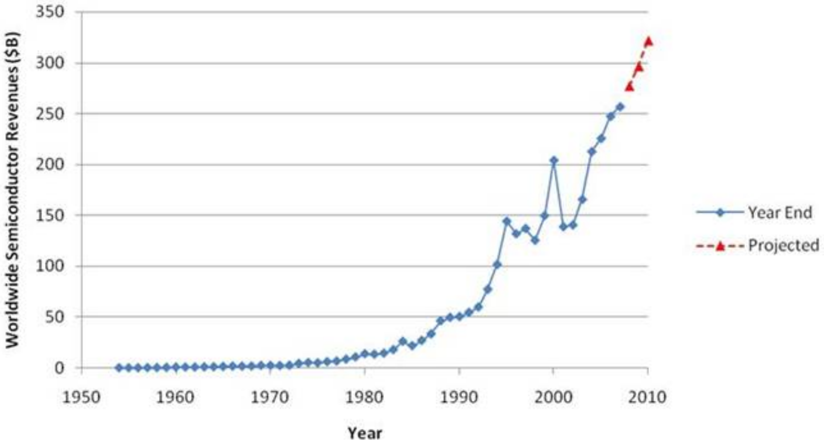


Figure 2.1. Global annual revenues from 1952 to 2007

2.2.1 Technology Scaling

Throughout the history of the industry, the processes used to fabricate semiconductor circuits have continuously changed to meet scaling and performance goals. The common metric used to describe the scale of a given circuit generation, the "technology node," is equivalent to the DRAM half-pitch, which is based on the average line width and space between lines connecting DRAM cells. This metric is based on the lithographic process because, historically, the advance from one technology node to the next was determined by lithographic technology. For example, the introduction of deep-UV in the late 1980's enabled the development of 0.5 micron node DRAM [7]. More recently scaling has been constrained by the ramifications of reduced feature size on the performance of the transistor, and the ability of process engineers to overcome these effects. An early example of scaling-related performance limitation is the parasitic capacitance and cross-talk in metal lines which occurred due to the insufficient insulation between neighboring metal lines. This issue was overcome with the use of advanced low-permittivity (low-κ) dielectrics in the lower, denser interconnect lines. More recently, sub-threshold leakage current, increased junction leakage, gate tunneling and other deleterious effects have necessitated further material and process innovations, such as substrate biasing, source drain extensions, raised source/drain geometries, high-κ gate dielectrics and many other process innovations. These ongoing design and process improvements have roughly doubled the transistor density of low-cost circuits every 24 months, allowing Moore's Law to hold, for over 35 years.

As each new technology generation is released, additional production capacity is either built or converted from older manufacturing facilities. This ongoing conversion of manufacturing capacity is illustrated by the volumes of capacity per each technology node, for the years 2005-2007, shown in Figure 2.2.

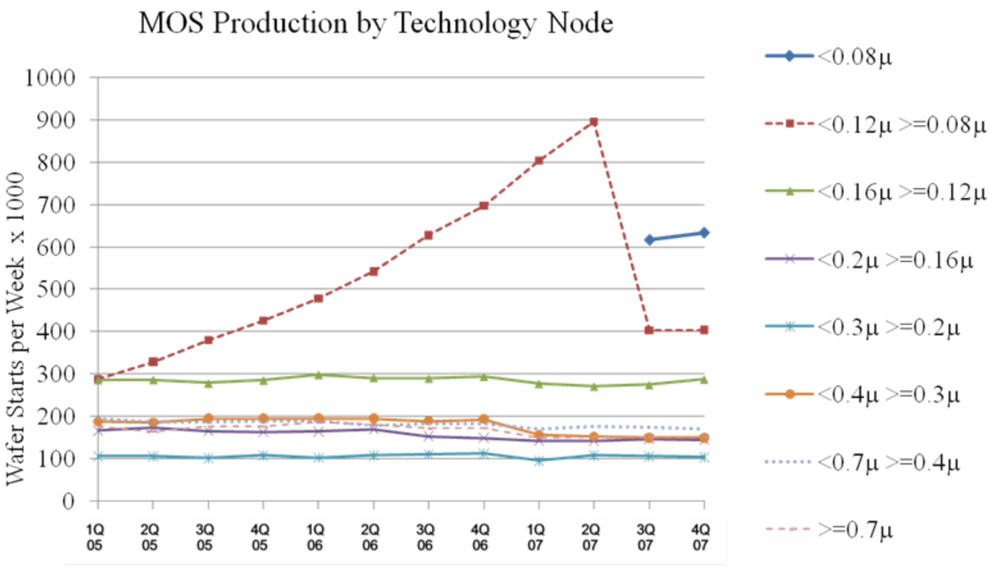


Figure 2.2. Worldwide MOS Production Capacity by technology node

2.2.2 Dominant Circuit Elements: the Transition from Bipolar to CMOS Transistors

The first transistor, designed at Bell Labs in 1947, was a bipolar junction transistor (BJT). Bipolar phased out of digital logic in the late 1970s, replaced by faster n-type metal oxide semiconductor field effect transistors (n-type MOSFET or NMOS). In the mid-1980s, the complementary MOS (CMOS) structure became the dominant element of digital logic due to the advantageous features of lower static power consumption and higher allowable circuit density inherent in the CMOS structure.

Bipolar comprised only about 7% of semiconductor device production capacity in 2007 [94], with the remainder dedicated to MOS-based circuits. The small fraction of fabrication capacity is a reflection of the dominance of MOS in digital applications as well as the replacement of bipolar transistors in some traditionally bipolar applications. Bipolar elements have a high output resistance and are thus particularly useful for amplification and switching, making them the typical the building block of analog IC and power components. More recently some traditionally bipolar-based analog applications such as radio frequency (RF) communication have been implemented completely in CMOS, however. For example, double-diffused MOS (DMOS), a power transistor design based on the CMOS structure, are used in power supplies and low-voltage motors. In mixed-signal devices (e.g., cell phone chips), bipolar transistors are now frequently used in conjunction with CMOS transistors using a combined process flow known as bi-CMOS. Though their higher allowable voltage make bipolar transistors critical for certain power and signal applications, bipolar production of has been declining consistently for several years, as shown in Figure 2.2.

CMOS transistors are the most common form of MOS and the dominant basic circuit element in random access memory (RAM), microprocessor units (MPU) and other digital logic chips. Nearly all digital logic and most current dynamic random access memory (DRAM) and electrically-erasable read-only memory (EEPROM, a.k.a. Flash) technologies are also based on CMOS transistors.

2.2.3 Products

The semiconductor market is split among several major product types, with the largest fractions being MOS logic (composing 26% of the market), MOS microprocessing units (MPU) (14% of the market), analog circuits (14%) and MOS microcomputers (MCU) (9%). DRAM and Flash EEPROM memory comprise 13% and 9% of the market respectively, though the Flash EEPROM market is expected to grow rapidly in the next few years, and the DRAM market is contracting.

The fastest growing market segments are Flash memory, analog IC and MPU. The projected growth for Flash revenue during the 2007 to 2010 period is 20.0%, and in 2010, it is forecast that Flash will contribute to 13% of the global market. The growth of Flash memory has been driven by the increasing use of the technology in consumer electronics such as MP3 players. Analog IC and MPU are projected to grow by 8.3% and 8.1% respectively during the same period. The MPU market follows computer sales, which are expected to remain strong in the foreseeable future. Analog ICs are used, along with other logic components, in phones and other mobile communications devices. The analog IC market sector has thus been one of the fastest growing product sectors in recent years, due to increased demand from mobile consumer electronics manufacturers [3]. As more and more people use mobile devices to perform many of the same tasks traditionally carried out on a personal computer, the analog IC sector may be expected to have strong growth in the longer term.

In 2010, the DRAM market is forecast to contribute to 11% of global revenues, down from 13% in 2007 [93]. While revenue for this sector is not expected to decline in 2007-2010, the forecast growth rate is only 1.5%, the lowest of any of the product sectors. Flash memory has replaced DRAM in certain consumer electronics products, contributing to this slowing in growth. Also, the price of DRAM has experienced volatility and extreme price drops in recent years due to spates of overproduction. DRAM is a component necessary for personal computers and due to the relatively stable demand from the computer market, the DRAM sector is not expected to contract in the next several years.

Other classes of semiconductor products include discrete components (e.g. individual transistors, rectifiers, diodes and sensors), optical components (e.g. LEDs, charge coupled devices, light sensors, laser devices, character displays) and analog electronics (e.g. power supply components, op-amps, automotive control chips, radio frequency (RF) communication chips, telecommunications equipment components). The composition of global semiconductor market revenue in 2007 is illustrated in Figure 2.3.

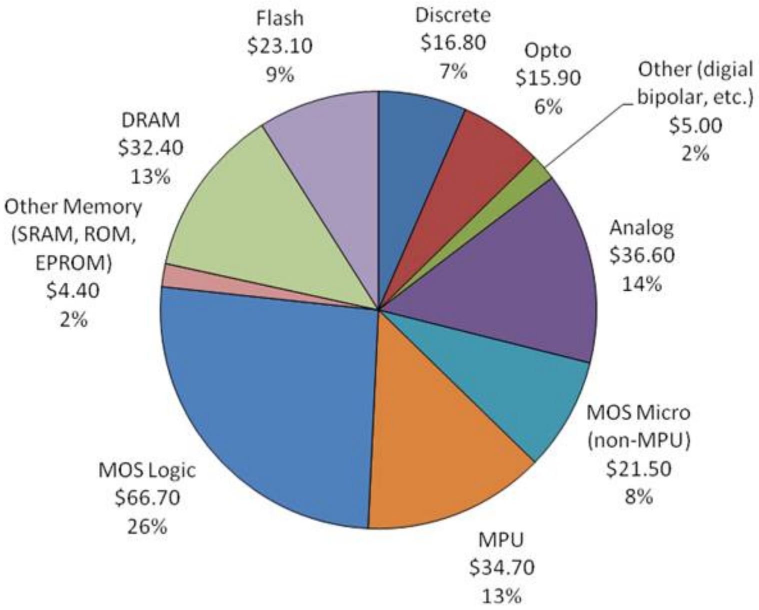


Figure 2.3. 2007 Worldwide revenues by product type

In order to clarify the relative popularity of the various device types, the Table 2.1 lists product categories and their associated device types by their percentage contribution to world revenue. The product types of MOS logic, MPU, and MOS micro, shown in Figure 2.3, are composed most commonly of CMOS logic. CMOS logic, as a fundamental circuit type, composed the largest fraction of world semiconductor production in 2007.

Table 2.1. Semiconductor products and their dominant device types, by market volume

Product category	Percentage of world revenue	Dominant circuit element
MOS Logic	26%	primarily CMOS, also NMOS, PMOS or BiCMOS
Memory	23%	CMOS, NMOS, PMOS or BiCMOS
Analog	14%	bipolar, MOS or BiMOS
MPU	13%	CMOS
MOS Micro (non-MPU)	8%	primarily CMOS, MOS or BiMOS
Discrete	7%	diodes, MOS, bipolar
Opto	6%	diodes, MOS, bipolar
Other IC	2%	bipolar, MOS

2.2.4 Geographic Concentration of Production

The semiconductor industry extends globally and many companies operate internationally. The dominant model of operation among US-based manufacturers is to locate research and design activities in the US, wafer manufacturing at another site, and chip and component assembly in a location with a low cost of labor. The location of wafer manufacturing is usually not based on labor costs, but rather a combination of factors, including tax incentives, availability and cost of capital, access to reliable power and water supplies and the ease of the regulatory environment [14].

During the last decade, some semiconductor companies have chosen to outsource some or all of their wafer production to foundries rather than owning their own fabrication facilities. This trend in outsourcing has been driven by the increasing capital cost of wafer fabrication plants ("fabs"). The increasing complexity of process flows requires that each fab contain more individual pieces of equipment, while increases in wafer size have increased equipment footprints and thereby the overall size of each fab. A typical 200mm CMOS logic wafer fab in 1997 would have cost about \$800 million, while an advanced 300mm wafer fab in 2001 cost approximately \$2 billion and a fab in 2007 could cost as much as \$18 billion [49] Approximately 14% of worldwide manufacturing capacity is held by foundries with a concentration in Southeast Asia [94]. The largest contract foundries are Taiwan Semiconductor Manufacturing Corporation (TSMC) and United Microelectronics Corporation (UMC), which are based in Taiwan, Chartered Semiconductor of Singapore and Semiconductor Manufacturing International Corporation (SMIC) of China. Some major semiconductor and consumer product companies are outsourcing all of their production to foundries. Examples of this strategy are the "fabless" Qualcomm, Broadcom, LSI Logic and Nvidia . Other companies only use foundries selectively, for older products with well-established production processes and lower margins, or for products which are not related to the technical competence of the firm. STMicroelectronics, Analog Devices and Freescale each have about 20% of their production performed externally.

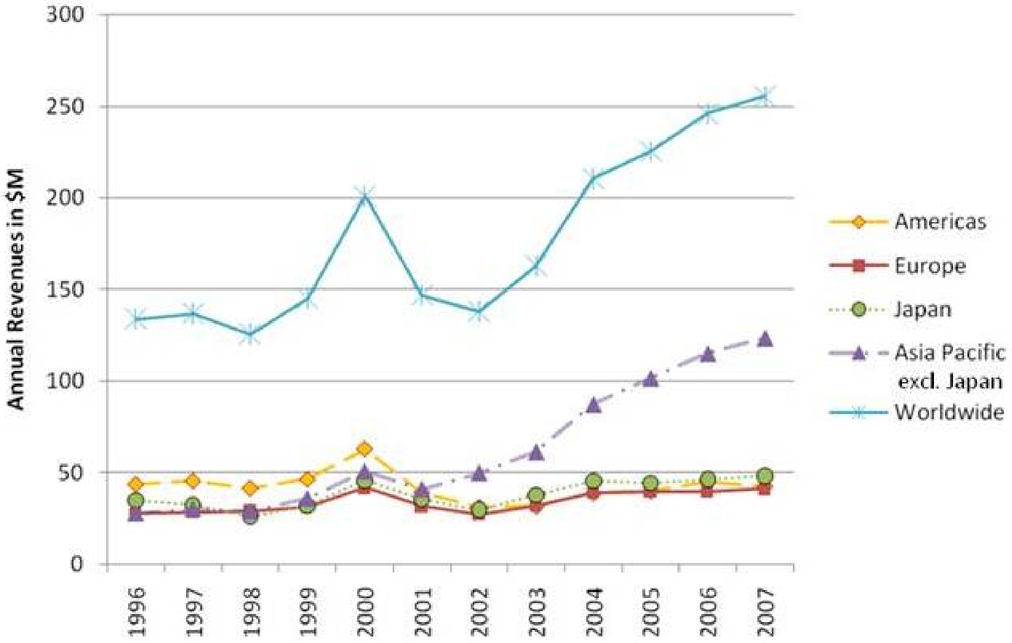


Figure 2.4. 2007 Worldwide revenues by geographic region

SIA worldwide revenue reports show dramatic growth in East Asia (Figure 2.4). Although revenue and sales information related to a company or market can give a broad overview of trends in the industry, it cannot be used as a proxy for information concerning the location and volume of actual wafer fabrication capacity. For example, Intel is headquartered in California but owns fabs in 12 countries around the world, and, although TSMC is based in Taiwan, the company runs foundries in Singapore, Taiwan, China and the US. Also, revenue figures may not be representative of actual production, as the price of certain semiconductor products, such as DRAM, can experience extreme drops in price, often due to overproduction. Industry reports describing capacity, however, also cannot describe the production volume of any given product type with certainty because many companies produce a range of similar products in the same facilities. For example, most companies who produce DRAM also produce Flash memory in the same fab, and some contract foundries will produce a set of product types, such as CMOS logic and bi-CMOS, in the same fab. Thus reports concerning capacity cannot always be representative of the actual product being produced as these manufacturers switch between product types in order to maximize profit and capacity utilization. Industry reports on revenues or capacity can give an overview of general trends, but, for the purposes of determining the production volume of a given product type, must be interpreted with an understanding of the production dynamics internal to each firm. With these qualifications in mind, the industry trend of fabrication relocation to, and capacity growth in, Taiwan and China is evident from company-specific research.

There is a clear expansion in wafer manufacturing in Taiwan and China which is occurring through the growth of Chinese and Taiwanese foundries, as well as the relocation of manufacturing capacity by established firms to China and joint development agreements between European or US firms and Taiwanese or Chinese firms. Chinese wafer fabrication companies which have plans to build new capacity in China between 2008 and 2011 include SMIC (Semiconductor Manufacturing International Corp.), He Jian Technology, Grace Semiconductor, Hua Hong NEC, Shanghai SIM-BCD, Jilin Sino-Microelectronics and CSMC (Central Semiconductor Manufacturing Corporation) Technologies Co. These firms operate for the most part as contract foundries, with some design and assembly services and represent capacity that is being out-sourced from companies largely in the US. Some established companies are also expanding their existing capacity or building fabs for the first time in China and Taiwan. A prominent example of the latter is Intel's plan to build a \$2.5B, 90-nm node, 300mm fab by 2010 in Dalian, on the coast of Northern China [18]. Other examples include Philips Electronics' partnership with Jilin Sino-Microelectronics Co. Ltd (JSMC) through a joint firm named Philips JiLin to produce bipolar power controllers, and the partnership between ST Microelectronics, a Swiss company, and Hynix, a Korean company, to build a fab in China. (Due to Chinese government regulation, the creation of a partnership or joint venture between a foreign and Chinese firm is much more common than an investment in wholly owned manufacturing facilities in China by a foreign company.)

The growth in capacity located in Taiwan and China is underscored by trends in semiconductor manufacturing equipment sales. The semiconductor equipment market grew by 20% and 14% in Taiwan and China, respectively [112]. This revenue data includes sales of chip assembly as well as wafer processing equipment, but wafer equipment purchases accounted for 81% of the Taiwanese semiconductor equipment market in 2007.

2.3 Conclusions

Semiconductor products are an important topic for life cycle assessment due to the magnitude and growth of the production of these products. CMOS-based digital logic, used in micro-processors and controllers, accounts for close to half of worldwide semiconductor production and represents the largest proportion of the market by device type. Due to its widespread production and use, CMOS logic is chosen as the first subject of investigation and represents the topic of study in the bulk of this thesis. Due to the rapid growth in production of flash memory, and the forecast that this product type will be the second largest product sector by 2010, flash memory is chosen as the second subject of study in this thesis. DRAM, which is forecast to be the third most widely produced product type in 2010, and is also a critical component to computers, is chosen as the third subject of study in this thesis.

The growth of new capacity and re-location of production to Taiwan, Singapore, Malaysia and China is also noted as an important topic of analysis, due to the lack of PFC-abatement policy in these countries as well as the high global warming intensity of electricity in China. In each LCA study in this thesis, the relative impacts of wafer production with and without PFC abatement are determined. In Chapter 3, which focuses on the energy-related impacts of CMOS logic, two geographical cases are presented, one in the US and the other in China, to clarify the influence of the electricity mix at the production site on total life-cycle global warming impacts.

Chapter 3

Life-cycle Energy and Global Warming Emissions of CMOS Logic

3.1 Introduction

Information and communication technology (ICT) has the potential to reduce the impact of human activities on the environment. In order to fully understand the environmental benefits of ICT, the life-cycle impacts of computer systems must be compared with those of the products and services they replace. The questions of whether reading news on a handheld device rather than newspaper, or purchasing books from an online retailer instead of from a bookstore reduces environmental impact are two examples of this sort of comparison in the recent literature [103, 50, 81]. While, initially, the replacement of traditional products such as newspapers by a small fractional increase in the use of a handheld mobile device seems a winning environmental trade-off, there has been increasing concern over the large energy demands of the internet infrastructure, with data center energy demand in the U.S. reaching 1.5% of the national total in 2006 and estimates of 2011 demand surpassing 10 billion kWh [26].

Among the numerous parts which compose the IT infrastructure, semiconductor chips are among the most resource-intensive to produce as well as the most difficult to characterize for the purposes of life-cycle assessment (LCA). While it may be possible to estimate the environmental impacts of a cable or plastic computer housing knowing only their masses and material types, the impacts associated with a semiconductor chip are not represented well by the substance of the device itself. While a logic chip may weigh only a few grams, the chemicals and water required to produce it weigh many kilograms. In many LCA studies of electronics, the lack of LCA data for computer chips has been noted as an important topic for future work and the need for a more detailed and transparent life-cycle inventory for semiconductor products has been noted previously [76, 75, 62, 109, 11, 104].

Complementary metal oxide semiconductor (CMOS) is the dominant device structure for digital logic. The central processing unit (CPU) in desktops, laptops, handheld devices and servers, as well as nearly all embedded logic (the chips in appliances and toys) are CMOS-based. Every one to three years, a new generation or technology node of CMOS is introduced, based on design laws which have been established through industrial collaboration. Due to the cooperation necessary to plan and achieve the goals for each generation, there is considerable homogeneity among the devices manufactured by the major logic producers at each technology node. A generic version of CMOS may thus be used to represent logic products from many different manufacturers.

This chapter provides a life-cycle energy analysis for CMOS chips over 7 technology generations with the purpose of comparing energy demand and global warming potential (GWP) impacts of the life-cycle stages, examining trends in these impacts over time and evaluating their sensitivity to data uncertainty and changes in production metrics such as yield. Chips of generic CMOS logic, produced at a fab located in Santa Clara, California are evaluated at each technology node over a 15 year period, from the 350 nm node (circa 1995), to the 45 nm node (circa 2010. This study is composed of production-related LCA data, based on emissions measurements, process formulas and equipment electrical tests, combined with previously published LCA data for chemicals, electricity and water, as well as publicly available use-phase data for computer chips. A hybrid life-cycle inventory (LCI) model is used. Wafer production, electricity generation, water supply and certain materials are represented by process LCA data, while the remaining materials are described using economic input-output life cycle assessment (EIO-LCA) methods [15]. While life-cycle energy and GWP of emissions have increased on the basis of a wafer or die as the functional unit, these impacts have been reducing per unit of computational power. Sensitivity analysis of the model shows that impacts have the highest relative sensitivity to wafer yield, line yield and die size and largest absolute sensitivity to the use-phase power demand of the chip.

3.2 Methodology

This LCA includes materials production, wafer processing, die packaging, transportation and use of the logic chip (Figure 4.1). The LCA model is hybrid, using a combination of process-based LCA and economic input-output (EIO) LCA data (Table 3.1). The functional unit is one packaged die, but in order to allow further analysis and to investigate trends, results are also presented per wafer and per million instructions per second (MIPS).

silicon	process LCA
chemicals	process and EIO-LCA
infrastructure and equipment	EIO-LCA
fabrication	process LCA
electricity	process and EIO-LCA
water	process and EIO-LCA
transportation	process LCA
use	process LCA

Table 3.1. Summary of data sources

At end-of-life, it is assumed that there is no recoverable energy value in the chip. Other end-of-life impacts are not included because the functional unit of this LCA is the chip alone and past studies of e-waste impacts have concerned the computer as a whole. A great deal of effort has been focused on the end-of-life of computer systems because irresponsible recycling practices can produce dramatic and visible human health and environmental impacts. The major pollutants associated with e-waste (flame retardants, polychlorinated biphenyls, dioxins/furans, polycyclic aromatic hydrocarbons, lead, cadmium and mercury) are largely emitted from the incineration or chemical breakdown of circuit boards, wiring, housing and displays. Although there may be harmful emissions from the decomposition or combustion of a logic chip, these have not yet been measured in isolation, but remain an important topic for future work. Because there is no positive energy value and no global warming impacts at end-of-life, the net impact in this life-cycle stage is zero.

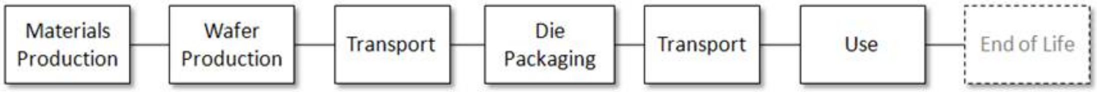


Figure 3.2. Life-cycle stages

3.2.1 Inventory model structure

In order to clarify the model structure and in order to demonstrate the sensitivity of results to variation in model parameters, the inventory model is described algebraically. The contributors to the life-cycle energy requirements (e_{total}) and global warming potential (GWP) of life-cycle emissions (g_{total}) are illustrated in Equations 3.1 and 3.2.

$$e_{total} = e_{up} + e_{inf} + e_{prod} + e_{trans} + e_{use} \tag{3.1}$$

e_{up} : energy for upstream materials

e_{inf} : energy for infrastructure

e_{prod} : energy for production

e_{trans} : energy for transportation

e_{use} : use phase energy

$$g_{total} = g_{up} + g_{inf} + g_{prod} + g_{trans} + g_{use} \tag{3.2}$$

g_{up} : GWP of emissions due to upstream materials

g_{inf} : GWP of emissions due to infrastructure

g_{prod} : GWP of emissions due to production

g_{trans} : GWP of emissions due to transportation

g_{use} : GWP of emissions due to use phase energy

Energy and global warming potentials for chemical production, i.e., upstream activity, are given by e_{up} in Equation 3.3 and g_{up} in equation 3.5. Process chemicals are split into two sets, the first set of m chemicals for which EIO-LCA data are used [15], and a second set of q chemicals for which process LCA data are used. The term $e_j^{\$}$ is the energy consumption per dollar value of chemical j, c_j is the cost per unit mass of j and m_{ij} is the mass of j consumed in process step i. The wafer yield (Y_{wafer}) is the percentage of good die per wafer, the line yield (Y_{line}) is the percentage of finished wafers of those started, and gross yield (n_{die}) is the number of dice per wafer.

$$e_{up} = \frac{1}{Y_{wafer} Y_{line} \ n_{die}} \left[\sum_{j=1}^{m} e_j^{\$} c_j \sum_{i=1}^{n} m_{ij} + \sum_{k=1}^{q} e_k^{m} \sum_{i=1}^{n} m_{ik} \right] \tag{3.3}$$

$$\tag{3.4}$$

$e_j^{\$}$: energy consumption per dollar value of chemical j

c_j : cost per unit mass of j

m_{ij} : mass of j consumed in process step i

e_k^m : energy consumption per unit mass of chemical k

m_{ik} : mass of k consumed in process step i

$$g_{up} = \frac{1}{Y_{wafer} Y_{line} \ n_{die}} \left[\sum_{j=1}^{m} g_j^{\$} c_j \sum_{i=1}^{n} m_{ij} + \sum_{k=1}^{q} g_k^{m} \sum_{i=1}^{n} m_{ij} \right] \tag{3.5}$$

$g_j^{\$}$: GWP of emissions per dollar value of chemical j

c_j : cost per unit mass of j

m_{ij} : mass of j consumed in process step i

g_k^m : GWP of emissions per unit mass of chemical k

m_{ik} : mass of k consumed in process step i

The energy and greenhouse gas (GHG) emissions due to facility infrastructure and capital equipment are found using the EIO-LCA method.CMU EIO-LCA method. This method is summarized by equation (3.6), where A is the $n \times n$ economy-wide transactions matrix, R is the $n \times m$ impacts matrix where r_{ij} is the i^{th} type impact of sector j. The demand vector $\hat{c}_{inf}$ is an n item vector with the costs of construction and equipment at the positions corresponding to their industrial sectors in A. The resulting vector $\hat{b}$ is the set of life-cycle energy demands and global warming emissions of the sectors used in this study. The EIO-LCA model is described completely in the literature [40, 41].

$$\hat{b} = R\,(I - A)^{-1}\,\hat{c}_{inf} \tag{3.6}$$

The total energy used in production (e_{prod}) consists of all electricity and natural gas used by production tools and the facility infrastructure, as given in equation (3.8). Equation (3.9) describes the GWP of production which includes both energy-related emissions and direct GHG releases.

$$e_{prod} = \frac{1}{Y_{wafer} Y_{line}\, n_{die}} \left[\sum_{i=1}^{n} \left(\frac{t_i\, p_i + e_{CH_4} t_i\, m_{i,CH_4} + \hat{e}_w^v\, \hat{w}_i\, t_i}{\varepsilon_i\, u} \right) \right. \tag{3.7}$$

$$\left. + \left(\frac{p_{hvac} + p_{lt} + p_{trt} + p_{cda} + p_{exh}}{c} \right) \right] \tag{3.8}$$

t_i: duration of process i

p_i: process tool and POU abatement power consumption for process i,, per chamber

e_{CH_4}: energy per unit mass methane

m_{i,CH_4}: mass flow of methane for process i

$\hat{e}_w$: vector of volumetric energy requirements for ultrapure, process cooling and city water flow, per chamber

$\hat{w}_i$: vector of ultrapure, process cooling and city water flows for process i,, per chamber

ε_i: process utilization for process step i

u : tool utilization

p_{hvac} : facility HVAC power consumption

p_{lt} : facility lighting power consumption

p_{trt} : facility treatment system power consumption

p_{cda} : facility CDA power consumption

p_{exh} : facility exhaust system power consumption

Energy and emissions due to transportation are given in equations (3.10) and (3.11) by e_{trans} and g_{trans}, where the two legs of transportation refer to transport from the fab to assembly plant, and from assembly site to use. The terms e_{trans} and g_{trans} are derived from transport distances d for each leg i, where t denotes truck; r, rail; b, boat and a, air freight, and the product and packaging mass for leg i, m_i.

$$g_{prod} = \frac{1}{Y_{wafer} Y_{line}\; n_{die}} \left(\sum_{i=1}^{n} t_i \hat{m}_i \hat{g} + l \right) + e_{prod}\; g_e^{prod} \tag{3.9}$$

t_i: duration of process i

$\hat{m}_i$: vector of mass flows of all process chemicals for process i

$\hat{g}$: vector of GWP per unit mass of all process chemicals

g_e^{prod} : GWP of use phase electricity used in production

$$e_{trans} = \frac{1}{Y_{wafer} Y_{line}\; n_{die}} \left[\sum_{i=1}^{2} \left(d_{i,t}\; e_t^d\; m_i + d_{i,r}\; e_r^d\; m_l + d_{i,b}\; e_b^d\; m_l + d_{i,air}\; e_{air}^d\; m_l \right) \right] \tag{3.10}$$

$$g_{trans} = \frac{1}{Y_{wafer} Y_{line}\; n_{die}} \left[\sum_{i=1}^{2} \left(d_{i,t}\; g_t^d\; m_i + d_{i,r}\; g_r^d\; m_l + d_{i,b}\; g_b^d\; m_l + d_{i,air}\; g_{air}^d\; m_l \right) \right] \tag{3.11}$$

e_t^d: energy use per mass transported unit distance

g_t^d: GWP per mass transported unit distance

m_i: product and packaging mass over leg i

$d_{i,x}$: distance over leg i transported by mode x

In equation (3.12), the use-phase energy consumption is found as the product of device power (p_{use}) and lifespan (t_{life}). Equation (3.13)) describes use-phase GWP emissions as the GWP intensity of use-phase electricity (g_e^{use}) applied to use-phase energy consumption.

$$e_{use} = p_{use}\; t_{life} \tag{3.12}$$

$$g_{use} = g_e^{use}\; e_{use} \tag{3.13}$$

3.2.2 "Upstream" Materials

Chemicals

Among the life-cycle impacts of semiconductor products, the importance of energy-related emissions from the production of high purity chemicals has been noted previously [104, 109, 75, 58]. The limited LCA data available for exotic and/or high purity semiconductor process chemicals remains a challenge in quantifying these impacts. The production processes and formulas for advanced semiconductor processing materials are closely held intellectual property. Chemical textbooks and handbooks simply do not contain information about the production processes used to make them, and it is nearly impossible to identify the dominant production method among patent filings, as enterprises will at times file multiple patents describing different production pathways, or describe production recipes broadly so as to obfuscate the preferred method. While LCA data are available for some basic chemicals used in wafer manufacturing, such as elemental gases, metals and common acids, it is usually representative of the industrial grade, with a purity of 99% or lower, rather than ultra-high purity or semiconductor grade (99.9997% to 99.9999999% pure).

This study uses a method of LCA data collection by which data based on process descriptions are used where available, and data from the Carnegie Mellon EIO-LCA database are used where costs are known. When no process LCA data and no cost information is known, an estimate for the energy intensity of chemical manufacturing developed by Overcash is used [51]. In this study, the "pharmaceuticals and medicines" rather than "photographic film and chemicals" commodity sector (NAICS #325400) is used in the EIO analysis for those materials which are high value specialty chemicals (those with a purchase price over $1,000 per kg), since the economic value of these materials is represented more closely by the former sector. The organic chemicals (NAICS #325190) and inorganic chemicals (NAICS #325180) commodities are used for the remaining materials, as appropriate. Although additional impact categories are available for those materials analyzed using EIO-LCA, the inventory is limited to primary energy demand and the GWP of emissions. Data sources for all inventory materials are given in Tables 3.2, 3.3, 3.4 and 3.5.

The uncertainty of process data from textbooks and manuals is assumed to be zero, because it is unknown but assumed to be small as compared with other chemical LCA data sources. All data sources and impact values for materials using published process energy data are given in Table 3.2.

Chemical	Energy Intensity MJ/kg	Carbon Intensity gCO_2eq/g	Source
Al	260	22	[4]
Ar	3.6	0.31	[4]
C_2F_4	20	1.7	[106]
CH_4	38	3.3	[68]
CO	0.52	0.04	[34]
Cu	4.7	0.40	[9]
F_2	61	5.3	[30]
H_2	8.5	67	[4]
H_2O_2	12	1.0	[4]
H_2SO_4	0.040	0.00	[44]
HCl	0.91	0.08	[39]
He	0.83	0.07	[37]
HF (gas)	18	1.5	[79]
HF (liquid)	18	1.5	[4]
N_2	0.66	0.06	[42]
NF_3	40	3.4	[20]
NH_3	31	2.7	[1]
NH_4OH	15	1.3	[1]
O_2	1.8	0.15	[42]
Pb	2.0	0.2	[6]

Table 3.2. Chemical LCA Data Sources, part 1: Process data

Chemical	Energy Intensity MJ/kg	Carbon Intensity gCO_2eq/g	Source
polyamides	115.0	9.9	[6]
Pt	270	23	[22]
SiH_4	2321	200	[32]
Sn	122	11	[6]
Ti	140	12	[1]
utility N_2	0.02	0.06	[42]

Table 3.3. Chemical LCA Data Sources, part 2: Process data

While EIO-LCA results for toxic releases or other impacts may have a lower precision, an uncertainty range of +/- 10% is assumed for EIO-LCA energy consumption and +/- 20% for GWG emissions based on the sources used by the CMU model for energy data. Chemicals using EIO-LCA data are given in Table 3.4.

Chemical	Energy Intensity MJ/kg	Carbon Intensity gCO_2eq/g
1,1-dichloro-1-fluoroethane	17	1.4
AsH_3	6.2E+04	5.2E+03
BCl_3	4.0	0.35
benzotriazole	17	1.4
bis tertiary-butylamino silane	5.9E+04	4.9E+03
C_2F_6	1.4E+03	120
C_4F_6	1.3	0.11
C_4F_8	0.8	0.07
CF_4	1.0E+03	86
CHF_3	59	5.1
Cl_2	1.3	0.11
CMP polishing solution	17	1.4
CuS silica slurry	17	1.4
DCS	5.3	0.45
HCl (gas)	0.7	0.06
NH_4OH	76	6.6
PH_3	1.9E+05	1.6E+04
$SiCl_4$	1.5E+03	130
SiF_4	3.3	0.29
SiH_4	2.3E+03	200
surfactant solution	17	1.4
TDMAT	5.5E+04	4.6E+03
TEOS	1.3E+03	100
TMS	2.8E+04	2.3E+03

Table 3.4. Chemical LCA Data Sources, part 3: EIO-LCA data

Data from the Kim/Overcash study has an uncertainty of +25%/-75% as described in their analysis [51]. The list of chemicals using this common value for energy and GWP per mass is given in Table 3.5.

Energy Intensity	Carbon Intensity
MJ/kg	gCO_2eq/g
3.1	0.26

ArH	ethyl lactate	O_3
As	Fe_2O_3	OMCTS
Au	formaldehyde (CH_2O)	oxide CMP slurry
B_2H_6	GeH_4	p-cresol
BF_3	H_3PO_4	PDMAT
Br_2	HBr	PGME
C_2H_2	HCOOH	PGMEA
C_2H_4	HMDS	polyimide laminate
C_2H5OH	laminate solvent	Sn
citric acid	m-Cresol	SO_2
CMP abrasive	MMA	Ta
Cr	N_2O	TDEAH
$CuCl_2$	Na_2B_4O7	TDMAS
$CuSO_4$	Ni	TMAH
DEA	n-methyl-2-pyrollidone	W
DMA	NO	W CMP slurry
	NO_2	WF_6

Table 3.5. Chemical LCA Data Sources, part 3: Process-based common value [51]

Silicon

Silicon is the purest substance used among all semiconductor process materials. There are several processing steps that raw silica takes to become a pure silicon wafer, the substrate of semiconductor devices. Raw silica is refined into metallurgical grade silicon, which is twice refined to produce a single crystal ingot that is then sliced into wafers. The high embedded energy of the final product (approx. 2000 KWh/kg) is due not only to the energy intensity of these processes, but also a cumulative low yield caused by the losses at each step. Full descriptions of the energy requirements and environmental emissions of high purity silicon production are available from previous sources [109, 71]. The LCA data provided by Williams and used in this study [109] is duplicated here for clarity (Table 3.6).

Table 3.6. Energy Intensity of Silicon Production

Process step	electrical energy/kg Si out (KWh)	Si yield (%)
refining silica to mg-Si	13	90%
mg-Si to trichlorosilane	50	90%
trichlorosilane to polysilicon	250	42%
crystallization of polysilicon to sc-Si ingot	250	50%
sawing sc-Si ingot to Si wafer	240	56%
process chain from silica to wafers	2127	9.5%

Water

The environmental impacts associated with the Santa Clara water supply are modeled using information from the Santa Clara Valley Water District and previous work on LCA of California water supplies by Stokes [98].

The Santa Clara Valley Water District infrastructure is composed of 3 treatment plants for local and imported water, one recycled water treatment facility, 142 miles of pipelines and 3 pumping stations. According to a report from the district board, approximately 51% of the water used in Santa Clara is imported, while 45% comes from local sources and the remaining 4% from recycled stocks [110]. (A regional desalination project is planned for construction; however, no water is desalinated by the Santa Clara water district at the time of writing.) Most water imported to Santa Clara comes from the Sacramento-San Joaquin River Delta via the South Bay Aqueduct, though a small fraction also comes from the Hetch-Hetchy reservoir via the San Francisco water system. Local water sources include groundwater basins and 10 surface reservoirs.

The life-cycle environmental impacts evaluated by Stokes for imported and recycled water from the Oceanside Water District in San Diego are applied, on a per volume basis, to the imported and recycled fractions of water in the Santa Clara system. Life-cycle environmental impacts associated with Santa Clara's locally sourced water are estimated based on the energy required for treatment and distribution of imported water in Stokes' model of Marin's water treatment works. The global warming emissions intensity for the power utility in Santa Clara (Pacific Gas and Electric), 280 gCO_2eq./kWh, is used. The energy intensity and percent contribution of each source is presented in Table 3.7. The resulting global warming emissions per liter of water provided in Santa Clara is 0.6 gCO_2eq.

Table 3.7. Global Warming Intensity of Santa Clara Water

	Local Supply	Imported	Recycled
Contribution of source	45%	51%	4%
kWh/liters	0.0021	0.0019	0.0002

3.2.3 Infrastructure and Equipment

The energy use and GWP for infrastructure and equipment are evaluated using EIO-LCA . Rock's Law is used to estimate the total cost of the fabrication facility and the costs of wafer fabrication equipment are taken as 70% of the total cost of the fab, based on a commonly stated approximation. Expenditures are depreciated over a 10 year period, using a straight line schedule, yielding an annual cost which is corrected to 1997 dollar values using the average U.S. inflation rate over the 1995-2008 period of 2.7%. Total costs for the building and equipment for each technology node are provided in Table 3.8.

Table 3.8. Cost of Fab Infrastructure and Equipment

year		1995	1998	1999	2001	2004	2007	2010
technology node		350	250	180	130	90	65	45
equip. cost, depreciated	$M/year	42	71	84	119	200	336	400
construction cost, depreciated	$M/year	18	21	25	30	36	43	51

3.2.4 Electricity

The emissions associated with electricity use at the different geographical locations of each life-cycle stage are reflected in the model. In the fabrication and use stages, emissions factors for electricity are specific to California, while the stages of chemical and infrastructure production are represented by each US industry average GWP emissions factors, via EIO-LCA [15].

GWP of Electricity

The environmental impacts associated with electricity supplied to the California plant are evaluated using two previous LCA of electricity generation, data from the EPA and information from Santa Clara's electric utility, Pacific Gas and Electric.

The electricity mix of Pacific Gas and Electric in 2008 was 47% natural gas, 23% nuclear, 13% large-scale hydroelectric, 4% coal, 4% biomass or other waste combustion, 4% geothermal, 3% small-scale hydroelectric, 2% wind and 0.1% solar photovoltaic [70]. The life-cycle GHG emission factors (g CO_2eq./kWh) for natural gas, coal, large scale hydroelectric and solar photovoltaic power are taken from the work of Pacca and Horvath [67], while that for nuclear electricity is taken from a study by Fthenakis [33]. Direct GHG emissions for geothermal and biomass combustion are taken from the EPA [28]. Small hydro is considered to have the same impacts as large hydro. A national average for the Chinese grid of 877 gCO_2eq/kWh, based on a previous LCA [24], is used for the production scenario in China.

Electricity Mix		Carbon Intensity gCO$_2$eq/kWh	Source
Coal	4%	811	Horvath, Pacca [67]
Nat Gas	47%	450	Horvath, Pacca
Nuclear	23%	25	Fthenakis [33]
Large Hydro	13%	41	Horvath, Pacca
Biomass/waste	4%	0	EPA [28]
Geothermal	4%	35	EPA
Small Hydro	3%	41	Horvath, Pacca
Wind	2%	7	Horvath, Pacca
Solar	0.1%	90	Horvath, Pacca

Table 3.9. GWP Intensity of Electricity

Primary energy use in electricity generation

In order to facilitate comparison with preceding studies, for most life-cycle stages, the convention of 10.7 MJ of primary energy per kWh electricity is used. This represents a worldwide average value for fuel consumption in electricity production [109]. The primary energy intensity of electricity supplied in Santa Clara is not documented, and since there have been no studies which provide net fuel intensity of nuclear, geothermal, wind or the other non-combustion generation technologies used by the California grid, the fuel intensity of the electricity used in fabrication is taken as the this worldwide average. In actuality, the primary energy intensity of Santa Clara electricity is estimated as the world average. A comparison of the contribution of each generation type is given in Table 3.10. Since most of the thermal generation in California is combined cycle natural gas combustion, and the contribution of renewables and nuclear are higher than the world average, the net primary energy demand for electricity production is somewhat lower than 10.7 MJ/kWh. For the purposes of this study, however, the global average is used.

	Conventional thermal	Hydro.	Nuclear	Geothermal, solar, wind, and waste/biomass
World average	69%	19%	9%	3%
California (PG&E)	52%	16%	23%	10%

Table 3.10. Electricity Generation by Type, World Average vs. California

The fuel intensity of electricity in China, however, is higher, with an average value of 12. MJ per kWh of electricity, due to an average lower conversion efficiency of power plants as well as higher losses in transmission and distribution [24].

3.2.5 Semiconductor Manufacturing

In this analysis the primary model for wafer manufacturing is located in Santa Clara, California, in the U.S. A separate scenario for production in China is developed in order to demonstrate the environmental effects of using China's electricity supply mix and neglecting per-fluorinated compound (PFC) abatement. Although PFC emissions may be abated in some fabs in China, the assumption is made that there are no controls on PFC emissions at the Chinese production site.

The mass and material flows are accounted at the level of the fab and equipment.

Process flows

A summary of changes to the process flow for each device is given in Table 3.11. The process change which has allowed the greatest reduction in GWP from one technology node to the next is the switch from in-situ plasma generation to remote plasma generation for etch and post-dielectric deposition chamber cleaning. (The impact of this particular technology change is not described in further detail in this thesis as it has been well-documented in previous literature [78].)

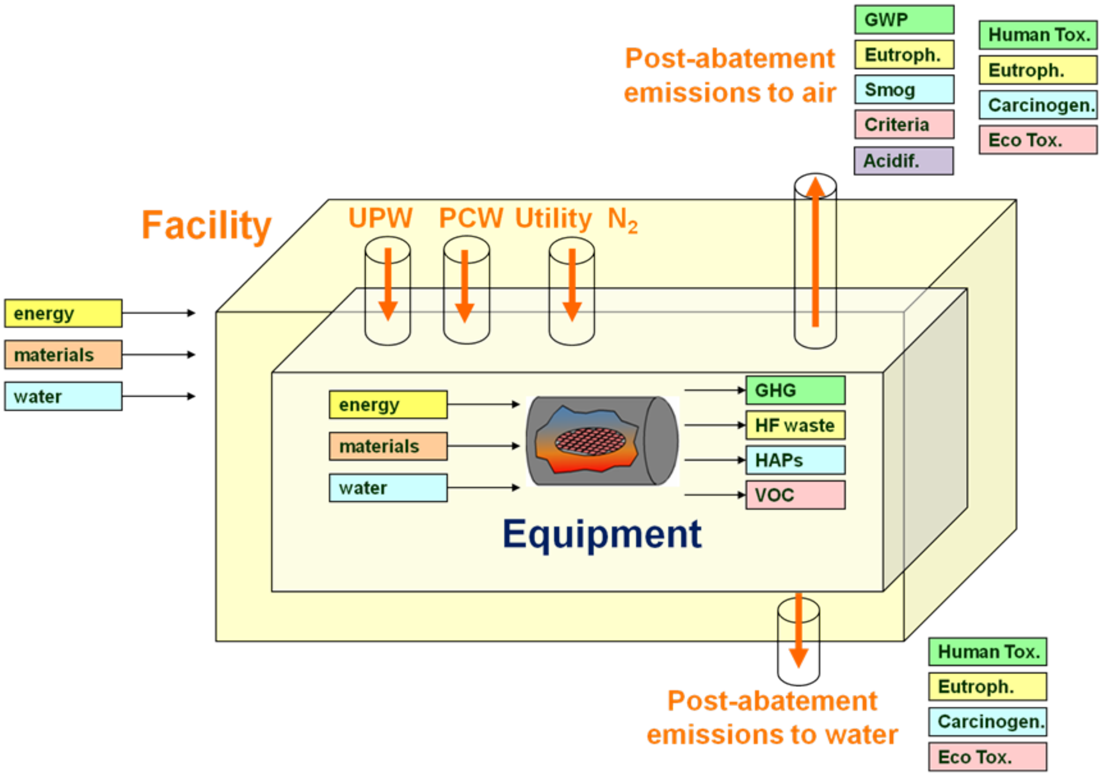


Figure 3.3. Overview of mass and energy flows considered in the fab model

Table 3.11. Summary of process changes for each technology generation, part 1

Node (nm)	**350**	**250**	**180**	**130**
Wafer size (mm)	200	200	300	300
Interconnect	4 layer Al	5 layer Al	6 layer Al	6 layer Cu, Ta barrier
Starting wafer				SOI
Dielectric	USG PMD, USG ILD M1-M4	USG PMD, USG ILD M1-M5	FSG PMD, FSG ILD (Remote Clean) M1-M3, USG M4-M6	FSG PMD, FSG ILD (Remote Clean) M1-M3, USG M4-M6 (Remote Clean)
Contact	Ti silicide	Ti silicide	Ti silicide	Co Silicide
Strain Engineering				
Gate	RTO gate oxide Nitride spacer for LDD	RTO gate oxide Nitride spacer for LDD	RTO gate oxide Nitride spacer for LDD	RTO gate oxide Nitride spacer for LDD
PR Strip	SPM - wet PR strip	SPM - wet PR strip	SPM - wet PR strip	dry plasma PR strip
Other				

Table 3.12. Summary of process changes for each technology generation, part 2

Node (nm)	**90**	**65**	**45**
Wafer size (mm)	300	300	300
Interconnect	7 layer Cu, Ta barrier	8 layer Cu, Ta barrier	9 layer Cu, Ta barrier
Starting wafer	SOI	SOI	SOI
Dielectric	FSG PMD, BD with BloK ILD M1-M3, USG M4-M7 (Remote Clean)	TEOS HARP PMD, BD with BloK ILD M1-M3, USG M4-M7 (Remote Clean)	TEOS HARP PMD, BD with BloK ILD M1-M4, USG M5-M9 (Remote Clean)
Contact	Co Silicide	Ni Silicide, "Siconi"	Ni Silicide, "Siconi"
Strain Engineering	Nitride Cap, Spacer	Nitride Cap, Spacer	Epi SiGe, Nitride Cap
Gate	RTO gate oxide	niriridation of oxide: ONO gate stack	ALD high-k dielectric
	Nitride spacer for LDD	Nitride spacer for LDD	Nitride spacer for LDD
PR Strip	dry plasma PR strip	dry plasma PR strip	dry plasma PR strip
Other	Source-Drain extension implant	Source-Drain extension implant	Source-Drain extension implant

Facility and Process Equipment Energy Demand

While device design, process complexity and the length of the process flow grow relentlessly, total fab energy consumption has not increased at the same pace, and has at times decreased in the past decade due in large part to facility efficiency improvements. These changes are reflected in the model; At each technology node, improvements are made to certain facility equipment, such as the water chillers or exhaust pumps, which allow reduced energy consumption.

Rising energy costs as well as pressure to achieve GHG emission reduction goals set by the World Semiconductor Council, have driven fabs to reduce their total energy consumption. These efforts are reflected in the industry goals set in the ITRS, which show an ongoing effort to reduce facility energy consumption to between 0.5 and 0.7 kWh per cm^2 wafer area in the 1999-2005 time period [84, 86, 87, 88]. The trend may be verified using an EIO perspective. By normalizing per unit of silicon area used, rather than by economic value of production, energy consumption can be analyzed independent from increases in off-shoring and outsourcing of fabrication by US companies or the increasing economic value of products. U.S. Census data from 1995 to 2005 show that the total electricity consumed by the semiconductor industry in the U.S., when normalized per area of silicon consumed by the industry, did not increase significantly from 1995 to 2005 [108, 2]. The energy consumption per area of silicon consumed increases and decreases slightly over time, but was roughly the same in 2005 as in 1995, approximately 1.5 kWh/cm^2 [109, 2].

Energy efficiency goals have largely been achieved through changes to fab facility systems. Throughout the industry, improvements have been made to the energy efficiency of nearly all of the major fab systems: water cooling, exhaust flow, water distribution, clean room airflow, clean dry air (CDA) and facility nitrogen delivery systems, and chamber vacuum pumps. Facility energy efficiency improvements can be classified as advancements in both the technologies and in the techniques applied in fab design and operation. Higher efficiency pumps and fans, variable speed drives and improvements in ducting and clean room airflow arrangement such as mini-environments represent technological developments. Reduction of pressures in CDA and exhaust systems, optimization of clean room temperature and air speed and the use of larger of cooling towers to allow reduced chiller size are examples of operational improvements.

These advancements are reflected in the model for each technology node in this study. A summary of these changes is given in Table 3.13. At the 250nm node, the pressure maintained in the CDA delivery system is increased to support stepper systems required for this generation's photolithography tools. (This change does not enhance energy efficiency but was necessary to enable pneumatic stepping for lithography.) At the 180nm node, the air change-over rate (ACR) is reduced in the clean room heating ventilation and air conditioning (HVAC) system, allowing fans speed to be lowered, the scrubber exhaust pumps are upgraded, a smaller and more efficient chiller, using a variable speed drive (VSD) is installed; Chiller use is also reduced by increasing the size of the cooling towers. Total facility energy consumption is cross-verified against industry reports and published literature [85, 46].

Table 3.13. Facility system changes by technology node

	technology node (nm)
Increased CDA system pressure for advanced lithography	250
HVAC: Reduce ACR in cleanroom HVAC	180
House Scrubber: Use high efficiency VFD exhaust pumps and reduce pressure drop to scrubber	180
Increased sizing of cooling towers to allow reduced size of chillers	180
New PCW chiller with VSD	180
All facility system capacities are resized for 300mm wafer fab	130
HVAC: Mini-environments, using Fan Filter Units with VFD	130
HVAC: Reduce fan sizes via redesign of air handling system	130

The wafer yield (good chips per wafer), line yield (finished wafers per wafer starts) and chip size are key variables which influence the environmental impacts per chip, as described in the Sensitivity section. The values for these parameters at each technology node are based on industry average data (Table 3.14) [85].

Table 3.14. Yields and chip sizes for each technology generation

technology node (nm)	350	250	180	130	90	65	45
line yield							
(finished wafer/wafer start)	58%	68%	73%	83%	83%	88%	88%
gross yield							
(chips/wafer)	117	201	249	429	429	463	590
net yield							
(good chips/wafer)	88	151	187	322	322	347	443
chip size (mm^2)	196	150	125	140	140	140	111

Power data for process tools are based on measurements taken using three phase power measurement equipment, which have a maximum error of +/- 2.6%. Power requirements for facility systems are determined using mass flow analysis and facility energy consumption models, which are developed based on data from industry and technical reports [66, 59]. Power and facilities requirements for process tools are from process equipment measurements [55] and requirements for abatement equipment requirements are based on manufacturers' specifications, which have an undefined error.

Process Emissions

The abatement of some PFC emissions are regulated by the Kyoto Protocol (in Annex I and II nations) and, in 1999, the World Semiconductor Council (WSC), which includes the semiconductor industry associations of Japan, Europe, Korea, Taiwan and the United States, issued a position paper which committed members to PFC emissions reduction by 10% of 1995 or 1999 baseline levels by the end of 2010. However, more than half of semiconductor production occurs outside of Kyoto Protocol Annex I and II nations, and, in 2008, almost 20% of semiconductor production capacity was held in China, Singapore and Malaysia , where the industrial consortia have not joined in the WSC. Thus, although PFC emissions may be abated in some fabs in China, the assumption is made that there are no controls on PFC emissions at the Chinese production site.

GWG emissions from each process step have been determined, pre- and post-abatement, using in-situ mass spectrometry and FT-IR analysis by a procedure which requires mass balance to be closed within 10% of chamber inputs. Each of these measurements thus has a maximum uncertainty of +/- 10% for each element. For most materials, the uncertainty of the total mass of emissions per finished wafer can be considered as a uniform distribution with variance equal to $(10\%)^2$ of the expected value. For NF_3 which is at more than 30 points during processing of a single wafer the uncertainty is reduced via the central limit theorem, and the total mass flow is modeled as a normal distribution with variance equal to $(3.3\%)^2$ of the expected value. Global warming potentials are taken from [48].

3.2.6 Transportation

Chips are typically cut and packaged at a facility separate from the wafer fabrication site, often in a different country or on a separate continent altogether [14]. Semiconductor products therefore travel twice within the production phase: wafers are transported from the fab to an assembly plant, where they are cut into die, packaged into chips and tested and finished chips are then transported to the place of eventual use.

The global industry of semiconductor packaging and testing, or "back-end" processing, is clustered in Vietnam, Malaysia, Costa Rica, Puerto Rico, China and the Philippines. Costa Rica is the closest location to Santa Clara and is therefore the location of assembly designated in this study.

Travel from the wafer fab to the assembly facility is taken as 50 miles by truck and 3000 miles by plane, and from assembly to the final point of use, travel is 3000 miles by air and 200 miles by truck. Energy consumption and GWP of emissions for truck and air freight are from Facanha [29]. The distance of each travel leg and its corresponding GWP impact and energy intensity is given in Table 3.15.

	Distance, fab. to assembly (miles)	Distance, assembly to use (miles)	CO_2 intensity (gCO_2/ton-mile)	Energy Intensity (MJ/ton-mile)
Truck	50	200	187	2.7
Air freight	3000	3000	18	0.38

Table 3.15. GWP Intensity of Transportation

It is assumed that between wafer production and assembly, the finished wafer is transported in a wafer carrier and additional casing with a total weight of 500 g per 200mm wafer or 700 g per 300mm wafer. Between assembly and use, the product and packaging has an assumed weight of 20g regardless of technology node. The total energy and GWP intensity of transport for each technology node is presented in Table 3.16.

technology node (nm)	350	250	180	130	90	65	45
wafer and carrier weight (g)	646	646	1029	1029	1029	1029	1029
net die per wafer	88	151	187	322	322	347	443
transported mass, fab. to asm. (g/die)	7.4	4.3	5.5	3.2	3.2	3.0	2.3
transported mass, asm. to use (g/die)	20	20	20	20	20	20	20
CO_2eq, fab. to asm. (g/die)	33	19	24	14	14	13	10
CO_2eq, asm. to use (g/die)	89	89	89	89	89	89	89
total GWP (g CO_2eq/die)	122	108	114	103	103	102	99
energy, fab. to asm. (kJ)	470	273	351	204	204	189	148
energy, asm. to use (kJ)	1283	1283	1283	1283	1283	1283	1283
total energy (MJ/die)	1.8	1.6	1.6	1.5	1.5	1.5	1.4

Table 3.16. Transportation Energy and CO_2 Emissions by Technology Node

3.2.7 Use phase

The use phase represents the power consumption of the chip assuming an average power supply efficiency of 70%. The lifetime of the chip is taken to be 6,000 hours (3 years, being used 8 hours a day, 5 days per week, 50 weeks per year) in a 70% active state, representing a business user. An assumption of 3 years is consistent with the literature, which identifies the typical lifespan of personal computers as 2-3 years in business applications and 4-5 years in residential use [21, 82, 108]. The lifetime assumed in this study would also be equivalent to an 18-month lifespan of a data center processor, operating continuously, with 95% uptime, at a 30% activity rate.

As listed in Table 4.2, the average power requirements for logic chips are taken from the 2001-2007 International Semiconductor Manufacturing Roadmap reports [86, 87, 88, 89] and, for years previous, from manufacturer's specifications. These power values represent operation at full capacity, or at a 100% activity rate.

technology node (nm)	350	250	180	130	90	65	45
year	1995	1998	1999	2001	2004	2007	2008
power (W)	14	23	25	61	84	104	146

Table 3.17. Use phase power by technology node

The average chip power demand has risen from 14 to over 140 watts over the past 15 years. The steady increase in power requirements for logic chips is the main cause of rising energy-related life-cycle impacts, as will be shown in the Results section.

In order to compare impacts on a common basis of operational performance, MIPS is used, rather than clock speed or transistor density, as a common metric of computational capacity. Transistor density is not ideal as a computational power metric because while increased transistor density usually results in increased computational power, the relation is not necessarily proportional. Although clock speed, which is dependent on transistor density, is used as a popular measure of a CPU performance, computational power is determined by the CPU's architecture, instruction set, cache size and memory speed as well as clock rate. The rate of instructions performed, usually denoted in million instructions per second (MIPS) accounts for both the speed and design of the chip but is still highly dependent on the instruction sequences used to define the metric. Though instruction rate falls short of providing a perfect description of a CPU's performance as processors with different instruction sets or architectures are not comparable, instruction rate is a more representative metric than clock rate or transistor density and is a commonly reported measure of performance. MIPS is thereby used in this analysis as a metric for comparison based on computational performance.

3.3 Results and discussion

As technology has progressed, life-cycle energy use and greenhouse gas emissions have in general been increasing per wafer and per die but decreasing when normalized by computational power. Figure 3.4 shows how total life-cycle energy demands per wafer, per die and per 1000 MIPS have changed over the period under study.

The increases in per-wafer and per-die life-cycle impacts have one dominant cause: the escalation of use-phase chip power. The growth in per-wafer impacts, however, is also due to the lengthening of the manufacturing process flow and concomitant

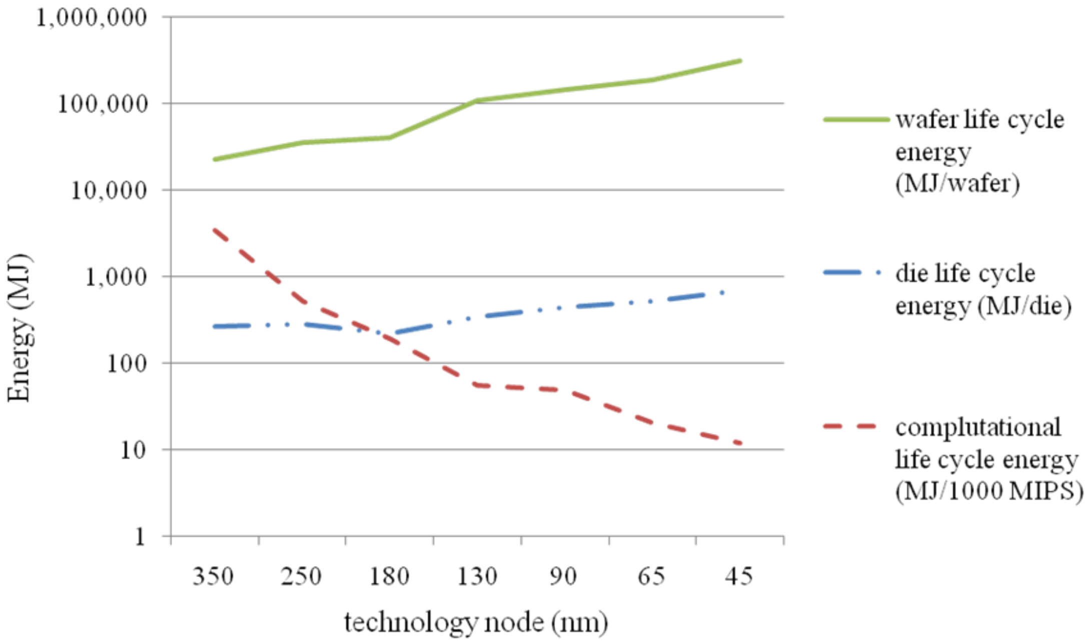


Figure 3.4. Energy use per die, per wafer and per 1000 MIPS by technology node

expansion in manufacturing infrastructure and equipment, as shown in Figure 3.5. At each technology node, the complexity of device design has increased, and the number of process steps required to produce a finished wafer has escalated. In this model, for example, production of a finished wafer entails 147 process steps at the 350 nm node, while the process flow for a 45 nm device consists of a total of 251 process steps. The lengthening of the process flow follows from increasingly detailed construction necessary to scale down the device's transistors as well as additional interconnect layers to wire them together.

Growth in manufacturing and materials-related impacts over time has been counteracted by shrinking die sizes, which allow more die to fit on each wafer. Thus, use-phase power is the lone reason for increases in impacts per die. For all technology generations, the use phase represents the largest proportion of energy-related impacts per die among the life-cycle phases. The dominance of the use phase has also increased over time, with use contributing about 51% of life-cycle GWP consumption per die at the 350 nm node, and over 95% per die at the 45 nm node. Despite the long distances that semiconductor wafers and chips are typically shipped during production and prior to use GWP of transportation is almost insignificant due to the small mass of the product (Figures 3.6 and 3.7).

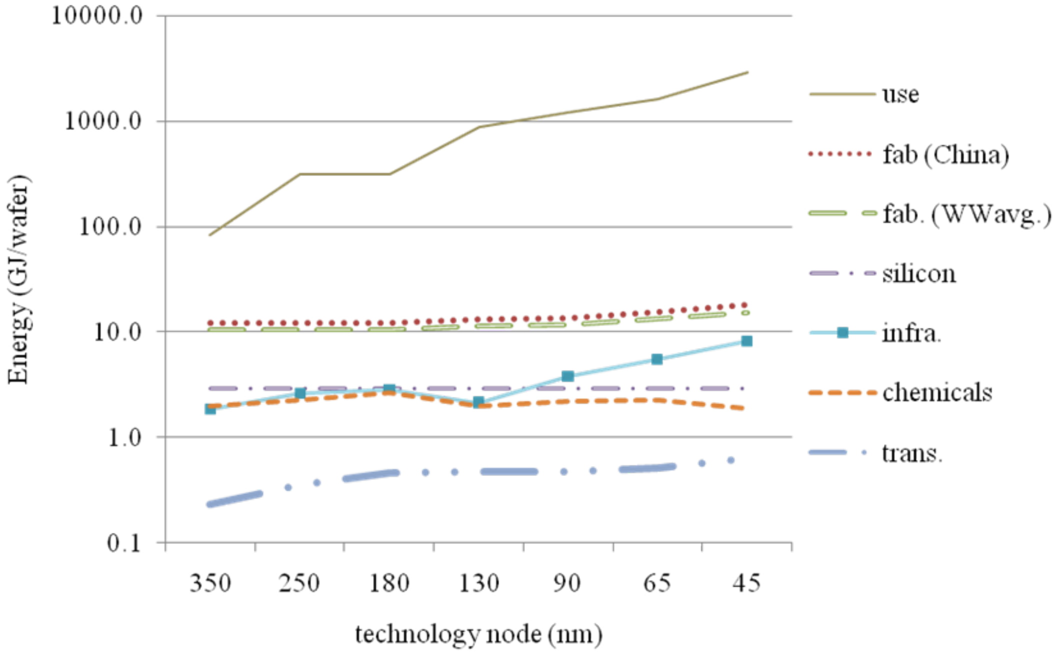


Figure 3.5. Energy use per 300mm wafer equivalent, by life-cycle stage, over seven technology nodes

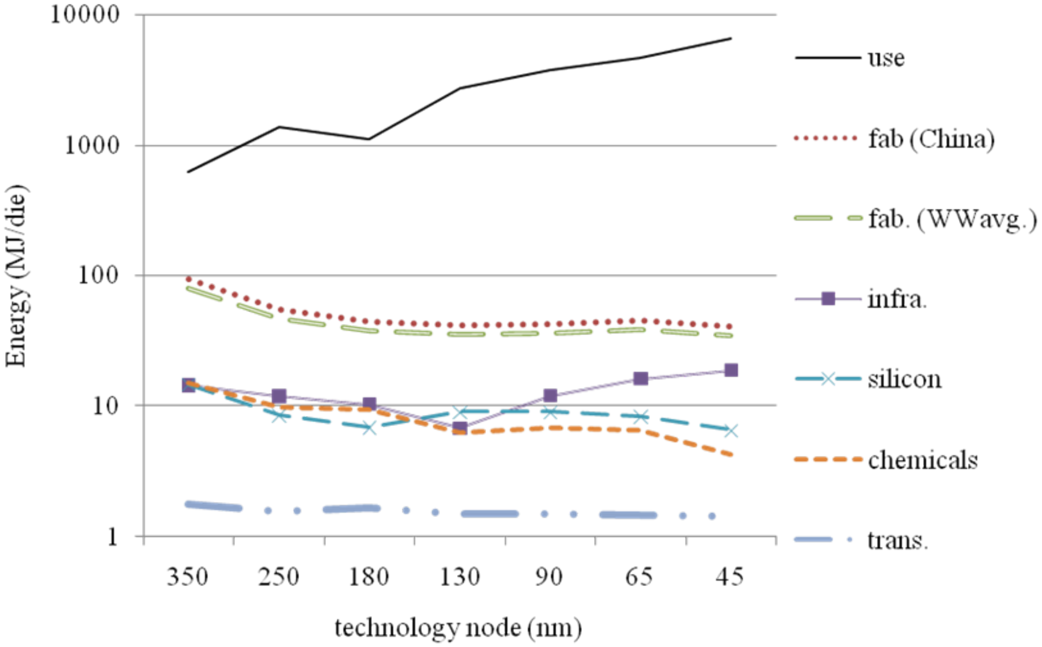


Figure 3.6. Energy use per die, by life-cycle stage, over seven technology nodes

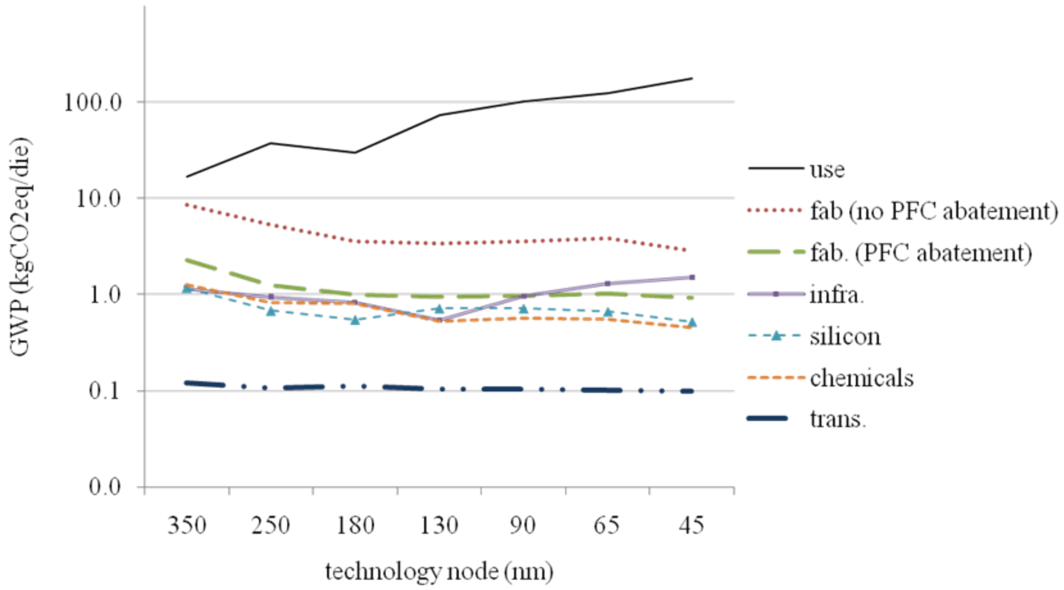


Figure 3.7. GWP per die, by life-cycle stage, over seven technology nodes

The total lifecycle GWP of emissions are distributed over the life-cycle stages similarly to life-cycle energy, with a slightly larger fraction of impacts represented in the Chinese production phase due to the additional GWP of PFC emissions, as shown in Figure 3.7. GWP of GHG emissions for the fab in China are much higher than those of the plant in California due to differences in electricity supply and the assumed lack of PFC abatement in the Chinese fab. Notably, NF_3 is not regulated by the Kyoto Protocol, but is among the PFCs GWG which are used in highest volume in the semiconductor industry [77, 43]. Although NF_3 is largely broken down into F_2 during processing, a small amount (about 1%) leaves the chamber unreacted. In this model, at the most recent technology generation, NF_3 is emitted at a rate of 4.8 grams per wafer before abatement. For a fab with a capacity of 10,000 wafer-starts per week and no PFC abatement, this would result in GWP of close to 17,000 metric tons of CO_2 equivalent per year.

The improvement of several production performance metrics has allowed reductions in the manufacturing energy and GWP per chip. Line yield reflects wasted processing used for process monitoring, testing and wafer loss in the form of damage or breakage. Although wafer damage has remained the same over the years, at about 2%, the number of test or monitor wafers per finished wafer has been reduced over the last decade, resulting in higher average line yields [113, 45, 105, 31]. Although reduced feature sizes have made maintaining wafer yield difficult, industry reports indicate that wafer yields for full scale production have not fallen with decreasing device dimensions. Mature wafer yield is assumed to be 75% for all technology nodes, based on ITRS reports [84, 86, 87, 88].

Over the period observed in this study, the computational power of an average

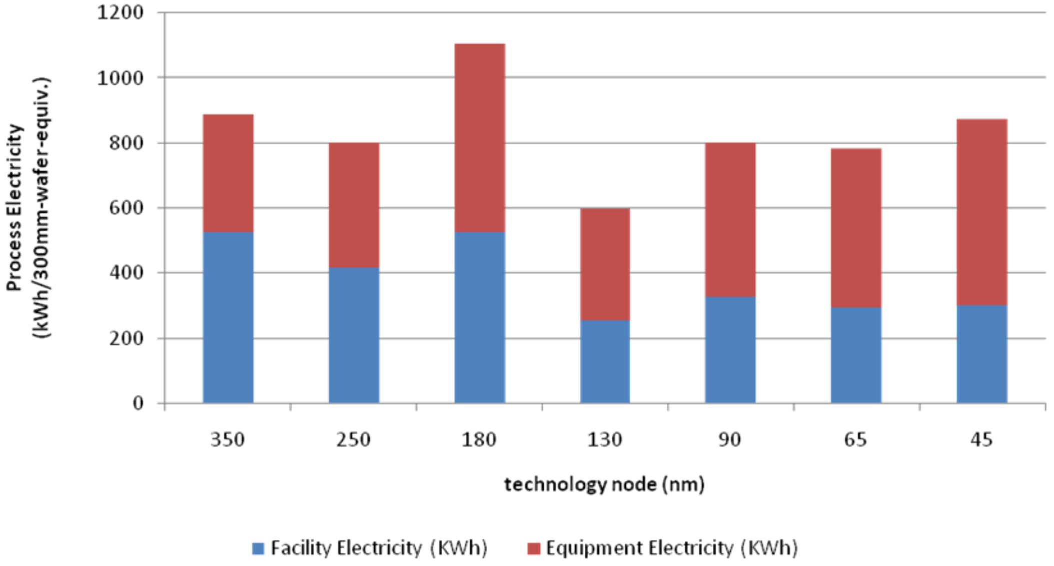


Figure 3.8. Energy use per wafer by facility and process equipment, over seven technology nodes

CPU grows approximately exponentially, which results in a significant reduction in the environmental impact per computational unit of chip (Figures 3.9 and 3.10). The question as to whether the appropriate functional unit is a single chip or 1000 MIPS worth of chip is not clear-cut because as the computational capacity per area of finished wafer has increased, the computational demands of computing have also increased. (This topic of discussion is expanded in Chapters 4 and 6.)

As web-based applications and thin clients such as cell phones are used more frequently, computational load shifts to data centers on the internet and away from desktops and laptops. In this arrangement, data center servers can allocate memory and operational demands to reduce the number of active devices, such that the functional unit may more appropriately be a metric of computing power than a physical device. However, the additional demands of communication over a network also add to total energy consumption of internet-based applications. The question as to whether a specific case of network-based thin client computing would have a lower environmental impact than local desktop computing requires consideration of additional factors concerning the application and network, however, and the results of this study should not be considered as favorable to either computing structure.

Results for energy use and GWP data per die for each life-cycle stage at every generation are provided in the Appendix, in Tables **??** and **??**. To determine impact values for a specific logic chip, the appropriate technology generation (e.g., 65 nm) and chip size should be used. (The average chip areas used in this study are listed in Table 3.14). Dual core and quad core CPUs, which are larger, will have higher impact values for all life-cycle stages before use. If the chip power is known, recalculate the use phase power, as the device's rated power is the most important variable in

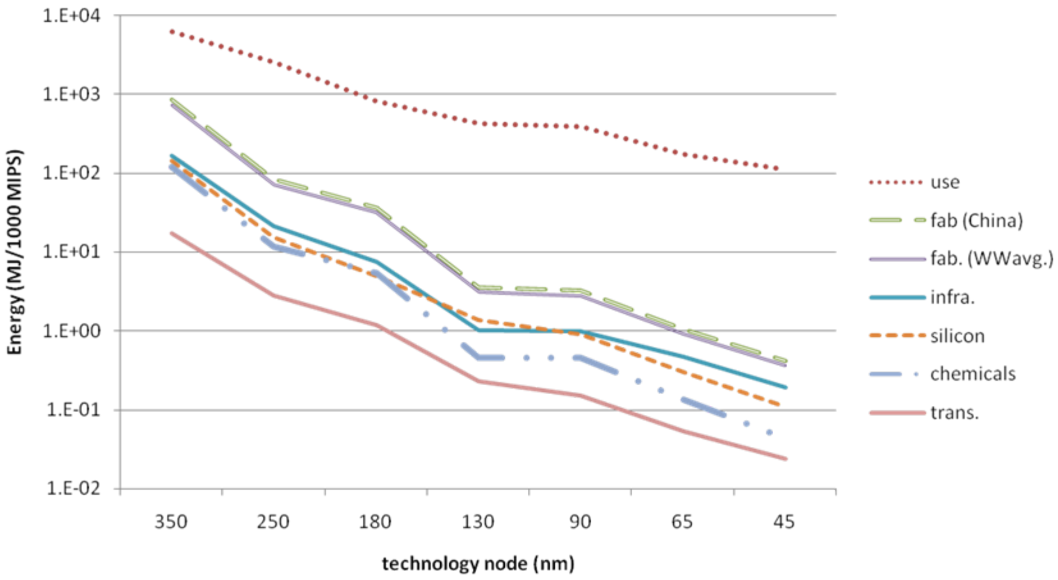


Figure 3.9. Life-cycle energy use per computational power

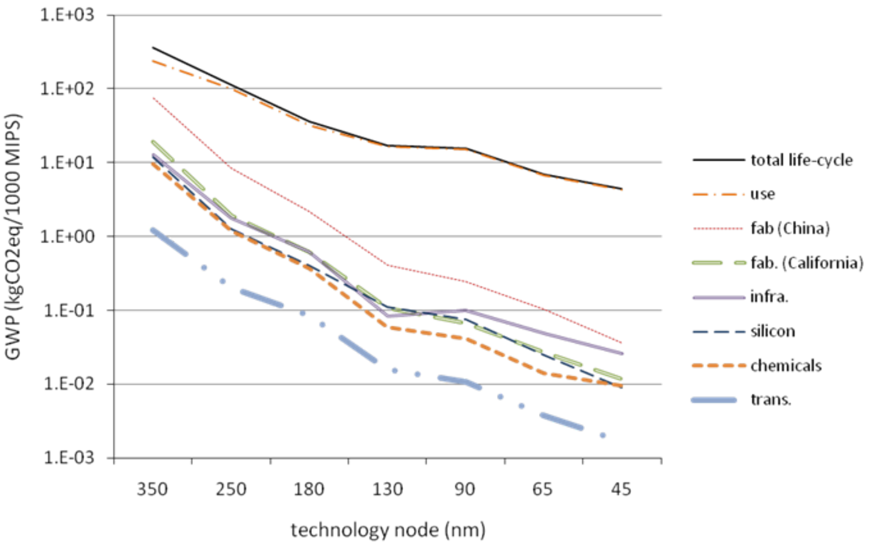


Figure 3.10. GWP per computational power

determining life-cycle energy demand. If the subject of the LCA is a computer or other electronic applicance, the efficiency of the power supply should be considered.

3.3.1 Uncertainty Assessment

The value of this or any LCA is wholly dependent on the quality, accuracy and precision of the underlying data. Results are presented here with their associated uncertainty to provide a more accurate representation of the possible range of impacts, and uncertainties are analyzed to evaluate their impact on the results. Best case, worst case and expected values of results are calculated from lower bound, upper bound and nominal model parameters. The energy and GWP of emissions at each life-cycle stage are presented with their uncertainty ranges for earliest technology generation, the 350nm node in Figures 3.11 and 3.12, the most recent 45 nm, Figures 3.13 and 3.14.

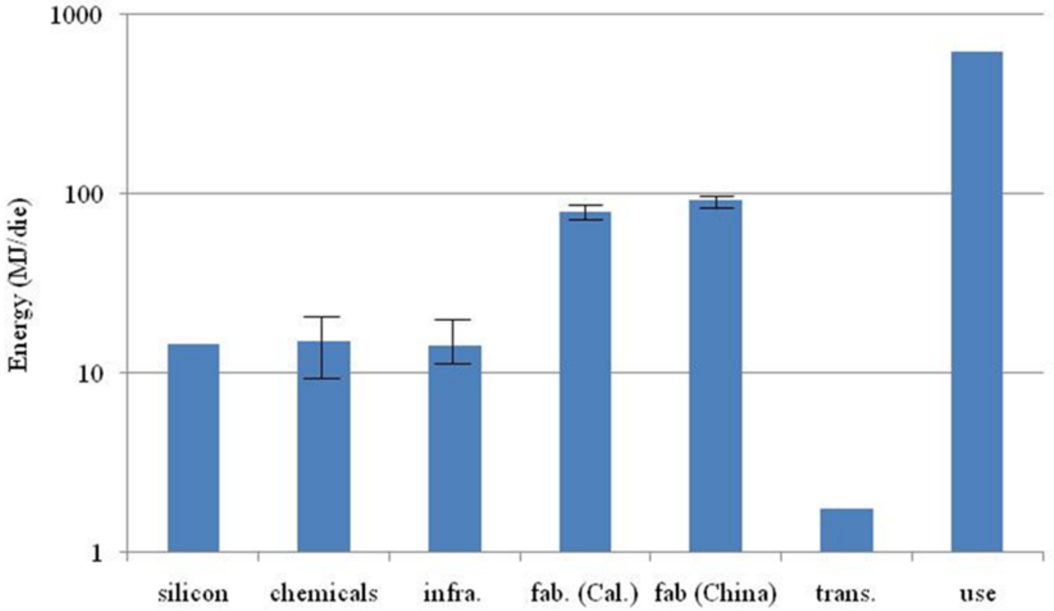


Figure 3.11. Energy use per die by life-cycle phase, 350 nm node

The life-cycle stage with the greatest data uncertainty is chemical production. Of the chemicals included in the model, 30 are represented by process data from textbooks and manuals, 27 are accounted for by using EIO-LCA and the remaining 53 are assigned a common value based on a previous study of chemical life-cycle inventory modeling [51]. The data for the latter group has an uncertainty range of 75% below and 25% above the nominal value [51], which constitutes the largest contribution to uncertainty in the model's chemicals data. The chemicals with the greatest contribution to uncertainty differ for each technology generation, but the top contributors

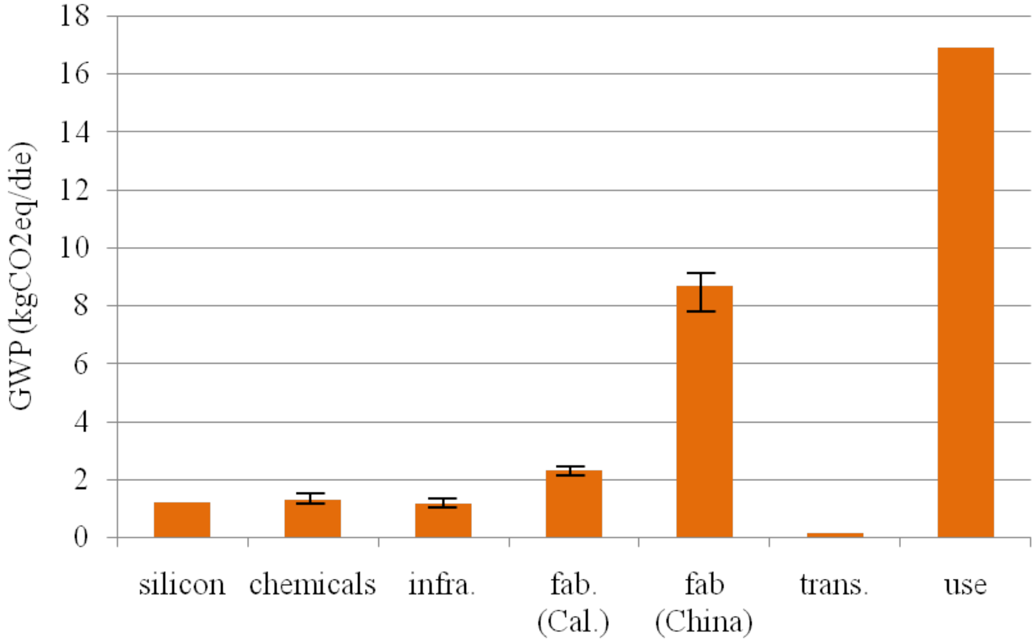


Figure 3.12. GWP of emissions per die by life-cycle phase, 350 nm node

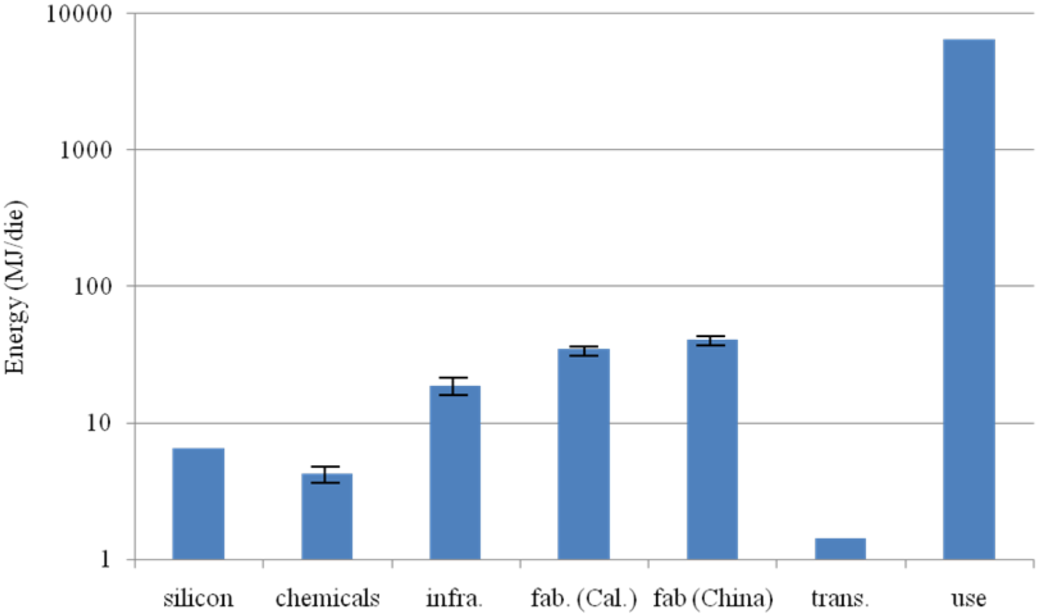


Figure 3.13. Energy use per die by life-cycle stage, 45 nm node

Note: log scale attenuates appearance of uncertainty

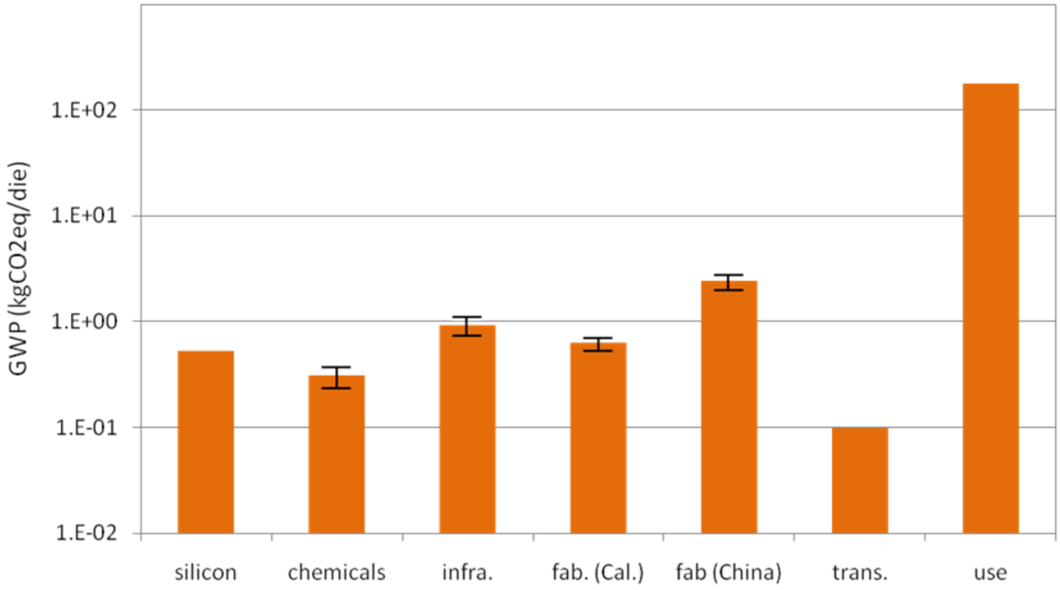


Figure 3.14. GWP of emissions per die by life-cycle phase, 45 nm node

Note: log scale attenuates appearance of uncertainty

for all nodes include ammonia, CMP slurries and agents, phosphine (PH_3), carbon tetrafluoride (CF_4), hydrogen and silane (SiH_4). Life-cycle data for ultra high purity forms of these chemicals would have the greatest benefit to uncertainty reduction in future LCA of semiconductors.

3.3.2 Sensitivity Analysis

To evaluate the ramifications of changes to model parameters, a sensitivity analysis is performed. Given that the parameter values are limited within a finite range, and because the output of the model is monotonic over these values, the sensitivity of the model is evaluated using local methods via differential analysis [65]. The simple derivative is used to determine the absolute (S_x^E) and relative sensitivities ($\overline{S}_x^E$) of energy consumption and global warming potential to each model parameter (Equations 3.14 and 3.15). Energy and GWP impacts have the highest relative sensitivity to wafer yield, line yield and net die per wafer, followed by tool and facility utilization factors. Although the relative sensitivity of impacts to use-phase power is lower than to other parameters, processor power demand is the variable with the most absolute influence over life-cycle energy in all technology generations. The energy and GWP intensity of chemical production, which have the largest uncertainty of all model variables, are among the parameters to which impacts results are least sensitive.

$$\text{Absolute sensitivity:} \qquad S_x^E = \left.\frac{\delta E}{\delta x}\right|_o \tag{3.14}$$

$$\text{Relative sensitivity:} \qquad \overline{S}_x^E = \left.\frac{\delta E}{\delta x}\right|_o \frac{x_o}{E(x_o)} \tag{3.15}$$

Sensitivity of Energy Consumption

Of all production-related parameters, the total life-cycle energy per die is most sensitive to the line yield (Y_{line}), wafer yield (Y_{wafer}), and gross die per wafer (n_{die}), as shown in equations (3.16), (3.17) and (3.18). These relations reveal that the lower the original yield, the greater the influence a percentage change in yield improvement has on energy consumption. At the 350 nm node, for example, the line yield is 58% and the wafer yield is 75%, so improvement in line yield should be a higher priority than wafer yield. At the 45 nm node, however, the line yield is at 88% while the wafer yield is 75%, so an increase in the latter would have a greater effect.

$$\frac{\delta\left(e_{total}\right)}{\delta Y_{line}} = -\left(Y_{line}\right)^{-2} e_{subtot} \tag{3.16}$$

$$\frac{\delta\left(e_{total}\right)}{\delta Y_{wafer}} = -\left(Y_{wafer}\right)^{-2} e_{subtot} \tag{3.17}$$

$$\frac{\delta\left(e_{total}\right)}{\delta n_{die}} = -\left(n_{die}\right)^{-2} e_{subtot} \tag{3.18}$$

$$\begin{aligned} where\ e_{subtot} &= \left[\sum_{j=1}^{m} e_j^{\$} c_j \sum_{i=1}^{n} m_{ij} + \sum_{k=1}^{q} e_k^m \sum_{i=1}^{n} m_{ij}\right] \\ &+ \left[\sum_{i=1}^{n} \frac{t_i\, p_i + \hat{e}_w^v\, \hat{w}_i\, t_i}{\varepsilon_i\, u} + \left(\frac{p_{hvac} + p_{lt} + p_{trt} + p_{cda} + p_{exh}}{c}\right)\right] \\ &+ \left[\sum_{l=1}^{2} \left(d_t\, e_t^d\, m_l + d_r\, e_r^d\, m_l + d_b\, e_b^d\, m_l + d_{air}\, e_{air}^d\, m_l\right)\right] \end{aligned}$$

The energy used in production alone is also equally sensitive to both the tool and process utilizations (the percentage time that the tool is on and the percentage of time that it is active while it is on) as to yield. Although the idle power is lower than active power, any time spent in idle mode results in wasted power. Equivalently, any decrease in tool utilization results in wasted power at the facility level, because fans, pumps and facility systems continue to operate during tool downtime. Because utilization factors affect only the production stage rather than all life-cycle stages, their influence on life-cycle impacts is weaker than that of the yield parameters.

$$\frac{\delta\left(e_{total}\right)}{\delta\varepsilon_i} = \varepsilon_i^{-2}\left(\frac{1}{u\,Y_{wafer}Y_{line}\,n_{die}}\right)\left[\sum_{i=1}^{n} t_i\,p_i + \hat{e}_w^v\,\hat{w}_i\,t_i\right] \tag{3.19}$$

$$\frac{\delta\left(e_{total}\right)}{\delta u} = u^{-2}\left(\frac{1}{\varepsilon_i\,Y_{wafer}Y_{line}\,n_{die}}\right)\left[\sum_{i=1}^{n} t_i\,p_i + \hat{e}_w^v\,\hat{w}_i\,t_i\right] \tag{3.20}$$

The capacity of the facility, i.e., the number of wafers produced per day or week, can also raise or lower the energy consumption, as shown in equation (3.21). However, capacity is limited by a number of factors. Production volume is governed by throughput, the number of manufacturing tools in the fab and the design of the production flow. The quantity of tools can be increased only up to a point before facility systems must be resized, or their efficacy suffers. In other words, capacity (c) is limited by the facility power consumption parameters $p_hvac, p_lt, p_trt, p_cda$ and p_exh in a relationship that is described outside of this model.

$$\frac{\delta\left(e_{total}\right)}{\delta c} = \frac{1}{c^2}\frac{1}{Y_{wafer}Y_{line}\,n_{die}}\left(p_{hvac} + p_{lt} + p_{trt} + p_{cda} + p_{exh}\right) \tag{3.21}$$

Changes in yield, utilization and capacity have a nonlinear effect on life-cycle energy and global warming emissions, and thus have high relative sensitivity values (equation (3.23)) while the use-phase power, the global warming intensity of electricity (at the locations of production and of use) and the power consumption of facility systems and individual tools all have a direct relationship (equation (3.22)), with varying degrees of influence.

$$\frac{\delta\left(e_{total}\right)}{\delta p_{fac}} = \frac{1}{Y_{wafer}Y_{line}\,n_{die}}\left(p_{fac}\right) \tag{3.22}$$

$$\left|\frac{\delta\left(e_{total}\right)}{\delta Y_{wafer}}\right|_{Y_{wafer}^{45nm}} = -\left(Y_{wafer}^{45nm}\right)^{-2} e_{subtot}^{45nm} \tag{3.23}$$

The rank of these variables according to their influence over life-cycle energy and GWP emissions differs for each technology node. However, impacts have the highest absolute sensitivity to use-phase power consumption at all technology nodes. (The fraction of life-cycle energy consumption taken by the use phase changes over the generations but remains high, as illustrated in the Results section.) At the 45 nm node, life-cycle energy consumption has the next highest absolute sensitivity to the primary energy intensity of use-phase electricity followed by the power consumption of wafer fabrication equipment and facility operations.

Sensitivity of GWP Impacts

Life-cycle GWP, like energy, has the highest relative sensitivity to line and wafer yields, and net die per wafer. At the 45 nm node, GWP has the highest absolute sensitivity to the power consumption of electricity in the use phase, followed by the GWP intensity of use-phase electricity, the global warming intensity of transportation, the GWP of electricity used in wafer manufacturing and the energy consumption of wafer fabrication in descending order.

$$\frac{\delta\left(g_{total}\right)}{\delta g_e^{use}} = e_{use} \tag{3.24}$$

$$\frac{\delta\left(g_{total}\right)}{\delta g_x^{d}} = \frac{1}{Y_{wafer} Y_{line}\; n_{die}} \sum_{i=1}^{2} \left(d_{i,x}\; m_i\right) \tag{3.25}$$

$$\frac{\delta\left(g_{total}\right)}{\delta g_e^{prod}} = e_{prod} \tag{3.26}$$

3.3.3 Data Quality

A data quality assessment following the template of Weidema is provided in Table 3.18 [107]. The quality of data is high: all of the LCA data, with the exception of chemical and infrastructure data, come from sources that are specific to the process, geographical location and time period of the study.

	Reliability	Completeness	Temporal correlation	Geograph. correlation	Technical equival.
Chemicals (Process LCA)	2	5	5	2	2-3
Chemicals (EIO-LCA)	2	1	4	2	3
Process electricity (California mix)	1	1	1	1	1
All other electricity (world mix)	2	3	2	2	2
Wafer fabrication: atmospheric furnace and litho.	2	1	3	n/a	2
Wafer fabrication: all other processes	1	1	1	n/a	1
Point-of-use abatement	1	1	1	n/a	1
Facility abatement	2	2	2	n/a	1
Transportation	2-3	1	1	2	2
Use (chip power, performance)	1	2	1	1	1

Table 3.18. Data quality assessment

3.4 Discussion

The results of this study enable LCA practitioners to answer important questions concerning the energy-related environmental impacts of computing with greater certainty than ever before. The life-cycle impacts for energy and GWP of semiconductor chips presented in this analysis are more complete, accurate and transparent than those of any previous study, and data are presented for chips spanning many generations, from 1995 to 2010. The quality of data is high: all of the LCA data, with the exception of chemical and infrastructure data, are specific to the process, geographical location and time period of the study. Though life-cycle energy and emissions data for high purity chemicals would be useful for future semiconductor LCA, the uncertainty in chemical data is mitigated by the comparatively small contribution of upstream activity to total life-cycle energy and GWP. Energy and GWP impacts for semiconductor logic chips are clearly dominated by the use phase. Chip power demand and the GWP of use-phase electricity are thus the variables with the largest influence over energy-related life-cycle impacts. Production yield, die size, geographical location or electrical energy supply of the plant and the choice to abate

PFCs are the most important metrics and decisions to be made concerning energy and GWP impacts in the production stage.

Chapter 4

Life-cycle Assessment of CMOS Logic

4.1 Introduction

Determination of the life-cycle environmental and human health impacts of semiconductor logic is essential to a better understanding of the role information technology can play in achieving energy efficiency or global warming potential reduction goals. This study provides a life-cycle assessment for digital logic chips over 7 technology generations, spanning from 1995 through 2010. Environmental indicators include global warming potential, acidification, eutrophication, ground-level ozone (smog) formation, potential human cancer and non-cancer health effects, ecotoxicity and water use. While impacts per device area related to fabrication infrastructure and use-phase electricity and have increased steadily, those due to transportation and fabrication direct emissions have fallen as a result of changes in process technology, device and wafer sizes and yields over the generations. Electricity, particularly in the use phase, and direct emissions from fabrication are the most important contributors to life-cycle impacts. Despite the large quantities of water used in fabrication, water consumption is primarily driven by electricity generated for use-phase power. Reducing power consumption in the use phase is the most effective way to limit impacts, particularly for the more recent generations of logic.

The complementary metal oxide semiconductor (CMOS) transistor structure is the most common form of digital logic used in electronics today. This chapter presents a life-cycle assessment (LCA) for generic CMOS logic at each technology node over a 15 year period, from the 1995-era 350 nm node to the 45 nm node, which will enter large scale production in 2010. The purpose of this chapter is to provide a detailed, complete, transparent and accurate inventory of the environmental impacts of many generations of logic chips in order to investigate trends in emissions over time and to allow LCA practitioners to more accurately model electronic equipment, as well as services enabled by electronics. Previous published work in the area of semiconductor LCA has included four environmental impact studies from industry [100, 83, 99, 111] which report impacts for wafer fabrication and, in some cases, also use and the production of materials. Most do not include impacts associated with the production of facility infrastructure or process chemicals (aka, 'upstream' impacts). Possibly because these reports have all been conference papers supported by spoken presentations, they lack complete explanation of data collection methodologies and do not report complete inventory data. None of these studies mention the use of measurement to determine the mass of emissions from the fabrication facility but rather use estimation methods or do not explain whether or how they account for facility emissions. These studies also do not report data uncertainty or discuss the influence of data uncertainty on results. Several researchers have noted that the lack of LCA data for semiconductor devices is a stumbling block in LCA of electronics, and that there is particular need for more complete or transparent LCA of semiconductors [76, 75, 62, 109, 11, 104, 10]. Academic work related to semiconductor LCA includes a study from Murphy which presents a methodology for parametric semiconductor life cycle inventory (LCI) models based on process specifications [62]. Williams has reported energy consumption in logic manufacturing [23] and created an LCA of a memory chip, using both economic-level data and data provided from anonymous industrial contributors, and highlights the importance of upstream impacts and the need for more accurate LCI data for high purity chemicals [109, 108, 58]. Plepys also underscores the need for accounting of the life-cycle stages preceeding wafer fabrication in semiconductor LCA [76, 75]. In an earlier paper, Plepys explored a rebound effect in ICT consumption, analogous to the rebound effect of dropping energy prices, whereby advancing technology inciteps the need for ever faster and more powerful ICT and counteracts the environmental efficiencies of technology advancement [74]. A more recent paper from Williams re-introduces this topic with an examination of different functional units in semiconductor LCA [23], and the discussion of functional unit choice is continued in this chapter.

In this study, the issues with industry-reported LCA studies described above are addressed. Material demands and emissions have been determined using Fourier-transform infrared and mass spectrometric measurement of process inputs, chamber emissions and post- point-of-use abatement emissions. Upstream impacts associated with fabrication facility (fab) infrastructure and process chemicals, as well as water supply are included. The uncertainty associated with each type of data is reported and the sensitivity of results to uncertainty and changes in model parameters is evaluated. Methodology, model assumptions, and inventory data are stated so that the study is transparent, reproducible and adaptable so as to be useful in downstream LCA of electronics. By presenting LCA data for many generations of logic, different types of electronics may be modeled. Chips at the 350 nm node (first produced in volume in 1995) are still currently used in embedded logic for appliances and toys, while an average new personal computer purchased today would contain 65 nm logic. The term 'technology node' and the measurements of 350 to 45 nm refer to the half-width of the first interconnect layer associated with memory of a given technology generation, and are used as shorthand for relative transistor sizes[85].

4.2 Methods

These life-cycle inventories (LCIs) describe a production scenario with wafer manufacturing in Santa Clara, California, using chemicals, equipment and construction materials produced in the U.S. "Back-end" operations (die packaging and testing) are located 3000 miles away. The inventory is a hybrid model, containing primarily process data, supplemented by economic input-output LCA (EIO-LCA) data from the Carnegie Mellon database [15] where process data are unavailable. The functional unit of the study is one die over a lifetime of 6,000 hours, though data are provided in the Supporting Information to reevaluate these results for a different use phase chip power or lifetime and to allow normalization by computational power or number of transistors.

The functional unit drastically alters how the life-cycle impacts of semiconductors appear and there are arguments for every option of functional unit: an average device, a certain device area, a metric of computational power or a given number of transistors. The natural first choice is a measure of computational power, such as one million transistors, because this seems to reflect a constant functionality. However, the functionality of one million transistors has decreased over time, as the average personal computer has required increasing computational power to serve roughly the same purposes over the past 15 years. Presenting impacts per million transistors shows dramatic decreases in impacts over time which do not match real-world dynamics [74, 13] as, for example, one million transistors today do not provide the same functionality as a decade ago in personal computing applications. Because this study spans a fifteen year period, results reported per million transistors would exhibit misleading trends. The functional unit of an average-sized personal computer (PC) central processor for each year reflects a set functionality over time because this unit serves the same product function within its corresponding timeframe. The functional unit used in this study is thus one average-sized die, as defined for cost-performance CMOS logic by the International Technology Roadmap for Semiconductors (ITRS) [85] but these results may also be adapted to represent any CMOS logic-based chip, if the chip size or number of transistors is known.

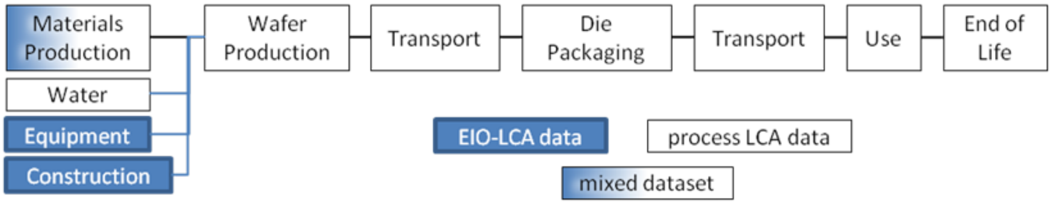


Figure 4.1. Life-cycle stages with data source types

The LCIs for wafer production are built on a set of process, device and fab spreadsheet models. Each process model represents one process step (e.g., chemical vapor deposition) with a set of energy and mass flows per wafer into and out of the manufacturing equipment, based on measurements taken at the process chamber inlet, chamber outlet and post point-of-use (POU) abatement. Each device model defines the device size, wafer size and typical yield for the device's technology generation as well as the process flow - the order and number of process steps used to make the device. Chip sizes and yield models are those developed through ITRS[85]. Each fab model represents all of the infrastructure and fab facility systems beyond the process tools and POU abatement equipment, which are characteristic to each technology node. The energy and resource demands for each fab model are based on the capacity of its facility systems, which change with wafer size, as well as the demands for utility nitrogen, process cooling water, industrial city water and abatement chemicals, as determined by the process flow at each technology node. The fab models also reflect technology and operational changes which have resulted in facility energy efficiency improvements over the last fifteen years.

These LCIs represent the impacts associated with all life-cycle stages, though data for end-of-life effects are limited. Studies of end-of-life electronics have measured the end effects of computer disposal which largely represent emissions (dioxins, brominated flame retardants, etc.) from the breakdown or combustion of a computer's more massive components. In this study, EOL impacts include only the lead emissions from wire-bonding solder contained inside the packaged chip. While there may be other environmental or human health effects from the decomposition of a logic chip, none have yet been measured. EOL lead emissions stop at 2006, when the European Union's Restriction on Hazardous Substances (RoHS) regulation banned lead-containing solders. (By 2006, most manufacturers switched to lead-free solder for products shipped worldwide even though RoHS only affects products sold in Europe.)

4.2.1 Manufacturing process power and emissions

The mass flows for each process step, with the exception of lithography and certain thermal steps, have been determined using in-line mass spectrometry and Fourier transform infrared (FT-IR) spectroscopy. (Details of the process models can be found in a previous, related study of an individual chip [55].) Each emission measurement closes mass balance within 10% of chamber or POU abatement system inputs and thus has a maximum uncertainty of +/- 10%. Process equipment power consumptions are based on measurements taken at Applied Materials which have an associated error of +/- 2.5%. [55] Emissions and power consumption of photolithographic and thermal processes are taken from the process measurements from Murphy [62], supplemented by data from an unpublished academic report from Peterson[69].

4.2.2 Facility energy efficiency

The techniques used in industry to optimize the sizing and operation of fabs include a long list of practices, including more efficient cleanroom airflow (including the use of mini-environments), reduced clean dry air (CDA) and nitrogen pressures, reduced exhaust system pressures and increased sizing of cooling towers to allow reduced chiller sizes. More information concerning the sizing and design of facility systems in the fab models is given in the previous chapter (Table 3.13).

4.2.3 Abatement

Both point of use (POU) and central facility abatement systems are included in the model. The central abatement systems in each fab model include a central acid scrubber, an ammonia scrubber, a volatile organic compound (VOC) oxidizer and an acid waste neutralization unit as well as copper CMP and fluoride wastewater treatment systems. The abatement efficiencies of these central systems for gaseous acids, ammonia and VOCs and are based on measurements published by semiconductor industry members [91, 60, 16, 17, 97, 90]. Conversion of liquid waste is calculated based on expected reactions and the pH requirements of effluents to the public water treatment system. Combustion and water scrubbing, plasma oxidation and cold bed adsorption POU systems are associated with certain process steps (see Supporting Information). The abatement efficacies of POU units are taken from pre- and post-POU abatement emissions measurements[55].

The oldest and most prominent member of the facility abatement systems is the "house scrubber", an enclosed, water-sprayed matrix of inert mesh. This system captures gaseous inorganic emissions, largely acids, which are sent as liquid effluent to the acid waste neutralization (AWN) system.

Gaseous ammonia is emitted in small quantities from most nitride chemical vapor deposition (CVD) processes, either as unreacted precursor or as a byproduct emission. Fabs with gaseous ammonia exhaust are fitted with a separate ammonia exhaust system and scrubber in order to prevent particulate formation, clogging and corrosion in the acid exhaust system. Gaseous ammonia waste is captured using a water scrubber similar in design to the facility acid scrubber but about a tenth of the size [66].

CMOS logic fabs use large quantities of both liquid ammonia and sulfuric acid in wafer cleaning processes. Liquid ammonia, collected via drain, may be recycled on site using membrane filtration or distillation, or treated using sulfuric acid to produce ammonium sulfate. In this model, the latter is assumed and thus ammonium sulfate, which results from the neutralization of ammonia and sulfuric acid effluents in the AWN system, is among the liquid wastes produced in the highest volume by wafer fabrication in this model.

There are several combinations of treatment methods which may be used to address the liquid effluent of copper CMP processes. Copper CMP waste treatment is modeled from the work of Krishnan [57, 54] as a sequence of ion exchange, microfiltration, activated carbon filtering and filter pressing. An ion exchange resin bed removes copper and is regenerated at the fab using sulfuric acid, to produce $CuSO_4$ liquid waste. Slurry particles are filtered and pressed into a solid non-hazardous waste which is sent to a landfill. The remaining water contains less than 2 ppm dissolved copper and is sent to the acid waste neutralization (AWN) system. The concentrated $CuSO_4$ liquid is sent offsite as hazardous waste to be electrowinned for copper recovery or possibly purified into a useable byproduct.

The fluoride waste system treats fluoride wastewater using CaOH and a flocculant material to produce non-hazardous solids containing calcium fluorite (CaF_2). This process is modeled stoichiometrically with a worst-case HF abatement efficiency assumed as 90%.

A summary of the process types requiring POU abatement systems is given in table 4.1. CVD steps emitting PFCs require combustion and water scrubbing or plasma POU abatement because water scrubbing alone does not break down these compounds (and in some cases may form reactive fluorinated byproducts). CVD steps emitting silane or hydrogen above flammable concentrations also require immediate combustion of their emissions in POU systems due to the risk of explosion in exhaust lines. Implant processes emitting phosphine and arsine are abated using cold bed adsorption systems.

POU abatement type	Processes
Plasma	Nitride, oxide, advanced lo-k dielectric and undoped silicate glass (USG) etch
Burn and scrub	all other CVD and etch processes emitting PFCs or flammable gases
Cold bed adsorption	Implant

Table 4.1. POU abatement

4.2.4 Facility Energy Efficiency

The techniques used in industry to optimize the sizing and operation of fabs include a long list of practices, including more efficient cleanroom airflow (including the use of mini-environments), reduced CDA and nitrogen pressures, reduced exhaust system pressures and increased sizing of cooling towers to allow reduced chiller sizes. The facility models in this study are described completely in the previous chapter (Table 3.13).

4.2.5 Abatement

Both POU and central facility abatement systems are included in the model. The central abatement systems in each fab model include a central acid scrubber, an ammonia scrubber, a volatile organic compound (VOC) oxidizer and an acid waste neutralization unit as well as copper CMP and fluoride wastewater treatment systems. The abatement efficiencies of these central systems for gaseous acids, ammonia and VOCs and are based on measurements published by semiconductor industry members [91, 60, 16, 17, 97, 90]. Conversion of liquid waste is calculated based on expected reactions and the pH requirements of effluents to the public water treatment system. Combustion and water scrubbing, plasma oxidation and cold bed adsorption POU systems are associated with certain process steps (see Supporting Information). The abatement efficacies of POU units are taken from pre- and post-POU abatement emissions measurements [55].

4.2.6 Environmental impact metrics

Environmental effects are characterized using the mid-point impact factors established in the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI), a program developed by the US EPA. About a third of the TRACI impact factors used in the model are specific to California, and the remaining are representative of the United States in general. All photochemical smog formation impact factors are for California, and for some chemicals acidification, eutrophication, human health criteria and human non-cancer health impact factors are also California-specific. Impacts for ecotoxicity and carcinogenic human health effects are all US-general. Because impact factors specific to Costa Rica are not available, the same factors are used for wafer manufacturing and back-end operations. Global warming potentials are those defined in the 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report [48]. Because wafer production dominates water consumption among the life-cycle stages, water use is reported as equivalent to the direct quantity utilized in wafer manufacturing. Land use is omitted from the inventory due to a lack of land use data for all life-cycle stages.

4.2.7 Electricity generation emissions factors

The life-cycle GWP of electricity from coal, natural gas and large-scale hydroelectric and solar are taken from Pacca [67], while that of nuclear power is from Fthenakis [33]. EPA GWP emissions factors are used for geothermal and biomass electricity [28]. For non-greenhouse gases, only direct emissions from Santa Clara's electric utility (Pacific Gas and Electric) are included in the model. Average NO_x, SO_2, and mercury emissions for Pacific Gas and Electric's conventional fuel plants are taken from the EPA's eGrid database [27]. Water consumed in electricity generation is taken as the U.S. average of 1.76 liter/kWh[52].

4.2.8 Use phase power

The average power requirements for logic chips are taken from the 2001-2007 International Semiconductor Manufacturing Roadmap reports [85] and, for years previous, from manufacturers' specifications (table 4.2)

year	1995	1998	1999	2001	2004	2007	2010
technology node (nm)	350	250	180	130	90	65	45
power (W)	14	23	25	61	84	104	146

Table 4.2. Use phase power by technology node

The use phase power consumption of the chip is calculated assuming an average power supply efficiency of 70% and a product lifetime of 6,000 hours (3 years, 8 hours per day, 5 days per week, 50 weeks per year) consistent with the literature [21, 82]. For the base case, a CPU activity rate of 17% is used, based on the SYSMark standard [72] and an average activity of a workday [47], to represent the applications and use patterns of a business user. For the upper bound, a data center case is represented with 33% activity rate, 24 hours per day operation (with 95% uptime), and a lifetime of 18 months. The lower bound characterizes residential use, with 3 hours of use per day, 250 days per year at 15% activity, for 5 years.

The average chip power demand has risen from 14 to over 140 watts over the past 15 years. The steady increase in power requirements for logic chips is the main cause of rising energy-related life-cycle impacts, as shown in the Results section.

4.3 Results and discussion

4.3.1 Global warming potential

Global warming emissions per die have risen at each successive technology node (Figure 4.2). Use-phase electricity consumption generates the majority of life-cycle GWP impacts at all nodes, with an increasing share over time. Device power in the use phase contributes an average of 75% across all nodes, and 92% at 45 nm. If POU abatement is used for PFC-emitting wafer processes, as assumed for these results, fabrication (including electricity and natural gas use, and direct emissions) emits on average 6% of life-cycle GWP in all years, and 2% at the most recent generation. (Without PFC abatement, fab emissions are 8 to 17 times higher and become the second largest origin of GWP after the use phase.) GWP from production of silicon, process chemicals and the facility infrastructure (the fab building and equipment) each account for less than 7% of life-cycle GWP at the 350 nm node, and represent successively smaller fractions in the following years. The sensitivity of life-cycle energy and GWP to production factors is analyzed in the previous chapter.

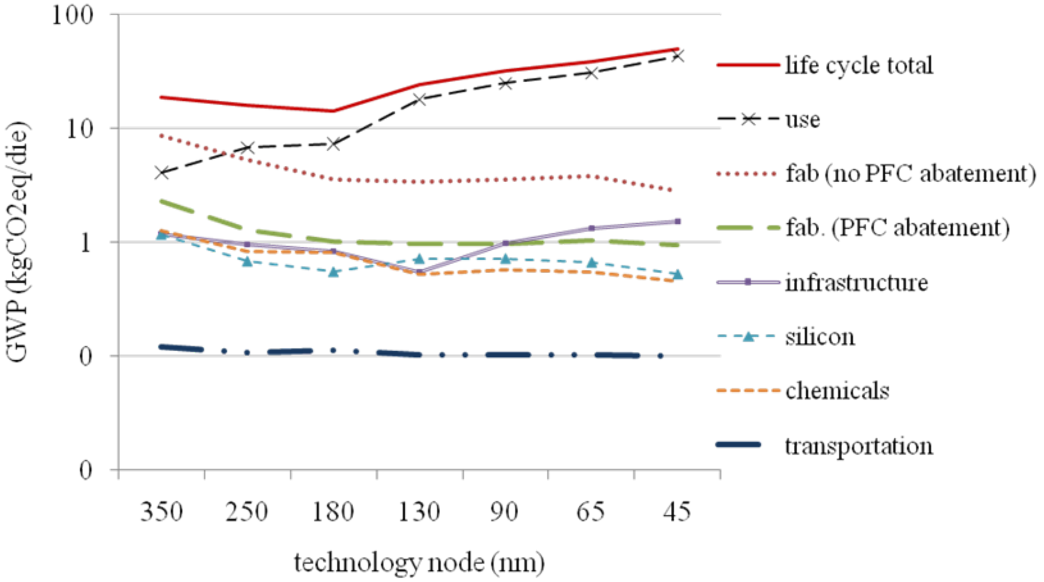


Figure 4.2. Global warming potential per die by life-cycle stage, over 7 technology nodes

4.3.2 Water use

Life-cycle water consumption is dominated by electricity generation and the overall increase in water use is driven by climbing use-phase power as illustrated in Figure 4.3. Water used in fabrication has fallen significantly per device over the period under study due to a number of changes in wafer processing. At the 130 nm node front-end-of-line (FEOL) photoresist removal steps switch from a wet sulfuric acid-hydrogen peroxide mixture (SPM) strip, to a dry plasma process which reduces the number of "wet" steps (in which the wafer is submerged in an UPW-based solution). As with transportation and fabrication emissions, the switch to 300 mm wafers at the 130 nm node results in a reduction in water use but in this case the process change plays a greater role. Recycling of post-process UPW is not assumed in any of this study's fabs.

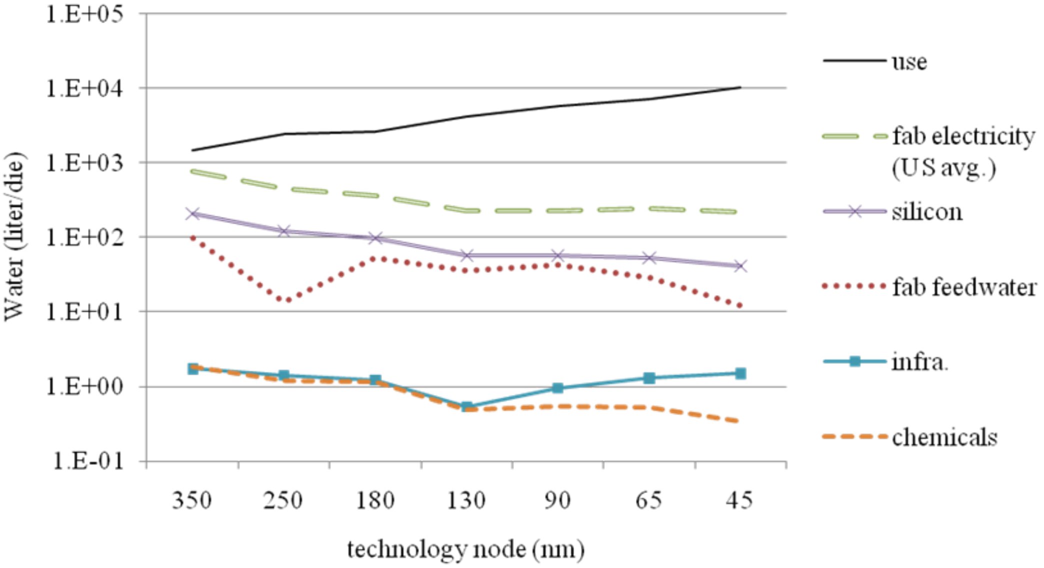


Figure 4.3. Water use per die, by life-cycle stage, over 7 technology generations

Land use is not included in this study because data concerning the land utilization for processes throughout the life-cycle were not attainable, and the land occupied by the fab alone is not sufficiently representative of the entire life-cycle.

4.3.3 Photochemical oxidant formation, acidification and eutrophication impacts via air emissions

Impacts from air emissions in the categories of photochemical oxidant formation (POF), acidification and eutrophication are primarily caused by use-phase electricity. Taking an average across all technology nodes, use phase electricity is accountable for 81% of smog formation, 80% of acidification and 81% of eutrophication impacts via air, and over 94% of all of these categories at the most recent technology node. Over the generations, impacts related to use phase electricity have grown due to escalation of device power demand, which is the dominating factor defining the variation over time in POF, acidification, eutrophication and criteria health impacts per die which follow a common pattern, as shown in figures 4.4 through 4.7. This common trend results from a number of influencing factors: escalation over time is driven by increases in use-phase electricity as well as a steady rise in the size and complexity of fab infrastructure, while a jump in net die yield causes the countervailing drop in per-die infrastructure, transportation and fabrication emissions at the 130nm node. (The switch to 300 mm wafers results in a higher number of die harvested from a transported wafer and less transportation wasted on unused wafer area and packaging.)

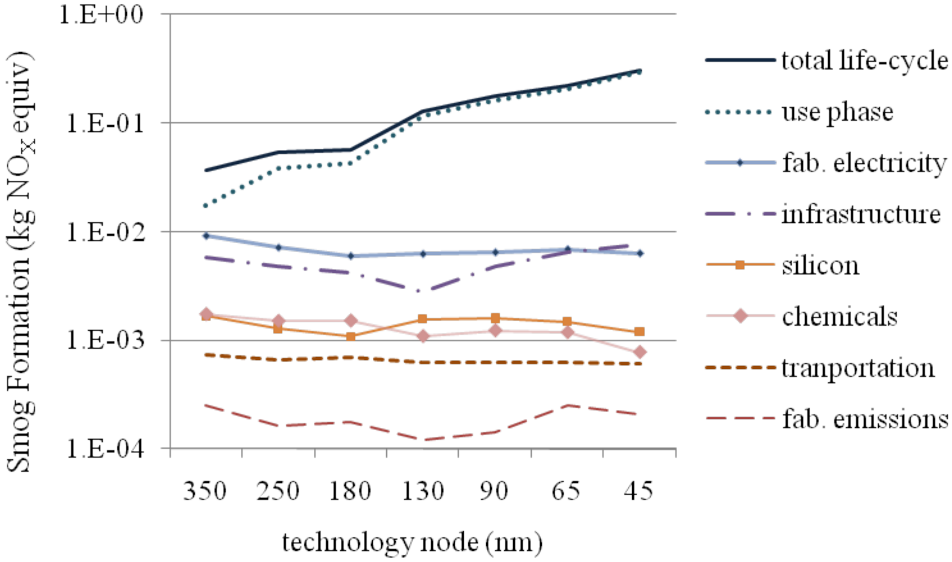


Figure 4.4. Smog formation per die by technology node

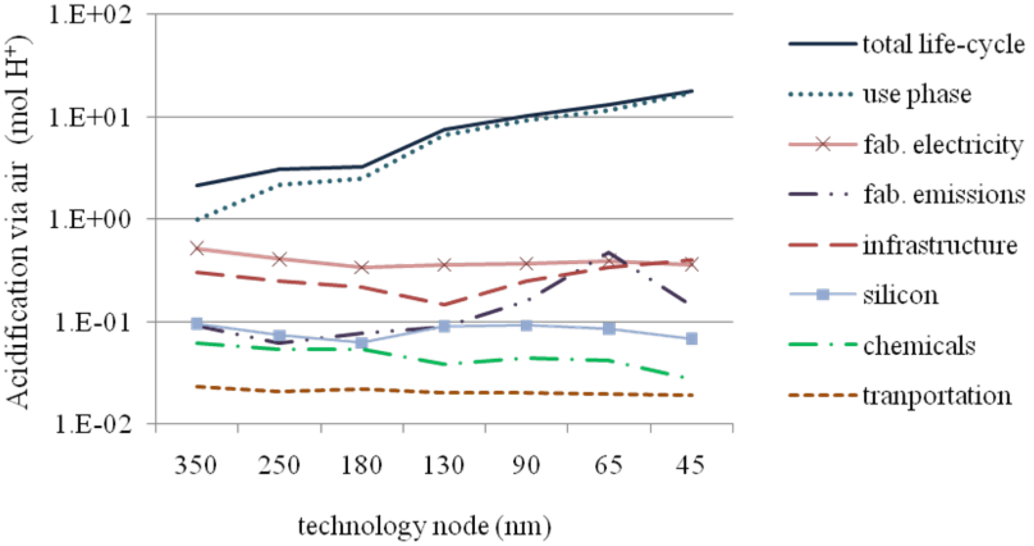


Figure 4.5. Acidification per die by technology node

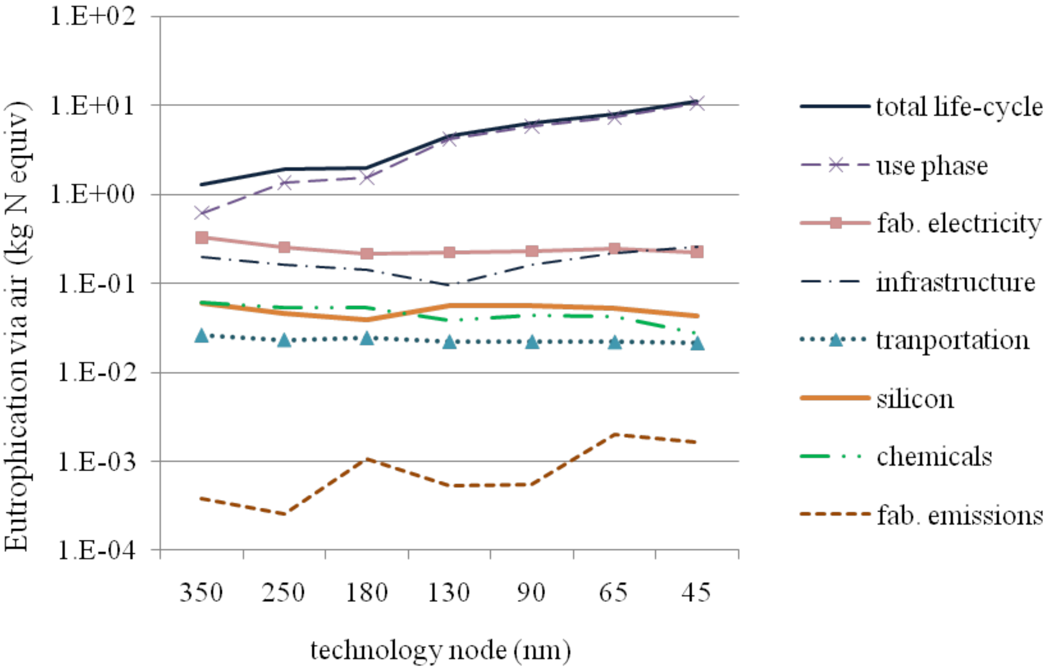


Figure 4.6. Eutrophication via air emissions per die by technology node

4.3.4 Human health impacts

EPA criteria human health impacts are public health damages, measured in disability affected life-years (DALY), resulting from particulate matter, NO_x and SO_2 emitted during electricity production and transportation. Over the period of study, use phase electricity is the cause of an average of 77% of these health impacts. Life-cycle emissions from the fabrication building and equipment account for an average of 12% of criteria health impacts over this 15 year period (Figure 4.7).

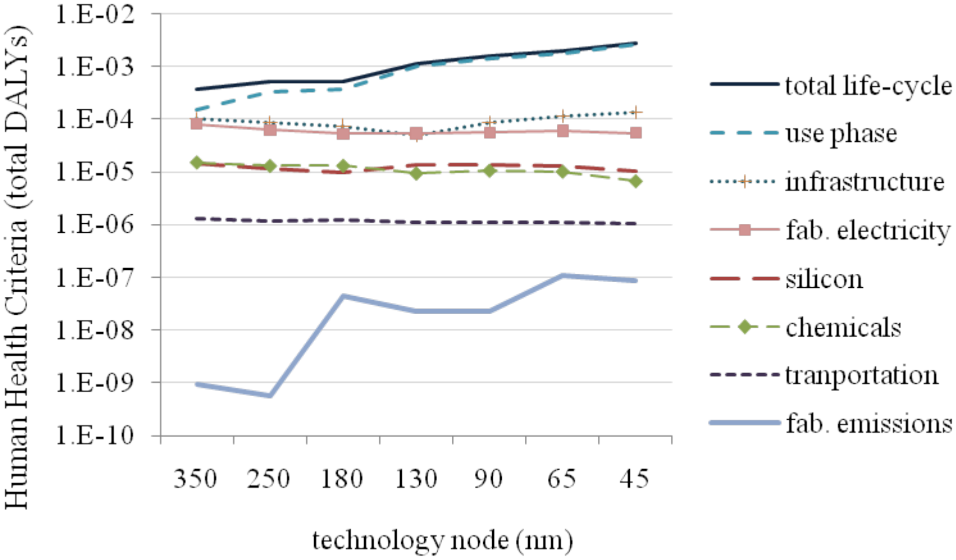


Figure 4.7. EPA criteria human health impacts per die by technology node

Non-cancer human health effects (such as developmental or neurological toxicity) are caused by the lead contained in chips produced before 1996 (350 nm through 90 nm nodes), electricity-related mercury emissions, lead emissions occurring throughout the upstream life-cycle of facility infrastructure as well as hydrochloric acid releases to water from wafer fabrication. At the most recent technology generation, 75% of non-cancer human health impacts are caused by use phase electricity, via mercury emissions, 9% were caused by fab direct emissions, 8

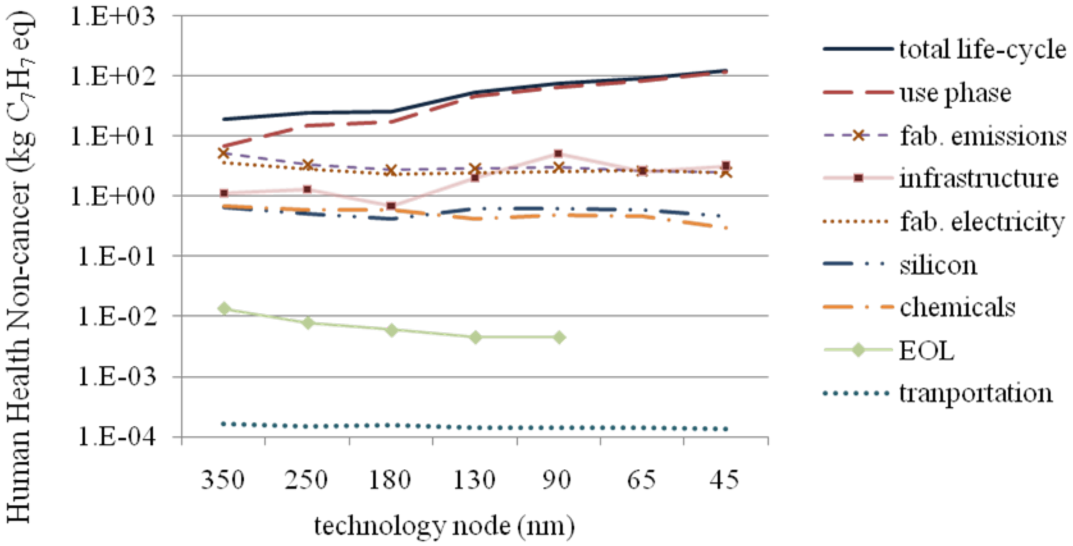


Figure 4.8. Human non-cancer health impacts per die by technology node

Human carcinogenicity results from the lead content of the chip disposed at end of life (EOL), as well as lead emitted in production of facility construction and manufacturing equipment and emissions from wafer fabrication. Among the fab emissions, formaldehyde and ammonia are the largest causes of these impacts. The v-shaped trend in impact magnitude over time reflects a decrease in fab-related emissions per die, due to yield improvements, combined with a steady increase in the size of the fab building and quantity of manufacturing equipment (Figure 4.9).

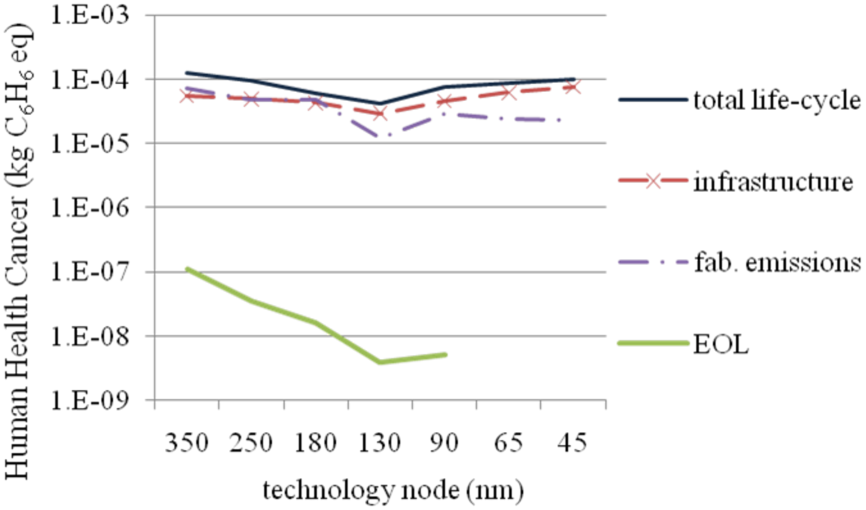


Figure 4.9. Human carcinogenic impacts per die by technology node

Ecotoxicity impacts are largely due to airborne mercury emitted during electricity generation. EPA data for plants operated by Pacific Gas and Electric are estimated to emit 0.0038 grams of mercury per MWh of electricity produced. The trend in ecotoxic impacts over time is influenced by that of life-cycle electricity demand (Figure 4.10). Fabrication emissions in the form of waterborne copper waste from die packaging and copper chemical mechanical polishing (CMP) account for less than 1% of ecotoxicity at all technology nodes.

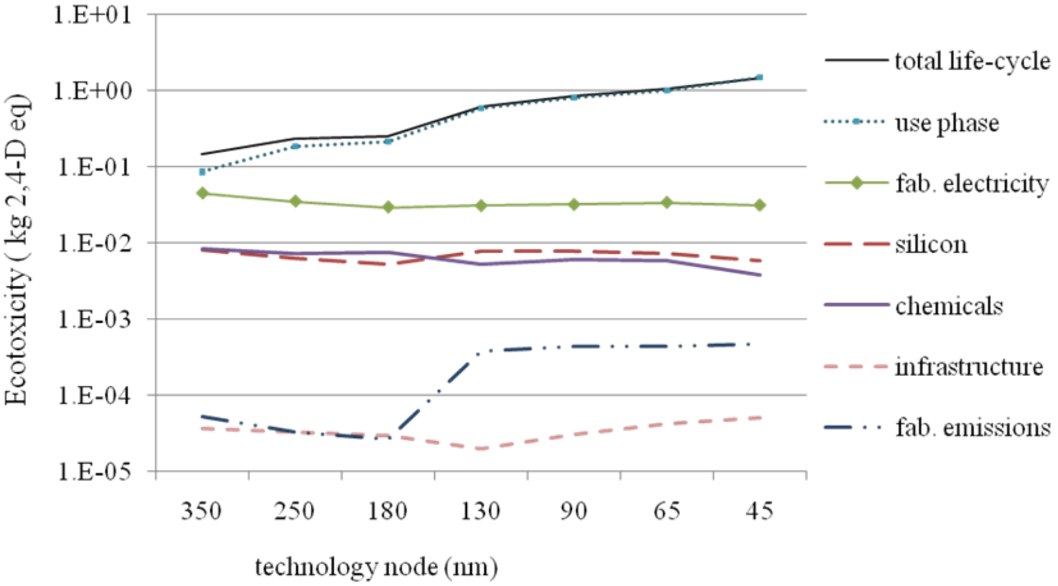


Figure 4.10. Ecotoxicity per die by technology node

Evaluation of the eutrophication potential of waterborne emissions is complicated by the fact that modern fabs do not release any untreated liquid waste directly into the environment, but rather pass treated wastewater into the municipal sewer system. CMOS logic fabs use large quantities of both ammonia and sulfuric acid in wafer cleaning processes. Liquid ammonia may be recycled on site using membrane filtration or distillation, or sent to the acid waste neutralization (AWN) system. In this model, the latter is assumed and thus ammonium sulfate, which results from the neutralization of ammonia and sulfuric acid effluents, is among the liquid wastes produced in the highest volume by wafer fabrication. Ammonium sulfate may experience a number of possible reactions in the municipal wastewater treatment system, but unless the waste is de-nitrified in a bioreactor, it will likely be released to surface or coastal water as dilute ammonium. The worst case eutrophication impacts, assuming no downstream reaction or treatment of liquid waste, are presented in Figure 4.11.

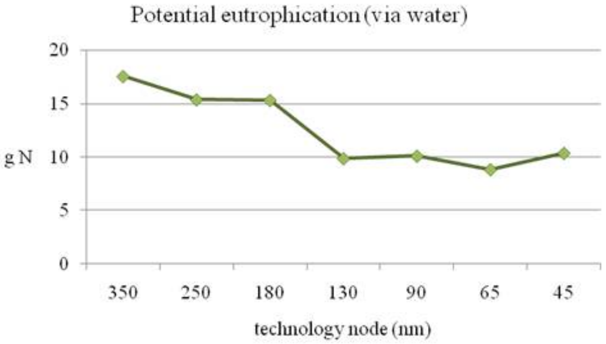


Figure 4.11. Worst-case eutrophication impacts (via water) per die by technology node

4.4 Uncertainty

Abatement products have inherently high uncertainty because uncertainty in the mass of process exhaust is compounded by variation in abatement efficiency. (Abatement efficiency is typically defined as the molar ratio for a target species of abated output to system input.) The uncertainty associated with the output of abatement is thus always higher than input flows, but small mass flows of untreated materials have a particularly high uncertainty. For example, if the removal efficiency of a particular species falls between 97% and 99%, the uncertainty in the mass of untreated material will be +/- 50%. As the efficacy of treatment approaches 100% and the mass flow of untreated compound falls, uncertainty associated with that flow is magnified. Consequently, the uncertainty of impacts from fabrication emissions which are treated by facility abatement is much higher than for energy or water use, or PFC emissions, which have been measured post-abatement.

4.4.1 Sensitivity Analysis

Human health cancer impacts have the highest absolute sensitivity to lead emission factors for production of materials in the supply chain of fab equipment and building construction, and the highest relative sensitivity to abatement efficiencies. The impact category of water-bourne eutrophication, which results only from fab emissions, has the greatest sensitivity to fab abatement efficiencies for nitrogen compounds (mainly ammonia).

All other impact categories have the highest absolute sensitivity to use phase power demand and utilization, power supply efficiency, and to a lesser extent fabrication yields. A more detailed report of the quantitative sensitivity analysis of the model and findings for the sensitivity of life-cycle energy use and GWP to data uncertainty and model assumptions is presented in the previous chapter.

4.4.2 Unaccounted impacts

While less than 0.5% of life-cycle POF is due to wafer fabrication releases, 8 of the 17 VOCs used in semiconductor fabrication do not have impact factors, neither in TRACI nor among the EPA Reactivity Factors, and thus are unaccounted for in the model. While these releases amount to less than 0.02% of the total mass of VOCs throughout the life-cycle (contributing to about 40% of fabrication VOC releases by mass), the need for POF impact factors for the omitted chemicals (listed in the Supporting Information) are noted in Table 4.3.

TDMAT (tetrakis dimethylamino titanium)
TMS (tetramethyl silane)
TEOS (tetraethyl orthosilicate)
TMAH (tetramethylammonium hydroxide)
TDEAH (tetrakis-diethylamido-hafnium)
TDMAS (silicon tetrakis (dimethylamide))
DEA (diethamine)
PDMAT (petra-dimethyl amine tantalum)

Table 4.3. VOCs lacking POF impact metrics

Ecotoxicity, human health cancer and non-cancer impact factors also lack for a number of process chemicals (e.g., hexa-methyl disilizane, octamethylcyclotetrasiloxane, ruthenium compounds) which, while emitted in small quantities, have undefined impact factors. Chemicals used during semiconductor manufacturing which lack human health and ecological impact factors are listed in Table 4.4. Though toxicological studies have been completed for most (if not all) of these materials, they lack impact factors.

Al	N2O
ArH	NF3
Au	n-methyl-2-pyrrolidone
B2H6	NO
BCl3	NO2
BF3	O3
bis tertiary-butylamino silane	OMCTS (octamethyl-cyclo-tetrasiloxane)
BTA (benzotriazole)	p-cresol
Cl2	PDMAT (petra-dimethyl amine tantalum)
CO	PGME (propylene glycol monomethyl ether)
COF2	PGMEA (polypropylene glycol monomethyl ether acetate)
DCS (dichlorosilane)	PH3
DEA (diethamine)	Pt
DMA (dimethyl amine)	SiCl4
ethyl lactate	SiF4
F2	Ta
GeH4	TDEAH (tetrakis diethylamido hafnium)
H2O2	TDMAS (tetrakis dimethylamide silicon)
H2SO4	TDMAT (tetrakis dimethylamino titanium)
HBr	TEOS (tetraethyl orthosilicate)
HCl (gas)	Ti
HF	TMAH (tetramethylammonium hydroxide)
HMDS (hexamethyldisilizane)	TMS (tetramethyl silane)
m-cresol	W
MMA (methyl methacrylate)	WF6

Table 4.4. Chemicals lacking toxicity impact metrics

Estimated components and proportions were used for CMP slurries, which have proprietary formulas. Knowledge of the exact composition of copper, oxide and tungsten CMP chemicals would enable more accurate LCA in the future.

Because many sources of process inventory data for chemicals describe only energy use, the impacts associated with chemicals production in this model only include primary energy use, water consumption, GWP, and no other emissions. This lack of information on environmental emissions from the production of chemicals is noted as an area of data scarcity.

Due to the lack of available data, values representative of chemical production of relatively low purity industrial products are used for chemicals of high purity. Data for the energy consumed in purification of semiconductor chemicals, particularly the elemental gases (N_2, Ar, He, O_2) and common process reactants such as silane, to semiconductor requirements (99.9999997%) would enable more accurate semiconductor LCA in the future.

4.5 Discussion and Conclusions

A complete and transparent LCA of semiconductor logic has hitherto been unavailable to LCA practitioners seeking to assess the impacts of electronic systems and devices. This lack of data has limited the analysis of information and communication technology (ICT) as a tool in energy efficiency and GWP goals. The efficacy of a particular application of ICT in reducing net energy use or GWP can be more definitively evaluated using the values for the environmental and human health impacts of semiconductor logic presented here. Many generations of CMOS logic are evaluated in this study, with earlier generations representing logic currently used in lower performance applications such as embedded logic in appliances and the later generations, computers and servers. The lack of life cycle inventory data for high purity chemicals and environmental impact factors for exotic or specialty chemicals continues to be a difficulty in semiconductor LCA, however. Listed in the appendix are process emission which may be of environmental concern but lack impact factors, as well as chemicals for which, in this study, a generic energy intensity value is used in place of specific inventory data.

By viewing the LCA results over time we can see trends in impacts per die. As use-phase power consumption and the complexity of fabrication have escalated so have electricity- and infrastructure-related emissions. Reductions in fabrication emissions have been achieved at certain points with a few key process changes, as well as the limitation of test and monitor wafer runs which results in higher line yield (the ratio of finished wafers to processed wafers). Average line yield increased from 68 to 88% in the period under study, but as this metric approaches its practical limit, its benefits taper. As device complexity lengthens the process flow, fabrication impacts per die can be expected to rise in the future unless process technologies and fab operations can continue to adapt to meet emissions targets.

Emissions due to electricity consumed in the use phase dominate most impact categories, particularly in the more recent technology generations. At the latest 45 nm technology node 93% of smog formation, 92% of acidification, 93% of eutrophication via air, 99% of ecotoxicity as well as 88% of human non-cancer health effects and 88% of EPA criteria health impacts are due to use phase electricity. Limiting use-phase power consumption, through technical or operational means, is the most effective way to limit the life-cycle impacts of digital logic as we go forward.

Chapter 5

Life-cycle Assessment of Flash Memory

5.1 Introduction

Solid state drives (SSD) show the potential for environmental benefits over magnetic data storage due to their lower power consumption. In this study, a complete life-cycle assessment (LCA) of flash memory over five technology generations (150 nm, 120 nm, 90 nm, 65 nm, and 45 nm) is presented to investigate this idea. The inventory of materials and energy used in NAND flash manufacturing is based on process data, while the impacts associated with chemicals, equipment, fab construction, electricity, and water are determined using economic input-output life-cycle analysis (EIO-LCA) and hybrid LCA. Sensitivity analysis shows that the most influential factors which can reduce the environmental impact of flash memory are perfluorinated compound (PFC) abatement in wafer fabrication and electricity use in manufacturing. A comparison between the complete life-cycle of 96 GB of flash memory and the use and transportation stages of a 2.5” hard disk drive (HDD) shows that the flash memory consumes less primary energy and water and results in lower global warming potential (GWP), ecotoxicity and smog formation than the magnetic HDD, though the relative benefit of flash-based SSD in other impact areas cannot be determined without a complete LCA of HDD.

Flash memory is one of the fastest growing semiconductor product types and is becoming competitive with magnetic hard disk drives (HDD) as computer storage. While solid state drives (SSD) are assumed to have a lower environmental impact than HDD because they require less power during operation, the life-cycle environmental impacts of Flash-based drives have not yet been studied. While SSD have low power consumption, their manufacture is highly energy and resource intensive as compared with most consumer goods. In this analysis, we present the life-cycle environmental impacts of NAND flash and compare the energy-related environmental impacts of SSD with those of HDD storage.

Flash memory was developed from a combination of erasable, programmable read-only memory (EPROM) and electronically-erasable, programmable ROM (EEPROM) technologies in the mid-1980s and became widely produced for consumers in the mid-1990s. Because flash memory can store and access data with no moving parts, unlike magnetic storage, it has been applied to a variety of memory applications in consumer electronics and is widely used in digital music players and small-capacity, portable data storage. As a result, flash EPROM has been among the fastest growing types of semiconductor products in recent years [92, 93]. NAND and NOR flash are composed at the lowest level of transistors which implement logical NAND and NOR operations, respectively, with NAND being the denser but slightly slower design option. When the density of flash storage capacity recently reached 4 and 8 GB per cm^2 chip area, it became possible to package flash into products which could replace traditional hard disk drives (HDD). Flash-based solid-state drives (SSD) which are initially being introduced in laptops may also become competitive in desktop and data center applications, if scaling and cost challenges are overcome. Because flash memory is a fast growing semiconductor product segment which has the potential to expand further if SSD become more common in computer storage, the life-cycle environmental impacts are of particular interest.

5.2 Methodology

This study presents a life-cycle assessment (LCA) of five generations (150 nm, 120 nm, 90 nm, 65 nm, and 45 nm) of flash memory with wafer fabrication in Santa Clara, California, using chemicals, equipment and construction materials produced in the U.S. The mass of process chemicals consumed and emitted in each process step have been determined using in-line measurement, while equipment utility demands such as power, cooling water and utility nitrogen are based on both equipment measurements and specifications. Fab utility system capacities and resource demands are modeled using data from Sematech [85] and reflect industry-standard efficiency improvements over the 9 year period under study [13]. Direct emissions from electricity generation are specific to California, based on data from the EPA [27] and primary energy use in electricity generation is taken from International Energy Agency data as 12 MJ/kWh, an average for the U.S.[80]. Life-cycle impacts due to water supply and product transportation are based on previous hybrid LCA studies [29, 98]. Chemical production and fab infrastructure (facility construction and equipment) are accounted for in this analysis using energy consumption and emissions determined using economic input-output LCA (EIO-LCA) [15]. Water consumed in the generation of electricity used in manufacturing, chemicals and fab infrastructure production and the product use phase is determined using a U.S. average of 1.76 liter/kWh from a previous study[52]. IPCC global warming potential (GWP) impact factors are used for per-fluorinated compounds [48] and all other environmental and human health effects of emissions are evaluated using TRACI mid-point impact metrics, which are specific to the U.S. and California [64]. At end of life, it is assumed that there is no recoverable value from a discarded flash chip and the only significant impacts associated with disposal are the release of lead. The LCA methodology used in this study has been explained in further detail [13] and inventory data reported on a per-process basis [55] in previous articles.

The functional unit of this study is one GB memory over a typical lifetime of 100,000 cycles. For all generations, wafer size is 300 mm and packaging is TSOP. Assumed line and wafer yields and a summary of the process technologies at each node are given in the appendix. All process flows and device memory capacities represent single-level cells (SLC, aka single-bit cells). Multilevel cells (MLC), which have become more widely produced in recent years, allow a doubling of bits per cell (or quadrupling in the case of 4xMLC). Because MLC can be manufactured without a significant increase in the number of steps in the manufacturing process flow versus SLC, MLC have roughly half of the environmental impacts as SLC per GB capacity. However, because MLC have shorter lifetimes and slower programming speeds than SLC and thus do not represent equivalent functionality, SLC are used throughout the study for consistency.

5.3 Results

Because use phase power per bit has been reducing or constant and the number of process steps required in wafer production has not increased considerably over these five flash technology nodes, the environmental impact of flash memory per chip has remained relatively flat over the past decade. Over the same period of time, device scaling as well as system-level enhancements of flash technology have allowed almost 16 times more memory capacity per device area. The combination of these trends results in a dramatic decrease in environmental impacts per unit of memory capacity for NAND Flash. An example of the results of these paired trends, primary energy consumption per gigabyte (GB) memory capacity by life-cycle stage is shown in Figure 5.1. It should be noted, however, that despite the reductions in impacts per unit memory capacity, the environmental and human health impacts caused by flash memory as an industry, or flash memory product worldwide, is on the rise, due to the even more rapid expansion of the production and use of these products.

Flash scaling, for SLC, does not entail additional interconnect layers. For this, among other, reasons, the number of steps in the generic NAND process flow has not increased as rapidly as in the case of other semiconductor product types, par-

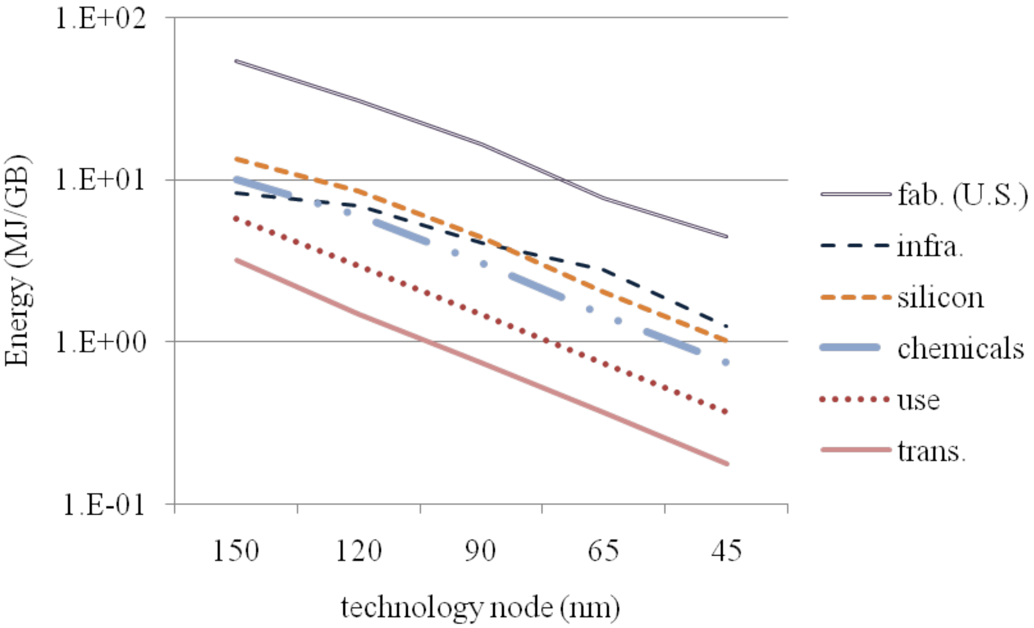


Figure 5.1. Primary energy consumption per memory capacity (MJ/GB), over five technology nodes

ticularly CMOS logic[13]. Because the process flow has not expanded dramatically, direct emissions from wafer fabrication have not increased markedly over the period under study and, correspondingly, per-wafer impacts associated with the production of process chemicals have been relatively flat. In Figure 5.2 the trends over the five technology nodes in ecotoxicity, acidification, eutrophication and smog formation are shown illustrating how minimal increases in per-wafer impacts result in notable reductions per GB. Ecotoxic impacts are due almost entirely to mercury emissions from electricity generation, with over 99% of life-cycle ecotoxicity coming from electricity generation and the remaining less than 1% due to formaldehyde emitted during wafer fabrication. About 50% of ecotoxic impacts are due to electricity used during manufacturing, a share which is also exemplified by the relative primary energy demand of manufacturing as shown in Figure 5.1. Acidification impacts are caused by life-cycle emissions of oxides of nitrogen (NO_X) caused by fab infrastructure (constituting between 62% and 72% of life-cycle acidification over the five technology nodes), NO_X and SO_2 from transportation (17-25% of the total) and electricity generation (7-11%), and HF emissions from fabrication (1-10%). Eutrophication is attributable to NO_X emissions related to infrastructure (composing between 55 and 65% of these impacts over the five generations), transport (19-24%) and electricity generation (16-19%), with a small fraction (<2%) occurring as a result of fab gaseous emissions of NO_X and ammonia. The largest share (53-62%) of smog formation is caused by NO_X and CO emissions produced due to fab infrastructure production, followed by NO_X and CO from transportation (17-23%) and electricity (15-18%). The remaining smog-forming impacts (4-7% of the life-cycle total) result from emissions (post-abatement) of isopropyl alcohol (IPA), CO, NO_X, ethyl lactate and other volatile organics from the fab.

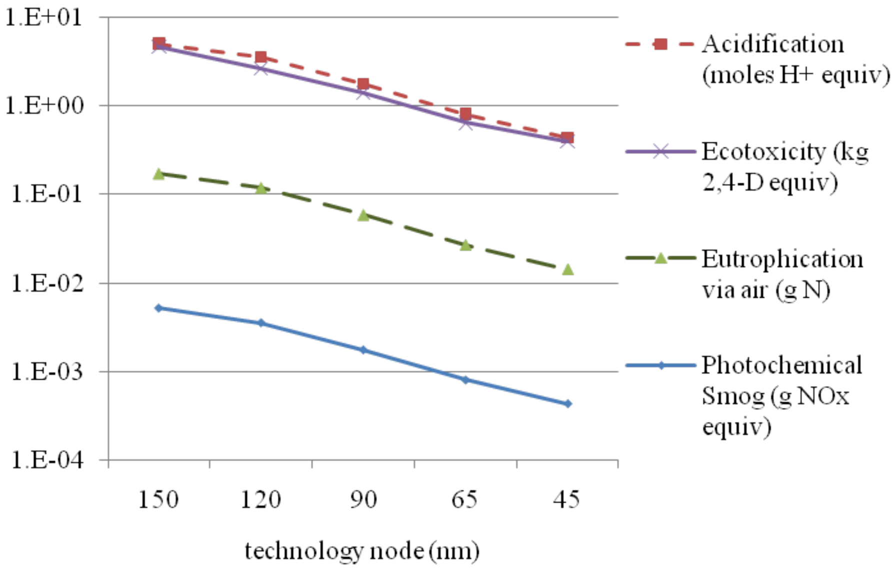
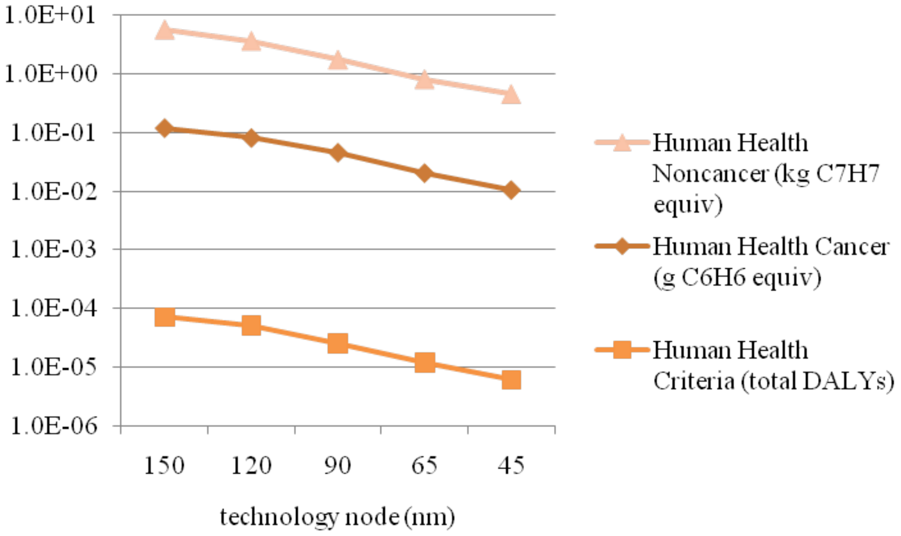


Figure 5.2. Environmental impacts due to air emissions per GB, over five technology nodes

Human health related impacts per wafer and device have shown the same stability over the past decade. Figure 5.3 shows human health impacts per GB over the five technology nodes. Non-cancer human health impacts (including developmental, reproductive and neurological toxicity) are primarily attributable to HF and other fluorine compounds, CO and dimethyl amine emitted, post-abatement, from wafer fabrication. Manufacturing represents between 66% and 72% of these non-cancer health impacts, with the remainder coming from infrastructure-related lead emissions (22-28%) and mercury released during electricity generation (6-7%). Carcinogenic human health effects principally result from manufacturing emissions of formaldehyde, which represent 72-75% of these impacts, while lead emissions resulting from fab infrastructure cause the remaining fraction. EPA criteria human health impacts, the most common public health threats resulting from smog, particulate matter (PM), lead, NO_2, SO_2 and CO, result from (in descending order) PM, SO_2 and NO_X emitted in throughout the supply chain in production of the manufacturing facility and equipment, which compose 68-75% of the life-cycle totals in this category over the period under study. SO_2 and NO_2 from electricity (19-23%) and transport (6-9%) also contribute to these human health effects.



DALY: disability-affected life years

Figure 5.3. Human health impacts due to air emissions per GB, over five technology nodes

Per-fluorinated compounds (PFCs) are an important group of emissions from semiconductor manufacturing due to their high infrared absorption, long lifetimes and consequential global impact. The World Semiconductor Council (WSC), which includes the semiconductor industry associations of Japan, Europe, Korea, Taiwan and the United States, has committed to PFC emissions reductions of 10% from 1995 or 1999 baseline levels by the end of 2010. However, in China, Singapore and Malaysia the semiconductor industry consortia have not made a commitment to control PFC emissions and in 2008, about 20% of semiconductor production capacity was held in these countries[8]. In Figure 5.4, GWP impacts are shown by life-cycle stage with two scenarios illustrated, one in the U.S., where PFC abatement is necessary to meet the WSC goal, and the other in China, where there is no such resolution and PFCs are not abated.

In the U.S. example, direct emissions from wafer fabrication (CO_2, N_2O, methane and PFCs) cause less than 2% of life-cycle GWP, because PFCs are broken down using point-of-use (POU) abatement. The largest contributing cause of GWP is the electricity used in wafer fabrication and chip assembly, followed closely by silicon production, chemicals and fab infrastructure. The relative contribution of each of these life-cycle stages is shown in Figure 5.4. If wafer fabrication is performed without PFC abatement, fab direct emissions constitute the largest fraction of GWP among all life-cycle stages and the total life-cycle GWP impacts of Flash memory increase by 24 to 30%, as demonstrated by the curve for fabrication and total life-cycle GWP for the China fab scenario in Figure 5.4.

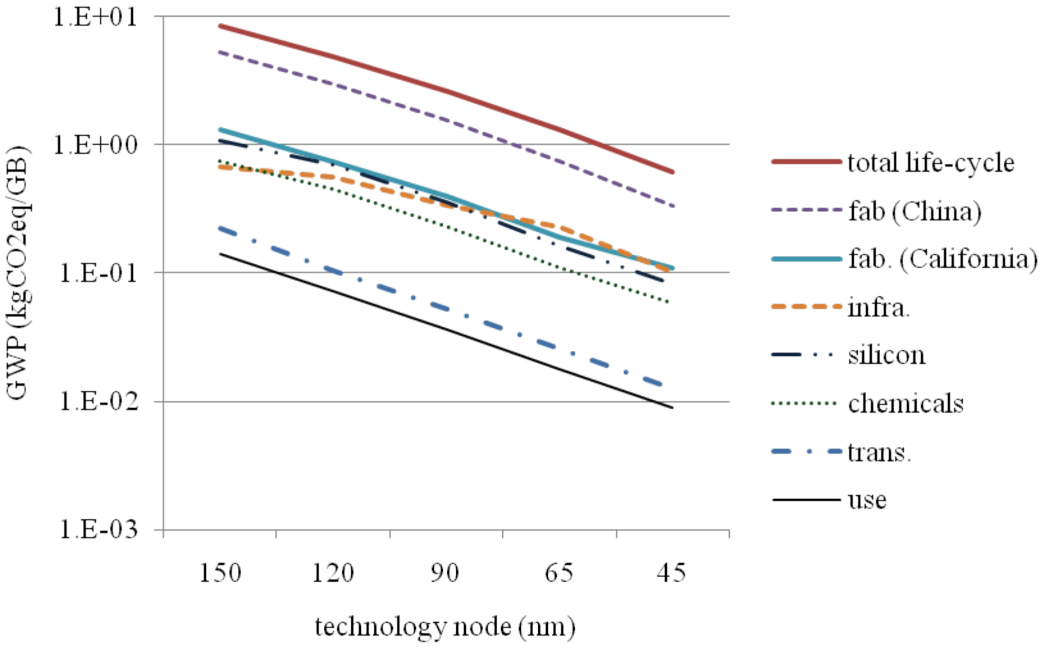


Figure 5.4. GWP per GB memory capacity, by life-cycle stage, over five technology nodes

Water consumption is dominated by electricity generation, as shown in Figure 5.5. At all technology nodes, water consumed in manufacturing represents less than 13% of life-cycle totals. (The fractional contributions of each life-cycle stage to total water consumption differ from those for primary energy use because not all energy use represents electricity.)

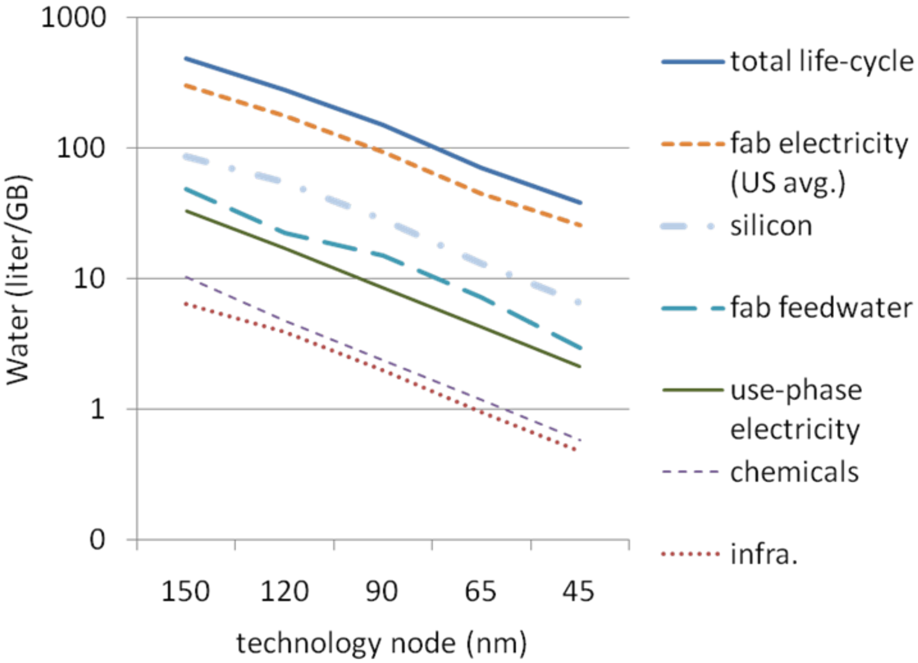


Figure 5.5. Water consumption per GB memory capacity, by life-cycle stage, over the five nodes

5.4 Discussion: Solid state drives vs. Hard disk drives

Although a LCA of magnetic storage has not been reported in the literature, we find that considering only use-phase and transportation data for a hard drive, these HDD impacts outweigh those of the full life-cycle of flash in most impact categories. A laptop-sized drive composed of 96 GB of 45 nm SLC flash (12 x 8 GB chips) is used for comparison with an equivalent capacity HDD. Each flash chip is assumed to have a mean time to failure of 100,000 erase cycles which, with wear leveling, allows a lifetime of at least 3 to 5 years. The magnetic HDD is assumed to have a read/write power of 4.7 W and an idle power of 3.6 W, based on an average of several manufacturers' specifications. With 20% active, 80% idle operation over a 4-year lifespan of 25,400 hours, the HDD would consume 93.3 kWh of electricity. (Although lifetimes of HDD are variable, a life-span of 4 years in not uncommon and is chosen to match the functional unit.) The HDD use phase alone would result in 27 kg CO_2eq. in GWP, which is two orders of magnitude greater than the GWP impacts resulting from the full life-cycle of 96 GB flash. Each category of environmental and human health impacts are shown for the flash memory and limited inventory for HDD in Fig. 5.1.

Table 5.1. Full life-cycle of 96 GB flash memory vs. HDD transportation and use

		Complete life-cycle 96 GB flash	Use phase and transport of HDD
Primary energy consumption	MJ	724	1120
Water consumption	liters	3688	7173
GWP	kg CO_2 eq	0.54	27
Smog	kg NO_X eq	0.042	37
Acidification	moles H^+ eq	42	37
Ecotoxicity	g 2,4-D eq	38	86
Eutrophication	g N	1.4	1.3
Human Health Criteria	DALYs	5.8×10^{-4}	4.0×10^{-4}
Human Health Noncancer	kg C_7H_7 eq	43	6.9
Human Health Cancer	kg C_6H_6 eq	8.6×10^{-5}	N/A

5.4.1 Uncertainty

The environmental impact data with the greatest uncertainty range in the model are the emissions associated with fab construction and equipment production and the primary energy consumed in chemicals manufacturing. Due to the abstraction inherent in economic input-output modeling, EIO-LCA entails temporal and geographical uncertainty, as well as impact misallocation arising from generalization over each economic sector. The impacts associated with fab infrastructure and chemicals therefore have relatively high uncertainties, which are accounted for in the tabulated results (**??**). Fabrication emissions, because they are all post-abatement mass flows, have a high uncertainty that results from variation in the effective rate of facility abatement systems. An abatement system which operates at 99% efficiency with variation of $+/-1\%$ produces mass flows of abatement products with a magnified uncertainty range of $+/-100\%$.

The device performance data with the greatest uncertainty in this study are the lifetimes assumed for the HDD and flash memory. Though a peer-reviewed empirical study of flash memory durability is not available, a 4-year life span for SLC flash is conservative [19]. While a percentage of NAND flash bits fail over the life of the chip, data checking algorithms compensate for lost bits and catastrophic breakdown of a flash device is rare (in contrast to HDD). The performance of a flash drive will nevertheless diminish over time, and thus the lifetime of a SSD is an inherently fuzzy value. The MTBF for the HDD in this analysis is chosen to match that of the flash memory and though a 4 year lifetime is supported by a previous large-population HDD reliability study [73], there is a wide uncertainty range associated with this value.

5.4.2 Sensitivity Analysis

By comparing the results for fabrication with and without PFC abatement, it is apparent that the most crucial decision affecting the life-cycle GWP of flash is the presence of PFC abatement in the fab. To determine the importance of other variables in the model, we use sensitivity analysis, testing the change in impact values with alterations in model parameter values. Sensitivity analysis shows that, because the largest fractions of environmental impacts ultimately result from emissions and resource consumption due to electricity generation, the emission factors for electricity have the greatest influence over the most impacts categories. Emissions from electricity generation cause the largest fraction of impacts in the categories of primary energy consumption, water consumption, GWP and ecotoxicity, and contribute a significant fraction to smog formation, eutrophication, acidification, and EPA criteria human health impacts. Impacts attributed to infrastructure and chemicals production are also ultimately caused by electricity used in the supply chain for these products. The energy sources and technologies used to generate electricity used in manufacturing and in the use phase, as well as in the supply chain of chemicals, equipment and fab construction materials, are the most critical factors which decide the magnitude of environmental and human health impacts.

The high uncertainties in the masses of emissions, as described in the previous section, have a significant influence on the certainty of the final life-cycle impact values, as reflected in the tabulated results in the appendix.

5.5 Conclusions

The results of this LCA also show that the largest shares of NAND flash life-cycle environmental impacts come from electricity generation and fab infrastructure production. Because the largest fraction of electricity is used in the manufacturing stage, it is most important to source fab electricity from low-impact sources. By siting a fab on an electrical grid supplied with a high percentage of renewable energy sources, or by supplementing grid-supplied electricity with on-site renewable generation, a flash manufacturer can most effectively reduce the life-cycle environmental impacts of its products. The second largest contributor to environmental and human health impacts overall is fab infrastructure production, which results in the largest proportion of impacts in the categories of smog formation, acidification, eutrophication and EPA criteria human health effects. Although all of the upstream activities associated with fab construction and equipment supply are difficult to control, minimizing the impacts associated with fab construction should also be a concern, due to the high resource and emissions intensity of construction activities and materials. The results of this model also show that, although overall human health impacts are modest, the largest fractions of human cancer and non-cancer health effects (besides EPA criteria impacts) occur as a result of direct fab emissions. Effective abatement and monitoring of fab emissions is essential to minimizing human health risks. Comparison between flash from facilities with and without PFC controls shows that without PFC abatement, PFC emissions cause the largest fraction of GWP impacts throughout the life-cycle. Abating PFCs is therefore the most important step towards reducing the global warming impact of flash memory.

This study validates the common assumption that flash-based SSD have a lower environmental impact versus HDD due to their significantly lower use-phase power consumption. Although the production of flash memory is highly energy and resource intensive, in the areas of primary energy and water consumption, GWP, smog formation and ecotoxicity, they are lower than those produced in the transportation and use phases of a typical HDD. The relative impacts of SSD versus HDD in other impact categories can be determined with an environmental impact study for HDD of an equivalent scope to the study presented here, such that it includes manufacturing and tributary activities (e.g., materials production).

Chapter 6

Life-cycle Assessment of Dynamic Random Access Memory

6.1 Introduction

Dynamic random access memory (DRAM) is the most common type of volatile memory and is a component of all laptop and desktop computers. In this study, life-cycle impacts of DRAM are determined for 250, 180, 130, 90, 70, and 57 nm technology nodes, representing DRAM manufactured in large scale production from 1997 through 2008. Primary energy and water consumption, as well as global warming potential, acidification, eutrophication, ground-level ozone (smog) formation, potential human cancer and non-cancer health effects, and ecotoxicity are evaluated. The life-cycle inventory is a hybrid model, using process data for wafer fabrication and die packaging, electricity production and some chemicals. Hybrid LCA data from previous studies are used for transportation and impacts associated with the water supply infrastructure. Economic input-output LCA (EIO-LCA) data from the Carnegie Mellon database [15] are used for the fabrication facility and manufacturing equipment, as well as some chemicals for which process data are unavailable.

Results are presented using, as the functional unit, the memory requirements to run an operating system (OS). As discussed in Chapter 4, the choice of functional unit has a great influence over how impact trends appear over time. While the environmental and human health impacts per gigabyte (GB) of DRAM have decreased over the time period of this study, those associated with the memory required to run an average desktop computer have not. The manufacturing inventory and life-cycle impact results on a per-GB basis, which are more readily usable by LCA practitioners, H

Table 6.1. Year and OS memory requirements for each technology node

Year	Technology node (nm)	Windows RAM requirements (MB)
1997	250	4
1999	180	16
2001	130	32
2004	90	64
2006	70	64
2008	57	512

are presented in the appendix. Results in this chapter are presented per OS to investigate the influence of software memory efficiency on the life-cycle impacts of computing.

6.2 Methodology

The life cycle inventory methodology follows that of the previous chapter, with the process flow for DRAM replacing that of flash memory. For each technology node, the fab facility system configurations for the corresponding year are used. Details on fab facility efficiency improvements are detailed in Chapter 3 (see Table 3.13. For each technology node, the minimum memory capacity required to run the latest version of the Windows OS, in the year corresponding to that node, is used. The memory requirements for the OS used at each technology node are given in Table 6.1. GWP intensity of electricity is specific to California (300 gCO_2eq/kWh), primary energy consumption in electricity generation is 12 MJ/kWh, an average for the US [80] and water consumption is 1.78 liter/kWh, based on the most recent available (1995) USGS data [52].

Impact assessment also follows the methodologies of the previous chapters. TRACI mid-point impact metrics, which are specific to the U.S. and California [64], are used for smog formation, acidification, eutrophication, ecotoxicity and human health impact factors of emissions. IPCC global warming potential (GWP) impact factors are used for per-fluorinated compounds [48].

Chip sizes and memory capacity are based on International Technology Roadmap for Semiconductor standards for chip size at production and memory density[85] (Table 6.2). Chip power demand is determined using a manufacturer's data sheets [61], as listed in Table 6.2. The lifetime of the chip is assumed as 3 years, with 6,000 hours of total use, consistent with the literature[21]. Power supply efficiency is accounted for in use phase energy consumption and is assumed to be 75/

Table 6.2. Chip size and power demand for each technology node

Technology node (nm)	250	180	130	90	70	57
Memory capacity (GB)	0.128	0.256	0.512	1	2	2
Chip size (mm^2)	128	176	127	93	110	74
Power demand (W)	0.35	0.38	0.47	0.50	0.53	0.53

6.3 Results

6.3.1 Resource Consumption

Primary energy consumption per OS memory capacity by life-cycle stage is shown in Fig 6.1. In recent years, the use phase is the largest contributor to life-cycle energy consumption despite the low operating power of DRAM (less than 1 W). Use phase energy consumption has increased by about 50% over the period of study, while energy used in the wafer fabrication stage, per die, has decreased due to smaller die sizes [85]. Energy used in supplying water to the fab is so small that it falls well below the other contributions shown in Figure 6.1, and is excluded to avoid distortion.

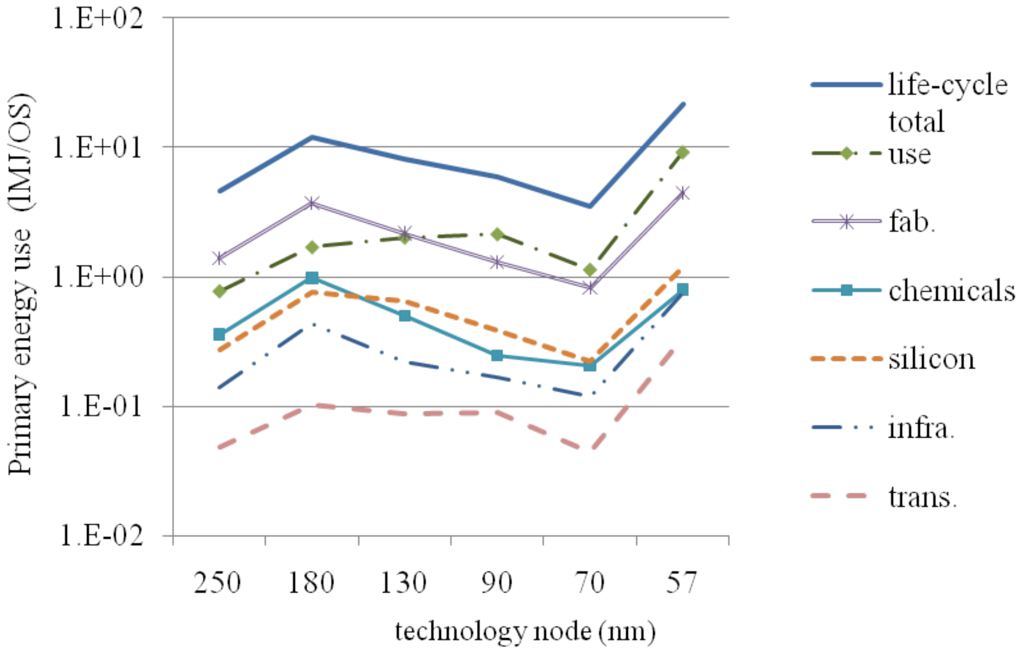


Figure 6.1. Primary energy consumption per memory capacity (MJ/OS), over five technology nodes

Water consumption is dominated by electricity generation, as shown in Fig 6.2. The dominant consumers of water in the life-cycle of DRAM are fabrication and use phase electricity. At all technology nodes, water consumed directly in manufacturing (fab feedwater), e.g. to produce ultra-pure water, represents less than 8% of life-cycle totals.

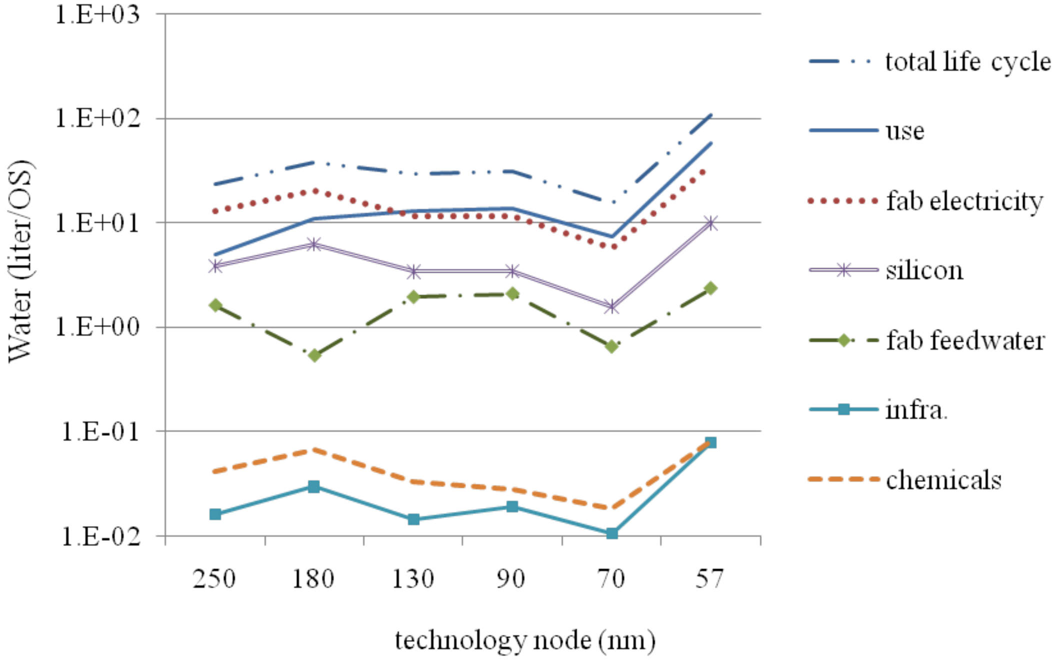


Figure 6.2. Water consumption per OS memory capacity, by life-cycle stage, over five technology nodes

6.3.2 Environmental Impacts

Members of the World Semiconductor Council (WSC), the semiconductor industry associations of Japan, Europe, Korea, Taiwan and the United States, agreed in 1999 to limit PFC emissions using targets according to Kyoto-like baseline years. However, the semiconductor industry associations in Singapore, Taiwan, Malaysia and China have not joined in the WSC agreement. To show the effect of the lack of PFC abatement in wafer fabrication, both WSC and non-WSC scenarios are presented for GWP impacts.

PFC abatement is a very important determining factor in life-cycle GWP as illustrated in Fig 6.3. In the non-WSC case, PFC emissions are the greatest contributor to life-cycle GWP. Without PFC abatement, in the non-WSC scenario, life-cycle GWP jumps by between 42% and 88%.

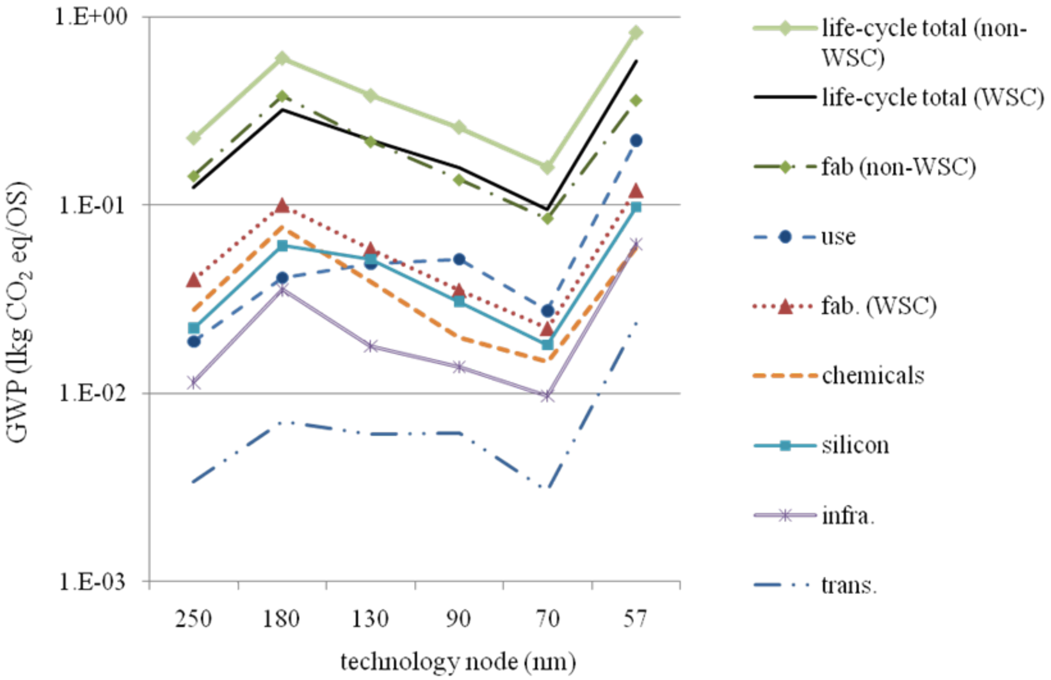


Figure 6.3. GWP per OS memory capacity, by life-cycle stage, over five technology nodes

The largest contributors to smog formation are fab infrastructure (building construction and semiconductor manufacturing equipment) production, use phase electricity, and transportation. The ground-level smog from fab infrastructure is ultimately due in large part to NO_X emissions from truck transportation and power used in the supply chain. Less than 8% of smog formation is attributable to direct volatile organic compound (VOC) emissions from wafer production.

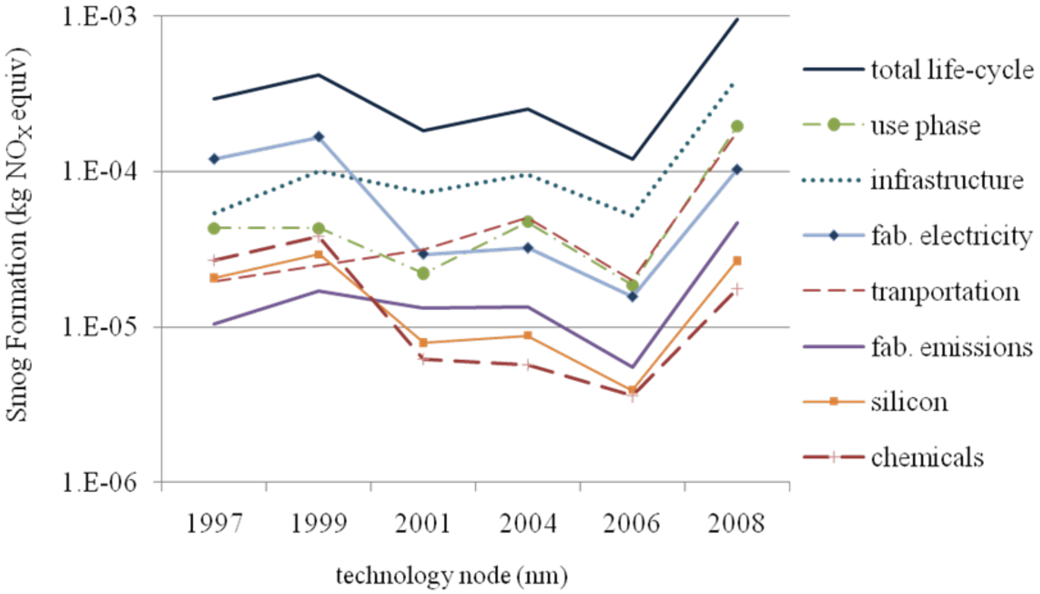


Figure 6.4. Smog formation per OS by technology node

Infrastructure construction, fab direct emissions, fab electricity and use phase electricity are the largest factors in acidification impacts. The largest causes of acidification within fab infrastructure production are NO_X and SO_2 emitted from truck transportation, power generation and cement and aluminum manufacturing. HF emissions from wafer fabrication amount to, on average, about one third of life-cycle acidification for DRAM.

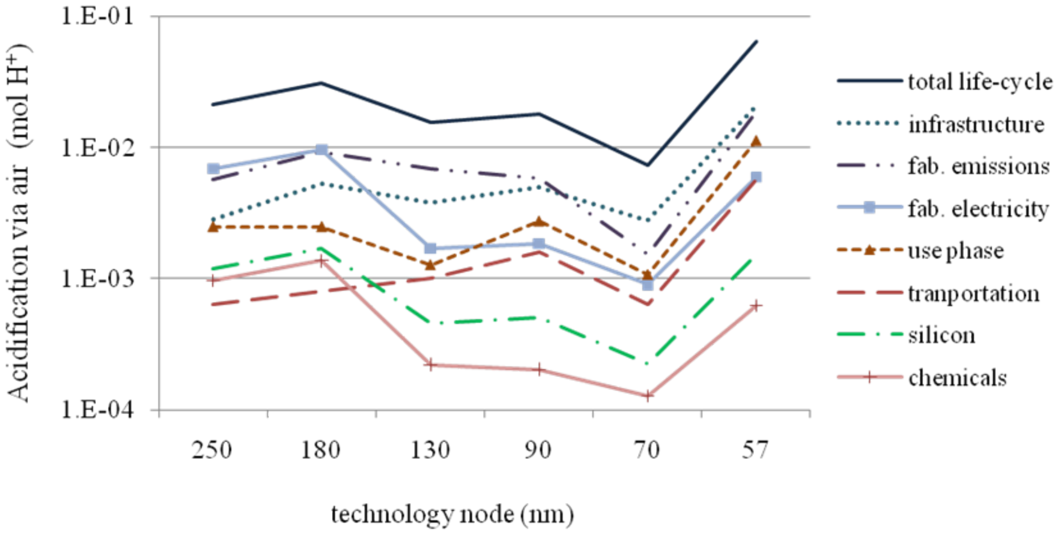


Figure 6.5. Acidification per OS by technology node

The largest contributors to eutrophication are fab infrastructure, use phase electricity, transportation and fab electricity. The largest contributors to eutrophication occurring in the production of the fab facility infrastructure are NO_X emitted by truck and rail transportation, and in cement manufacturing. Only a very small fraction of eutrophication (about 1%) occurs as a result of gaseous emissions of NO_X and ammonia from wafer fabrication.

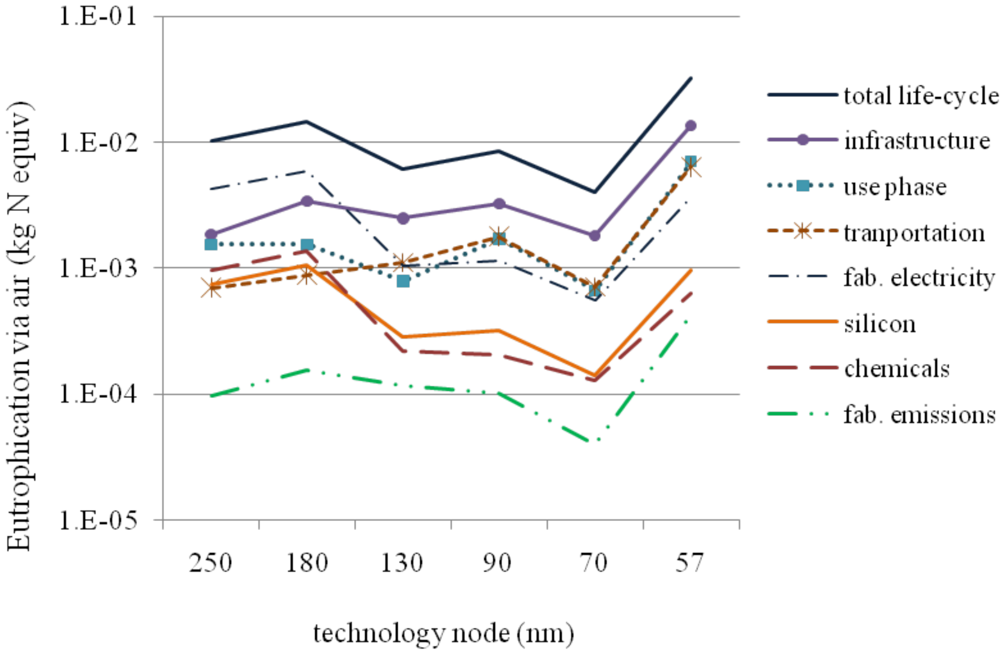


Figure 6.6. Eutrophication via air emissions per OS by technology node

Ecotoxicity is largely caused by mercury emitted in the generation of electricity used in production and the use phase, as shown in Figure 6.10. Chemicals, silicon and infrastructure production also contribute to this impact category through electricity-related mercury emissions. Infrastructure production also contributes, to a small extent, via lead emissions which occur in mining and refining certain metals. Wafer fabrication contributes to ecotoxicity through trace emissions of formaldehyde, which amounts to less than 2% of life-cycle ecotoxicity.

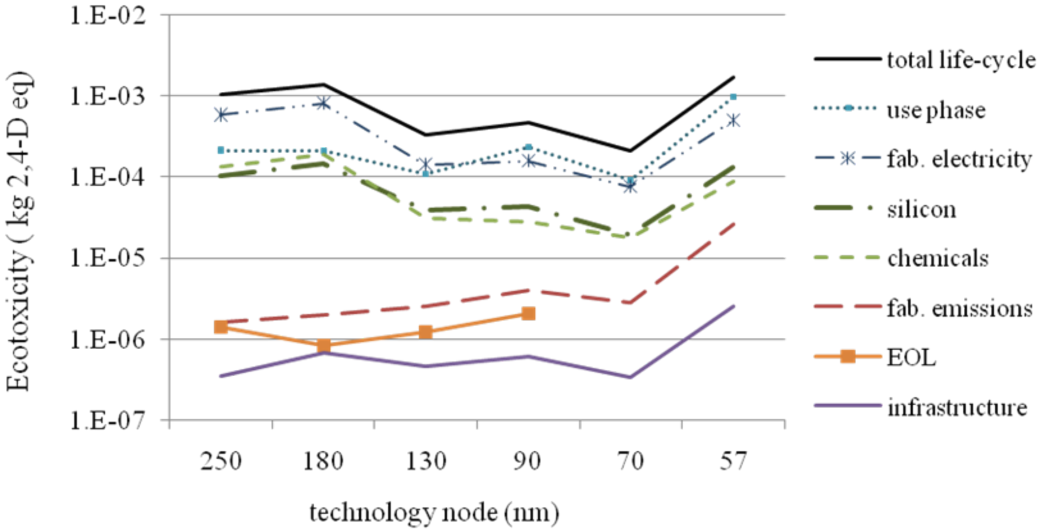


Figure 6.7. Ecotoxicity per OS by technology node

6.3.3 Human Health Impacts

EPA criteria human health impacts, the most common public health threats resulting from smog, particulate matter (PM), lead, NO_2, SO_2 and CO. Life-cycle criteria health impacts for DRAM largely result from PM, SO_2 and NO_X emitted during production of the manufacturing facilities and equipment, and SO_2 and NO_X emitted due to electricity use in manufacturing and product use.

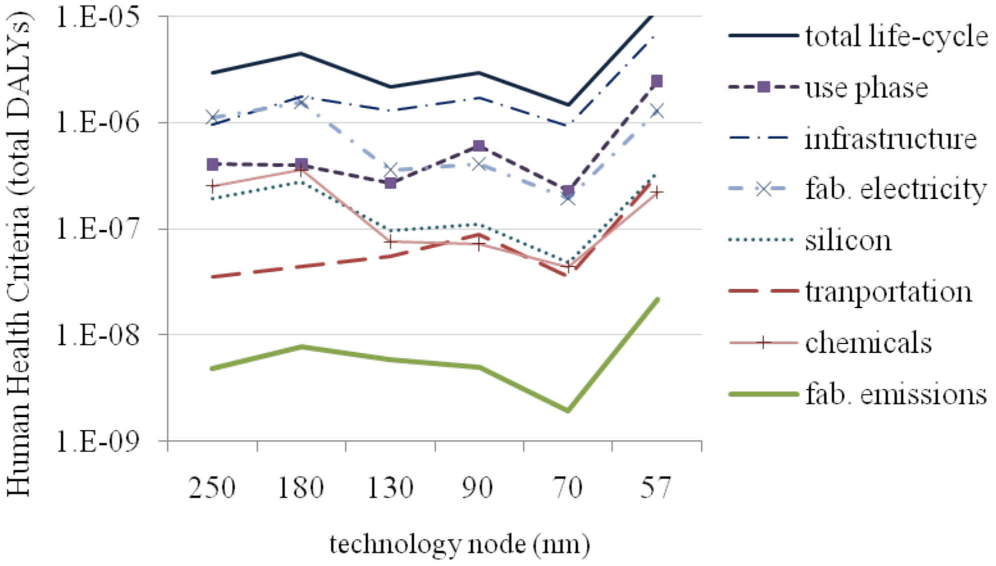


Figure 6.8. Criteria human health impacts per OS by technology node

Carcinogenic human health effects primarily result from manufacturing emissions of formaldehyde, followed by lead emitted in fab infrastructure production. Lead contained within the package of the DRAM chip, which is emitted into the environment at end of life (EOL) is a significant contributor in years up to 2006, when RoHS banned the presence of lead in electronics.

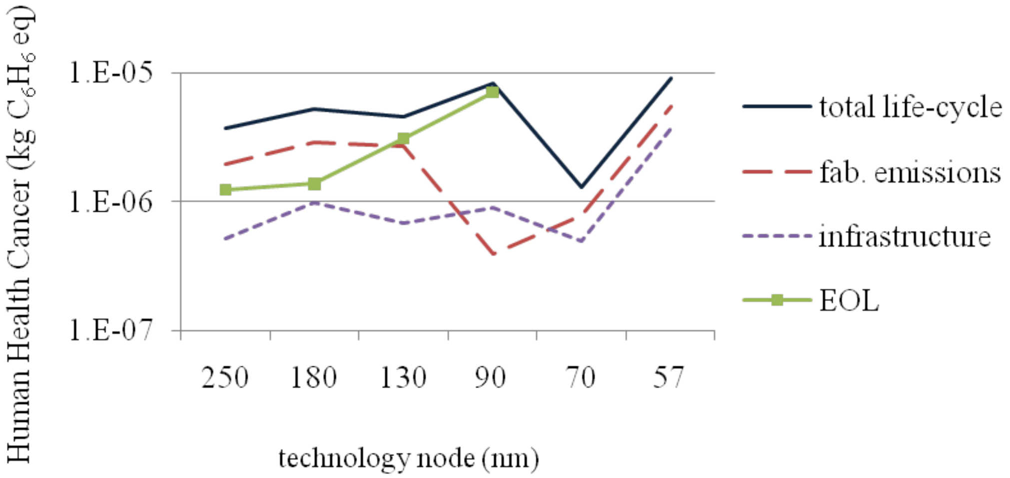


Figure 6.9. Carcinogenicity per OS by technology node

Non-cancer human health impacts (including developmental, reproductive and neurological toxicity) are primarily attributable to HF and other fluorine compounds, CO and dimethyl amine emitted, post-abatement, from wafer fabrication. Mercury, released during generation electricity used in manufacturing and use, and lead emitted in the production of the fab facilities, are also substantial sources of non-cancer health impacts. EOL lead emissions are also a significant contributor in years up to 2006. Health impacts from electricity (used in the use phase, wafer manufacturing and chemicals and silicon production) are principally due to mercury emissions from generating plants.

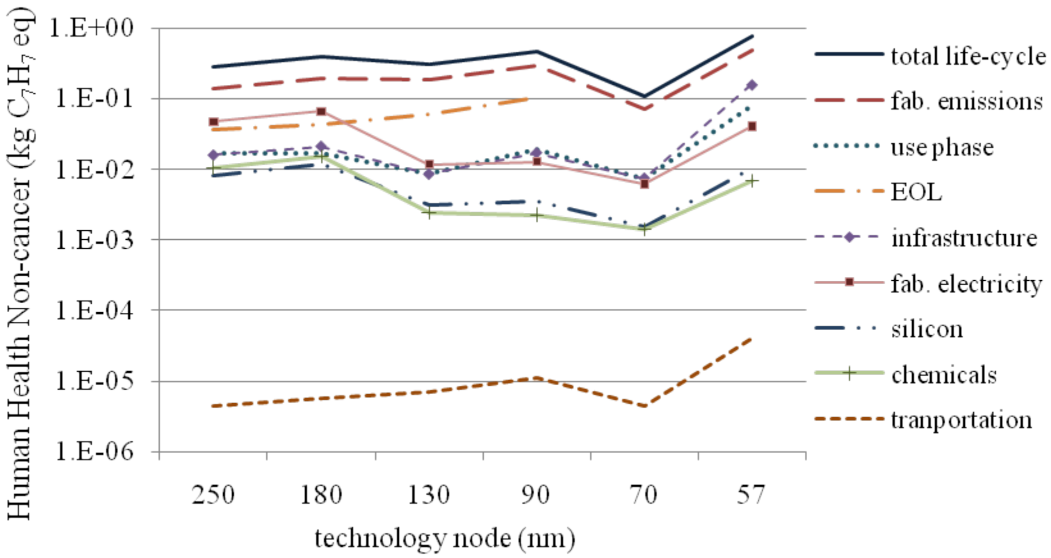


Figure 6.10. Non-cancer human health impacts per OS by technology node

6.4 Discussion

6.4.1 Comparison with existing work

Manufacturing inventory results from this study may be compared with a materials flow analysis of a DRAM chip by Williams[109]. The purpose of the Williams study was to bring attention to the energy and materials intensity of semiconductor production, which lies in contrast to the notion of de-materialization associated with the "information age." The subject of the paper is a 32 MB DRAM chip, which corresponds to 600 nm node DRAM, so a chip from the earliest technology node of this study, a 250 nm node chip with a capacity of 128 MB, is used for comparison. Given the earlier manufacturing technologies and simpler functional unit of the Williams paper, the results are expected to differ.

Williams investigates emissions as well as the energy and quantity of chemicals required to produce a DRAM chip using data from an anonymous industry member which he compares with several other data sources: a report from UNIDO, an unpublished study by an American industrial consortium, data from the Electronics Industry Association of Japan (EIAJ), and Toxics Release Inventory (TRI) data from the US government. Williams finds that the anonymous industry data is within an order of magnitude of the mass inventory data from all of these data sources except TRI, which is known to be incomplete. Williams stressed that the process inventory data he reported was not exact, but he cross-checks the mass inventory with several other industrial and government sources, it is worthwhile to use it for comparison, with an understanding of the difference in functional unit, and limitations due to data availability of that study. The Williams data is normalized to 1 cm^2 finished wafer area and adjusted to account for additional factors which are included in this analysis but not in his: line yield (which accounts for non-product wafers run in production) as well as lifetime of the chip (Williams assumes a 4,380 hour life) and power supply efficiency in the use phase.

Comparison of the energy and materials inventory results of the two studies shows that they differ but fall within an order of magnitude of one another. The divergence in results for energy use in fabrication is due to the fact that Williams uses an average of industry-level energy consumption for the semiconductor industries of Japan and the US to determine this value, which includes demand beyond the manufacturing facilities themselves, as well as data from an unpublished industrial consortium for 150-mm wafer production, which is less efficient than 200-mm wafer production. In the use phase, chips at the 250 nm node consume more power per unit area than chips at the 500 nm node, resulting in higher use phase energy expenditure of the 128 MB chip.

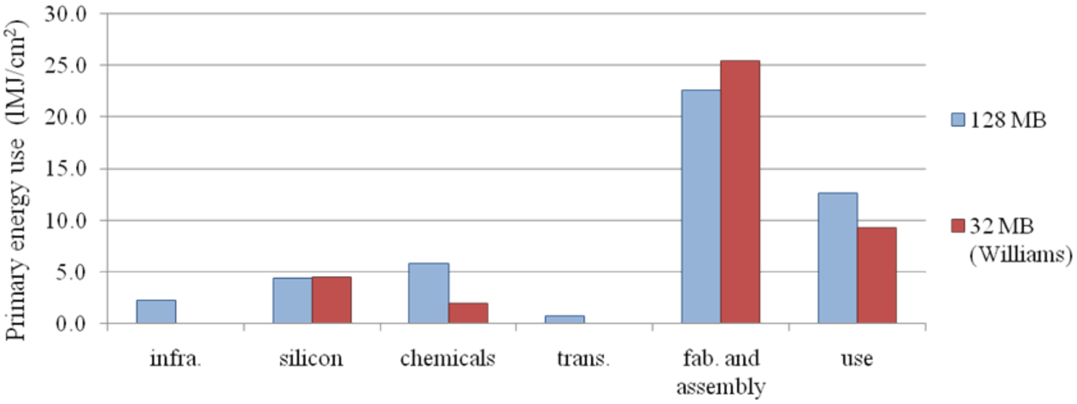


Figure 6.11. Comparison with Williams: Energy use at each life-cycle stage

While the totals for all chemicals and elemental gases used in production are similar between the two studies, the breakdown between elemental gases and other chemicals differ significantly. This disparity in materials inventory data is not clearly attributable to the difference in process technology between the two generations. Currently, and since the 180 and 130 nm nodes, certain wafer cleaning and thermal steps are performed in single-wafer systems which have higher per-wafer material demands. One of the most significant changes in material efficiency in semiconductor processing has been this switch, for certain more delicate steps, from batch process wet cleaning and thermal steps, to single-wafer cleaning and rapid thermal processing (RTP). In batch-based wet cleans, the cleaning solution can be more easily recycled, and, in furnace-based thermal processing, many wafers would be annealed or oxidized at once, requiring a smaller quantity of process chemicals and gases per wafer. At the 250 nm node wet cleaning and thermal steps are performed by batch process, as at the 500 nm node, so demands for inputs to individual wet process or thermal steps should be similar between the two studies. At the 250 nm node, however, there are more layers of metallization as well as additional steps used for electrical isolation of the gate and likely more implant steps to control distribution of dopants in the channel area. Because the process technology of the DRAM in the Williams study is not described, it is difficult to say with certainty that process technology is not a major factor, but, because the process flow necessary to construct 128 MB DRAM entails more steps than that for 32 MB DRAM, the device complexity is the clearest cause of the discrepancy. Also, the data for process inputs in the Williams study are described as an estimation provided by an expert within industry, so the values for the mass inventory are approximate. Because the inventory results of this and the Williams study fall within an order of magnitude, the difference can be attributed, generally, to the simpler functional unit, as well as the approximate nature of the Williams data.

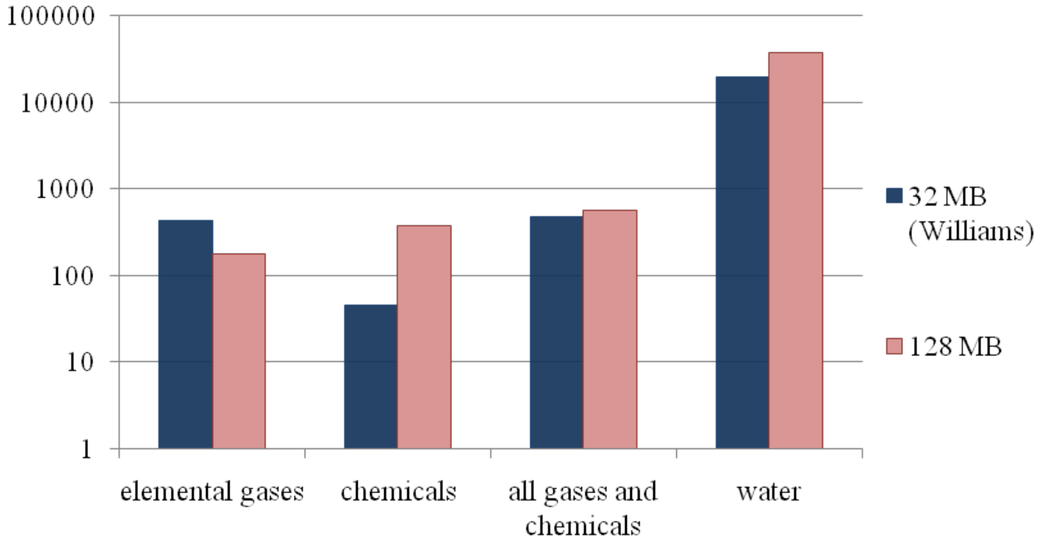


Figure 6.12. Comparison with Williams: Mass of process chemicals and gases

Water use results compare as expected between the two studies, as the production of a later device technology will have higher water demands, due to the relatively larger number of wafer cleaning steps.

It is important to point out that one assumption stated by Williams should not be repeated in future semiconductor process inventory studies:

> "Given that nearly all chemicals used in semiconductor processing do not end up in the final product, mass balance dictates that use and emissions of chemicals should be nearly identical."

Although this is true at the chamber level, and makes sense from a theoretical standpoint for the fab as a whole, the masses of input materials and emissions at the facility level differ in actuality due to chemical transformations which occur during processing and abatement with elements which may not be counted as "inputs" to the process (air, water and abatement materials). The largest mass fractions of semiconductor process waste are liquids used in wafer cleaning (HF, H_2SO_4, HCl, H_2O_2, NH_4OH). All of these liquids, with the exception of HF, are diluted and neutralized on site to a pH which is safe to drain into the public wastewater system. Because these wastes are non-toxic and can be released safely, they may not be counted as emissions by some studies. Also, in some localities, environmental permits for these releases are regulated by pH limits, rather than by the mass of waste flow, so there is no reason to measure or monitor the mass of these wastes. Fluorinated chemicals and HF liquids are converted into a matrix of calcium fluorite and flocculants, which is usually hauled off-site as non-hazardous waste. In this case, a record of the waste stream would be reported but the mass of materials in the waste product would dramatically over-estimate the mass of the initial process chemicals. One gram of HF used in process would be converted to almost seven grams of non-hazardous waste. While mass balance closes at the chamber level (minus chamber wall residues in the case of deposition steps), the same is not true at the facility level, and the mass of total waste from a fab cannot be used as a proxy for the mass of input process materials.

6.5 Conclusions

The overall trends in impacts reveal that software efficiency is an important factor in determining the life-cycle environmental impacts of computer memory. While impacts per GB memory capacity have fallen over the past decade, the life-cycle environmental and human health effects associated with the memory requirements of a typical operating system have risen.

At the most recent technology nodes, use phase energy consumption has been the largest contributor to energy and water consumption, ecotoxicity and, in the case of wafer production within the WSC, GWP impacts. Infrastructure production is the largest cause of smog formation, acidification, eutrophication, and human health criteria. Fab direct emissions are the largest source of carcinogenicity and non-cancer human health impacts. Results from this study compare with results from a previous manufacturing inventory for DRAM as anticipated, given the differences in data sources and functional unit.

Chapter 7

Summary and Conclusions

In this thesis, LCAs of CMOS logic, flash memory and DRAM are presented. Together, these LCA results enable a wide variety of electronic devices to be modeled, and thus allows comparison between a broad set of IT services and traditional products. The manufacturing inventory and life-cycle impact data provided in the appendices, which allow more accurate life cycle assessment of a wide variety of electronics, represent the most important contributions of this thesis. These LCA are transparent and complete, overcoming the limitations of previously published semiconductor LCA studies. No other previous study has included process emissions as well as impacts associated with the production of process chemicals. Water consumed in electricity production as well as transportation emissions are also newly introduced to semiconductor LCA methodology in this thesis. This research is also the first to analyze many generations of a particular semiconductor product, in order to investigate trends in impacts over time.

One of the major challenges to LCA of semiconductors is the rapid advancement of technology and requisite frequent changes to manufacturing processes. The use of process specific data is a particular strength of the LCA in this thesis, because using data at the equipment level rather than the fab level allows a more adaptable inventory model which can be used to analyze various devices. By applying the material and energy demands and chemical emissions for a set of processes to a device-specific process flow, many different vintages of a semiconductor device can be evaluated, including semiconductor products which have not yet reached full-scale production.

Among the results of the LCA in this thesis, the global warming impacts associated with PFC emissions from wafer manufacturing are particularly relevant to policy. As stated in Chapter 2, semiconductor manufacturing capacity is growing most rapidly in countries which lack government or industrial policy to control PFC emissions. The LCA results for CMOS logic, flash memory and DRAM show that emitting PFCs without abatement results in a dramatic increase in life-cycle GWP for these products. Increasing awareness of the consequences of PFC emissions could encourage the industrial consortia of these countries to join the World Semiconductor Council in setting quantitative PFC emission reduction goals.

An important conclusion concerning the functional unit in semiconductor LCA arose in the process of performing LCA for these products. Choice of functional unit is a not a straightforward decision for semiconductor products because, as software has increased its computational requirements in response to the greater supply of computing capacity, a given amount of computational power and memory has provided diminishing functionality, by some measures. This effect, which was described by Plepys as a rebound effect [74], has been explored further in this thesis by charting the life-cycle impacts of the minimum random access memory (RAM) requirements for a popular operating system (OS) over time. While the impacts per GB of DRAM have fallen over the past decade, the impacts associated with the amount of DRAM required to run the OS have not. An important finding of this thesis is that software efficiency is a critical factor in the environmental impact of computing.

7.1 Future work

7.1.1 Life-cycle inventory and impact factors for semiconductor chemicals

The life-cycle stage for which data collection proved the most difficult is the production of high-purity and specialty chemicals used in wafer fabrication. There is still a considerable need for life-cycle inventory data for the energy used in and emissions from semiconductor chemicals production. While LCI data for many common industrial chemicals have been defined and populate LCA databases and software, equivalent information for chemicals which are specific to semiconductor production are not currently available. Many specialty chemicals used in wafer fabrication also do not have defined environmental or human health impact factors. In order to improve the accuracy of semiconductor LCA, energy consumption and emissions data for the production of semiconductor grade ($> 99.9999997\%$) elemental gases (N_2, Ar, He, O_2). LCI data and impacts factors for certain specialty chemicals which are used in high volume, particularly CMP agents, would be most helpful.

The category of the process chemicals which currently have the highest consumption by mass in logic production, after elemental gases, but which lack LCI or impact data, are CMP slurries. CMP slurries have proprietary formulas, so the components and proportions can only be estimated from basic process knowledge. Aggregate data for the energy and emissions of production, and impact factors for each type of

CMP slurry, or the exact composition for generic copper, oxide and tungsten CMP chemicals would enable more accurate LCA in the future.

Following elemental gases and CMP chemicals, agents used in photolithography are among the chemicals used in highest volume in wafer processing. These materials are for the most part volatile organics, which have the potential to produce ground-level ozone and smog, though they may also have some health effects or toxicity. A list of the volatile organic chemicals which lack environmental impact and human health factors are given in Table 4.3.

There are several semiconductor chemicals which have undergone toxicity studies but lack environmental and human health impact factors. A list of the chemicals which are used in highest volume, and which show the potential to damage environmental or human health but lack impact factors are listed in Table 4.4.

7.1.2 LCA of networked thin client versus local desktop computing

As more computing becomes dependent on the internet, some users are switching from larger, independent personal computers to thin clients, such as smart phones and "netbooks." These electronics, while having lower individual power consumption than a desktop PC require, constant interaction with servers over wireless internet, and in some cases also telecommunications networks. While the trend towards thin clients appears on the surface to be a positive environmental trend, due to their lower power consumption and smaller physical dimensions, the impacts associated with operation of network equipment and servers also need to be considered in the comparison.

7.1.3 Comparative LCA of IT versus traditional products and services

There are many applications for the data developed in this thesis to be used in LCA of electronics, which would be particularly useful for comparison with traditional products and services. Two good examples of these types of studies are a comparative life cycle analysis of reading news on a newspaper versus on a hand-held device [103] and a study of the life-cycle impacts of telecommuting versus commuting to work [53]. Other products and services that deserve analysis are the use of electronic books, online videos, internet encyclopedias and online banking in place of their traditional hard media equivalents.

7.1.4 Further study of the "rebound effect" of computational power and memory capacity

As computational power and memory have become cheaper and more accessible, software has expanded to consume the processor capability and space afforded to it, and computer users have consumed more processing power and memory capacity. In this thesis, this effect is tested in the case of the memory capacity required for a standard operating system. This area of study can be expanded in both quantitative and qualitative directions. For example, the computational power for operating systems and common applications may be evaluated to illustrate trends in processor demand over time. Also, this topic can also be addressed at higher level of analysis. As technology advances and software applications consume more computational and memory capacity, users benefit from the depth and variety of tasks that software can perform. Some applications, given the additional computational power, have evolved beyond their original purposes. For example, internet browsing was originally used primarily for information and entertainment, and is now used for video communication, shopping, banking, interactive blogging and more. At the same time, some computer applications have continued to perform the same tasks (email communication, word processing, spreadsheet calculation), only using much more memory. Whether additional resources used to enhance existing applications and perform new tasks are being used effectively and efficiently is a complex question, but nevertheless an interesting area of deeper inquiry.

The manufacturing inventory and LCA impact data presented in this thesis enable more accurate and confident study of the potential environmental benefits of IT. My hope is that this research facilitates more intelligent and deliberate adoption of IT as a replacement for existing products and services, to allow continued technological progress, innovation and growth without damaging or endangering the environment or human health.

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Appendix A

Acronyms and abbreviations

CMOS: complementary metal oxide semiconductor
CMP: chemical mechanical polishing DRAM: dynamic random access memory
EOL: end-of-life
GWP: global warming potential
NAICS: North American Industry Classification System
PFC: per-fluorinated compound

Table A.1. Acronyms

BTBAS: bis tertiary-butylamino silane
DEA: diethyl-amine
HMDS: hexa-methyl disilizane
IPA: isopropyl alcohol
OMCTS: octamethylcyclotetrasiloxane
PDMAT: pentakis(dimethylamido)tantalum
PGMEA: propylene glycol monomethyl-ether acetate
TMAH: tetramethyl ammonium hydroxide
TDEAH: tetrakis(diethylamino)hafnium
TDMAS: tris(dimethylamino)silane

Table A.2. Chemical abbreviations

Appendix B

CMOS logic: manufacturing inventory and impact data

B.1 CMOS logic manufacturing inventory data

Energy (MJ/die)							
year	1995	1998	1999	2001	2004	2007	2010
technology node (nm)	350	250	180	130	90	65	45
use	151	250	271	666	917	1135	1593
fab (China)	93	55	44	41	42	45	40
fab. (WWavg.)	80	47	38	35	36	38	35
infra.	14	12	10	6.7	12	16	19
silicon	15	8.5	6.8	8.9	8.9	8.3	6.5
chemicals	15	10	9.5	6.2	6.9	6.5	4.2
trans.	1.8	1.6	1.6	1.5	1.5	1.5	1.4
life cycle total	370	384	381	766	1,024	1,250	1,699

* Note: Life-cycle totals have an accuracy of two significant digits, but are reported here unrounded

Table B.1. Energy consumption per die by life-cycle stage

year	1995	1998	1999	2001	2004	2007	2010
technology node (nm)	350	250	180	130	90	65	45
use	1454	2403	2604	4264	5872	7270	10206
fab feedwater	98	13	53	36	42	29	12
fab electricity (US avg.)	767	452	361	227	231	245	221
silicon	210	122	99	57	57	53	42
infrastructure	1.7	1.4	1.2	0.5	1.0	1.3	1.5
chemicals	1.8	1.2	1.1	0.5	0.6	0.5	0.3
life cycle water	2,533	2,993	3119	4,585	6,204	7,598	10,483

* Note: Life-cycle totals have an accuracy of two significant digits, but are reported here unrounded

Table B.2. Water consumption per die by life-cycle stage

GWP (kgCO$_2$eq/die)							
year	1995	1998	1999	2001	2004	2007	2010
technology node (nm)	350	250	180	130	90	65	45
use	4.1	6.8	7.4	18.1	24.9	30.8	43.2
fab (no PFC abatement)	8.7	5.3	3.6	3.4	3.6	3.9	2.8
fab. (PFC abatement)	2.3	1.4	1.1	1.0	1.0	1.1	1.0
infrastructure	1.2	1.0	0.8	0.5	1.0	1.3	1.5
silicon	1.2	0.7	0.6	0.7	0.7	0.7	0.5
chemicals	1.3	0.8	0.8	0.5	0.6	0.5	0.5
transportation	0.12	0.11	0.11	0.10	0.10	0.10	0.10
life cycle total	10	11	11	21	28	35	47

Table B.3. GWP per die by life-cycle stage

350 nm			350 nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	4.74E-02		SiH_4	8.39E-03
CHF_3	8.69E-04		H_2	2.20E-01
C_2F_6	0.00E+00		DCS	0.00E+00
CH_4	4.36E-01		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	0.00E+00
NF_3	2.02E-02		GeH_4	0.00E+00
C_4F_6	0.00E+00		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	1.20E-01
SiF_4	4.41E-05		Ar	6.56E-01
C_4F_8	3.24E-04		N_2	4.86E-01
C_2F_4	0.00E+00		CMP polishing solution	0.00E+00
COF_2	0.00E+00		H_2O_2	1.04E+01
HCl (gas)	0.00E+00		abrasive	0.00E+00
Cl_2	5.38E-03		silica slurry	0.00E+00
$SiCl_4$	0.00E+00		benzotriazole	0.00E+00
PH_3	2.45E-04		CMP surfactants	2.35E-01
BTBAS	1.05E-03		citric acid	1.31E-01
AsH_3	0.00E+00		tungsten CMP slurry	1.13E+01
BCl_3	6.25E-03		Al	3.74E-04
Pb	1.10E-05		As	0.00E+00
WF_6	7.99E-02		Cu	1.55E-04
HBr	4.33E-03		Pt	0.00E+00
Br_2	0.00E+00		Ti	2.61E-05
HMDS	1.36E-01		He	3.66E-04
OMCTS	0.00E+00		NH_3	1.11E-02

Table B.4. CMOS manufacturing inventory per wafer, 350 nm node

350 nm			350 nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	2.04E-03
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	2.06E-01
SO_2	0.00E+00		H_2SO_4	1.13E+02
N_2O	3.59E-02		HCl	2.31E+00
O_3	0.00E+00		NH_4OH	4.12E+00
			IPA	5.73E+00
VOC			oxide CMP slurry, chemicals	1.30E+01
DMA	0.00E+00		BF_3	0.00E+00
MMA	0.00E+00		Cr	0.00E+00
TDMAT	4.94E-04		Au	4.48E-05
TMS	0.00E+00		Sn	3.04E-06
TEOS	0.00E+00		Co	2.39E-05
formaldehyde	1.61E-02		Ni	2.01E-03
m-cresol	1.02E-02		polyimide laminate	2.03E-03
p-cresol	1.01E-02		laminate solvent	0.00E+00
PGMEA	1.30E-01		$H3PO_4$	0.00E+00
n-methyl-2-pyrollidone	9.09E-03		$CuCl_2$	1.17E-06
PGME	1.71E-01		W	4.15E-07
ethyl lactate	1.64E-01		Ta	0.00E+00
TMAH	1.76E-02		Cu ECP additive X	5.93E-04
TDEAH	0.00E+00		Cu ECP Additive Y	2.94E-04
TDMAS	0.00E+00		$Na_2B_4O_7$	7.63E-03
DEA	0.00E+00			
PDMAT	0.00E+00			

Table B.5. CMOS manufacturing inventory per wafer, 350 nm node

250nm			250nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	5.51E-02		SiH_4	8.73E-03
CHF_3	9.43E-04		H_2	2.56E-01
C_2F_6	0.00E+00		DCS	0.00E+00
CH_4	4.75E-01		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	0.00E+00
NF_3	2.10E-02		GeH_4	0.00E+00
C_4F_6	0.00E+00		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	1.21E-01
SiF_4	4.41E-05		Ar	7.37E-01
C_4F_8	3.24E-04		N_2	6.59E-01
C_2F_4	0.00E+00		CMP polishing solution	0.00E+00
COF_2	0.00E+00		H_2O_2	1.14E+01
HCl (gas)	0.00E+00		abrasive	0.00E+00
Cl_2	6.12E-03		silica slurry	0.00E+00
$SiCl_4$	0.00E+00		benzotriazole	0.00E+00
PH_3	2.45E-04		CMP surfactants	2.82E-01
BTBAS	1.05E-03		citric acid	1.57E-01
AsH_3	0.00E+00		tungsten CMP slurry	1.36E+01
BCl_3	7.30E-03		Al	4.68E-04
Pb	1.10E-05		As	0.00E+00
WF_6	9.32E-02		Cu	2.67E-04
HBr	4.33E-03		Pt	0.00E+00
Br_2	0.00E+00		Ti	2.61E-05
HMDS	1.51E-01		He	7.32E-04
OMCTS	0.00E+00		NH_3	1.11E-02

Table B.6. CMOS manufacturing inventory per wafer, 250 nm node

250nm			250nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	2.04E-03
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	2.51E-01
SO_2	0.00E+00		H_2SO_4	1.21E+02
N_2O	4.09E-02		HCl	2.62E+00
O_3	0.00E+00		NH_4OH	4.75E+00
			IPA	6.05E+00
VOC			oxide CMP slurry, chemicals	1.52E+01
DMA	0.00E+00		BF_3	0.00E+00
MMA	0.00E+00		Cr	0.00E+00
TDMAT	9.88E-04		Au	7.69E-05
TMS	0.00E+00		Sn	3.04E-06
TEOS	0.00E+00		Co	4.10E-05
formaldehyde	1.79E-02		Ni	3.45E-03
m-cresol	1.14E-02		polyimide laminate	2.03E-03
p-cresol	1.13E-02		laminate solvent	0.00E+00
PGMEA	1.45E-01		$H3PO_4$	0.00E+00
n-methyl-2-pyrollidone	9.09E-03		$CuCl_2$	1.17E-06
PGME	1.90E-01		W	4.15E-07
ethyl lactate	1.82E-01		Ta	0.00E+00
TMAH	1.96E-02		Cu ECP additive X	5.93E-04
TDEAH	0.00E+00		Cu ECP Additive Y	2.94E-04
TDMAS	0.00E+00		$Na_2B_4O_7$	8.48E-03
DEA	0.00E+00			
PDMAT	0.00E+00			

Table B.7. CMOS manufacturing inventory per wafer, 250 nm node

180 nm			180 nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	2.92E-03		SiH_4	9.31E-03
CHF_3	9.46E-04		H_2	2.73E-01
C_2F_6	5.94E-04		DCS	0.00E+00
CH_4	3.89E-01		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	0.00E+00
NF_3	9.96E-02		GeH_4	0.00E+00
C_4F_6	0.00E+00		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	8.24E-01
SiF_4	2.03E-03		Ar	2.67E+00
C_4F_8	3.01E-04		N_2	6.43E-01
C_2F_4	0.00E+00		CMP polishing solution	0.00E+00
COF_2	0.00E+00		H_2O_2	1.17E+01
HCl (gas)	0.00E+00		abrasive	0.00E+00
Cl_2	6.40E-03		silica slurry	0.00E+00
$SiCl_4$	0.00E+00		benzotriazole	0.00E+00
PH_3	2.28E-04		CMP surfactants	3.07E-01
BTBAS	9.75E-04		citric acid	1.70E-01
AsH_3	0.00E+00		tungsten CMP slurry	1.48E+01
BCl_3	7.77E-03		Al	5.23E-04
Pb	1.02E-05		As	0.00E+00
WF_6	9.92E-02		Cu	3.31E-04
HBr	4.03E-03		Pt	0.00E+00
Br_2	0.00E+00		Ti	2.43E-05
HMDS	1.54E-01		He	6.82E-04
OMCTS	0.00E+00		NH_3	1.04E-02

Table B.8. CMOS manufacturing inventory per wafer, 180 nm node

LateX tables				
180 nm			180 nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	1.90E-03
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	2.52E-01
SO_2	0.00E+00		H_2SO_4	1.27E+02
N_2O	5.27E-03		HCl	2.58E+00
O_3	0.00E+00		NH_4OH	4.82E+00
			IPA	5.34E+00
VOC			oxide CMP slurry, chemicals	1.62E+01
DMA	0.00E+00		BF_3	0.00E+00
MMA	0.00E+00		Cr	0.00E+00
TDMAT	9.21E-04		Au	9.52E-05
TMS	0.00E+00		Sn	2.83E-06
TEOS	0.00E+00		Co	5.08E-05
formaldehyde	1.84E-02		Ni	4.27E-03
m-cresol	1.16E-02		polyimide laminate	1.89E-03
p-cresol	1.15E-02		laminate solvent	0.00E+00
PGMEA	1.49E-01		H3PO$_4$	0.00E+00
n-methyl-2-pyrollidone	8.47E-03		$CuCl_2$	1.09E-06
PGME	1.95E-01		W	3.86E-07
ethyl lactate	1.86E-01		Ta	0.00E+00
TMAH	2.01E-02		Cu ECP additive X	5.53E-04
TDEAH	0.00E+00		Cu ECP Additive Y	2.74E-04
TDMAS	0.00E+00		$Na_2B_4O_7$	8.69E-03
DEA	0.00E+00			
PDMAT	0.00E+00			

Table B.9. CMOS manufacturing inventory per wafer, 180 nm node

130 nm			130 nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	7.94E-03		SiH_4	1.21E-02
CHF_3	1.39E-03		H_2	9.73E-02
C_2F_6	9.80E-04		DCS	1.73E-03
CH_4	5.60E-01		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	2.25E-03
NF_3	1.46E-01		GeH_4	3.92E-03
C_4F_6	4.34E-04		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	1.36E+00
SiF_4	2.84E-03		Ar	3.61E+00
C_4F_8	7.95E-04		N_2	1.47E+00
C_2F_4	0.00E+00		CMP polishing solution	1.67E+01
COF_2	0.00E+00		H_2O_2	1.84E+01
HCl (gas)	8.41E-02		abrasive	5.27E-01
Cl_2	1.71E-03		silica slurry	5.27E-01
$SiCl_4$	0.00E+00		benzotriazole	2.17E-02
PH_3	3.01E-04		CMP surfactants	4.05E-01
BTBAS	1.29E-03		citric acid	3.46E-02
AsH_3	0.00E+00		tungsten CMP slurry	2.78E+00
BCl_3	0.00E+00		Al	0.00E+00
Pb	1.35E-05		As	0.00E+00
WF_6	3.27E-02		Cu	1.10E-03
HBr	7.97E-03		Pt	0.00E+00
Br_2	0.00E+00		Ti	1.14E-07
HMDS	2.04E-01		He	8.99E-04
OMCTS	0.00E+00		NH_3	1.39E-02

Table B.10. CMOS manufacturing inventory per wafer, 130 nm node

130 nm			130 nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	1.75E-02
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	3.47E-01
SO_2	0.00E+00		H_2SO_4	1.92E+02
N_2O	6.96E-03		HCl	4.54E+00
O_3	0.00E+00		NH_4OH	5.99E+00
			IPA	1.58E+00
VOC			oxide CMP slurry, chemicals	5.33E+00
DMA	0.00E+00		BF_3	0.00E+00
MMA	0.00E+00		Cr	0.00E+00
TDMAT	1.21E-03		Au	1.64E-04
TMS	0.00E+00		Sn	3.74E-06
TEOS	0.00E+00		Co	8.76E-05
formaldehyde	2.42E-02		Ni	7.36E-03
m-cresol	1.54E-02		polyimide laminate	2.49E-03
p-cresol	1.52E-02		laminate solvent	0.00E+00
PGMEA	1.96E-01		$H3PO_4$	3.61E-02
n-methyl-2-pyrollidone	1.12E-02		$CuCl_2$	1.00E-05
PGME	2.57E-01		W	7.74E-06
ethyl lactate	2.46E-01		Ta	1.95E+00
TMAH	2.65E-02		Cu ECP additive X	5.10E-03
TDEAH	0.00E+00		Cu ECP Additive Y	2.53E-03
TDMAS	0.00E+00		$Na_2B_4O_7$	1.15E-02
DEA	0.00E+00			
PDMAT	0.00E+00			

Table B.11. CMOS manufacturing inventory per wafer, 130 nm node

90nm			90nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	1.18E-02		SiH_4	1.76E-02
CHF_3	3.38E-03		H_2	9.75E-02
C_2F_6	0.00E+00		DCS	6.93E-03
CH_4	6.91E-01		B_2H_6	2.37E-03
CO_2	0.00E+00		C_4F_8	1.07E-03
NF_3	1.64E-01		GeH_4	3.92E-03
C_4F_6	1.45E-04		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	3.13E+00
SiF_4	9.40E-04		Ar	1.98E+00
C_4F_8	7.95E-04		N_2	1.80E+00
C_2F_4	0.00E+00		CMP polishing solution	1.95E+01
COF_2	0.00E+00		H_2O_2	1.82E+01
HCl (gas)	8.41E-02		abrasive	6.15E-01
Cl_2	1.71E-03		silica slurry	6.15E-01
$SiCl_4$	0.00E+00		benzotriazole	2.53E-02
PH_3	3.01E-04		CMP surfactants	4.63E-01
BTBAS	1.29E-03		citric acid	3.50E-02
AsH_3	0.00E+00		tungsten CMP slurry	2.78E+00
BCl_3	0.00E+00		Al	0.00E+00
Pb	1.35E-05		As	0.00E+00
WF_6	3.27E-02		Cu	1.18E-03
HBr	7.97E-03		Pt	0.00E+00
Br_2	0.00E+00		Ti	1.60E-04
HMDS	2.59E-01		He	1.38E-01
OMCTS	4.69E-03		NH_3	1.62E-02

Table B.12. CMOS manufacturing inventory per wafer, 90 nm node

90nm			90nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	2.00E-02
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	3.33E-01
SO_2	0.00E+00		H_2SO_4	1.83E+02
N_2O	1.39E-02		HCl	4.73E+00
O_3	0.00E+00		NH_4OH	6.23E+00
			IPA	1.19E+00
VOC			oxide CMP slurry, chemicals	5.33E+00
DMA	0.00E+00		BF_3	0.00E+00
MMA	0.00E+00		Cr	0.00E+00
TDMAT	1.82E-03		Au	1.64E-04
TMS	2.94E-03		Sn	3.74E-06
TEOS	1.40E-03		Co	8.76E-05
formaldehyde	3.00E-02		Ni	7.36E-03
m-cresol	3.60E-02		polyimide laminate	2.49E-03
p-cresol	1.80E-02		laminate solvent	0.00E+00
PGMEA	2.55E-01		$H3PO_4$	2.43E-02
n-methyl-2-pyrollidone	3.35E-02		$CuCl_2$	1.05E-03
PGME	3.06E-01		W	6.74E-03
ethyl lactate	2.90E-01		Ta	1.37E+00
TMAH	3.13E-02		Cu ECP additive X	6.13E-03
TDEAH	0.00E+00		Cu ECP Additive Y	2.89E-03
TDMAS	0.00E+00		$Na_2B_4O_7$	2.55E-01
DEA	0.00E+00			
PDMAT	4.25E-03			

Table B.13. CMOS manufacturing inventory per wafer, 90 nm node

65 nm			65 nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	1.37E-02		SiH_4	1.70E-02
CHF_3	3.30E-03		H_2	1.02E-01
C_2F_6	0.00E+00		DCS	9.81E-03
CH_4	9.84E-01		B_2H_6	2.98E-03
CO_2	0.00E+00		C_4F_8	1.46E-03
NF_3	1.57E-01		GeH_4	7.40E-03
C_4F_6	2.05E-04		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	3.91E+00
SiF_4	3.07E-04		Ar	1.50E+00
C_4F_8	7.50E-04		N_2	1.65E+00
C_2F_4	0.00E+00		CMP polishing solution	2.10E+01
COF_2	0.00E+00		H_2O_2	1.93E+01
HCl (gas)	1.59E-01		abrasive	6.63E-01
Cl_2	2.15E-03		silica slurry	6.63E-01
$SiCl_4$	0.00E+00		benzotriazole	2.73E-02
PH_3	2.84E-04		CMP surfactants	4.91E-01
BTBAS	1.21E-03		citric acid	3.34E-02
AsH_3	0.00E+00		tungsten CMP slurry	2.62E+00
BCl_3	0.00E+00		Al	0.00E+00
Pb	0.00E+00		As	0.00E+00
WF_6	3.09E-02		Cu	1.28E-03
HBr	1.00E-02		Pt	0.00E+00
Br_2	0.00E+00		Ti	3.03E-05
HMDS	2.71E-01		He	3.08E-01
OMCTS	5.90E-03		NH_3	1.77E-02

Table B.14. CMOS manufacturing inventory per wafer, 65 nm node

65 nm			65 nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	2.12E-02
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	2.13E-01
SO_2	0.00E+00		H_2SO_4	2.08E+02
N_2O	1.31E-02		HCl	4.46E+00
O_3	4.85E-02		NH_4OH	5.87E+00
			IPA	1.13E+00
VOC			oxide CMP slurry, chemicals	5.03E+00
DMA	0.00E+00		BF_3	0.00E+00
MMA	0.00E+00		Cr	0.00E+00
TDMAT	1.15E-03		Au	1.77E-04
TMS	3.00E-03		Sn	3.44E-03
TEOS	2.62E-02		Co	9.45E-05
formaldehyde	3.14E-02		Ni	7.97E-03
m-cresol	3.59E-02		polyimide laminate	2.35E-03
p-cresol	1.89E-02		laminate solvent	0.00E+00
PGMEA	2.66E-01		$H3PO_4$	3.25E-02
n-methyl-2-pyrollidone	3.16E-02		$CuCl_2$	9.95E-04
PGME	3.22E-01		W	8.48E-03
ethyl lactate	3.05E-01		Ta	1.83E+00
TMAH	3.30E-02		Cu ECP additive X	6.47E-03
TDEAH	0.00E+00		Cu ECP Additive Y	3.07E-03
TDMAS	0.00E+00		$Na_2B_4O_7$	2.42E-01
DEA	0.00E+00			
PDMAT	9.35E-03			

Table B.15. CMOS manufacturing inventory per wafer, 65 nm node

45 nm			45 nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	3.46E-02		SiH_4	1.68E-02
CHF_3	3.30E-03		H_2	1.02E-01
C_2F_6	0.00E+00		DCS	3.27E-03
CH_4	1.01E+00		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	0.00E+00
NF_3	1.76E-01		GeH_4	7.40E-03
C_4F_6	2.05E-04		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	4.31E+00
SiF_4	4.09E-04		Ar	1.92E+00
C_4F_8	7.50E-04		N_2	1.66E+00
C_2F_4	0.00E+00		CMP polishing solution	2.36E+01
COF_2	0.00E+00		H_2O_2	2.33E+01
HCl (gas)	1.59E-01		abrasive	7.46E-01
Cl_2	2.35E-03		silica slurry	7.46E-01
$SiCl_4$	0.00E+00		benzotriazole	3.07E-02
PH_3	2.84E-04		CMP surfactants	5.45E-01
BTBAS	6.07E-04		citric acid	3.38E-02
AsH_3	7.10E-05		tungsten CMP slurry	2.62E+00
BCl_3	0.00E+00		Al	0.00E+00
Pb	0.00E+00		As	0.00E+00
WF_6	3.09E-02		Cu	1.53E-03
HBr	1.00E-02		Pt	0.00E+00
Br_2	0.00E+00		Ti	1.07E-07
HMDS	2.88E-01		He	3.21E-01
OMCTS	5.90E-03		NH_3	1.22E-02

Table B.16. CMOS manufacturing inventory per wafer, 45 nm node

45 nm			45 nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	7.58E-05		$CuSO_4$	2.36E-02
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	1.15E-01
SO_2	0.00E+00		H_2SO_4	2.53E+02
N_2O	1.31E-02		HCl	5.35E+00
O_3	4.85E-02		NH_4OH	6.97E+00
			IPA	1.11E+00
VOC			oxide CMP slurry, chemicals	5.03E+00
DMA	0.00E+00		BF_3	0.00E+00
MMA	0.00E+00		Cr	0.00E+00
TDMAT	1.15E-03		Au	2.26E-04
TMS	3.00E-03		Sn	4.38E-03
TEOS	2.62E-02		Co	1.20E-04
formaldehyde	3.35E-02		Ni	1.01E-02
m-cresol	3.72E-02		polyimide laminate	2.35E-03
p-cresol	2.02E-02		laminate solvent	0.00E+00
PGMEA	2.82E-01		$H3PO_4$	0.00E+00
n-methyl-2-pyrollidone	3.16E-02		$CuCl_2$	9.96E-04
PGME	3.44E-01		W	4.81E-07
ethyl lactate	3.27E-01		Ta	0.00E+00
TMAH	3.52E-02		Cu ECP additive X	7.16E-03
TDEAH	5.35E-05		Cu ECP Additive Y	3.41E-03
TDMAS	0.00E+00		$Na_2B_4O_7$	2.43E-01
DEA	0.00E+00			
PDMAT	1.20E-02			

Table B.17. CMOS manufacturing inventory per wafer, 45 nm node

B.2 CMOS logic manufacturing emissions data

350 nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF_4	1.09E-03	2.37E-02	9.48E-02
CHF_3	7.18E-05	4.35E-04	1.74E-03
C_2F_6	0.00E+00	0.00E+00	0.00E+00
CH_4	4.90E-05	2.18E-01	8.73E-01
CO_2	1.20E+00	0.00E+00	0.00E+00
NF_3	2.88E-05	1.01E-02	4.05E-02
C_4F_6	0.00E+00	0.00E+00	0.00E+00
N_2O	0.00E+00	0.00E+00	0.00E+00
HAZARDOUS			
F_2	2.76E-03	0.00E+00	0.00E+00
HF (gas)	1.53E-03	0.00E+00	0.00E+00
SiF_4	1.04E-05	2.21E-05	8.82E-05
C_4F_8	2.94E-07	1.62E-04	6.47E-04
C_2F_4	3.47E-06	0.00E+00	0.00E+00
COF_2	7.79E-06	0.00E+00	0.00E+00
HCl (gas)	6.40E-07	0.00E+00	0.00E+00
Cl_2	2.15E-04	2.69E-03	1.08E-02
$SiCl_4$	4.40E-06	0.00E+00	0.00E+00
PH_3	0.00E+00	1.23E-04	4.90E-04
BTBAS	8.25E-06	5.23E-04	2.09E-03
AsH_3	0.00E+00	0.00E+00	0.00E+00
BCl_3	8.96E-05	3.13E-03	1.25E-02
Pb	9.90E-06	5.50E-06	2.20E-05
WF_6	1.06E-02	3.99E-02	1.60E-01
HBr	0.00E+00	2.16E-03	8.65E-03
Br_2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	6.78E-02	2.71E-01
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	2.53E-03	0.00E+00	0.00E+00
NO	2.94E-05	0.00E+00	0.00E+00
NO_2	0.00E+00	0.00E+00	0.00E+00
SO_2	0.00E+00	0.00E+00	0.00E+00
N_2O	1.93E-03	1.79E-02	7.18E-02
O_3	0.00E+00	0.00E+00	0.00E+00

Table B.18. CMOS Manufacturing emissions per wafer, 350 nm node

350 nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	1.04E-06	0.00E+00	0.00E+00
MMA	2.40E-05	0.00E+00	0.00E+00
TDMAT	0.00E+00	2.47E-04	9.88E-04
TMS	0.00E+00	0.00E+00	0.00E+00
TEOS	0.00E+00	0.00E+00	0.00E+00
Formaldehyde (CH_2O)	7.98E-05	8.06E-03	3.22E-02
m-Cresol	5.06E-06	5.11E-03	2.04E-02
p-Cresol	5.01E-06	5.06E-03	2.03E-02
PGMEA	9.39E-03	6.52E-02	2.61E-01
n-Methyl-$_2$-Pyrollidone	0.00E+00	4.54E-03	1.82E-02
PGME	6.97E-03	8.56E-02	3.42E-01
ethyl lactate	8.02E-03	8.18E-02	3.27E-01
TMAH	8.82E-05	8.82E-03	3.53E-02
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH_4	2.97E-04	4.19E-03	1.68E-02
H_2	9.19E-03	1.10E-01	4.39E-01
DCS	0.00E+00	0.00E+00	0.00E+00
B_2H_6	0.00E+00	0.00E+00	0.00E+00
C_4F_8	0.00E+00	0.00E+00	0.00E+00
GeH_4	0.00E+00	0.00E+00	0.00E+00
C_2H_2			
OTHER CHEMICALS			
Ar	6.51E-01	3.28E-01	1.31E+00
N_2	4.49E-01	2.43E-01	9.72E-01
He	3.66E-04	1.83E-04	7.32E-04
O_2	3.88E-02	5.98E-02	2.39E-01
IPA	1.84E-02	2.87E+00	1.15E+01
NH_3	3.66E-04	1.83E-04	7.32E-04
Ti	8.33E-08	1.31E-05	5.22E-05
Cu	1.15E-07	7.77E-05	3.11E-04
Sn	2.74E-06	1.52E-06	6.08E-06

Table B.19. CMOS Manufacturing emissions per wafer, 350 nm node

250 nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF_4	1.28E-03	2.76E-02	1.10E-01
CHF_3	8.36E-05	4.71E-04	1.89E-03
C_2F_6	0.00E+00	0.00E+00	0.00E+00
CH_4	4.90E-05	2.38E-01	9.50E-01
CO_2	1.31E+00	0.00E+00	0.00E+00
NF_3	3.04E-05	1.05E-02	4.19E-02
C_4F_6	0.00E+00	0.00E+00	0.00E+00
N_2O	0.00E+00	0.00E+00	0.00E+00
HAZARDOUS			
F_2	3.16E-03	0.00E+00	0.00E+00
HF (gas)	1.80E-03	0.00E+00	0.00E+00
SiF_4	1.07E-05	2.21E-05	8.82E-05
C_4F_8	2.94E-07	1.62E-04	6.47E-04
C_2F_4	3.47E-06	0.00E+00	0.00E+00
COF_2	8.21E-06	0.00E+00	0.00E+00
HCl (gas)	7.47E-07	0.00E+00	0.00E+00
Cl_2	2.49E-04	3.06E-03	1.22E-02
$SiCl_4$	5.13E-06	0.00E+00	0.00E+00
PH_3	0.00E+00	1.23E-04	4.90E-04
BTBAS	8.25E-06	5.23E-04	2.09E-03
AsH_3	0.00E+00	0.00E+00	0.00E+00
BCl_3	1.05E-04	3.65E-03	1.46E-02
Pb	9.90E-06	5.50E-06	2.20E-05
WF_6	1.23E-02	4.66E-02	1.86E-01
HBr	0.00E+00	2.16E-03	8.65E-03
Br_2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	7.53E-02	3.01E-01
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	2.95E-03	0.00E+00	0.00E+00
NO	2.94E-05	0.00E+00	0.00E+00
NO_2	0.00E+00	0.00E+00	0.00E+00
SO_2	0.00E+00	0.00E+00	0.00E+00
N_2O	2.21E-03	2.05E-02	8.19E-02
O_3	0.00E+00	0.00E+00	0.00E+00

Table B.20. CMOS Manufacturing emissions per wafer, 250 nm node

250 nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	2.09E-06	0.00E+00	0.00E+00
MMA	4.80E-05	0.00E+00	0.00E+00
TDMAT	0.00E+00	4.94E-04	1.98E-03
TMS	0.00E+00	0.00E+00	0.00E+00
TEOS	0.00E+00	0.00E+00	0.00E+00
formaldehyde	8.87E-05	8.96E-03	3.58E-02
m-cresol	5.62E-06	5.68E-03	2.27E-02
p-cresol	5.57E-06	5.63E-03	2.25E-02
PGMEA	1.04E-02	7.25E-02	2.90E-01
n-methyl-$_2$-pyrollidone	0.00E+00	4.54E-03	1.82E-02
PGME	7.69E-03	9.51E-02	3.80E-01
ethyl lactate	8.91E-03	9.09E-02	3.64E-01
TMAH	9.80E-05	9.80E-03	3.92E-02
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH_4	3.46E-04	4.37E-03	1.75E-02
H_2	1.07E-02	1.28E-01	5.12E-01
DCS	0.00E+00	0.00E+00	0.00E+00
B_2H_6	0.00E+00	0.00E+00	0.00E+00
C_4F_8	0.00E+00	0.00E+00	0.00E+00
GeH_4	0.00E+00	0.00E+00	0.00E+00
C_2H_2			
OTHER CHEMICALS			
Ar	7.32E-01	3.68E-01	1.47E+00
N_2	6.05E-01	3.29E-01	1.32E+00
He	7.32E-04	3.66E-04	1.46E-03
O_2	4.02E-02	6.05E-02	2.42E-01
IPA	2.04E-02	3.03E+00	1.21E+01
NH_3	7.32E-04	3.66E-04	1.46E-03
Ti	8.33E-08	1.31E-05	5.22E-05
Cu	1.15E-07	1.33E-04	5.34E-04
Sn	2.74E-06	1.52E-06	6.08E-06

Table B.21. CMOS Manufacturing emissions per wafer, 250 nm node

180 nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF_4	2.80E-04	1.46E-03	5.83E-03
CHF_3	8.88E-05	4.73E-04	1.89E-03
C_2F_6	1.37E-05	2.97E-04	1.19E-03
CH_4	9.92E-05	1.95E-01	7.79E-01
CO_2	1.01E+00	0.00E+00	0.00E+00
NF_3	2.07E-04	4.98E-02	1.99E-01
C_4F_6	0.00E+00	0.00E+00	0.00E+00
N_2O	0.00E+00	0.00E+00	0.00E+00
HAZARDOUS			
F_2	3.67E-03	0.00E+00	0.00E+00
HF (gas)	1.67E-03	0.00E+00	0.00E+00
SiF_4	2.51E-05	1.01E-03	4.05E-03
C_4F_8	2.74E-07	1.51E-04	6.03E-04
C_2F_4	8.71E-06	0.00E+00	0.00E+00
COF_2	1.18E-05	0.00E+00	0.00E+00
HCl (gas)	7.95E-07	0.00E+00	0.00E+00
Cl_2	2.64E-04	3.20E-03	1.28E-02
$SiCl_4$	5.46E-06	0.00E+00	0.00E+00
PH_3	0.00E+00	1.14E-04	4.57E-04
BTBAS	7.69E-06	4.87E-04	1.95E-03
AsH_3	0.00E+00	0.00E+00	0.00E+00
BCl_3	1.11E-04	3.88E-03	1.55E-02
Pb	9.22E-06	5.12E-06	2.05E-05
WF_6	1.31E-02	4.96E-02	1.98E-01
HBr	0.00E+00	2.01E-03	8.06E-03
Br_2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	7.72E-02	3.09E-01
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	4.86E-02	0.00E+00	0.00E+00
NO	2.09E-03	0.00E+00	0.00E+00
NO_2	7.66E-04	0.00E+00	0.00E+00
SO_2	0.00E+00	0.00E+00	0.00E+00
N_2O	2.01E-04	2.64E-03	1.05E-02
O_3	0.00E+00	0.00E+00	0.00E+00

Table B.22. CMOS Manufacturing emissions per wafer, 180 nm node

180 nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	1.94E-06	0.00E+00	0.00E+00
MMA	4.47E-05	0.00E+00	0.00E+00
TDMAT	0.00E+00	4.60E-04	1.84E-03
TMS	0.00E+00	0.00E+00	0.00E+00
TEOS	0.00E+00	0.00E+00	0.00E+00
formaldehyde	9.09E-05	9.18E-03	3.67E-02
m-cresol	5.76E-06	5.82E-03	2.33E-02
p-cresol	5.71E-06	5.76E-03	2.31E-02
PGMEA	1.07E-02	7.43E-02	2.97E-01
n-methyl-$_2$-pyrollidone	0.00E+00	4.23E-03	1.69E-02
PGME	7.84E-03	9.74E-02	3.90E-01
ethyl lactate	9.13E-03	9.31E-02	3.72E-01
TMAH	1.00E-04	1.00E-02	4.02E-02
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH_4	5.43E-04	4.65E-03	1.86E-02
H_2	1.14E-02	1.36E-01	5.45E-01
DCS	0.00E+00	0.00E+00	0.00E+00
B_2H_6	0.00E+00	0.00E+00	0.00E+00
C_4F_8	2.74E-05	0.00E+00	0.00E+00
GeH_4	0.00E+00	0.00E+00	0.00E+00
C_2H_2			
OTHER CHEMICALS			
Ar	2.66E+00	1.33E+00	5.33E+00
N_2	5.93E-01	3.21E-01	1.29E+00
He	6.82E-04	3.41E-04	1.36E-03
O_2	3.40E-02	4.12E-01	1.65E+00
IPA	2.09E-02	2.67E+00	1.07E+01
NH_3	6.82E-04	3.41E-04	1.36E-03
Ti	7.76E-08	1.22E-05	4.87E-05
Cu	1.07E-07	1.65E-04	6.61E-04
Sn	2.55E-06	1.42E-06	5.66E-06

Table B.23. CMOS Manufacturing emissions per wafer, 180 nm node

130 nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF_4	7.32E-04	3.97E-03	1.59E-02
CHF_3	6.34E-06	6.97E-04	2.79E-03
C_2F_6	2.64E-05	4.90E-04	1.96E-03
CH_4	5.95E-04	2.80E-01	1.12E+00
CO_2	1.37E+00	0.00E+00	0.00E+00
NF_3	2.89E-04	7.29E-02	2.92E-01
C_4F_6	3.40E-05	2.17E-04	8.67E-04
N_2O	0.00E+00	0.00E+00	0.00E+00
HAZARDOUS			
F_2	1.75E-03	0.00E+00	0.00E+00
HF (gas)	5.46E-03	0.00E+00	0.00E+00
SiF_4	5.29E-05	1.42E-03	5.67E-03
C_4F_8	3.61E-06	3.98E-04	1.59E-03
C_2F_4	1.76E-05	0.00E+00	0.00E+00
COF_2	2.08E-05	0.00E+00	0.00E+00
HCl (gas)	0.00E+00	4.20E-02	1.68E-01
Cl_2	1.87E-05	8.57E-04	3.43E-03
$SiCl_4$	0.00E+00	0.00E+00	0.00E+00
PH_3	0.00E+00	1.51E-04	6.02E-04
BTBAS	1.01E-05	6.43E-04	2.57E-03
AsH_3	0.00E+00	0.00E+00	0.00E+00
BCl_3	0.00E+00	0.00E+00	0.00E+00
Pb	1.22E-05	6.76E-06	2.70E-05
WF_6	4.32E-03	1.64E-02	6.54E-02
HBr	0.00E+00	3.99E-03	1.59E-02
Br_2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	1.02E-01	4.07E-01
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	4.22E-03	0.00E+00	0.00E+00
NO	2.21E-03	0.00E+00	0.00E+00
NO_2	2.88E-04	0.00E+00	0.00E+00
SO_2	0.00E+00	0.00E+00	0.00E+00
N_2O	2.65E-04	3.48E-03	1.39E-02
O_3	0.00E+00	0.00E+00	0.00E+00

Table B.24. CMOS Manufacturing emissions per wafer, 130 nm node

130 nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	2.57E-06	0.00E+00	0.00E+00
MMA	5.90E-05	0.00E+00	0.00E+00
TDMAT	0.00E+00	6.07E-04	2.43E-03
TMS	0.00E+00	0.00E+00	0.00E+00
TEOS	0.00E+00	0.00E+00	0.00E+00
formaldehyde	1.20E-04	1.21E-02	4.84E-02
m-cresol	7.60E-06	7.68E-03	3.07E-02
p-cresol	7.53E-06	7.60E-03	3.04E-02
PGMEA	1.41E-02	9.80E-02	3.92E-01
n-methyl-$_2$-pyrollidone	0.00E+00	5.58E-03	2.23E-02
PGME	1.03E-02	1.29E-01	5.14E-01
ethyl lactate	1.20E-02	1.23E-01	4.91E-01
TMAH	1.33E-04	1.33E-02	5.30E-02
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH_4	3.56E-04	6.04E-03	2.42E-02
H_2	3.76E-03	4.86E-02	1.95E-01
DCS	0.00E+00	8.67E-04	3.47E-03
B_2H_6	0.00E+00	0.00E+00	0.00E+00
C_4F_8	2.25E-03	1.13E-03	4.50E-03
GeH_4	0.00E+00	1.96E-03	7.84E-03
C_2H_2			
OTHER CHEMICALS			
Ar	3.60E+00	1.80E+00	7.22E+00
N_2	1.41E+00	7.37E-01	2.95E+00
He	8.99E-04	4.50E-04	1.80E-03
O_2	4.79E-02	6.82E-01	2.73E+00
IPA	2.75E-02	7.92E-01	3.17E+00
NH_3	8.99E-04	4.50E-04	1.80E-03
Ti	1.02E-07	5.69E-08	2.28E-07
Cu	1.41E-07	5.48E-04	2.19E-03
Sn	3.36E-06	1.87E-06	7.47E-06

Table B.25. CMOS Manufacturing emissions per wafer, 130 nm node

90nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF_4	4.58E-04	5.91E-03	2.36E-02
CHF_3	1.21E-05	1.69E-03	6.77E-03
C_2F_6	3.86E-06	0.00E+00	0.00E+00
CH_4	1.29E-03	3.45E-01	1.38E+00
CO_2	1.68E+00	0.00E+00	0.00E+00
NF_3	3.01E-04	8.18E-02	3.27E-01
C_4F_6	1.13E-05	7.23E-05	2.89E-04
N_2O	0.00E+00	0.00E+00	0.00E+00
HAZARDOUS			
F_2	4.03E-03	0.00E+00	0.00E+00
HF (gas)	1.12E-02	0.00E+00	0.00E+00
SiF_4	5.46E-05	4.70E-04	1.88E-03
C_4F_8	1.69E-06	3.98E-04	1.59E-03
C_2F_4	8.53E-06	0.00E+00	0.00E+00
COF_2	5.45E-05	0.00E+00	0.00E+00
HCl (gas)	0.00E+00	4.20E-02	1.68E-01
Cl_2	1.87E-05	8.57E-04	3.43E-03
$SiCl_4$	0.00E+00	0.00E+00	0.00E+00
PH_3	0.00E+00	1.51E-04	6.02E-04
BTBAS	1.01E-05	6.43E-04	2.57E-03
AsH_3	0.00E+00	0.00E+00	0.00E+00
BCl_3	0.00E+00	0.00E+00	0.00E+00
Pb	1.22E-05	6.76E-06	2.70E-05
WF_6	4.32E-03	1.64E-02	6.54E-02
HBr	0.00E+00	3.99E-03	1.59E-02
Br_2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	1.30E-01	5.18E-01
OMCTS	0.00E+00	2.34E-03	9.38E-03
CRITERIA			
CO	2.66E-02	0.00E+00	0.00E+00
NO	2.19E-03	0.00E+00	0.00E+00
NO_2	3.80E-04	0.00E+00	0.00E+00
SO_2	0.00E+00	0.00E+00	0.00E+00
N_2O	5.30E-04	6.96E-03	2.78E-02
O_3	0.00E+00	0.00E+00	0.00E+00

Table B.26. CMOS Manufacturing emissions per wafer, 90 nm node

90nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	3.85E-06	0.00E+00	0.00E+00
MMA	8.85E-05	0.00E+00	0.00E+00
TDMAT	0.00E+00	9.11E-04	3.64E-03
TMS	1.96E-03	1.47E-03	5.87E-03
TEOS	1.37E-03	6.98E-04	2.79E-03
formaldehyde	1.42E-04	1.50E-02	6.00E-02
m-cresol	8.98E-06	1.80E-02	7.19E-02
p-cresol	8.90E-06	8.99E-03	3.59E-02
PGMEA	1.67E-02	1.27E-01	5.10E-01
n-methyl-$_2$-pyrollidone	0.00E+00	1.68E-02	6.70E-02
PGME	1.21E-02	1.53E-01	6.13E-01
ethyl lactate	1.42E-02	1.45E-01	5.81E-01
TMAH	1.57E-04	1.57E-02	6.27E-02
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	2.12E-03	8.50E-03
FLAMMABLE			
SiH_4	4.11E-04	8.78E-03	3.51E-02
H_2	3.76E-03	4.88E-02	1.95E-01
DCS	5.20E-03	3.47E-03	1.39E-02
B_2H_6	1.72E-03	1.18E-03	4.73E-03
C_4F_8	1.08E-03	5.33E-04	2.13E-03
GeH_4	0.00E+00	1.96E-03	7.84E-03
C_2H_2			
OTHER CHEMICALS			
Ar	1.97E+00	9.92E-01	3.97E+00
N_2	1.68E+00	9.00E-01	3.60E+00
He	1.35E-03	6.92E-02	2.77E-01
O_2	3.62E-02	1.56E+00	6.25E+00
IPA	3.25E-02	5.95E-01	2.38E+00
NH_3	1.35E-03	6.92E-02	2.77E-01
Ti	1.02E-07	8.00E-05	3.20E-04
Cu	1.41E-07	5.92E-04	2.37E-03
Sn	3.36E-06	1.87E-06	7.47E-06

Table B.27. CMOS Manufacturing emissions per wafer, 90 nm node

65 nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF_4	1.89E-03	9.44E-04	3.78E-03
CHF_3	1.15E-05	5.73E-06	2.29E-05
C_2F_6	1.18E-05	5.91E-06	2.36E-05
CH_4	4.92E-03	2.46E-03	9.83E-03
CO_2	1.61E+00	8.06E-01	3.22E+00
NF_3	4.06E-04	2.03E-04	8.13E-04
C_4F_6	4.27E-05	2.14E-05	8.55E-05
N_2O	2.50E-04	1.25E-04	5.00E-04
HAZARDOUS			
F_2	1.08E-03	5.38E-04	2.15E-03
HF (gas)	3.48E-02	1.74E-02	6.96E-02
SiF_4	9.73E-05	4.86E-05	1.95E-04
C_4F_8	4.32E-06	2.16E-06	8.64E-06
C_2F_4	8.05E-06	4.02E-06	1.61E-05
COF_2	1.33E-05	6.64E-06	2.66E-05
HCl (gas)	0.00E+00	0.00E+00	0.00E+00
Cl_2	2.35E-05	1.17E-05	4.69E-05
$SiCl_4$	0.00E+00	0.00E+00	0.00E+00
PH_3	0.00E+00	0.00E+00	0.00E+00
BTBAS	4.78E-06	2.39E-06	9.57E-06
AsH_3	0.00E+00	0.00E+00	0.00E+00
BCl_3	0.00E+00	0.00E+00	0.00E+00
Pb	0.00E+00	0.00E+00	0.00E+00
WF_6	2.04E-03	1.02E-03	4.08E-03
HBr	0.00E+00	0.00E+00	0.00E+00
Br_2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	0.00E+00	0.00E+00
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	6.00E-01	3.00E-01	1.20E+00
NO	6.78E-03	3.39E-03	1.36E-02
NO_2	6.46E-03	3.23E-03	1.29E-02
SO_2	0.00E+00	0.00E+00	0.00E+00
N_2O	2.50E-04	1.25E-04	5.00E-04
O_3	0.00E+00	0.00E+00	0.00E+00

Table B.28. CMOS Manufacturing emissions per wafer, 65 nm node

65 nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	1.21E-06	6.05E-07	2.42E-06
MMA	2.78E-05	1.39E-05	5.57E-05
TDMAT	0.00E+00	0.00E+00	0.00E+00
TMS	2.05E-06	1.02E-06	4.09E-06
TEOS	1.88E-07	9.38E-08	3.75E-07
formaldehyde	1.49E-04	7.45E-05	2.98E-04
m-cresol	9.45E-06	4.73E-06	1.89E-05
p-cresol	9.36E-06	4.68E-06	1.87E-05
PGMEA	1.75E-02	8.77E-03	3.51E-02
n-methyl-$_2$-pyrollidone	0.00E+00	0.00E+00	0.00E+00
PGME	1.27E-02	6.35E-03	2.54E-02
ethyl lactate	1.50E-02	7.49E-03	2.99E-02
TMAH	1.65E-04	8.24E-05	3.30E-04
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH_4	4.17E-04	2.09E-04	8.34E-04
H_2	3.24E-03	1.62E-03	6.49E-03
DCS	0.00E+00	0.00E+00	0.00E+00
B_2H_6	0.00E+00	0.00E+00	0.00E+00
C_4F_8	3.18E-04	1.59E-04	6.36E-04
GeH_4	0.00E+00	0.00E+00	0.00E+00
C_2H_2			
OTHER CHEMICALS			
Ar	1.77E+00	8.85E-01	3.54E+00
N_2	1.25E+00	6.25E-01	2.50E+00
He	1.35E-01	6.75E-02	2.70E-01
O_2	4.51E-02	2.26E-02	9.03E-02
IPA	3.42E-02	1.71E-02	6.84E-02
NH_3	1.35E-01	6.75E-02	2.70E-01
Ti	0.00E+00	0.00E+00	0.00E+00
Cu	0.00E+00	0.00E+00	0.00E+00
Sn	0.00E+00	0.00E+00	0.00E+00

Table B.29. CMOS Manufacturing emissions per wafer, 65 nm node

45 nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF_4	2.14E-03	1.07E-03	4.28E-03
CHF_3	1.26E-05	6.30E-06	2.52E-05
C_2F_6	5.00E-06	2.50E-06	1.00E-05
CH_4	4.47E-03	2.23E-03	8.94E-03
CO_2	1.78E+00	8.89E-01	3.56E+00
NF_3	4.30E-04	2.15E-04	8.59E-04
C_4F_6	1.60E-05	8.01E-06	3.20E-05
N_2O	0.00E+00	2.50E-04	1.00E-03
HAZARDOUS			
F_2	3.80E-03	1.90E-03	7.61E-03
HF (gas)	9.25E-03	4.62E-03	1.85E-02
SiF_4	8.87E-05	4.43E-05	1.77E-04
C_4F_8	2.05E-06	1.02E-06	4.09E-06
C_2F_4	8.05E-06	4.02E-06	1.61E-05
COF_2	5.66E-05	2.83E-05	1.13E-04
HCl (gas)	0.00E+00	0.00E+00	0.00E+00
Cl_2	2.35E-05	1.17E-05	4.69E-05
$SiCl_4$	0.00E+00	0.00E+00	0.00E+00
PH_3	2.84E-08	1.42E-08	5.68E-08
BTBAS	4.78E-06	2.39E-06	9.57E-06
AsH_3	3.55E-09	1.78E-09	7.10E-09
BCl_3	0.00E+00	0.00E+00	0.00E+00
Pb	0.00E+00	0.00E+00	0.00E+00
WF_6	4.08E-03	2.04E-03	8.16E-03
HBr	0.00E+00	0.00E+00	0.00E+00
Br_2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	0.00E+00	0.00E+00
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	6.29E-01	3.14E-01	1.26E+00
NO	6.98E-03	3.49E-03	1.40E-02
NO_2	6.69E-03	3.34E-03	1.34E-02
SO_2	0.00E+00	0.00E+00	0.00E+00
N_2O	5.00E-04	2.50E-04	1.00E-03
O_3	0.00E+00	0.00E+00	0.00E+00

Table B.30. CMOS Manufacturing emissions per wafer, 45 nm node

45 nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	2.42E-06	1.21E-06	4.84E-06
MMA	5.57E-05	2.78E-05	1.11E-04
TDMAT	0.00E+00	0.00E+00	0.00E+00
TMS	1.85E-03	9.26E-04	3.70E-03
TEOS	1.29E-03	6.45E-04	2.58E-03
formaldehyde	1.59E-04	7.97E-05	3.19E-04
m-cresol	1.01E-05	5.05E-06	2.02E-05
p-cresol	1.00E-05	5.00E-06	2.00E-05
PGMEA	1.87E-02	9.37E-03	3.75E-02
n-methyl-$_2$-pyrollidone	0.00E+00	0.00E+00	0.00E+00
PGME	1.35E-02	6.77E-03	2.71E-02
ethyl lactate	1.60E-02	8.00E-03	3.20E-02
TMAH	1.76E-04	8.81E-05	3.52E-04
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH_4	4.40E-04	2.20E-04	8.80E-04
H_2	5.07E-03	2.53E-03	1.01E-02
DCS	0.00E+00	0.00E+00	0.00E+00
B_2H_6	0.00E+00	0.00E+00	0.00E+00
C_4F_8	3.30E-04	1.65E-04	6.59E-04
GeH_4	0.00E+00	0.00E+00	0.00E+00
C_2H_2			
OTHER CHEMICALS			
Ar	1.91E+00	9.55E-01	3.82E+00
N_2	1.52E+00	7.60E-01	3.04E+00
He	1.49E-01	7.44E-02	2.98E-01
O_2	5.87E-02	2.93E-02	1.17E-01
IPA	3.65E-02	1.83E-02	7.30E-02
NH_3	1.49E-01	7.44E-02	2.98E-01
Ti	9.66E-08	4.83E-08	1.93E-07
Cu	5.22E-05	2.61E-05	1.04E-04
Sn	4.33E-03	2.17E-03	8.67E-03

Table B.31. CMOS Manufacturing emissions per wafer, 45 nm node

B.3 CMOS logic impact results

	Photochemical Smog kg NO_x expected value	lower bound	upper bound	Acidification mol H^+ expected value	lower bound	upper bound	Ecotoxicity kg 2,4-D expected value	lower bound	upper bound
transportation	6.04E-04	N/A	N/A	1.93E-02	N/A	N/A	0.00E+00	N/A	N/A
electricity (Si, fab. and use)	0.30	0.17	1.21	17.3	9.7	69.7	1.48	0.83	6.0
fab. emissions and EOL	2.09E-04	1.05E-04	4.18E-04	0.14	0.07	0.28	4.69E-04	3.89E-04	5.92E-04
infrastructure	7.60E-03	3.80E-03	1.14E-02	0.40	0.20	0.60	5.08E-05	2.54E-05	7.63E-05
total	0.31	0.17	1.2	18	10	71	1.5	0.83	6.0

	Human Health Cancer kg C_6H_6 expected value	lower bound	upper bound	Human Health Criteria total DALYs expected value	lower bound	upper bound	Human Health Noncancer kg C_7H_7 expected value	lower bound	upper bound
transportation	0.00E+00	N/A	N/A	1.06E-06	N/A	N/A	1.35E-04	N/A	N/A
electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	2.61E-03	1.45E-03	1.01E-02	119	67	479
fab. emissions and EOL	2.26E-05	1.99E-05	2.54E-05	8.84E-08	4.42E-08	1.77E-07	2.5	2.2	2.8
infrastructure	7.51E-05	3.76E-05	1.13E-04	1.35E-04	6.74E-05	2.02E-04	3.2	1.6	4.8
total	9.77E-05	5.75E-05	1.38E-04	2.75E-03	1.52E-03	1.03E-02	124	71	486

	Eutrophication, to air kg N expected value	lower bound	upper bound	Eutrophication, to water kg N expected value	lower bound	upper bound
transportation	2.13E-05	N/A	N/A			
electricity (Si, fab. and use)	1.08E-02	6.06E-03	4.33E-02	N/A	N/A	N/A
fab. emissions and EOL	1.62E-06	8.09E-07	3.23E-06	1.15E-02	5.86E-03	2.27E-02
infrastructure	2.59E-04	1.29E-04	3.88E-04	N/A	N/A	N/A
total	1.10E-02	6.19E-03	4.37E-02	1.15E-02	5.86E-03	2.27E-02

Table B.32. Life cycle impacts per die, 45 nm node

	Photochemical Smog			Acidification			Ecotoxicity		
	kg NO_x			mol H^+			kg 2,4-D		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	6.21E-04	N/A	N/A	1.98E-02	N/A	N/A	0.00E+00	N/A	N/A
electricity (Si, fab. and use)	0.22	0.12	0.86	12.4	7.1	49.2	1.06	0.60	4.2
fab. emissions and EOL	2.53E-04	1.27E-04	5.07E-04	0.48	0.24	0.96	4.38E-04	3.94E-04	4.82E-04
infrastructure	6.51E-03	3.26E-03	9.77E-03	0.34	0.17	0.51	4.18E-05	2.09E-05	6.27E-05
total	0.22	0.13	0.87	13	7.5	51	1.06	0.61	4.2

	Human Health Cancer			Human Health Criteria			Health Noncancer		
	kg C_6H_6			total DALYs			kg C_7H_7		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	0.00E+00	N/A	N/A	1.09E-06	N/A	N/A	1.39E-04	N/A	N/A
electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	1.87E-03	1.05E-03	7.05E-03	85	49	338
fab. emissions and EOL	2.43E-05	2.14E-05	2.72E-05	1.09E-07	5.45E-08	2.18E-07	2.6	2.3	3.0
infrastructure	6.18E-05	3.09E-05	9.27E-05	1.16E-04	5.80E-05	1.74E-04	2.6	1.3	3.9
total	8.61E-05	5.22E-05	1.20E-04	1.99E-03	1.11E-03	7.22E-03	90	52	345

	Eutrophication, to air			Eutrophication, to water		
	kg N			kg N		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	2.19E-05	N/A	N/A			
electricity (Si, fab. and use)	7.69E-03	4.40E-03	3.06E-02	N/A	N/A	N/A
fab. emissions and EOL	1.99E-06	9.96E-07	3.99E-06	1.24E-02	6.30E-03	2.44E-02
infrastructure	2.22E-04	1.11E-04	3.33E-04	N/A	N/A	N/A
total	7.94E-03	4.51E-03	3.09E-02	1.24E-02	6.30E-03	2.44E-02

Table B.33. Life cycle impacts per die, 65 nm node

	Photochemical Smog			Acidification			Ecotoxicity		
	kg NO_x			mol H^+			kg 2,4-D		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	6.27E-04	N/A	N/A	2.00E-02	N/A	N/A	0.00E+00	N/A	N/A
electricity (Si, fab. and use)	0.17	0.10	0.69	10.0	5.8	39.6	0.86	0.49	3.39
fab. emissions and EOL	1.42E-04	7.06E-05	2.82E-04	0.16	0.08	0.32	4.41E-04	3.96E-04	4.86E-04
infrastructure	4.81E-03	2.40E-03	7.21E-03	0.25	0.13	0.38	3.09E-05	1.54E-05	4.63E-05
total	0.18	0.10	0.70	10.5	6.0	40	0.86	0.49	3.4

	Human Health Cancer			Human Health Criteria			Health Noncancer		
	kg C_6H_6			total DALYs			kg C_7H_7		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	0.00E+00	N/A	N/A	1.10E-06	N/A	N/A	1.41E-04	N/A	N/A
electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	1.52E-03	8.59E-04	5.70E-03	69	39.6	272
fab. emissions and EOL	2.92E-05	2.52E-05	3.39E-05	2.29E-08	1.14E-08	4.57E-08	3.0	2.6	3.4
infrastructure	4.56E-05	2.28E-05	6.84E-05	8.56E-05	4.28E-05	1.28E-04	1.9	1.0	2.9
total	7.48E-05	4.80E-05	1.02E-04	1.60E-03	9.02E-04	5.83E-03	74	43	278

	Eutrophication, to air			Eutrophication, to water		
	kg N			kg N		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	2.21E-05	N/A	N/A			
electricity (Si, fab. and use)	6.23E-03	3.59E-03	2.46E-02	N/A	N/A	N/A
fab. direct emissions and EOL	5.43E-07	2.72E-07	1.09E-06	1.41E-02	7.20E-03	2.79E-02
infrastructure	1.64E-04	8.18E-05	2.46E-04	N/A	N/A	N/A
total	6.42E-03	3.67E-03	2.49E-02	1.41E-02	7.20E-03	2.79E-02

Table B.34. Life cycle impacts per die, 90 nm node

	Photochemical Smog kg NO_x			Acidification mol H^+			Ecotoxicity kg 2,4-D		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	6.27E-04	N/A	N/A	2.00E-02	N/A	N/A	0.00E+00	N/A	N/A
electricity (Si, fab. and use)	0.13	0.074	0.496	7.3	4.3	28.5	0.63	0.36	2.44
fab. direct emissions and EOL	1.21E-04	6.01E-05	2.40E-04	0.09	0.04	0.18	3.80E-04	3.41E-04	4.18E-04
infrastructure	2.79E-03	1.39E-03	4.18E-03	0.15	0.07	0.22	1.99E-05	9.96E-06	2.99E-05
total	0.13	0.08	0.50	7.6	4.4	29	0.63	0.37	2.4

	Human Health Cancer kg C_6H_6			Human Health Criteria total DALYs			Health Noncancer kg C_7H_7		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	0.00E+00	N/A	N/A	1.10E-06	N/A	N/A	1.41E-04	N/A	N/A
electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	1.11E-03	6.38E-04	4.16E-03	50	29.3	196
fab. emissions and EOL	1.21E-05	1.02E-05	1.48E-05	2.22E-08	1.11E-08	4.44E-08	2.9	2.5	3.2
infrastructure	2.94E-05	1.47E-05	4.42E-05	4.91E-05	2.46E-05	7.37E-05	1.2	0.6	1.9
total	4.16E-05	2.49E-05	5.89E-05	1.16E-03	6.63E-04	4.23E-03	54	32	201

	Eutrophication, to air kg N			Eutrophication, to water kg N		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	2.21E-05	N/A	N/A			
electricity (Si, fab. and use)	4.55E-03	2.65E-03	1.77E-02	N/A	N/A	N/A
fab. direct emissions and EOL	5.33E-07	2.67E-07	1.07E-06	1.38E-02	6.95E-03	2.75E-02
infrastructure	9.47E-05	4.74E-05	1.42E-04	N/A	N/A	N/A
total	4.66E-03	2.70E-03	1.79E-02	1.38E-02	6.95E-03	2.75E-02

Table B.35. Life cycle impacts per die, 130 nm node

	Photochemical Smog kg NO_x expected value	lower bound	upper bound	Acidification mol H^+ expected value	lower bound	upper bound	Ecotoxicity kg 2,4-D expected value	lower bound	upper bound
transportation	6.88E-04	N/A	N/A	2.20E-02	N/A	N/A	0.00E+00	N/A	N/A
electricity (Si, fab. and use)	0.053	0.033	0.190	3.0	1.9	10.9	0.26	0.16	0.94
fab. direct emissions and EOL	1.76E-04	8.78E-05	3.51E-04	0.08	0.04	0.15	2.64E-05	2.32E-05	3.03E-05
infrastructure	4.21E-03	2.10E-03	6.31E-03	0.22	0.11	0.33	2.92E-05	1.46E-05	4.38E-05
total	0.058	0.035	0.197	3.4	2.0	11.4	0.26	0.16	0.94

	Human Health Cancer kg C_6H_6 expected value	lower bound	upper bound	Human Health Criteria total DALYs expected value	lower bound	upper bound	Health Noncancer kg C_7H_7 expected value	lower bound	upper bound
transportation	0.00E+00	N/A	N/A	1.21E-06	N/A	N/A	1.55E-04	N/A	N/A
electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	4.63E-04	2.76E-04	1.44E-03	21	13.0	75
fab. emissions and EOL	1.68E-05	1.41E-05	2.03E-05	4.37E-08	2.19E-08	8.74E-08	2.7	2.4	3.1
infrastructure	4.31E-05	2.16E-05	6.47E-05	7.44E-05	3.72E-05	1.12E-04	1.8	0.9	2.7
total	5.99E-05	3.56E-05	8.50E-05	5.39E-04	3.14E-04	1.55E-03	25	16.3	81

	Eutrophication, to air kg N expected value	lower bound	upper bound	Eutrophication, to water kg N expected value	lower bound	upper bound
transportation	2.43E-05	N/A	N/A			
electricity (Si, fab. and use)	1.89E-03	1.18E-03	6.80E-03	N/A	N/A	N/A
fab. direct emissions and EOL	1.05E-06	5.25E-07	2.10E-06	1.92E-02	9.68E-03	3.82E-02
infrastructure	1.43E-04	7.15E-05	2.15E-04	N/A	N/A	N/A
total	2.06E-03	1.25E-03	7.01E-03	1.92E-02	9.68E-03	3.82E-02

Table B.36. Life cycle impacts per die, 180 nm node

	Photochemical Smog			Acidification			Ecotoxicity		
	kg NO_x			mol H^+			kg 2,4-D		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	6.56E-04	N/A	N/A	2.09E-02	N/A	N/A	0.00E+00	N/A	N/A
electricity (Si, fab. and use)	0.049	0.032	0.171	2.8	1.8	9.8	0.24	0.16	0.84
fab. emissions and EOL	1.64E-04	8.17E-05	3.27E-04	0.06	0.03	0.12	3.30E-05	2.90E-05	3.80E-05
infrastructure	4.83E-03	2.42E-03	7.25E-03	0.25	0.13	0.38	3.35E-05	1.68E-05	5.03E-05
total	0.055	0.034	0.179	3.2	2.0	10.3	0.24	0.16	0.84

	Human Health Cancer			Human Health Criteria			Health Noncancer		
	kg C_6H_6			total DALYs			kg C_7H_7		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	0.00E+00	N/A	N/A	1.16E-06	N/A	N/A	1.47E-04	N/A	N/A
electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	4.33E-04	2.63E-04	1.25E-03	19	13	68
fab. emissions and EOL	4.77E-05	4.11E-05	5.55E-05	5.58E-10	2.79E-10	1.12E-09	3.4	3.0	3.9
infrastructure	4.95E-05	2.48E-05	7.43E-05	8.55E-05	4.28E-05	1.28E-04	2.1	1.1	3.2
total	9.73E-05	6.59E-05	1.30E-04	5.19E-04	3.06E-04	1.38E-03	25	17	75

	Eutrophication, to air			Eutrophication, to water		
	kg N			kg N		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	2.31E-05	N/A	N/A			
electricity (Si, fab. and use)	1.76E-03	1.14E-03	6.12E-03	N/A	N/A	N/A
fab. direct emissions and EOL	2.59E-07	1.30E-07	5.19E-07	2.31E-02	1.18E-02	4.56E-02
infrastructure	1.64E-04	8.22E-05	2.47E-04	N/A	N/A	N/A
total	1.95E-03	1.22E-03	6.37E-03	2.31E-02	1.18E-02	4.56E-02

Table B.37. Life cycle impacts per die, 250 nm node

	Photochemical Smog			Acidification			Ecotoxicity		
	kg NO_x			mol H^+			kg 2,4-D		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	7.38E-04	N/A	N/A	2.35E-02	N/A	N/A	0.00E+00	N/A	N/A
electricity (Si, fab. and use)	0.033	0.024	0.092	1.9	1.4	5.3	0.16	0.12	0.45
fab. emissions and EOL	2.54E-04	1.27E-04	5.06E-04	0.09	0.05	0.18	5.23E-05	4.58E-05	6.04E-05
infrastructure	5.79E-03	2.90E-03	8.69E-03	0.30	0.15	0.45	3.72E-05	1.86E-05	5.58E-05
total	0.039	0.027	0.101	2.3	1.6	5.9	0.16	0.12	0.45

	Human Health Cancer			Human Health Criteria			Health Noncancer		
	kg C_6H_6			total DALYs			kg C_7H_7		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	0.00E+00	N/A	N/A	1.30E-06	N/A	N/A	1.66E-04	N/A	N/A
electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	2.88E-04	1.91E-04	5.60E-04	13	9.5	36
fab. emissions and EOL	7.18E-05	6.17E-05	8.40E-05	9.59E-10	4.80E-10	1.92E-09	5.2	4.5	6.0
infrastructure	5.49E-05	2.75E-05	8.24E-05	1.03E-04	5.15E-05	1.55E-04	2.3	1.2	3.5
total	1.27E-04	8.91E-05	1.66E-04	3.92E-04	2.42E-04	7.14E-04	20	15	46

	Eutrophication, to air			Eutrophication, to water		
	kg N			kg N		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound
transportation	2.60E-05	N/A	N/A			
electricity (Si, fab. and use)	1.16E-03	8.59E-04	3.27E-03	N/A	N/A	N/A
fab. direct emissions and EOL	3.88E-07	1.94E-07	7.76E-07	3.44E-02	1.75E-02	6.80E-02
infrastructure	1.97E-04	9.85E-05	2.96E-04	N/A	N/A	N/A
total	1.39E-03	9.57E-04	3.56E-03	3.44E-02	1.75E-02	6.80E-02

Table B.38. Life cycle impacts per die, 350 nm node

Appendix C

Flash Memory Life Cycle Inventory and Impact Results

C.1 Flash memory: manufacturing inventory data

150 nm			150 nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	1.63E+01		SiH_4	1.32E+01
CHF_3	3.52E+00		H_2	9.58E+01
C_2F_6	0.00E+00		DCS	0.00E+00
CH_4	5.32E+02		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	0.00E+00
NF_3	1.57E+02		GeH_4	0.00E+00
C_4F_6	0.00E+00		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	4.20E+02
SiF_4	1.15E-01		Ar	6.62E+02
C_4F_8	1.06E+00		N_2	7.71E+02
C_2F_4	0.00E+00		CMP polishing solution	0.00E+00
COF_2	0.00E+00		H_2O_2	1.30E+04
HCl (gas)	0.00E+00		abrasive	0.00E+00
Cl_2	2.79E+00		silica slurry	0.00E+00
$SiCl_4$	0.00E+00		benzotriazole	0.00E+00
PH_3	2.84E+00		CMP surfactants	1.23E+02
BTBAS	2.05E+00		citric acid	6.84E+01
AsH_3	2.62E-01		tungsten CMP slurry	5.92E+03
BCl_3	1.36E+00		Al	1.22E-01
Pb	7.19E-02		As	0.00E+00
WF_6	3.48E+01		Cu	8.35E-04
HBr	8.48E+00		Pt	0.00E+00
Br_2	0.00E+00		Ti	6.05E-04
HMDS	2.56E+02		He	4.78E-01
OMCTS	0.00E+00		NH_3	2.16E+01

Table C.1. Flash memory manufacturing inventory per wafer, 150 nm node

150 nm			150 nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	0.00E+00
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	1.43E+02
SO_2	0.00E+00		H_2SO_4	1.12E+05
N_2O	7.40E+00		HCl	4.23E+03
O_3	0.00E+00		NH_4OH	6.01E+03
			IPA	8.33E+02
VOC			oxide CMP slurry, chemicals	1.14E+04
DMA	0.00E+00		BF_3	2.05E-02
MMA	0.00E+00		Cr	0.00E+00
TDMAT	6.46E-01		Au	0.00E+00
TMS	0.00E+00		Sn	1.99E-02
TEOS	0.00E+00		Co	0.00E+00
formaldehyde	3.05E+01		Ni	0.00E+00
m-cresol	1.93E+01		polyimide laminate	2.65E+00
p-cresol	1.91E+01		laminate solvent	0.00E+00
PGMEA	2.46E+02		$H3PO_4$	0.00E+00
n-methyl-2-pyrollidone	1.19E+01		$CuCl_2$	0.00E+00
PGME	3.23E+02		W	2.71E-03
ethyl lactate	3.09E+02		Ta	0.00E+00
TMAH	3.21E+01		Cu ECP additive X	0.00E+00
TDEAH	0.00E+00		Cu ECP Additive Y	0.00E+00
TDMAS	0.00E+00		$Na_2B_4O_7$	1.39E+01
DEA	0.00E+00			
PDMAT	0.00E+00			

Table C.2. Flash memory manufacturing inventory per wafer, 150 nm node

120 nm			120 nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	5.88E+00		SiH_4	1.24E+01
CHF_3	3.31E+00		H_2	9.01E+01
C_2F_6	0.00E+00		DCS	0.00E+00
CH_4	5.00E+02		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	0.00E+00
NF_3	1.47E+02		GeH_4	0.00E+00
C_4F_6	0.00E+00		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	3.00E+02
SiF_4	1.08E-01		Ar	6.23E+02
C_4F_8	9.94E-01		N_2	7.24E+02
C_2F_4	0.00E+00		CMP polishing solution	0.00E+00
COF_2	0.00E+00		H_2O_2	1.23E+04
HCl (gas)	0.00E+00		abrasive	0.00E+00
Cl_2	2.63E+00		silica slurry	0.00E+00
$SiCl_4$	0.00E+00		benzotriazole	0.00E+00
PH_3	2.67E+00		CMP surfactants	1.16E+02
BTBAS	1.93E+00		citric acid	6.43E+01
AsH_3	2.75E-01		tungsten CMP slurry	5.56E+03
BCl_3	1.28E+00		Al	1.15E-01
Pb	6.76E-02		As	0.00E+00
WF_6	3.27E+01		Cu	7.85E-04
HBr	7.97E+00		Pt	0.00E+00
Br_2	0.00E+00		Ti	5.69E-04
HMDS	2.59E+02		He	4.50E-01
OMCTS	0.00E+00		NH_3	2.03E+01

Table C.3. Flash memory manufacturing inventory per wafer, 120 nm node

120 nm			120 nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	0.00E+00
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	1.34E+02
SO_2	0.00E+00		H_2SO_4	1.06E+05
N_2O	6.96E+00		HCl	3.98E+03
O_3	0.00E+00		NH_4OH	5.64E+03
			IPA	7.83E+02
VOC			oxide CMP slurry, chemicals	1.07E+04
DMA	0.00E+00		BF_3	1.92E-02
MMA	0.00E+00		Cr	0.00E+00
TDMAT	6.07E-01		Au	0.00E+00
TMS	0.00E+00		Sn	1.87E-02
TEOS	0.00E+00		Co	0.00E+00
formaldehyde	3.08E+01		Ni	0.00E+00
m-cresol	1.95E+01		polyimide laminate	2.49E+00
p-cresol	1.94E+01		laminate solvent	0.00E+00
PGMEA	2.49E+02		$H3PO_4$	0.00E+00
n-methyl-2-pyrollidone	1.12E+01		$CuCl_2$	0.00E+00
PGME	3.27E+02		W	2.55E-03
ethyl lactate	3.13E+02		Ta	0.00E+00
TMAH	3.25E+01		Cu ECP additive X	0.00E+00
TDEAH	0.00E+00		Cu ECP Additive Y	0.00E+00
TDMAS	0.00E+00		$Na_2B_4O_7$	1.41E+01
DEA	0.00E+00			
PDMAT	0.00E+00			

Table C.4. Flash memory manufacturing inventory per wafer, 120 nm node

90nm			90nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	5.88E+00		SiH_4	1.24E+01
CHF_3	3.31E+00		H_2	9.01E+01
C_2F_6	0.00E+00		DCS	0.00E+00
CH_4	5.32E+02		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	0.00E+00
NF_3	1.47E+02		GeH_4	0.00E+00
C_4F_6	0.00E+00		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	3.00E+02
SiF_4	1.08E-01		Ar	6.23E+02
C_4F_8	9.94E-01		N_2	7.24E+02
C_2F_4	0.00E+00		CMP polishing solution	0.00E+00
COF_2	0.00E+00		H_2O_2	1.23E+04
HCl (gas)	0.00E+00		abrasive	0.00E+00
Cl_2	2.63E+00		silica slurry	0.00E+00
$SiCl_4$	0.00E+00		benzotriazole	0.00E+00
PH_3	2.67E+00		CMP surfactants	1.16E+02
BTBAS	1.93E+00		citric acid	6.43E+01
AsH_3	2.75E-01		tungsten CMP slurry	5.56E+03
BCl_3	1.28E+00		Al	1.15E-01
Pb	0.00E+00		As	0.00E+00
WF_6	3.27E+01		Cu	1.57E-03
HBr	7.97E+00		Pt	0.00E+00
Br_2	0.00E+00		Ti	5.69E-04
HMDS	2.59E+02		He	4.50E-01
OMCTS	0.00E+00		NH_3	2.03E+01

Table C.5. Flash memory manufacturing inventory per wafer, 90 nm node

90nm			90nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	0.00E+00
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	1.34E+02
SO_2	0.00E+00		H_2SO_4	1.06E+05
N_2O	6.96E+00		HCl	3.98E+03
O_3	0.00E+00		NH_4OH	5.64E+03
			IPA	7.83E+02
VOC			oxide CMP slurry, chemicals	1.07E+04
DMA	0.00E+00		BF_3	1.92E-02
MMA	0.00E+00		Cr	0.00E+00
TDMAT	6.07E-01		Au	0.00E+00
TMS	0.00E+00		Sn	5.95E-02
TEOS	0.00E+00		Co	0.00E+00
formaldehyde	3.08E+01		Ni	0.00E+00
m-cresol	1.95E+01		polyimide laminate	2.49E+00
p-cresol	1.94E+01		laminate solvent	0.00E+00
PGMEA	2.49E+02		H3PO$_4$	0.00E+00
n-methyl-2-pyrollidone	1.12E+01		$CuCl_2$	0.00E+00
PGME	3.27E+02		W	2.55E-03
ethyl lactate	3.13E+02		Ta	0.00E+00
TMAH	3.25E+01		Cu ECP additive X	0.00E+00
TDEAH	0.00E+00		Cu ECP Additive Y	0.00E+00
TDMAS	0.00E+00		$Na_2B_4O_7$	1.41E+01
DEA	0.00E+00			
PDMAT	0.00E+00			

Table C.6. Flash memory manufacturing inventory per wafer, 90 nm node

65 nm			65 nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	5.86E+00		SiH_4	1.24E+01
CHF_3	3.36E+00		H_2	1.71E+02
C_2F_6	0.00E+00		DCS	0.00E+00
CH_4	5.57E+02		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	0.00E+00
NF_3	1.57E+02		GeH_4	0.00E+00
C_4F_6	0.00E+00		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	2.96E+02
SiF_4	1.02E-01		Ar	7.64E+02
C_4F_8	1.69E+00		N_2	8.90E+02
C_2F_4	0.00E+00		CMP polishing solution	0.00E+00
COF_2	0.00E+00		H_2O_2	1.22E+04
HCl (gas)	0.00E+00		abrasive	0.00E+00
Cl_2	3.88E+00		silica slurry	0.00E+00
$SiCl_4$	0.00E+00		benzotriazole	0.00E+00
PH_3	2.52E+00		CMP surfactants	1.64E+02
BTBAS	1.82E+00		citric acid	9.09E+01
AsH_3	2.59E-01		tungsten CMP slurry	7.87E+03
BCl_3	2.42E+00		Al	4.34E-01
Pb	0.00E+00		As	0.00E+00
WF_6	6.17E+01		Cu	1.48E-03
HBr	1.00E+01		Pt	0.00E+00
Br_2	0.00E+00		Ti	3.07E-02
HMDS	2.62E+02		He	8.48E-01
OMCTS	0.00E+00		NH_3	1.91E+01

Table C.7. Flash memory manufacturing inventory per wafer, 65 nm node

65 nm			65 nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	0.00E+00
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	1.14E+02
SO_2	0.00E+00		H_2SO_4	9.97E+04
N_2O	6.56E+00		HCl	4.11E+03
O_3	0.00E+00		NH_4OH	6.11E+03
			IPA	7.38E+02
VOC			oxide CMP slurry, chemicals	1.51E+04
DMA	0.00E+00		BF_3	1.81E-02
MMA	0.00E+00		Cr	0.00E+00
TDMAT	1.15E+00		Au	0.00E+00
TMS	0.00E+00		Sn	5.61E-02
TEOS	0.00E+00		Co	0.00E+00
formaldehyde	3.11E+01		Ni	0.00E+00
m-cresol	1.98E+01		polyimide laminate	2.35E+00
p-cresol	1.96E+01		laminate solvent	0.00E+00
PGMEA	2.52E+02		H3PO$_4$	0.00E+00
n-methyl-2-pyrollidone	1.05E+01		$CuCl_2$	0.00E+00
PGME	3.31E+02		W	2.40E-03
ethyl lactate	3.16E+02		Ta	0.00E+00
TMAH	3.30E+01		Cu ECP additive X	0.00E+00
TDEAH	0.00E+00		Cu ECP Additive Y	0.00E+00
TDMAS	0.00E+00		$Na_2B_4O_7$	1.43E+01
DEA	0.00E+00			
PDMAT	0.00E+00			

Table C.8. Flash memory manufacturing inventory per wafer, 65 nm node

45 nm			45 nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	2.19E+01		SiH_4	1.12E+01
CHF_3	3.63E+00		H_2	1.28E+02
C_2F_6	0.00E+00		DCS	0.00E+00
CH_4	5.49E+02		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	0.00E+00
NF_3	1.87E+02		GeH_4	0.00E+00
C_4F_6	1.36E-01		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	8.70E+02
SiF_4	3.58E-01		Ar	1.70E+03
C_4F_8	2.06E+00		N_2	6.71E+02
C_2F_4	0.00E+00		CMP polishing solution	7.87E+03
COF_2	0.00E+00		H_2O_2	1.34E+04
HCl (gas)	0.00E+00		abrasive	2.49E+02
Cl_2	3.01E+00		silica slurry	2.49E+02
$SiCl_4$	0.00E+00		benzotriazole	1.02E+01
PH_3	2.62E+00		CMP surfactants	2.73E+02
BTBAS	0.00E+00		citric acid	6.18E+01
AsH_3	2.59E-01		tungsten CMP slurry	5.24E+03
BCl_3	1.21E+00		Al	1.08E-01
Pb	0.00E+00		As	0.00E+00
WF_6	4.63E+01		Cu	1.48E-03
HBr	1.00E+01		Pt	0.00E+00
Br_2	0.00E+00		Ti	5.37E-04
HMDS	3.58E+02		He	4.24E-01
OMCTS	0.00E+00		NH_3	1.51E+00

Table C.9. Flash memory manufacturing inventory per wafer, 45 nm node

45 nm			45 nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	7.08E+00
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	1.15E+02
SO_2	0.00E+00		H_2SO_4	1.09E+05
N_2O	1.21E+01		HCl	4.47E+03
O_3	0.00E+00		NH_4OH	6.33E+03
			IPA	7.38E+02
VOC			oxide CMP slurry, chemicals	1.51E+04
DMA	0.00E+00		BF_3	1.81E-02
MMA	0.00E+00		Cr	0.00E+00
TDMAT	5.73E-01		Au	0.00E+00
TMS	0.00E+00		Sn	5.61E-02
TEOS	0.00E+00		Co	0.00E+00
formaldehyde	4.26E+01		Ni	2.98E-02
m-cresol	2.70E+01		polyimide laminate	2.35E+00
p-cresol	2.67E+01		laminate solvent	0.00E+00
PGMEA	3.44E+02		$H3PO_4$	0.00E+00
n-methyl-2-pyrollidone	1.05E+01		$CuCl_2$	4.06E-03
PGME	4.52E+02		W	2.40E-03
ethyl lactate	4.32E+02		Ta	0.00E+00
TMAH	4.55E+01		Cu ECP additive X	2.06E+00
TDEAH	0.00E+00		Cu ECP Additive Y	1.02E+00
TDMAS	0.00E+00		$Na_2B_4O_7$	1.97E+01
DEA	0.00E+00			
PDMAT	4.01E+00			

Table C.10. Flash memory manufacturing inventory per wafer, 45 nm node

C.2 Flash memory: manufacturing emissions data

150 nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF_4	5.86E-04	8.16E+00	3.27E+01
CHF_3	2.53E-05	1.76E+00	7.03E+00
C_2F_6	0.00E+00	0.00E+00	0.00E+00
CH_4	2.14E-04	2.66E+02	1.06E+03
CO_2	1.46E+00	0.00E+00	0.00E+00
NF_3	3.85E-04	7.84E+01	3.13E+02
C_4F_6	0.00E+00	0.00E+00	0.00E+00
N_2O	0.00E+00	0.00E+00	0.00E+00
HAZARDOUS			
F_2	4.18E-03	0.00E+00	0.00E+00
HF (gas)	2.79E-03	0.00E+00	0.00E+00
SiF_4	5.14E-05	5.77E-02	2.31E-01
C_4F_8	9.62E-07	5.29E-01	2.12E+00
C_2F_4	1.13E-05	0.00E+00	0.00E+00
COF_2	5.34E-05	0.00E+00	0.00E+00
HCl (gas)	1.39E-07	0.00E+00	0.00E+00
Cl_2	6.45E-05	1.40E+00	5.59E+00
$SiCl_4$	9.59E-07	0.00E+00	0.00E+00
PH_3	0.00E+00	1.42E+00	5.67E+00
Bis Tertiary-Butylamino Silane	1.62E-05	1.03E+00	4.11E+00
AsH_3	4.08E-06	1.31E-01	5.24E-01
BCl_3	1.95E-05	6.81E-01	2.73E+00
Pb	6.47E-05	3.60E-02	1.44E-01
WF_6	4.60E-03	1.74E+01	6.96E+01
HBr	0.00E+00	4.24E+00	1.70E+01
Br_2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	1.28E+02	5.12E+02
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	2.82E-01	0.00E+00	0.00E+00
NO	7.23E-03	0.00E+00	0.00E+00
NO_2	3.56E-03	0.00E+00	0.00E+00
SO_2	0.00E+00	0.00E+00	0.00E+00
N_2O	2.82E-04	3.70E+00	1.48E+01
O_3	0.00E+00	0.00E+00	0.00E+00

Table C.11. Flash memory manufacturing emissions per wafer, 150 nm node

150 nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	1.37E-06	0.00E+00	0.00E+00
MMA	3.14E-05	0.00E+00	0.00E+00
TDMAT	0.00E+00	3.23E-01	1.29E+00
TMS	0.00E+00	0.00E+00	0.00E+00
TEOS	0.00E+00	0.00E+00	0.00E+00
Formaldehyde (CH_2O)	1.40E-04	1.52E+01	6.09E+01
m-Cresol	9.19E-06	9.66E+00	3.86E+01
p-Cresol	4.83E-04	9.56E+00	3.83E+01
PGMEA	1.64E-02	1.23E+02	4.93E+02
n-Methyl-$_2$-Pyrollidone	6.82E-04	5.94E+00	2.38E+01
PGME	1.20E-02	1.62E+02	6.47E+02
ethyl lactate	1.40E-02	1.55E+02	6.18E+02
TMAH	6.46E-04	1.60E+01	6.41E+01
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH_4			
H_2	9.06E-04	6.59E+00	2.63E+01
DCS	4.01E-03	4.79E+01	1.92E+02
B_2H_6	0.00E+00	0.00E+00	0.00E+00
C_4F_8	0.00E+00	0.00E+00	0.00E+00
GeH_4	1.67E-04	0.00E+00	0.00E+00
C_2H_2	0.00E+00	0.00E+00	0.00E+00
C_2H_4			
OTHER CHEMICALS			
Ar	6.54E-01	3.31E+02	1.32E+03
N_2	7.21E-01	3.85E+02	1.54E+03
He	4.78E-04	2.39E-01	9.57E-01
O_2	9.82E-02	2.10E+02	8.41E+02
IPA	3.38E-02	4.16E+02	1.67E+03
NH_3	4.78E-04	2.39E-01	9.57E-01
Ti	5.45E-07	3.03E-04	1.21E-03
Cu	7.52E-07	4.18E-04	1.67E-03
Sn	1.79E-05	9.94E-03	3.97E-02

Table C.12. Flash memory manufacturing emissions per wafer, 150 nm node

120 nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF4	1.30E-04	2.94E+00	1.18E+01
CHF3	2.37E-05	1.65E+00	6.61E+00
C2F6	0.00E+00	0.00E+00	0.00E+00
CH4	2.01E-04	2.50E+02	9.99E+02
CO2	1.37E+00	0.00E+00	0.00E+00
NF3	3.62E-04	7.36E+01	2.95E+02
C4F6	0.00E+00	0.00E+00	0.00E+00
N2O	0.00E+00	0.00E+00	0.00E+00
HAZARDOUS			
F2	3.93E-03	0.00E+00	0.00E+00
HF (gas)	6.04E-04	0.00E+00	0.00E+00
SiF4	3.67E-05	5.42E-02	2.17E-01
C4F8	9.04E-07	4.97E-01	1.99E+00
C2F4	1.07E-05	0.00E+00	0.00E+00
COF2	5.02E-05	0.00E+00	0.00E+00
HCl (gas)	1.31E-07	0.00E+00	0.00E+00
Cl2	6.07E-05	1.31E+00	5.25E+00
SiCl4	9.01E-07	0.00E+00	0.00E+00
PH3	0.00E+00	1.33E+00	5.34E+00
bis tertiary-butylamino silane	1.52E-05	9.65E-01	3.86E+00
AsH3	4.29E-06	1.38E-01	5.50E-01
BCl3	1.84E-05	6.40E-01	2.56E+00
Pb	6.08E-05	3.38E-02	1.35E-01
WF6	4.32E-03	1.64E+01	6.54E+01
HBr	0.00E+00	3.99E+00	1.59E+01
Br2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	1.30E+02	5.18E+02
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	2.18E-02	0.00E+00	0.00E+00
NO	4.44E-03	0.00E+00	0.00E+00
NO2	4.52E-04	0.00E+00	0.00E+00
SO2	0.00E+00	0.00E+00	0.00E+00
N2O	2.65E-04	3.48E+00	1.39E+01
O3	0.00E+00	0.00E+00	0.00E+00

Table C.13. Flash memory manufacturing emissions per wafer, 120 nm node

120 nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	1.28E-06	0.00E+00	0.00E+00
MMA	2.95E-05	0.00E+00	0.00E+00
TDMAT	0.00E+00	3.04E-01	1.21E+00
TMS	0.00E+00	0.00E+00	0.00E+00
TEOS	0.00E+00	0.00E+00	0.00E+00
formaldehyde	1.42E-04	1.54E+01	6.16E+01
m-cresol	9.33E-06	9.77E+00	3.91E+01
p-cresol	4.54E-04	9.68E+00	3.87E+01
PGMEA	1.67E-02	1.25E+02	4.99E+02
n-methyl-2-pyrollidone	6.41E-04	5.58E+00	2.23E+01
PGME	1.21E-02	1.64E+02	6.54E+02
ethyl lactate	1.42E-02	1.56E+02	6.25E+02
TMAH	6.19E-04	1.63E+01	6.51E+01
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH4	8.51E-04	6.19E+00	2.48E+01
H2	3.76E-03	4.50E+01	1.80E+02
DCS	0.00E+00	0.00E+00	0.00E+00
B2H6	0.00E+00	0.00E+00	0.00E+00
C4F8	1.20E-05	0.00E+00	0.00E+00
GeH4	0.00E+00	0.00E+00	0.00E+00
OTHER CHEMICALS			
Ar	6.15E-01	3.11E+02	1.25E+03
N2	6.78E-01	3.62E+02	1.45E+03
He	4.50E-04	2.25E-01	8.99E-01
O2	9.23E-02	1.50E+02	6.01E+02
IPA	3.42E-02	3.91E+02	1.57E+03
NH3	4.50E-04	2.25E-01	8.99E-01
Ti	5.12E-07	2.84E-04	1.14E-03
Cu	7.06E-07	3.92E-04	1.57E-03
Sn	1.68E-05	9.34E-03	3.74E-02

Table C.14. Flash memory manufacturing emissions per wafer, 120 nm node

90nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF4	1.30E-04	2.94E+00	1.18E+01
CHF3	2.37E-05	1.65E+00	6.61E+00
C2F6	0.00E+00	0.00E+00	0.00E+00
CH4	2.01E-04	2.66E+02	1.06E+03
CO2	1.46E+00	0.00E+00	0.00E+00
NF3	3.62E-04	7.36E+01	2.95E+02
C4F6	0.00E+00	0.00E+00	0.00E+00
N2O	0.00E+00	0.00E+00	0.00E+00
HAZARDOUS			
F2	3.93E-03	0.00E+00	0.00E+00
HF (gas)	6.04E-04	0.00E+00	0.00E+00
SiF4	3.67E-05	5.42E-02	2.17E-01
C4F8	9.04E-07	4.97E-01	1.99E+00
C2F4	1.07E-05	0.00E+00	0.00E+00
COF2	5.02E-05	0.00E+00	0.00E+00
HCl (gas)	1.31E-07	0.00E+00	0.00E+00
Cl2	6.07E-05	1.31E+00	5.25E+00
SiCl4	9.01E-07	0.00E+00	0.00E+00
PH3	0.00E+00	1.33E+00	5.34E+00
bis tertiary-butylamino silane	1.52E-05	9.65E-01	3.86E+00
AsH3	4.29E-06	1.38E-01	5.50E-01
BCl3	1.84E-05	6.40E-01	2.56E+00
Pb	0.00E+00	0.00E+00	0.00E+00
WF6	4.32E-03	1.64E+01	6.54E+01
HBr	0.00E+00	3.99E+00	1.59E+01
Br2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	1.30E+02	5.18E+02
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	2.18E-02	0.00E+00	0.00E+00
NO	4.62E-03	0.00E+00	0.00E+00
NO2	4.52E-04	0.00E+00	0.00E+00
SO2	0.00E+00	0.00E+00	0.00E+00
N2O	2.65E-04	3.48E+00	1.39E+01
O3	0.00E+00	0.00E+00	0.00E+00

Table C.15. Flash memory manufacturing emissions per wafer, 90 nm node

90nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	1.28E-06	0.00E+00	0.00E+00
MMA	2.95E-05	0.00E+00	0.00E+00
TDMAT	0.00E+00	3.04E-01	1.21E+00
TMS	0.00E+00	0.00E+00	0.00E+00
TEOS	0.00E+00	0.00E+00	0.00E+00
formaldehyde	1.42E-04	1.54E+01	6.16E+01
m-Cresol	9.33E-06	9.77E+00	3.91E+01
p-Cresol	4.54E-04	9.68E+00	3.87E+01
PGMEA	1.67E-02	1.25E+02	4.99E+02
n-methyl-2-pyrollidone	6.41E-04	5.58E+00	2.23E+01
PGME	1.21E-02	1.64E+02	6.54E+02
ethyl lactate	1.42E-02	1.56E+02	6.25E+02
TMAH	6.19E-04	1.63E+01	6.51E+01
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH4	8.51E-04	6.19E+00	2.48E+01
H2	3.76E-03	4.50E+01	1.80E+02
DCS	0.00E+00	0.00E+00	0.00E+00
B2H6	0.00E+00	0.00E+00	0.00E+00
C4F8	1.20E-05	0.00E+00	0.00E+00
GeH4	0.00E+00	0.00E+00	0.00E+00
OTHER CHEMICALS			
Ar	6.15E-01	3.11E+02	1.25E+03
N2	6.78E-01	3.62E+02	1.45E+03
He	4.50E-04	2.25E-01	8.99E-01
O2	9.23E-02	1.50E+02	6.01E+02
IPA	3.42E-02	3.91E+02	1.57E+03
NH3	4.50E-04	2.25E-01	8.99E-01
Ti	5.12E-07	2.84E-04	1.14E-03
Cu	1.41E-06	7.85E-04	3.14E-03
Sn	5.89E-05	2.97E-02	1.19E-01

Table C.16. Flash memory manufacturing emissions per wafer, 90 nm node

65 nm kg/wafer	Emissions to Air expected value	low	high
GWG			
CF4	1.63E-04	8.13E-05	3.25E-04
CHF3	3.66E-05	1.83E-05	7.31E-05
C2F6	0.00E+00	0.00E+00	0.00E+00
CH4	2.11E-04	1.05E-04	4.22E-04
CO2	1.53E+00	7.66E-01	3.07E+00
NF3	3.93E-04	1.96E-04	7.85E-04
C4F6	0.00E+00	0.00E+00	0.00E+00
N2O	0.00E+00	0.00E+00	0.00E+00
HAZARDOUS			
F2	4.51E-03	2.25E-03	9.02E-03
HF (gas)	8.45E-04	4.22E-04	1.69E-03
SiF4	4.53E-05	2.27E-05	9.06E-05
C4F8	1.53E-06	7.67E-07	3.07E-06
C2F4	1.81E-05	9.05E-06	3.62E-05
COF2	4.55E-05	2.28E-05	9.10E-05
HCl (gas)	2.47E-07	1.24E-07	4.95E-07
Cl2	1.03E-04	5.13E-05	2.05E-04
SiCl4	1.70E-06	8.50E-07	3.40E-06
PH3	0.00E+00	0.00E+00	0.00E+00
bis tertiary-butylamino silane	1.43E-05	7.17E-06	2.87E-05
AsH3	4.05E-06	2.02E-06	8.09E-06
BCl3	3.46E-05	1.73E-05	6.93E-05
Pb	0.00E+00	0.00E+00	0.00E+00
WF6	8.16E-03	4.08E-03	1.63E-02
HBr	0.00E+00	0.00E+00	0.00E+00
Br2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	0.00E+00	0.00E+00
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	2.10E-02	1.05E-02	4.21E-02
NO	5.02E-03	2.51E-03	1.00E-02
NO2	4.58E-04	2.29E-04	9.17E-04
SO2	0.00E+00	0.00E+00	0.00E+00
N2O	2.50E-04	1.25E-04	5.00E-04

Table C.17. Flash memory manufacturing emissions per wafer, 65 nm node

65 nm kg/wafer	Emissions to Air expected value	low	high
VOC			
DMA	2.42E-06	1.21E-06	4.84E-06
MMA	5.57E-05	2.78E-05	1.11E-04
TDMAT	0.00E+00	0.00E+00	0.00E+00
TMS	0.00E+00	0.00E+00	0.00E+00
TEOS	0.00E+00	0.00E+00	0.00E+00
formaldehyde	1.44E-04	7.21E-05	2.88E-04
m-cresol	9.45E-06	4.72E-06	1.89E-05
p-cresol	4.29E-04	2.15E-04	8.58E-04
PGMEA	1.69E-02	8.47E-03	3.39E-02
n-methyl-2-pyrollidone	6.05E-04	3.02E-04	1.21E-03
PGME	1.23E-02	6.14E-03	2.46E-02
ethyl lactate	1.45E-02	7.23E-03	2.89E-02
TMAH	5.95E-04	2.98E-04	1.19E-03
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH4	1.02E-03	5.12E-04	2.05E-03
H2	8.06E-03	4.03E-03	1.61E-02
DCS	0.00E+00	0.00E+00	0.00E+00
B2H6	0.00E+00	0.00E+00	0.00E+00
C4F8	1.14E-05	5.68E-06	2.27E-05
GeH4	0.00E+00	0.00E+00	0.00E+00
OTHER CHEMICALS			
Ar	7.57E-01	3.79E-01	1.51E+00
N2	8.27E-01	4.13E-01	1.65E+00
He	8.48E-04	4.24E-04	1.70E-03
O2	9.94E-02	4.97E-02	1.99E-01
IPA	3.46E-02	1.73E-02	6.91E-02
NH3	8.48E-04	4.24E-04	1.70E-03
Ti	4.8295E-07	2.41475E-07	9.659E-07
Cu	1.33269E-06	6.66344E-07	2.66537E-06
Sn	0	0	0

Table C.18. Flash memory manufacturing emissions per wafer, 65 nm node

45 nm kg/wafer	Emissions to Air expected value	low	high
GWG			
CF4	8.57E-04	1.07E-03	4.28E-03
CHF3	2.63E-05	6.30E-06	2.52E-05
C2F6	3.64E-06	2.50E-06	1.00E-05
CH4	6.13E-04	2.23E-03	8.94E-03
CO2	1.51E+00	8.89E-01	3.56E+00
NF3	4.33E-04	2.15E-04	8.59E-04
C4F6	1.07E-05	8.01E-06	3.20E-05
N2O	0.00E+00	2.50E-04	1.00E-03
HAZARDOUS			
F2	4.10E-03	1.90E-03	7.61E-03
HF (gas)	1.03E-02	4.62E-03	1.85E-02
SiF4	8.47E-05	4.43E-05	1.77E-04
C4F8	2.78E-06	1.02E-06	4.09E-06
C2F4	2.21E-05	4.02E-06	1.61E-05
COF2	4.72E-05	2.83E-05	1.13E-04
HCl (gas)	1.24E-07	0.00E+00	0.00E+00
Cl2	6.31E-05	1.17E-05	4.69E-05
SiCl4	8.50E-07	0.00E+00	0.00E+00
PH3	0.00E+00	1.42E-08	5.68E-08
bis tertiary-butylamino silane	0.00E+00	2.39E-06	9.57E-06
AsH3	4.05E-06	1.78E-09	7.10E-09
BCl3	1.73E-05	0.00E+00	0.00E+00
Pb	0.00E+00	0.00E+00	0.00E+00
WF6	6.12E-03	2.04E-03	8.16E-03
HBr	0.00E+00	0.00E+00	0.00E+00
Br2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	0.00E+00	0.00E+00
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	2.89E-01	3.14E-01	1.26E+00
NO	7.40E-03	3.49E-03	1.40E-02
NO2	3.64E-03	3.34E-03	1.34E-02
SO2	0.00E+00	0.00E+00	0.00E+00
N2O	4.92E-04	2.50E-04	1.00E-03

Table C.19. Flash memory manufacturing emissions per wafer, 45 nm node

45 nm kg/wafer	Emissions to Air expected value	low	high
VOC			
DMA	1.21E-06	1.21E-06	4.84E-06
MMA	2.78E-05	2.78E-05	1.11E-04
TDMAT	0.00E+00	0.00E+00	0.00E+00
TMS	0.00E+00	9.26E-04	3.70E-03
TEOS	0.00E+00	6.45E-04	2.58E-03
formaldehyde	2.01E-04	7.97E-05	3.19E-04
m-Cresol	1.30E-05	5.05E-06	2.02E-05
p-Cresol	4.33E-04	5.00E-06	2.00E-05
PGMEA	2.36E-02	9.37E-03	3.75E-02
n-methyl-2-pyrollidone	6.05E-04	0.00E+00	0.00E+00
PGME	1.69E-02	6.77E-03	2.71E-02
ethyl lactate	2.01E-02	8.00E-03	3.20E-02
TMAH	6.58E-04	8.81E-05	3.52E-04
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH4	9.64E-04	2.20E-04	8.80E-04
H2	6.28E-03	2.53E-03	1.01E-02
DCS	0.00E+00	0.00E+00	0.00E+00
B2H6	0.00E+00	0.00E+00	0.00E+00
C4F8	1.70E-04	1.65E-04	6.59E-04
GeH4	0.00E+00	0.00E+00	0.00E+00
OTHER CHEMICALS			
Ar	1.69E+00	9.55E-01	3.82E+00
N2	6.31E-01	7.60E-01	3.04E+00
He	4.24E-04	7.44E-02	2.98E-01
O2	1.01E-01	2.93E-02	1.17E-01
IPA	4.72E-02	1.83E-02	7.30E-02
NH3	4.24E-04	7.44E-02	2.98E-01
Ti	4.83E-07	4.83E-08	1.93E-07
Cu	1.33E-06	2.61E-05	1.04E-04
Sn	5.55E-05	2.17E-03	8.67E-03

Table C.20. Flash memory manufacturing emissions per wafer, 45 nm node

C.3 Flash LCA: Tabulated results with uncertainty

	Photochemical Smog kg NO$_x$			Acidification mol H$^+$			Ecotoxicity kg 2,4-D		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	0.22	N/A	N/A	227	N/A	N/A	0.00	N/A	N/A
Electricity (Si, fab. and use)	0.21	0.20	0.23	126	117	134	1.06	1.03	1.08
Fab. direct emissions	0.089	0.045	0.18	65	32	129	5.8E-02	5.1E-02	6.5E-02
Infrastructure	0.99	0.49	1.24	1,133	566	1,416	7.6E-03	3.8E-03	9.5E-03
Total	1.51	0.96	1.86	1,549	942	1,906	1.12	1.09	1.2

Table C.21. Flash life cycle impacts per wafer, 45 nm node

	Human Health Cancer kg C_6H_6			Human Health Criteria total DALYs			Health Noncancer kg C_7H_7		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	0.00	N/A	N/A	0.00	N/A	N/A	0.05	N/A	N/A
Electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	3.48E-03	3.41E-03	3.55E-03	85	83	87
Fab. direct emissions	2.25E-02	1.47E-02	3.70E-02	3.16E-05	1.58E-05	6.32E-05	864	760	970
Infrastructure	1.12E-02	5.61E-03	1.40E-02	1.73E-02	8.67E-03	2.17E-02	476	238	595
Total	0.034	0.020	0.051	0.022	0.013	0.026	1,425	1,080	1,652

	Eutrophication, to air kg N			Eutrophication, to water kg N		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	7.69E-03	N/A	N/A			
Electricity (Si, fab. and use)	7.67E-03	7.29E-03	8.06E-03	N/A	N/A	N/A
Fab. direct emissions	6.36E-04	3.18E-04	1.27E-03	4.63	2.36	9.15
Infrastructure	0.034	0.017	0.042	N/A	N/A	N/A
Total	0.050	0.032	0.059	4.6	2.4	9.2

Table C.22. Flash life cycle impacts per wafer, 45 nm node

	Photochemical Smog kg NO_x Expected value	Lower bound	Upper bound	Acidification mol H^+ Expected value	Lower bound	Upper bound	Ecotoxicity kg 2,4-D Expected value	Lower bound	Upper bound
Transportation	0.22	N/A	N/A	234	N/A	N/A	0.00	N/A	N/A
Electricity (Si, fab. and use)	0.19	0.18	0.20	100	91	108	0.92	0.89	0.94
Fab. direct emissions	0.054	0.027	0.11	17	8	34	2.1E-03	1.5E-03	3.3E-03
Infrastructure	0.78	0.39	0.98	894	447	1,117	5.8E-03	2.9E-03	7.3E-03
Total	1.24	0.81	1.50	1,244	781	1,493	0.93	0.90	1.0

Table C.23. Flash life cycle impacts per wafer, 65 nm node

	Human Health Cancer kg C_6H_6			Human Health Criteria total DALYs			Health Noncancer kg C_7H_7		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	0.00	N/A	N/A	0.00	N/A	N/A	0.06	N/A	N/A
Electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	3.50E-03	3.43E-03	3.57E-03	74	72	75
Fab. direct emissions	2.22E-02	1.44E-02	3.66E-02	1.57E-05	7.84E-06	3.13E-05	777	683	873
Infrastructure	8.62E-03	4.31E-03	1.08E-02	1.37E-02	6.86E-03	1.71E-02	365	183	457
Total	0.031	0.019	0.047	0.019	0.012	0.022	1,216	937	1,406

	Eutrophication, to air kg N			Eutrophication, to water kg N		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	7.69E-03	N/A	N/A	N/A	N/A	N/A
Electricity (Si, fab. and use)	6.66E-03	6.31E-03	7.02E-03	N/A	N/A	N/A
Fab. direct emissions	3.66E-04	1.83E-04	7.33E-04	4.47	2.28	8.84
Infrastructure	0.027	0.013	0.033	N/A	N/A	N/A
Total	0.041	0.027	0.049	4.5	2.3	8.8

Table C.24. Flash life cycle impacts per wafer, 65 nm node

	Photochemical Smog kg NO_x Expected value	Lower bound	Upper bound	Acidification mol H^+ expected value	Lower bound	Upper bound	Ecotoxicity kg 2,4-D expected value	Lower bound	Upper bound
Transportation	0.20	N/A	N/A	211	N/A	N/A	0.00	N/A	N/A
Electricity (Si, fab. and use)	0.18	0.17	0.19	100	92	107	0.89	0.87	0.91
Fab. direct emissions	0.05	0.026	0.10	15	7.3	29	2.3E-03	1.4E-03	3.8E-03
Infrastructure	0.61	0.31	0.77	703	352	879	4.5E-03	2.2E-03	5.6E-03
Total	1.05	0.71	1.27	1,029	662	1,227	0.90	0.87	0.9

Table C.25. Flash life cycle impacts per wafer, 90 nm node

	Human Health Cancer kg C_6H_6 expected value	Lower bound	Upper bound	Human Health Criteria total DALYs Expected value	Lower bound	Upper bound	Health Noncancer kg C_7H_7 Expected value	Lower bound	Upper bound
Transportation	0.00	N/A	N/A	0.00	N/A	N/A	0.05	N/A	N/A
Electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	3.08E-03	3.02E-03	3.15E-03	72	70	73
Fab. direct emissions	2.23E-02	1.42E-02	3.75E-02	1.45E-05	7.26E-06	2.90E-05	751	660	843
Infrastructure	6.61E-03	3.31E-03	8.27E-03	1.08E-02	5.41E-03	1.35E-02	281	140	351
Total	0.029	0.018	0.046	0.015	0.010	0.018	1,103	870	1,267

	Eutrophication, to air kg N expected value	lower bound	upper bound	Eutrophication, to water kg N expected value	lower bound	upper bound
Transportation	7.17E-03	N/A	N/A	N/A	N/A	N/A
Electricity (Si, fab. and use)	6.48E-03	6.14E-03	6.82E-03	N/A	N/A	N/A
Fab. direct emissions	3.34E-04	1.67E-04	6.67E-04	4.13	2.10	8.16
Infrastructure	0.021	0.010	0.026	N/A	N/A	N/A
Total	0.035	0.024	0.041	4.1	2.1	8.2

Table C.26. Flash life cycle impacts per wafer, 90 nm node

	Photochemical Smog kg NO_x			Acidification mol H^+			Ecotoxicity kg 2,4-D		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	0.25	N/A	N/A	264	N/A	N/A	0.00	N/A	N/A
Electricity (Si, fab. and use)	0.18	0.17	0.19	78	70	86	0.86	0.84	0.88
Fab. direct emissions	0.052	0.026	0.10	14	7.1	29	3.3E-03	2.0E-03	5.9E-03
Infrastructure	0.56	0.28	0.70	638	319	798	4.1E-03	2.0E-03	5.1E-03
Total	1.04	0.72	1.24	994	660	1,177	0.87	0.85	0.90

Table C.27. Flash life cycle impacts per wafer, 120 nm node

	Human Health Cancer			Human Health Criteria			Health Noncancer		
	kg C_6H_6			total DALYs			kg C_7H_7		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	0.00	N/A	N/A	0.00	N/A	N/A	0.06	N/A	N/A
Electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	3.40E-03	3.33E-03	3.47E-03	69	68	71
Fab. direct emissions	1.96E-02	1.10E-02	3.64E-02	1.40E-05	7.00E-06	2.80E-05	842	706	1,026
Infrastructure	6.06E-03	3.03E-03	7.57E-03	9.81E-03	4.91E-03	1.23E-02	257	128	321
Total	0.026	0.014	0.044	0.015	0.010	0.017	1,169	902	1,418

		Eutrophication, to air		Eutrophication, to water		
	kg N			kg N		
	expected value	lower bound	upper bound	expected value	lower bound	upper bound
Transportation	8.95E-03	N/A	N/A	N/A	N/A	N/A
Electricity (Si, fab. and use)	6.27E-03	5.90E-03	6.64E-03	N/A	N/A	N/A
Fab. direct emissions	3.23E-04	1.61E-04	6.45E-04	4.19	2.11	8.34
Infrastructure	0.019	0.009	0.024	N/A	N/A	N/A
Total	0.034	0.024	0.040	4.2	2.1	8.3

Table C.28. Flash life cycle impacts per wafer, 120 nm node

	Photochemical Smog kg NO$_x$ Expected value	Lower bound	Upper bound	Acidification mol H$^+$ Expected value	Lower bound	Upper bound	Ecotoxicity kg 2,4-D Expected value	Lower bound	Upper bound
Transportation	0.25	N/A	N/A	264	N/A	N/A	0.00	N/A	N/A
Electricity (Si, fab. and use)	0.20	0.19	0.21	98	89	106	0.97	0.94	0.99
Fab. direct emissions	0.072	0.036	0.14	33	17	67	3.4E-03	2.0E-03	6.1E-03
Infrastructure	0.39	0.20	0.49	450	225	562	2.9E-03	1.4E-03	3.6E-03
Total	0.92	0.67	1.10	845	594	999	0.97	0.95	1.0

Table C.29. Flash life cycle impacts per wafer, 150 nm node

	Human Health Cancer kg C_6H_6 Expected value	Lower bound	Upper bound	Human Health Criteria total DALYs Expected value	Lower bound	Upper bound	Health Noncancer kg C_7H_7 Expected value	Lower bound	Upper bound
Transportation	0.00	N/A	N/A	0.00	N/A	N/A	0.06	N/A	N/A
Electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	3.59E-03	3.52E-03	3.66E-03	78	76	80
Fab. direct emissions	1.93E-02	1.10E-02	3.55E-02	3.09E-05	1.54E-05	6.17E-05	896	751	1,092
Infrastructure	4.23E-03	2.12E-03	5.29E-03	6.92E-03	3.46E-03	8.65E-03	179	90	224
Total	0.024	0.013	0.041	0.012	0.008	0.014	1,154	917	1,396

	Eutrophication, to air kg N Expected value	Lower bound	Upper bound	Eutrophication, to water kg N Expected value	Lower bound	Upper bound
Transportation	8.95E-03	N/A	N/A	N/A	N/A	N/A
Electricity (Si, fab. and use)	7.04E-03	6.65E-03	7.42E-03	N/A	N/A	N/A
Fab. direct emissions	6.17E-04	3.08E-04	1.23E-03	4.46	2.25	8.88
Infrastructure	0.013	0.007	0.017	N/A	N/A	N/A
Total	0.030	0.023	0.034	4.5	2.2	8.9

Table C.30. Flash life cycle impacts per wafer, 150 nm node

Appendix D

DRAM Life Cycle Inventory and Impact Results

D.1 DRAM manufacturing inventory data

250nm			250nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	9.37E-03		SiH_4	1.23E-02
CHF_3	9.60E-04		H_2	1.72E-01
C_2F_6	0.00E+00		DCS	0.00E+00
CH_4	2.36E-01		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	0.00E+00
NF_3	1.75E-01		GeH_4	0.00E+00
C_4F_6	0.00E+00		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	1.81E+00
SiF_4	6.14E-03		Ar	5.35E+00
C_4F_8	1.36E-03		N_2	1.49E+00
C_2F_4	0.00E+00		CMP polishing solution	0.00E+00
COF_2	0.00E+00		H_2O_2	1.09E+01
HCl (gas)	0.00E+00		abrasive	0.00E+00
Cl_2	3.63E-03		silica slurry	0.00E+00
$SiCl_4$	0.00E+00		benzotriazole	0.00E+00
PH_3	9.13E-04		CMP surfactants	1.75E-01
BTBAS	0.00E+00		citric acid	9.74E-02
AsH_3	0.00E+00		tungsten CMP slurry	8.43E+00
BCl_3	3.88E-03		Al	2.61E-04
Pb	1.63E-03		As	0.00E+00
WF_6	6.20E-02		Cu	2.56E-04
HBr	4.03E-03		Pt	0.00E+00
Br_2	0.00E+00		Ti	8.62E-08
HMDS	1.61E-01		He	3.07E-03
OMCTS	0.00E+00		NH_3	3.57E-04

Table D.1. DRAM manufacturing inventory per wafer, 250 nm node

250nm			250nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	0.00E+00
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	6.62E-02
SO_2	0.00E+00		H_2SO_4	1.26E+02
N_2O	5.27E-03		HCl	2.15E+00
O_3	0.00E+00		NH_4OH	3.76E+00
			IPA	4.15E+00
VOC			oxide CMP slurry, chemicals	1.62E+01
DMA	0.00E+00		BF_3	0.00E+00
MMA	0.00E+00		Cr	0.00E+00
TDMAT	4.14E-03		Au	7.38E-05
TMS	0.00E+00		Sn	4.52E-04
TEOS	0.00E+00		Co	3.94E-05
formaldehyde	1.92E-02		Ni	3.31E-03
m-cresol	1.22E-02		polyimide laminate	1.89E-03
p-cresol	1.21E-02		laminate solvent	0.00E+00
PGMEA	1.55E-01		H3PO$_4$	0.00E+00
n-methyl-2-pyrollidone	8.47E-03		$CuCl_2$	0.00E+00
PGME	2.04E-01		W	3.86E-07
ethyl lactate	1.95E-01		Ta	0.00E+00
TMAH	2.10E-02		Cu ECP additive X	0.00E+00
TDEAH	0.00E+00		Cu ECP Additive Y	0.00E+00
TDMAS	0.00E+00		$Na_2B_4O_7$	9.08E-03
DEA	0.00E+00			
PDMAT	0.00E+00			

Table D.2. DRAM manufacturing inventory per wafer, 250 nm node

180 nm			180 nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	9.37E-03		SiH_4	1.23E-02
CHF_3	9.60E-04		H_2	1.72E-01
C_2F_6	0.00E+00		DCS	0.00E+00
CH_4	2.36E-01		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	0.00E+00
NF_3	1.75E-01		GeH_4	0.00E+00
C_4F_6	0.00E+00		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	1.81E+00
SiF_4	6.14E-03		Ar	5.35E+00
C_4F_8	1.36E-03		N_2	1.49E+00
C_2F_4	0.00E+00		CMP polishing solution	0.00E+00
COF_2	0.00E+00		H_2O_2	1.09E+01
HCl (gas)	0.00E+00		abrasive	0.00E+00
Cl_2	3.63E-03		silica slurry	0.00E+00
$SiCl_4$	0.00E+00		benzotriazole	0.00E+00
PH_3	9.13E-04		CMP surfactants	1.75E-01
BTBAS	0.00E+00		citric acid	9.74E-02
AsH_3	0.00E+00		tungsten CMP slurry	8.43E+00
BCl_3	3.88E-03		Al	2.61E-04
Pb	1.20E-03		As	0.00E+00
WF_6	6.20E-02		Cu	1.87E-04
HBr	4.03E-03		Pt	0.00E+00
Br_2	0.00E+00		Ti	8.62E-08
HMDS	1.61E-01		He	3.07E-03
OMCTS	0.00E+00		NH_3	3.57E-04

Table D.3. DRAM manufacturing inventory per wafer, 180 nm node

180 nm			180 nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	0.00E+00
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	6.62E-02
SO_2	0.00E+00		H_2SO_4	1.26E+02
N_2O	5.27E-03		HCl	2.15E+00
O_3	0.00E+00		NH_4OH	3.76E+00
			IPA	4.15E+00
VOC			oxide CMP slurry, chemicals	1.62E+01
DMA	0.00E+00		BF_3	0.00E+00
MMA	0.00E+00		Cr	0.00E+00
TDMAT	4.14E-03		Au	5.39E-05
TMS	0.00E+00		Sn	3.31E-04
TEOS	0.00E+00		Co	2.88E-05
formaldehyde	1.92E-02		Ni	2.42E-03
m-Cresol	1.22E-02		polyimide laminate	1.89E-03
p-Cresol	1.21E-02		laminate solvent	0.00E+00
PGMEA	1.55E-01		H3PO$_4$	0.00E+00
n-methyl-2-pyrollidone	8.47E-03		$CuCl_2$	0.00E+00
PGME	2.04E-01		W	3.86E-07
ethyl lactate	1.95E-01		Ta	0.00E+00
TMAH	2.10E-02		Cu ECP additive X	0.00E+00
TDEAH	0.00E+00		Cu ECP Additive Y	0.00E+00
TDMAS	0.00E+00		$Na_2B_4O_7$	9.08E-03
DEA	0.00E+00			
PDMAT	0.00E+00			

Table D.4. DRAM manufacturing inventory per wafer, 180 nm node

130 nm			130 nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	2.07E-03		SiH_4	1.63E-02
CHF_3	1.03E-03		H_2	2.27E-01
C_2F_6	0.00E+00		DCS	0.00E+00
CH_4	2.59E-01		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	3.75E-04
NF_3	2.31E-01		GeH_4	0.00E+00
C_4F_6	7.23E-05		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	2.28E+00
SiF_4	8.10E-03		Ar	7.05E+00
C_4F_8	1.79E-03		N_2	1.96E+00
C_2F_4	0.00E+00		CMP polishing solution	0.00E+00
COF_2	0.00E+00		H_2O_2	1.47E+01
HCl (gas)	0.00E+00		abrasive	0.00E+00
Cl_2	1.14E-03		silica slurry	0.00E+00
$SiCl_4$	0.00E+00		benzotriazole	0.00E+00
PH_3	1.20E-03		CMP surfactants	2.31E-01
BTBAS	0.00E+00		citric acid	1.29E-01
AsH_3	0.00E+00		tungsten CMP slurry	1.11E+01
BCl_3	0.00E+00		Al	0.00E+00
Pb	5.07E-03		As	0.00E+00
WF_6	8.18E-02		Cu	7.97E-04
HBr	5.32E-03		Pt	0.00E+00
Br_2	0.00E+00		Ti	1.14E-07
HMDS	2.31E-01		He	4.05E-03
OMCTS	0.00E+00		NH_3	4.71E-04

Table D.5. DRAM manufacturing inventory per wafer, 130 nm node

130 nm			130 nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	0.00E+00
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	1.03E-01
SO_2	0.00E+00		H_2SO_4	1.67E+02
N_2O	6.96E-03		HCl	3.03E+00
O_3	0.00E+00		NH_4OH	5.19E+00
			IPA	6.26E+00
VOC			oxide CMP slurry, chemicals	2.13E+01
DMA	0.00E+00		BF_3	0.00E+00
MMA	0.00E+00		Cr	0.00E+00
TDMAT	5.47E-03		Au	2.30E-04
TMS	0.00E+00		Sn	1.40E-03
TEOS	0.00E+00		Co	1.23E-04
formaldehyde	2.75E-02		Ni	1.03E-02
m-Cresol	1.75E-02		polyimide laminate	2.49E-03
p-Cresol	1.73E-02		laminate solvent	0.00E+00
PGMEA	2.23E-01		$H3PO_4$	6.02E-03
n-methyl-2-pyrollidone	1.12E-02		$CuCl_2$	0.00E+00
PGME	2.92E-01		W	1.71E-06
ethyl lactate	2.79E-01		Ta	3.25E-01
TMAH	3.01E-02		Cu ECP additive X	0.00E+00
TDEAH	0.00E+00		Cu ECP Additive Y	0.00E+00
TDMAS	0.00E+00		$Na_2B_4O_7$	1.30E-02
DEA	0.00E+00			
PDMAT	0.00E+00			

Table D.6. DRAM manufacturing inventory per wafer, 130 nm node

90nm			90nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	6.38E-03		SiH_4	2.10E-02
CHF_3	3.50E-03		H_2	1.35E-01
C_2F_6	0.00E+00		DCS	0.00E+00
CH_4	4.89E-01		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	0.00E+00
NF_3	2.09E-01		GeH_4	0.00E+00
C_4F_6	0.00E+00		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	1.98E+00
SiF_4	5.80E-03		Ar	5.61E+00
C_4F_8	1.79E-03		N_2	3.34E-01
C_2F_4	0.00E+00		CMP polishing solution	0.00E+00
COF_2	0.00E+00		H_2O_2	1.33E+01
HCl (gas)	0.00E+00		abrasive	0.00E+00
Cl_2	2.28E-03		silica slurry	0.00E+00
$SiCl_4$	0.00E+00		benzotriazole	0.00E+00
PH_3	1.81E-03		CMP surfactants	1.73E-01
BTBAS	0.00E+00		citric acid	9.64E-02
AsH_3	0.00E+00		tungsten CMP slurry	8.34E+00
BCl_3	0.00E+00		Al	0.00E+00
Pb	5.07E-03		As	0.00E+00
WF_6	4.91E-02		Cu	7.97E-04
HBr	1.06E-02		Pt	0.00E+00
Br_2	0.00E+00		Ti	1.14E-07
HMDS	2.87E-01		He	4.50E-04
OMCTS	0.00E+00		NH_3	9.79E-04

Table D.7. DRAM manufacturing inventory per wafer, 90 nm node

90nm			90nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	0.00E+00
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	1.06E-01
SO_2	0.00E+00		H_2SO_4	1.15E+02
N_2O	1.39E-02		HCl	4.16E+00
O_3	0.00E+00		NH_4OH	6.37E+00
			IPA	0.00E+00
VOC			oxide CMP slurry, chemicals	2.13E+01
DMA	0.00E+00		BF_3	0.00E+00
MMA	0.00E+00		Cr	0.00E+00
TDMAT	6.07E-04		Au	2.30E-04
TMS	2.20E-03		Sn	1.40E-03
TEOS	1.40E-03		Co	1.23E-04
formaldehyde	3.33E-02		Ni	1.03E-02
m-Cresol	3.81E-02		polyimide laminate	2.49E-03
p-Cresol	2.00E-02		laminate solvent	0.00E+00
PGMEA	2.82E-01		$H3PO_4$	0.00E+00
n-methyl-2-pyrollidone	3.35E-02		$CuCl_2$	1.04E-03
PGME	3.41E-01		W	5.10E-07
ethyl lactate	3.24E-01		Ta	0.00E+00
TMAH	3.49E-02		Cu ECP additive X	3.00E-04
TDEAH	5.67E-05		Cu ECP Additive Y	0.00E+00
TDMAS	0.00E+00		$Na_2B_4O_7$	2.56E-01
DEA	0.00E+00			
PDMAT	0.00E+00			

Table D.8. DRAM manufacturing inventory per wafer, 90 nm node

70 nm			70 nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	6.16E-03		SiH_4	1.77E-02
CHF_3	3.56E-03		H_2	1.27E-01
C_2F_6	0.00E+00		DCS	0.00E+00
CH_4	5.27E-01		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	0.00E+00
NF_3	1.61E-01		GeH_4	0.00E+00
C_4F_6	0.00E+00		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	6.52E-01
SiF_4	3.07E-04		Ar	1.49E+00
C_4F_8	2.06E-03		N_2	3.27E-01
C_2F_4	0.00E+00		CMP polishing solution	0.00E+00
COF_2	0.00E+00		H_2O_2	1.31E+01
HCl (gas)	0.00E+00		abrasive	0.00E+00
Cl_2	2.15E-03		silica slurry	0.00E+00
$SiCl_4$	0.00E+00		benzotriazole	0.00E+00
PH_3	4.83E-03		CMP surfactants	1.64E-01
BTBAS	0.00E+00		citric acid	9.09E-02
AsH_3	0.00E+00		tungsten CMP slurry	7.87E+00
BCl_3	0.00E+00		Al	0.00E+00
Pb	0.00E+00		As	0.00E+00
WF_6	4.63E-02		Cu	6.74E-04
HBr	1.00E-02		Pt	0.00E+00
Br_2	0.00E+00		Ti	1.07E-07
HMDS	2.62E-01		He	4.24E-04
OMCTS	0.00E+00		NH_3	9.57E-04

Table D.9. DRAM manufacturing inventory per wafer, 70 nm node

70 nm			70 nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	0.00E+00
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	1.36E-01
SO_2	0.00E+00		H_2SO_4	1.08E+02
N_2O	1.31E-02		HCl	4.28E+00
O_3	0.00E+00		NH_4OH	6.39E+00
			IPA	0.00E+00
VOC			oxide CMP slurry, chemicals	1.76E+01
DMA	0.00E+00		BF_3	0.00E+00
MMA	0.00E+00		Cr	0.00E+00
TDMAT	5.73E-04		Au	1.94E-04
TMS	2.08E-03		Sn	3.77E-03
TEOS	1.32E-03		Co	1.04E-04
formaldehyde	3.04E-02		Ni	8.70E-03
m-Cresol	3.52E-02		polyimide laminate	2.35E-03
p-Cresol	1.83E-02		laminate solvent	0.00E+00
PGMEA	2.57E-01		$H3PO_4$	0.00E+00
n-methyl-2-pyrollidone	3.16E-02		$CuCl_2$	9.83E-04
PGME	3.11E-01		W	4.81E-07
ethyl lactate	2.95E-01		Ta	0.00E+00
TMAH	3.18E-02		Cu ECP additive X	2.83E-04
TDEAH	5.35E-05		Cu ECP Additive Y	0.00E+00
TDMAS	0.00E+00		$Na_2B_4O_7$	2.41E-01
DEA	0.00E+00			
PDMAT	0.00E+00			

Table D.10. DRAM manufacturing inventory per wafer, 70 nm node

57 nm			57 nm	
Inputs	g/wafer		Inputs	g/wafer
GWG			FLAMMABLE	
CF_4	2.19E-02		SiH_4	1.85E-02
CHF_3	3.41E-03		H_2	2.13E-01
C_2F_6	0.00E+00		DCS	0.00E+00
CH_4	6.48E-01		B_2H_6	0.00E+00
CO_2	0.00E+00		C_4F_8	0.00E+00
NF_3	2.05E-01		GeH_4	0.00E+00
C_4F_6	0.00E+00		C_2H_2	0.00E+00
N_2O	0.00E+00		C_2H_4	0.00E+00
HAZARDOUS				
F_2	0.00E+00		OTHER CHEMICALS	
HF (gas)	0.00E+00		O_2	7.04E-01
SiF_4	2.56E-04		Ar	1.46E+00
C_4F_8	1.31E-03		N_2	5.37E-01
C_2F_4	0.00E+00		CMP polishing solution	0.00E+00
COF_2	0.00E+00		H_2O_2	1.31E+01
HCl (gas)	0.00E+00		abrasive	0.00E+00
Cl_2	3.77E-03		silica slurry	0.00E+00
$SiCl_4$	0.00E+00		benzotriazole	0.00E+00
PH_3	2.49E-03		CMP surfactants	2.18E-01
BTBAS	0.00E+00		citric acid	1.21E-01
AsH_3	6.21E-04		tungsten CMP slurry	1.05E+01
BCl_3	0.00E+00		Al	0.00E+00
Pb	0.00E+00		As	0.00E+00
WF_6	7.71E-02		Cu	1.00E-03
HBr	1.75E-02		Pt	0.00E+00
Br_2	0.00E+00		Ti	1.07E-07
HMDS	2.88E-01		He	8.48E-04
OMCTS	0.00E+00		NH_3	9.23E-04

Table D.11. DRAM manufacturing inventory per wafer, 57 nm node

57 nm			57 nm	
Inputs	g/wafer		Inputs	g/wafer
CRITERIA			OTHER CHEMICALS	
CO	0.00E+00		$CuSO_4$	0.00E+00
NO	0.00E+00		ArH	0.00E+00
NO_2	0.00E+00		100% HF liquid	1.30E-01
SO_2	0.00E+00		H_2SO_4	9.92E+01
N_2O	1.31E-02		HCl	4.64E+00
O_3	0.00E+00		NH_4OH	6.99E+00
			IPA	0.00E+00
VOC			oxide CMP slurry, chemicals	1.51E+01
DMA	0.00E+00		BF_3	0.00E+00
MMA	0.00E+00		Cr	0.00E+00
TDMAT	1.15E-03		Au	2.89E-04
TMS	2.08E-03		Sn	5.60E-03
TEOS	1.32E-03		Co	1.54E-04
formaldehyde	3.35E-02		Ni	1.29E-02
m-Cresol	3.72E-02		polyimide laminate	2.35E-03
p-Cresol	2.02E-02		laminate solvent	0.00E+00
PGMEA	2.82E-01		$H3PO_4$	0.00E+00
n-methyl-2-pyrollidone	3.16E-02		$CuCl_2$	9.83E-04
PGME	3.44E-01		W	4.81E-07
ethyl lactate	3.27E-01		Ta	0.00E+00
TMAH	3.52E-02		Cu ECP additive X	2.83E-04
TDEAH	1.07E-04		Cu ECP Additive Y	0.00E+00
TDMAS	0.00E+00		$Na_2B_4O_7$	2.43E-01
DEA	0.00E+00			
PDMAT	0.00E+00			

Table D.12. DRAM manufacturing inventory per wafer, 57 nm node

D.2 DRAM manufacturing emissions data

250nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF_4	5.20E-04	4.69E-03	1.87E-02
CHF_3	4.60E-05	4.80E-04	1.92E-03
C_2F_6	0.00E+00	0.00E+00	0.00E+00
CH_4	1.46E-04	1.18E-01	4.73E-01
CO_2	6.51E-01	0.00E+00	0.00E+00
NF_3	3.77E-04	8.74E-02	3.50E-01
C_4F_6	0.00E+00	0.00E+00	0.00E+00
N_2O	0.00E+00	0.00E+00	0.00E+00
HAZARDOUS			
F_2	2.98E-03	0.00E+00	0.00E+00
HF (gas)	2.52E-03	0.00E+00	0.00E+00
SiF_4	4.03E-05	3.07E-03	1.23E-02
C_4F_8	1.23E-06	6.78E-04	2.71E-03
C_2F_4	1.45E-05	0.00E+00	0.00E+00
COF_2	4.12E-06	0.00E+00	0.00E+00
HCl (gas)	3.97E-07	0.00E+00	0.00E+00
Cl_2	1.37E-04	1.82E-03	7.26E-03
$SiCl_4$	2.73E-06	0.00E+00	0.00E+00
PH_3	0.00E+00	4.57E-04	1.83E-03
BTBAS	0.00E+00	0.00E+00	0.00E+00
AsH_3	0.00E+00	0.00E+00	0.00E+00
BCl_3	5.57E-05	1.94E-03	7.77E-03
Pb	1.63E-04	8.17E-04	3.27E-03
WF_6	8.20E-03	3.10E-02	1.24E-01
HBr	0.00E+00	2.01E-03	8.06E-03
Br_2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	8.07E-02	3.23E-01
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	2.18E-01	0.00E+00	0.00E+00
NO	5.01E-03	0.00E+00	0.00E+00
NO_2	3.16E-03	0.00E+00	0.00E+00
SO_2	0.00E+00	0.00E+00	0.00E+00
N_2O	2.01E-04	2.64E-03	1.05E-02
O_3	0.00E+00	0.00E+00	0.00E+00

Table D.13. DRAM manufacturing emissions per wafer, 250 nm node

250nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	8.75E-06	0.00E+00	0.00E+00
MMA	2.01E-04	0.00E+00	0.00E+00
TDMAT	0.00E+00	2.07E-03	8.29E-03
TMS	0.00E+00	0.00E+00	0.00E+00
TEOS	0.00E+00	0.00E+00	0.00E+00
formaldehyde	9.50E-05	9.60E-03	3.84E-02
m-cresol	6.02E-06	6.08E-03	2.43E-02
p-cresol	5.97E-06	6.03E-03	2.41E-02
PGMEA	1.12E-02	7.76E-02	3.11E-01
n-methyl-$_2$-pyrollidone	0.00E+00	4.23E-03	1.69E-02
PGME	8.18E-03	1.02E-01	4.07E-01
ethyl lactate	9.54E-03	9.74E-02	3.89E-01
TMAH	1.05E-04	1.05E-02	4.20E-02
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH_4	4.32E-04	6.16E-03	2.47E-02
H_2	7.13E-03	8.59E-02	3.44E-01
DCS	0.00E+00	0.00E+00	0.00E+00
B_2H_6	0.00E+00	0.00E+00	0.00E+00
C_4F_8	1.28E-04	0.00E+00	0.00E+00
GeH_4	0.00E+00	0.00E+00	0.00E+00
C_2H_2			
OTHER CHEMICALS			
Ar	5.34E+00	2.67E+00	1.07E+01
N_2	1.33E+00	7.43E-01	2.97E+00
He	3.07E-03	1.53E-03	6.14E-03
O_2	4.42E-02	9.05E-01	3.62E+00
IPA	2.18E-02	2.08E+00	8.31E+00
NH_3	3.07E-03	1.53E-03	6.14E-03
Ti	7.76E-08	4.31E-08	1.72E-07
Cu	1.07E-07	1.28E-04	5.13E-04
Sn	4.06E-04	2.26E-04	9.03E-04

Table D.14. DRAM manufacturing emissions per wafer, 250 nm node

180 nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF_4	5.20E-04	4.69E-03	1.87E-02
CHF_3	4.60E-05	4.80E-04	1.92E-03
C_2F_6	0.00E+00	0.00E+00	0.00E+00
CH_4	1.46E-04	1.18E-01	4.73E-01
CO_2	6.51E-01	0.00E+00	0.00E+00
NF_3	3.77E-04	8.74E-02	3.50E-01
C_4F_6	0.00E+00	0.00E+00	0.00E+00
N_2O	0.00E+00	0.00E+00	0.00E+00
HAZARDOUS			
F_2	2.98E-03	0.00E+00	0.00E+00
HF (gas)	2.52E-03	0.00E+00	0.00E+00
SiF_4	4.03E-05	3.07E-03	1.23E-02
C_4F_8	1.23E-06	6.78E-04	2.71E-03
C_2F_4	1.45E-05	0.00E+00	0.00E+00
COF_2	4.12E-06	0.00E+00	0.00E+00
HCl (gas)	3.97E-07	0.00E+00	0.00E+00
Cl_2	1.37E-04	1.82E-03	7.26E-03
$SiCl_4$	2.73E-06	0.00E+00	0.00E+00
PH_3	0.00E+00	4.57E-04	1.83E-03
BTBAS	0.00E+00	0.00E+00	0.00E+00
AsH_3	0.00E+00	0.00E+00	0.00E+00
BCl_3	5.57E-05	1.94E-03	7.77E-03
Pb	1.20E-04	5.98E-04	2.39E-03
WF_6	8.20E-03	3.10E-02	1.24E-01
HBr	0.00E+00	2.01E-03	8.06E-03
Br_2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	8.07E-02	3.23E-01
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	2.18E-01	0.00E+00	0.00E+00
NO	5.01E-03	0.00E+00	0.00E+00
NO_2	3.16E-03	0.00E+00	0.00E+00
SO_2	0.00E+00	0.00E+00	0.00E+00
N_2O	2.01E-04	2.64E-03	1.05E-02
O_3	0.00E+00	0.00E+00	0.00E+00

Table D.15. DRAM manufacturing emissions per wafer, 180 nm node

180 nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	8.75E-06	0.00E+00	0.00E+00
MMA	2.01E-04	0.00E+00	0.00E+00
TDMAT	0.00E+00	2.07E-03	8.29E-03
TMS	0.00E+00	0.00E+00	0.00E+00
TEOS	0.00E+00	0.00E+00	0.00E+00
formaldehyde	9.50E-05	9.60E-03	3.84E-02
m-cresol	6.02E-06	6.08E-03	2.43E-02
p-cresol	5.97E-06	6.03E-03	2.41E-02
PGMEA	1.12E-02	7.76E-02	3.11E-01
n-methyl-$_2$-pyrollidone	0.00E+00	4.23E-03	1.69E-02
PGME	8.18E-03	1.02E-01	4.07E-01
ethyl lactate	9.54E-03	9.74E-02	3.89E-01
TMAH	1.05E-04	1.05E-02	4.20E-02
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH_4	4.32E-04	6.16E-03	2.47E-02
H_2	7.13E-03	8.59E-02	3.44E-01
DCS	0.00E+00	0.00E+00	0.00E+00
B_2H_6	0.00E+00	0.00E+00	0.00E+00
C_4F_8	1.28E-04	0.00E+00	0.00E+00
GeH_4	0.00E+00	0.00E+00	0.00E+00
C_2H_2			
OTHER CHEMICALS			
Ar	5.34E+00	2.67E+00	1.07E+01
N_2	1.33E+00	7.43E-01	2.97E+00
He	3.07E-03	1.53E-03	6.14E-03
O_2	4.42E-02	9.05E-01	3.62E+00
IPA	2.18E-02	2.08E+00	8.31E+00
NH_3	3.07E-03	1.53E-03	6.14E-03
Ti	7.76E-08	4.31E-08	1.72E-07
Cu	1.07E-07	9.36E-05	3.75E-04

Table D.16. DRAM manufacturing emissions per wafer, 180 nm node

130 nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF_4	2.28E-04	1.03E-03	4.13E-03
CHF_3	3.43E-06	5.13E-04	2.05E-03
C_2F_6	4.82E-07	0.00E+00	0.00E+00
CH_4	2.53E-04	1.29E-01	5.18E-01
CO_2	7.12E-01	0.00E+00	0.00E+00
NF_3	4.97E-04	1.15E-01	4.61E-01
C_4F_6	5.66E-06	3.61E-05	1.45E-04
N_2O	0.00E+00	0.00E+00	0.00E+00
HAZARDOUS			
F_2	3.69E-03	0.00E+00	0.00E+00
HF (gas)	1.02E-03	0.00E+00	0.00E+00
SiF_4	4.01E-05	4.05E-03	1.62E-02
C_4F_8	2.11E-06	8.95E-04	3.58E-03
C_2F_4	1.92E-05	0.00E+00	0.00E+00
COF_2	5.73E-06	0.00E+00	0.00E+00
HCl (gas)	0.00E+00	0.00E+00	0.00E+00
Cl_2	1.24E-05	5.71E-04	2.28E-03
$SiCl_4$	0.00E+00	0.00E+00	0.00E+00
PH_3	0.00E+00	6.02E-04	2.41E-03
BTBAS	0.00E+00	0.00E+00	0.00E+00
AsH_3	0.00E+00	0.00E+00	0.00E+00
BCl_3	0.00E+00	0.00E+00	0.00E+00
Pb	4.56E-03	2.53E-03	1.01E-02
WF_6	1.08E-02	4.09E-02	1.64E-01
HBr	0.00E+00	2.66E-03	1.06E-02
Br_2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	1.16E-01	4.63E-01
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	4.32E-03	0.00E+00	0.00E+00
NO	4.08E-03	0.00E+00	0.00E+00
NO_2	7.90E-04	0.00E+00	0.00E+00
SO_2	0.00E+00	0.00E+00	0.00E+00
N_2O	2.65E-04	3.48E-03	1.39E-02
O_3	0.00E+00	0.00E+00	0.00E+00

Table D.17. DRAM manufacturing emissions per wafer, 130 nm node

130 nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	1.15E-05	0.00E+00	0.00E+00
MMA	2.66E-04	0.00E+00	0.00E+00
TDMAT	0.00E+00	2.73E-03	1.09E-02
TMS	0.00E+00	0.00E+00	0.00E+00
TEOS	0.00E+00	0.00E+00	0.00E+00
formaldehyde	1.36E-04	1.38E-02	5.50E-02
m-cresol	8.64E-06	8.73E-03	3.49E-02
p-cresol	8.55E-06	8.64E-03	3.46E-02
PGMEA	1.60E-02	1.11E-01	4.45E-01
n-methyl-$_2$-pyrollidone	0.00E+00	5.58E-03	2.23E-02
PGME	1.17E-02	1.46E-01	5.84E-01
ethyl lactate	1.37E-02	1.40E-01	5.58E-01
TMAH	1.51E-04	1.51E-02	6.02E-02
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH_4	5.70E-04	8.13E-03	3.25E-02
H_2	9.41E-03	1.13E-01	4.53E-01
DCS	0.00E+00	0.00E+00	0.00E+00
B_2H_6	0.00E+00	0.00E+00	0.00E+00
C_4F_8	3.75E-04	1.88E-04	7.50E-04
GeH_4	0.00E+00	0.00E+00	0.00E+00
C_2H_2			
OTHER CHEMICALS			
Ar	7.05E+00	3.53E+00	1.41E+01
N_2	1.75E+00	9.80E-01	3.92E+00
He	4.05E-03	2.02E-03	8.09E-03
O_2	5.83E-02	1.14E+00	4.56E+00
IPA	3.12E-02	3.13E+00	1.25E+01
NH_3	4.05E-03	2.02E-03	8.09E-03
Ti	1.02E-07	5.69E-08	2.28E-07
Cu	1.41E-07	3.98E-04	1.59E-03
Sn	1.26E-03	7.00E-04	2.80E-03

Table D.18. DRAM manufacturing emissions per wafer, 130 nm node

90nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF_4	2.00E-04	3.19E-03	1.28E-02
CHF_3	1.02E-05	1.75E-03	7.01E-03
C_2F_6	0.00E+00	0.00E+00	0.00E+00
CH_4	2.27E-04	2.45E-01	9.78E-01
CO_2	1.35E+00	0.00E+00	0.00E+00
NF_3	4.32E-04	1.04E-01	4.18E-01
C_4F_6	0.00E+00	0.00E+00	0.00E+00
N_2O	0.00E+00	0.00E+00	0.00E+00
HAZARDOUS			
F_2	4.97E-03	0.00E+00	0.00E+00
HF (gas)	8.02E-04	0.00E+00	0.00E+00
SiF_4	5.78E-05	2.90E-03	1.16E-02
C_4F_8	1.63E-06	8.95E-04	3.58E-03
C_2F_4	1.92E-05	0.00E+00	0.00E+00
COF_2	5.05E-05	0.00E+00	0.00E+00
HCl (gas)	0.00E+00	0.00E+00	0.00E+00
Cl_2	2.49E-05	1.14E-03	4.57E-03
$SiCl_4$	0.00E+00	0.00E+00	0.00E+00
PH_3	0.00E+00	9.04E-04	3.61E-03
BTBAS	0.00E+00	0.00E+00	0.00E+00
AsH_3	0.00E+00	0.00E+00	0.00E+00
BCl_3	0.00E+00	0.00E+00	0.00E+00
Pb	4.56E-03	2.53E-03	1.01E-02
WF_6	6.49E-03	2.45E-02	9.81E-02
HBr	0.00E+00	5.32E-03	2.13E-02
Br_2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	1.43E-01	5.74E-01
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	2.38E-02	0.00E+00	0.00E+00
NO	3.52E-03	0.00E+00	0.00E+00
NO_2	8.10E-04	0.00E+00	0.00E+00
SO_2	0.00E+00	0.00E+00	0.00E+00
N_2O	5.30E-04	6.96E-03	2.78E-02
O_3	0.00E+00	0.00E+00	0.00E+00

Table D.19. DRAM manufacturing emissions per wafer, 90 nm node

90nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	1.28E-06	0.00E+00	0.00E+00
MMA	2.95E-05	0.00E+00	0.00E+00
TDMAT	0.00E+00	3.04E-04	1.21E-03
TMS	1.96E-03	1.10E-03	4.40E-03
TEOS	1.37E-03	6.98E-04	2.79E-03
formaldehyde	1.58E-04	1.67E-02	6.66E-02
m-cresol	1.00E-05	1.90E-02	7.61E-02
p-cresol	9.92E-06	1.00E-02	4.01E-02
PGMEA	1.86E-02	1.41E-01	5.63E-01
n-methyl-$_2$-pyrollidone	0.00E+00	1.68E-02	6.70E-02
PGME	1.35E-02	1.71E-01	6.83E-01
ethyl lactate	1.59E-02	1.62E-01	6.48E-01
TMAH	1.75E-04	1.75E-02	6.99E-02
TDEAH	0.00E+00	2.84E-05	1.13E-04
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH_4	4.51E-04	1.05E-02	4.19E-02
H_2	5.65E-03	6.75E-02	2.70E-01
DCS	0.00E+00	0.00E+00	0.00E+00
B_2H_6	0.00E+00	0.00E+00	0.00E+00
C_4F_8	1.20E-05	0.00E+00	0.00E+00
GeH_4	0.00E+00	0.00E+00	0.00E+00
C_2H_2			
OTHER CHEMICALS			
Ar	5.60E+00	2.81E+00	1.12E+01
N_2	2.69E-01	1.67E-01	6.68E-01
He	4.50E-04	2.25E-04	8.99E-04
O_2	7.39E-02	9.89E-01	3.95E+00
IPA	3.61E-02	0.00E+00	0.00E+00
NH_3	4.50E-04	2.25E-04	8.99E-04
Ti	1.02E-07	5.69E-08	2.28E-07
Cu	1.41E-07	3.98E-04	1.59E-03
Sn	1.26E-03	7.00E-04	2.80E-03

Table D.20. DRAM manufacturing emissions per wafer, 90 nm node

70 nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF_4	1.89E-03	9.44E-04	3.78E-03
CHF_3	1.15E-05	5.73E-06	2.29E-05
C_2F_6	1.18E-05	5.91E-06	2.36E-05
CH_4	4.92E-03	2.46E-03	9.83E-03
CO_2	1.61E+00	8.06E-01	3.22E+00
NF_3	4.06E-04	2.03E-04	8.13E-04
C_4F_6	4.27E-05	2.14E-05	8.55E-05
N_2O	2.50E-04	1.25E-04	5.00E-04
HAZARDOUS			
F_2	1.08E-03	5.38E-04	2.15E-03
HF (gas)	3.48E-02	1.74E-02	6.96E-02
SiF_4	9.73E-05	4.86E-05	1.95E-04
C_4F_8	4.32E-06	2.16E-06	8.64E-06
C_2F_4	8.05E-06	4.02E-06	1.61E-05
COF_2	1.33E-05	6.64E-06	2.66E-05
HCl (gas)	0.00E+00	0.00E+00	0.00E+00
Cl_2	2.35E-05	1.17E-05	4.69E-05
$SiCl_4$	0.00E+00	0.00E+00	0.00E+00
PH_3	0.00E+00	0.00E+00	0.00E+00
BTBAS	4.78E-06	2.39E-06	9.57E-06
AsH_3	0.00E+00	0.00E+00	0.00E+00
BCl_3	0.00E+00	0.00E+00	0.00E+00
Pb	0.00E+00	0.00E+00	0.00E+00
WF_6	2.04E-03	1.02E-03	4.08E-03
HBr	0.00E+00	0.00E+00	0.00E+00
Br_2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	0.00E+00	0.00E+00
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	6.00E-01	3.00E-01	1.20E+00
NO	6.78E-03	3.39E-03	1.36E-02
NO_2	6.46E-03	3.23E-03	1.29E-02
SO_2	0.00E+00	0.00E+00	0.00E+00
N_2O	2.50E-04	1.25E-04	5.00E-04
O_3	0.00E+00	0.00E+00	0.00E+00

Table D.21. DRAM manufacturing emissions per wafer, 70 nm node

70 nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	1.21E-06	6.05E-07	2.42E-06
MMA	2.78E-05	1.39E-05	5.57E-05
TDMAT	0.00E+00	0.00E+00	0.00E+00
TMS	2.05E-06	1.02E-06	4.09E-06
TEOS	1.88E-07	9.38E-08	3.75E-07
formaldehyde	1.44E-04	7.20E-05	2.88E-04
m-cresol	9.13E-06	4.56E-06	1.83E-05
p-cresol	9.04E-06	4.52E-06	1.81E-05
PGMEA	1.69E-02	8.47E-03	3.39E-02
n-methyl-$_2$-pyrollidone	0.00E+00	0.00E+00	0.00E+00
PGME	1.23E-02	6.14E-03	2.46E-02
ethyl lactate	1.45E-02	7.23E-03	2.89E-02
TMAH	1.59E-04	7.95E-05	3.18E-04
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH_4	4.17E-04	2.09E-04	8.34E-04
H_2	3.24E-03	1.62E-03	6.49E-03
DCS	0.00E+00	0.00E+00	0.00E+00
B_2H_6	0.00E+00	0.00E+00	0.00E+00
C_4F_8	3.18E-04	1.59E-04	6.36E-04
GeH_4	0.00E+00	0.00E+00	0.00E+00
C_2H_2			
OTHER CHEMICALS			
Ar	1.77E+00	8.85E-01	3.54E+00
N_2	1.25E+00	6.25E-01	2.50E+00
He	1.35E-01	6.75E-02	2.70E-01
O_2	4.51E-02	2.26E-02	9.03E-02
IPA	3.31E-02	1.65E-02	6.61E-02
NH_3	1.35E-01	6.75E-02	2.70E-01
Ti	0.00E+00	0.00E+00	0.00E+00
Cu	0.00E+00	0.00E+00	0.00E+00
Sn	0.00E+00	0.00E+00	0.00E+00

Table D.22. DRAM manufacturing emissions per wafer, 70 nm node

57 nm	Emissions to Air		
kg/wafer	expected value	low	high
GWG			
CF_4	8.44E-04	4.22E-04	1.69E-03
CHF_3	9.87E-06	4.93E-06	1.97E-05
C_2F_6	0.00E+00	0.00E+00	0.00E+00
CH_4	2.95E-04	1.48E-04	5.91E-04
CO_2	1.78E+00	8.92E-01	3.57E+00
NF_3	4.95E-04	2.47E-04	9.89E-04
C_4F_6	0.00E+00	0.00E+00	0.00E+00
N_2O	0.00E+00	0.00E+00	0.00E+00
HAZARDOUS			
F_2	5.23E-03	2.61E-03	1.05E-02
HF (gas)	1.52E-03	7.61E-04	3.04E-03
SiF_4	6.55E-05	3.28E-05	1.31E-04
C_4F_8	1.19E-06	5.97E-07	2.39E-06
C_2F_4	1.41E-05	7.04E-06	2.82E-05
COF_2	5.17E-05	2.59E-05	1.03E-04
HCl (gas)	0.00E+00	0.00E+00	0.00E+00
Cl_2	4.10E-05	2.05E-05	8.21E-05
$SiCl_4$	0.00E+00	0.00E+00	0.00E+00
PH_3	2.49E-07	1.24E-07	4.97E-07
BTBAS	0.00E+00	0.00E+00	0.00E+00
AsH_3	3.11E-08	1.55E-08	6.21E-08
BCl_3	0.00E+00	0.00E+00	0.00E+00
Pb	0.00E+00	0.00E+00	0.00E+00
WF_6	1.02E-02	5.10E-03	2.04E-02
HBr	0.00E+00	0.00E+00	0.00E+00
Br_2	0.00E+00	0.00E+00	0.00E+00
HMDS	0.00E+00	0.00E+00	0.00E+00
OMCTS	0.00E+00	0.00E+00	0.00E+00
CRITERIA			
CO	3.85E-01	1.92E-01	7.69E-01
NO	9.16E-03	4.58E-03	1.83E-02
NO_2	4.82E-03	2.41E-03	9.64E-03
SO_2	0.00E+00	0.00E+00	0.00E+00
N_2O	5.00E-04	2.50E-04	1.00E-03
O_3	0.00E+00	0.00E+00	0.00E+00

Table D.23. DRAM manufacturing emissions per wafer, 57 nm node

57 nm	Emissions to Air		
kg/wafer	expected value	low	high
VOC			
DMA	2.42E-06	1.21E-06	4.84E-06
MMA	5.57E-05	2.78E-05	1.11E-04
TDMAT	0.00E+00	0.00E+00	0.00E+00
TMS	1.85E-03	9.25E-04	3.70E-03
TEOS	1.29E-03	6.45E-04	2.58E-03
formaldehyde	1.59E-04	7.97E-05	3.19E-04
m-cresol	1.01E-05	5.05E-06	2.02E-05
p-cresol	1.00E-05	5.00E-06	2.00E-05
PGMEA	1.87E-02	9.37E-03	3.75E-02
n-methyl-$_2$-pyrollidone	0.00E+00	0.00E+00	0.00E+00
PGME	1.35E-02	6.77E-03	2.71E-02
ethyl lactate	1.60E-02	8.00E-03	3.20E-02
TMAH	1.76E-04	8.81E-05	3.52E-04
TDEAH	0.00E+00	0.00E+00	0.00E+00
TDMAS	0.00E+00	0.00E+00	0.00E+00
DEA	0.00E+00	0.00E+00	0.00E+00
PDMAT	0.00E+00	0.00E+00	0.00E+00
FLAMMABLE			
SiH_4	1.22E-03	6.11E-04	2.45E-03
H_2	9.83E-03	4.92E-03	1.97E-02
DCS	0.00E+00	0.00E+00	0.00E+00
B_2H_6	0.00E+00	0.00E+00	0.00E+00
C_4F_8	2.27E-04	1.14E-04	4.55E-04
GeH_4	0.00E+00	0.00E+00	0.00E+00
C_2H_2			
OTHER CHEMICALS			
Ar	1.44E+00	7.22E-01	2.89E+00
N_2	4.55E-01	2.27E-01	9.09E-01
He	8.48E-04	4.24E-04	1.70E-03
O_2	8.47E-02	4.23E-02	1.69E-01
IPA	3.65E-02	1.83E-02	7.30E-02
NH_3	8.48E-04	4.24E-04	1.70E-03
Ti	9.66E-08	4.83E-08	1.93E-07
Cu	6.66E-05	3.33E-05	1.33E-04
Sn	5.54E-03	2.77E-03	1.11E-02

Table D.24. DRAM manufacturing emissions per wafer, 57 nm node

D.3 DRAM LCA: Tabulated results with uncertainty

	Photochemical Smog kg NO_x			Acidification mol H^+			Ecotoxicity kg 2,4-D		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	0.33	N/A	N/A	10.7	N/A	N/A	0.00	N/A	N/A
Electricity (Si, fab. and use)	0.64	0.63	0.64	37	36	37	3.1	3.10	3.15
Fab. direct emissions	0.086	0.043	0.17	34	17	69	4.9E-02	2.5E-02	9.6E-02
Infrastructure	0.73	0.37	1.10	38	19.2	57	4.7E-03	2.4E-03	7.1E-03
Total	1.79	1.37	2.25	120	83	174	3.18	3.13	3.26

Table D.25. DRAM life cycle impacts per wafer, 57 nm node

	Human Health Cancer kg C_6H_6			Human Health Criteria total DALYs			Health Noncancer kg C_7H_7		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	0.00	N/A	N/A	0.00	N/A	N/A	0.07	N/A	N/A
Electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	7.99E-03	7.95E-03	8.04E-03	251	249	253
Fab. direct emissions	1.01E-02	8.88E-03	1.14E-02	4.00E-05	2.00E-05	8.00E-05	885	776	996
Infrastructure	6.95E-03	3.48E-03	1.04E-02	1.30E-02	6.52E-03	1.96E-02	295	147	442
Total	0.017	0.012	0.022	0.022	0.0151	0.0283	1,431	1,173	1,691

	Eutrophication, to air kg N			Eutrophication, to water kg N		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	1.18E-02	N/A	N/A	N/A	N/A	N/A
Electricity (Si, fab. and use)	2.27E-02	2.25E-02	2.30E-02	N/A	N/A	N/A
Fab. direct emissions	7.90E-04	3.95E-04	1.58E-03	5.11	2.61	10.11
Infrastructure	0.025	0.012	0.037	N/A	N/A	N/A
Total	0.060	0.047	0.074	5.1	2.6	10.1

Table D.26. DRAM life cycle impacts per wafer, 57 nm node

	Photochemical Smog kg NO_x			Acidification mol H^+			Ecotoxicity kg 2,4-D		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	0.23	N/A	N/A	7.5	N/A	N/A	0.00	N/A	N/A
Electricity (Si, fab. and use)	0.49	0.48	0.49	28	28	28	2.4	2.37	2.42
Fab. direct emissions	0.064	0.032	0.13	18	9.0	36	3.3E-02	1.7E-02	6.5E-02
Infrastructure	0.61	0.31	0.92	32	16.1	48	3.9E-03	2.0E-03	5.9E-03
Total	1.40	1.05	1.78	85	60	120	2.43	2.39	2.5

Table D.27. DRAM life cycle impacts per wafer, 70 nm node

	Human Health Cancer			Human Health Criteria			Health Noncancer		
	kg C_6H_6			total DALYs			kg C_7H_7		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	0.00	N/A	N/A	0.00	N/A	N/A	0.05	N/A	N/A
Electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	5.95E-03	2.77E-03	-3.40E-03	192	190	194
Fab. direct emissions	9.18E-03	8.07E-03	1.03E-02	2.24E-05	1.12E-05	4.47E-05	815	715	915
Infrastructure	5.83E-03	2.91E-03	8.74E-03	1.09E-02	5.47E-03	1.64E-02	247	124	371
Total	0.015	0.011	0.019	0.017	0.0087	0.0135	1,254	1,029	1,480

	Eutrophication, to air			Eutrophication, to water		
	kg N			kg N		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	8.24E-03	N/A	N/A			
Electricity (Si, fab. and use)	1.74E-02	1.71E-02	1.77E-02	N/A	N/A	N/A
Fab. direct emissions	4.60E-04	2.30E-04	9.21E-04	4.68	2.38	9.25
Infrastructure	0.021	0.010	0.031	N/A	N/A	N/A
Total	0.047	0.036	0.058	4.7	2.4	9.2

Table D.28. DRAM life cycle impacts per wafer, 70 nm node

	Photochemical Smog			Acidification			Ecotoxicity		
	kg NO_x			mol H^+			kg 2,4-D		
	Expected value	Lower bound	Upper bound	expected value	Lower bound	Upper bound	expected value	Lower bound	Upper bound
Transportation	0.27	N/A	N/A	8.7	N/A	N/A	0.00	N/A	N/A
Electricity (Si, fab. and use)	0.51	0.50	0.51	29	29	29	2.5	2.47	2.52
Fab. direct emissions	0.072	0.036	0.14	31	16	63	2.2E-02	1.2E-02	4.2E-02
Infrastructure	0.52	0.26	0.77	27	13.5	40	3.3E-03	1.7E-03	5.0E-03
Total	1.37	1.06	1.70	96	67	141	2.52	2.48	2.6

Table D.29. DRAM life cycle impacts per wafer, 90 nm node

	Human Health Cancer kg C_6H_6 expected value	Lower bound	Upper bound	Human Health Criteria total DALYs Expected value	Lower bound	Upper bound	Health Noncancer kg C_7H_7 Expected value	Lower bound	Upper bound
Transportation	0.00	N/A	N/A	0.00	N/A	N/A	0.06	N/A	N/A
Electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	6.41E-03	3.74E-03	-1.43E-03	200	198	202
Fab. direct emissions	4.01E-02	2.84E-02	6.07E-02	2.69E-05	1.34E-05	5.37E-05	2,103	1,560	2,952
Infrastructure	4.89E-03	2.44E-03	7.33E-03	9.17E-03	4.58E-03	1.38E-02	207	104	311
Total	0.045	0.031	0.068	0.016	0.0088	0.0129	2,510	1,862	3,465

	Eutrophication, to air kg N Expected value	Lower bound	Upper bound	Eutrophication, to water kg N Expected value	Lower bound	Upper bound
Transportation	9.57E-03	N/A	N/A			
Electricity (Si, fab. and use)	1.81E-02	1.79E-02	1.84E-02	N/A	N/A	N/A
Fab. direct emissions	5.44E-04	2.72E-04	1.09E-03	4.67	2.38	9.23
Infrastructure	0.018	0.009	0.026	N/A	N/A	N/A
Total	0.046	0.036	0.055	4.7	2.4	9.2

Table D.30. DRAM life cycle impacts per wafer, 90 nm node

	Photochemical Smog kg NO$_x$			Acidification mol H$^+$			Ecotoxicity kg 2,4-D		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	0.17	N/A	N/A	5.4	N/A	N/A	0.00	N/A	N/A
Electricity (Si, fab. and use)	0.36	0.35	0.36	20	20	21	1.8	1.73	1.78
Fab. direct emissions	0.072	0.036	0.14	38	19	75	1.4E-02	7.7E-03	2.6E-02
Infrastructure	0.40	0.20	0.59	21	10.3	31	2.5E-03	1.3E-03	3.8E-03
Total	0.99	0.75	1.27	84	55	132	1.77	1.74	1.8

Table D.31. DRAM life cycle impacts per wafer, 130 nm node

	Human Health Cancer			Human Health Criteria			Health Noncancer		
	kg C_6H_6			total DALYs			kg C_7H_7		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	0.00	N/A	N/A	0.00	N/A	N/A	0.04	N/A	N/A
Electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	4.36E-03	2.30E-03	-1.65E-03	141	139	142
Fab. direct emissions	2.12E-02	1.46E-02	3.31E-02	3.20E-05	1.60E-05	6.41E-05	1,347	1,014	1,863
Infrastructure	3.75E-03	1.88E-03	5.63E-03	7.04E-03	3.52E-03	1.06E-02	159	80	239
Total	0.025	0.017	0.039	0.012	0.0061	0.0093	1,647	1,232	2,244

	Eutrophication, to air			Eutrophication, to water		
	kg N			kg N		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	6.03E-03	N/A	N/A			
Electricity (Si, fab. and use)	1.27E-02	1.25E-02	1.30E-02	N/A	N/A	N/A
Fab. direct emissions	6.37E-04	3.19E-04	1.27E-03	3.87	1.95	7.70
Infrastructure	0.013	0.007	0.020	N/A	N/A	N/A
Total	0.033	0.026	0.040	3.9	1.9	7.7

Table D.32. DRAM life cycle impacts per wafer, 130 nm node

	Photochemical Smog kg NO_x Expected value	Lower bound	Upper bound	Acidification mol H^+ Expected value	Lower bound	Upper bound	Ecotoxicity kg 2,4-D Expected value	Lower bound	Upper bound
Transportation	0.07	N/A	N/A	2.4	N/A	N/A	0.00	N/A	N/A
Electricity (Si, fab. and use)	0.83	0.83	0.83	48	47	48	4.1	4.06	4.09
Fab. direct emissions	0.051	0.025	0.10	27	14	54	6.1E-03	3.6E-03	1.1E-02
Infrastructure	0.30	0.15	0.45	16	7.8	24	2.0E-03	1.0E-03	3.0E-03
Total	1.25	1.08	1.46	93	71	128	4.08	4.06	4.1

Table D.33. DRAM life cycle impacts per wafer, 180 nm node

	Human Health Cancer kg C_6H_6			Human Health Criteria total DALYs			Health Noncancer kg C_7H_7		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	0.00	N/A	N/A	0.00	N/A	N/A	0.02	N/A	N/A
Electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	7.74E-03	6.19E-03	3.19E-03	327	326	328
Fab. direct emissions	1.27E-02	9.57E-03	1.80E-02	2.34E-05	1.17E-05	4.67E-05	718	563	948
Infrastructure	2.97E-03	1.48E-03	4.45E-03	5.33E-03	2.66E-03	7.99E-03	126	63	189
Total	0.016	0.011	0.022	0.013	0.009	0.011	1,171	952	1,465

	Eutrophication, to air kg N			Eutrophication, to water kg N		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	2.63E-03	N/A	N/A	N/A	N/A	N/A
Electricity (Si, fab. and use)	2.96E-02	2.95E-02	2.97E-02	N/A	N/A	N/A
Fab. direct emissions	4.67E-04	2.33E-04	9.34E-04	2.76	1.41	5.45
Infrastructure	0.010	0.005	0.015	N/A	N/A	N/A
Total	0.043	0.037	0.049	2.8	1.4	5.5

Table D.34. DRAM life cycle impacts per wafer, 180 nm node

	Photochemical Smog kg NO_x Expected value	Lower bound	Upper bound	Acidification mol H^+ Expected value	Lower bound	Upper bound	Ecotoxicity kg 2,4-D Expected value	Lower bound	Upper bound
Transportation	0.10	N/A	N/A	3.0	N/A	N/A	0.00	N/A	N/A
Electricity (Si, fab. and use)	1.02	1.01	1.02	58	58	59	5.0	4.99	5.02
Fab. direct emissions	0.051	0.025	0.10	27	14	54	7.9E-03	4.5E-03	1.5E-02
Infrastructure	0.26	0.13	0.39	14	6.8	21	1.7E-03	8.4E-04	2.5E-03
Total	1.43	1.27	1.61	102	82	137	5.01	4.99	5.03

Table D.35. DRAM life cycle impacts per wafer, 250 nm node

	Human Health Cancer kg C_6H_6			Human Health Criteria total DALYs			Health Noncancer kg C_7H_7		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	0.00	N/A	N/A	0.00	N/A	N/A	0.02	N/A	N/A
Electricity (Si, fab. and use)	0.00E+00	0.00E+00	0.00E+00	9.53E-03	8.16E-03	5.55E-03	401	400	402
Fab. direct emissions	1.54E-02	1.13E-02	2.23E-02	2.34E-05	1.17E-05	4.67E-05	832	638	1,126
Infrastructure	2.48E-03	1.24E-03	3.72E-03	4.66E-03	2.33E-03	6.99E-03	105	53	158
Total	0.018	0.013	0.026	0.014	0.011	0.013	1,338	1,090	1,687

	Eutrophication, to air kg N			Eutrophication, to water kg N		
	Expected value	Lower bound	Upper bound	Expected value	Lower bound	Upper bound
Transportation	3.37E-03	N/A	N/A	N/A	N/A	N/A
Electricity (Si, fab. and use)	3.63E-02	3.62E-02	3.65E-02	N/A	N/A	N/A
Fab. direct emissions	4.67E-04	2.33E-04	9.34E-04	2.76	1.41	5.45
Infrastructure	0.009	0.004	0.013	N/A	N/A	N/A
Total	0.049	0.044	0.054	2.8	1.4	5.5

Table D.36. DRAM life cycle impacts per wafer, 250 nm node