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Sarah Boyd, Arpad Horvath, and David Dornfeld

Abstract—**Solid state drives (SSDs) show potential for environmental benefits over magnetic data storage due to their lower power consumption. To investigate this possibility, a life-cycle assessment (LCA) of NAND flash over five technology generations (150 nm, 120 nm, 90 nm, 65 nm, and 45 nm) is presented to quantify environmental impacts occurring in flash production and to investigate their trends over time. The inventory of resources and emissions in flash manufacturing, electricity generation and some chemicals are based on process data, while that of fab infrastructure, water and the remaining chemicals are determined using economic input-output life-cycle analysis (EIO-LCA) or hybrid LCA. Over the past decade, impacts have fallen in all impact categories per GB. Sensitivity analysis shows that the most influential factors over the life-cycle global warming potential (GWP) of flash memory are abatement of perfluorinated compounds (PFCs) and reduction of electricity-related emissions in manufacturing. A limited comparison between the life-cycle energy use and GWP of a 100 GB laptop SSD and hard disk drive shows higher impacts for SSD in many use phase scenarios. This comparison is not indicative for all impact categories, however, and is not conclusive due to differences in boundary and functional unit.**

Index Terms—**Environmental factors, Production management, Energy conservation, EPROM**

I. INTRODUCTION

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 (SSDs) 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 SSDs have low power consumption, their manufacture is complex and energy and resource intensive. In this analysis, we present the life-cycle environmental impacts of NAND flash and endeavor to compare the life-cycle impacts of SSD storage with those of HDD.

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 [1], [2]. 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 HDDs. Flash-based SSDs, which are initially being introduced as a high-end option in laptops and data center applications, may also become competitive in standard laptops and desktops 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 SSDs become more common in computer storage, the life-cycle environmental impacts are of particular interest.

Previous studies of the environmental impacts of producing computer memory include two conference papers in 2001. One describes a life-cycle inventory (LCI) model for a wafer production at a Motorola plant [3]. 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. No absolute impact results were shown by process, rather only the proportional contribution of each process module. Schischke described an equipment-centric inventory method whereby mass and energy flows are accounted for in modules specific to process types and facility infrastructure. This model structure is also used in the current study. However, the inventory inputs reported by Schischke were collected by questionnaire and outputs are estimated as fractions of the input flows. In the current study, mass and energy flows are based on equipment measurements. The second reported a gate-to-gate life-cycle inventory (LCI) analysis for an 8Mbit ST Microelectronics EPROM chip [4]. The inventory of the masses of materials is reported, however, process and facility emissions were not included. Direct emissions from the fab are an important aspect of the environmental impact of production and are therefore included in this study.

The first peer-reviewed journal article presenting LCA of semiconductor memory was a study by Williams in 2002 which provided an estimate of the energy and materials demands for a 32 MB DRAM chip [5]. The paper provided a list of key material inputs to semiconductor fabrication from an anonymous industry source, compared these estimated process data with previous results and called for more accurate process-level LCI for semiconductor chips. Williams also cross-checked the process-level energy results against economic data, which is a valuable method for verification.

The process flows for DRAM, EPROM and EEPROM memories are relatively similar, making existing studies of DRAM and EPROM useful for comparison. These memory ICs differ more significantly from semiconductor logic. When

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comparing technologies newly entering production in the same year, flash products require fewer process steps and less complex packaging than advanced logic. Results for IC logic thus may not provide a fair representation of impacts of memory products, though LCI and LCA studies of semiconductor logic have also been reported.

II. METHODOLOGY

A. *Goal and Scope*

This study presents a life-cycle assessment (LCA) of flash memory over five generations (150 nm, 120 nm, 90 nm, 65 nm, and 45 nm), representing full-scale production in the years 2000 through 2009. The goal of this study is to examine the changes in impacts per unit of memory capacity over time during the 2000-2009 period. The functional unit is one GB memory worth of NAND flash chip with a use scenario representing a chip in a laptop SSD. The base case lifetime is taken as 8,000 hours of operation (eight hours per day, 250 days per year, for four years), with lifetime limited by the use case. (While the mean time to failure of a NAND flash chip is 100,000 to 1 million erase cycles, the lifetime is assumed to be limited by the obsolescence of the laptop or drive.)

All wafer production 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 than SLC, SLC are used throughout the study for consistency.

The scope of this analysis includes electricity generation, production of process chemicals, fab construction, equipment manufacturing, municipal water delivery, wafer fabrication, transportation, chip assembly, product use and end of life. The type of data source for inventory evaluation at each life-cycle stage is summarized in Fig. 1 and will be explained in detail in the following section.

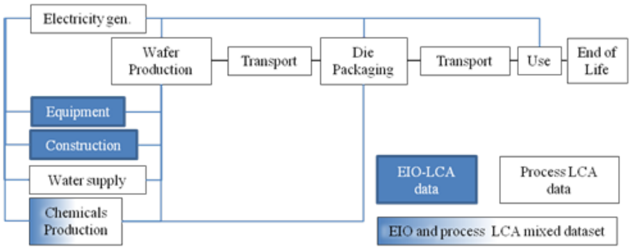


Fig. 1. Life-cycle stages included in the study

Additionally, this study compares life-cycle energy, GWP and water for 100 GB of flash memory produced in 2009 with a comparable memory capacity of hard disc drive (HDD), to test the assumption that SSDs have a lower environmental impact than HDD. In the comparison between the SSD and HDD, a laptop-sized drive composed of 96 GB of 45 nm SLC flash (12 x 8 GB chips) is evaluated against a 100 GB 2.5” laptop HDD.

B. *Inventory evaluation*

Wafer fabrication and assembly take place in Santa Clara, California. The mass of process chemicals consumed and emitted in each wafer fabrication process step was determined using in-line mass measurement [6]. Energy used by wafer processing equipment was established using 3-phase power measurement [6]. Utility demands such as cooling water and utility nitrogen are based on equipment specifications. The mass, energy and utilities inventories of each individual process step are reported in a 2008 paper [6]. These process steps were combined into process flows, summarized in Tab IV, which are specific to each flash technology generation. The sets of process technologies modeled at each generation do not represent those of any single manufacturer. Inventory data for 45 nm node flash wafer fabrication is published online by the author [7]. Die yields are assumed to be 75%, based on an the average used in the ITRS, while line yields are estimated assuming 2% wafer breakage or loss across the entire process flow, and 1 test or monitor per run per ten output wafer passes, based on estimates recommended by an industry member.

Fab utility system capacities and resource demands which are modeled using data from Sematech [8] reflect industry-standard efficiency improvements over the 9 year period under study [9] and are checked against clean-room energy use and efficiency studies reported by Lawrence Berkeley Laboratory [10]. 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) [11]. Energy use in production of chemicals is based on process data from LCA databases, textbooks and patents. Where process data was unavailable, EIO-LCA results are used [11] and, in cases where process data and representative price information were not obtainable, generic values for inorganic and organic chemicals from Overcash are used [12]. The materials used in the chip package are based on the standard composition of a thin small outline package (TSOP), which is a common package for NAND flash, and data for material and chemical inputs to packaging are collected using the same methods as used for process chemicals. Energy consumed in dicing, chip assembly, and testing is 0.34 kWh/cm^2, based on average data from an earlier study [5], [13]. Energy use and emissions due to water supply and product transportation are based on previous hybrid LCA studies [14], [15]. The distance between wafer fabrication and assembly, and between assembly and use, is 3000 miles. Finished wafers are transported 3000 miles by air freight and 50 miles by truck, and finished die are transported 3000 miles by air and 200 miles by truck to the location of use.

Direct emissions from electricity generation are specific to California, based on data from the EPA’s eGrid database [16], with a GWP emissions factor of 290 g $CO_2 eq.$/kWh and primary energy use in electricity generation is taken from International Energy Agency data as 12 MJ/kWh, an average for the U.S. [17]. Water consumed in the generation of electricity is determined using a U.S. average of 1.76 liter/kWh [18]. In this model, water consumed in generation of electricity is included for all life-cycle phases.

For each generation of NAND flash, data per unit memory capacity for the use phase represents power use at the level of the chip, for the flash memory alone. Use phase power at chip level does not include additional system-level power demands which may occur in a solid state drive. Chip-level power for flash is based on manufacturer datasheets [19]–[21].

In the comparison between a SSD and HDD, power values for the drives are used. The SSD idle power is 0.6 W and active (read/write) power is 1.3 W, which is an average of measured values from an independent industry report [22]. The magnetic HDD is has an idle power of 0.9 W and a read/write power of 3.1 W, based on an average from a set of independent tests from the same source [23]. With 30% active, 70% idle operation over a 4-year lifespan of 8,000 hours, the SSD would use 6.4 kWh of electricity and the HDD would consume 12.7 kWh.

At end of life, it is assumed that there is no recoverable value from a discarded flash chip and that in the process of disposal or decomposition the lead contained within the package is released into the environment.

C. *Impact characterization factors*

Global warming potential (GWP) impact factors from the Intergovernmental Panel on Climate Change are used for perfluorinated compounds (PFCs) [24]. Eutrophication, acidification, smog formation, ecotoxicity and human health impacts are evaluated using TRACI mid-point impact metrics, which are specific to the U.S. and California [25].

III. 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 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 as shown in Fig 2. 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 all flash memory 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 necessarily 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 common semiconductor products, particularly CMOS logic [9]. 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 Fig 3 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 Fig 2. 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, CO, NO_x, ethyl lactate and other volatile organics from the fab.

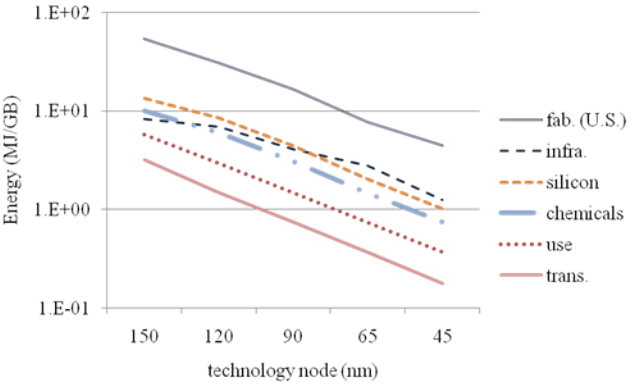


Fig. 2. Primary energy consumption per memory capacity (MJ/GB), over five technology nodes

Human health-related impacts per wafer and device have shown the same stability over the past decade. Fig 4 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

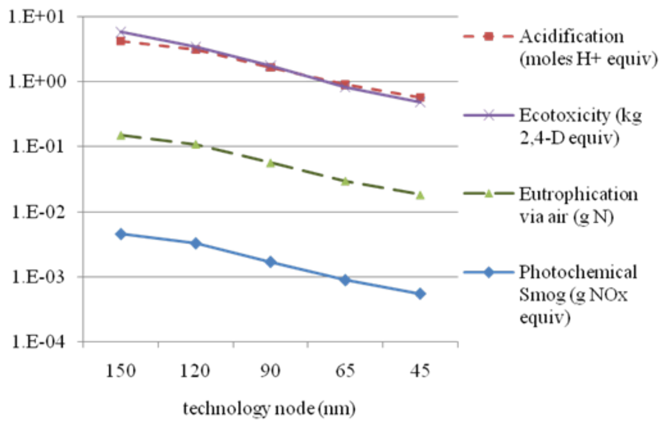
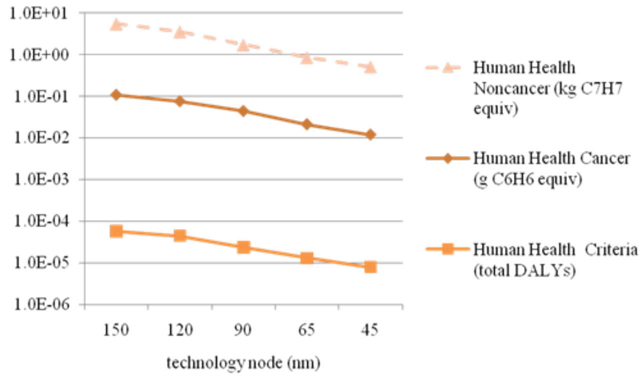


Fig. 3. Environmental impacts due to air emissions per GB, over five technology nodes

emissions of formaldehyde, which represent 72-75% of these impacts, while lead emissions resulting from fab infrastructure cause the remaining fraction. Human health impacts from the U.S. EPA's criteria air emissions are reported in disability-adjusted life years (DALYs), a measure of potential years of healthy life lost as a result of pollution. These impacts result from (in descending order of contribution) particulate matter (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-adjusted life years

Fig. 4. Human health impacts due to air emissions per GB, over five technology nodes

Perfluorinated 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 [26]. In Fig 5, 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 Fig 5. 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 Fig 5.

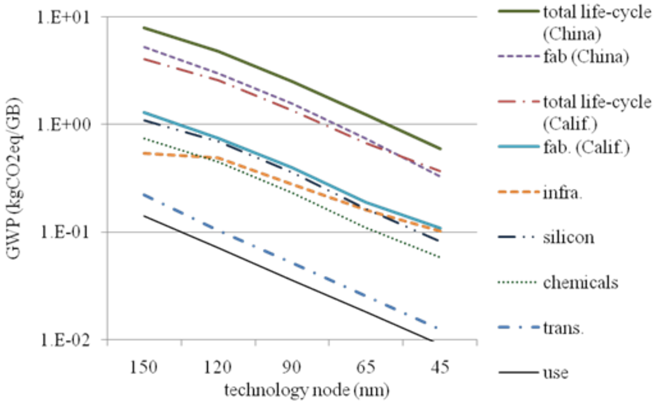


Fig. 5. GWP per GB memory capacity, by life-cycle stage, over five technology nodes

Water consumption is dominated by electricity generation, as shown in Fig 6. 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.)

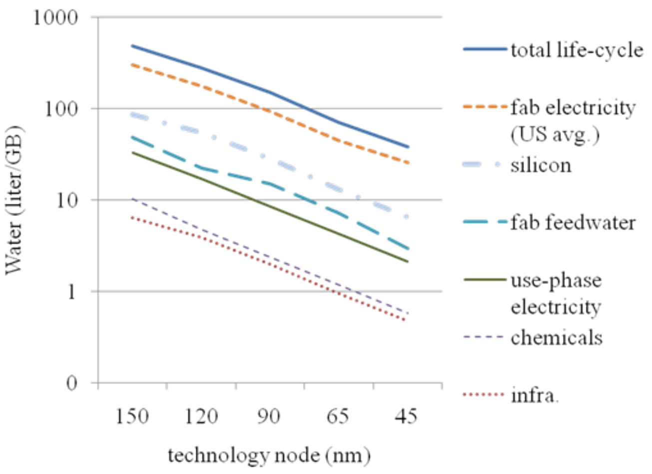


Fig. 6. Water consumption per GB memory capacity, by life-cycle stage, over the five nodes

TABLE I
COMPARISON OF PRIMARY ENERGY USE AND GWP IMPACTS OF SSD VS. HDD

		Primary energy consumption MJ	GWP kg CO_2 eq
96 GB flash laptop SSD	base case	690	28
	lower bound	620	24
	upper bound	790	33
100 GB, 2.5” laptop HDD	base case	262	8.6
	lower bound	217	7.5
	upper bound	357	23

IV. DISCUSSION: SOLID STATE DRIVES VS. HARD DISK DRIVES

Although a LCA of a magnetic HDD with an equivalent scope and boundary has not been reported in the literature, we use available inventory and impact data for HDD production to make a rough comparison between HDD and SDD computer storage. In order to simplify the comparison the same inventory data is used for the housing and printed wiring board of each drive, as provided in the Ecoinvent database. The energy and GWP associated with production of the aluminum platter of the HDD in the base case scenario is also from the Ecoinvent database. Because process chemicals are not included in the Ecoinvent inventory for a laptop HDD, the boundary for the SSD excludes the impacts in production of process chemicals for this comparison.

Primary energy consumption and GWP impacts are shown for the flash SSD and HDD in Table I. The upper bound in both cases reflects the highest drive power demand reported for a 96 GB SSD and 100 GB HDD, as well as a more intensive use phase scenario for a data center drive (a lifetime of 2.5 years, 24-hour operation, 90% uptime, in 30% active, 70% idle operation).

Because the life-cycle inventory for production of the HDD reflects older technology, the most recent environmental report from Western Digital is used as an additional source for comparison. In the 2009 fiscal year, Western Digital produced 146 million drives [27]. The carbon impact of manufacturing operations, including direct emissions of perfluorinated gases (SF6, CF4, etc.) is reported as 0.708 million metric tons $CO_2 eq$. for the same one year period [28]. Because this value represents an average of many types of drives, the value of 4.85 kg $CO_2 eq$. is used as the upper bound for HDD manufacturing.

This comparison indicates that HDD are currently preferable to SSD in terms of energy consumption and GWP. The production of flash memory is highly energy and resource intensive, and also requires the use of larger quantities of PFCs than used in production of the read/write head in HDD. In particular, when PFCs are unabated in production of the SSD flash, the difference between the HDD and SSD expands and the HDD has a considerable advantage over the SSD.

In this comparison, the relatively low emissions factor for electricity in the use phase in California (290 g $CO_2 eq$./kWh) results in a significantly better life-cycle performance by the HDD in terms of energy and GWP. When the use phase emissions factor is higher, the margin narrows between the SSD and HDD results. However, the SSD does not become preferable for even the highest electricity emissions factors when the HDD and SDD are compared in the base case scenario, based on the limited data available for HDD production.

This study is not conclusive when the use scenario is operationally intensive, as in a data center, when the use phase becomes a larger fraction of total energy use. Also, the more rapid read/write performance of the SSD changes the comparability of the HDD and SDD functional units, particularly in a data center application.

A. *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 (Table III in the appendix). Fabrication emissions, because they are all post-abatement mass flows, have a high uncertainty that results from variation in the effective destruction or removal rate of facility abatement systems. An abatement system which operates at a 99% abatement efficiency with a variation of $+/-1\%$ produces a mass flow of an abatement product with an uncertainty range of $+/-100\%$ (varying between 0 and 2% of the input flow).

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 [29]. 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 [30], there is a wide uncertainty range associated with this value.

B. *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 Appendix C.

V. CONCLUSIONS

The results of this LCA 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 locating 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.

While the comparison of life-cycle impacts for 100 GB solid state and magnetic laptop drives cannot be conclusive given a lack of manufacturing inventory data for a comparable HDD functional unit, this study challenges the common assumption that SSDs have a lower environmental impact versus HDDs due to lower use-phase power consumption. The production of flash memory is highly energy and resource intensive, and also requires the use of larger quantities of PFCs than used in production of HDD. Results from this comparison indicate that if PFCs are unabated in production of the NAND flash, the HDD will almost certainly have lower life-cycle GWP impacts than the SSD in any geographic location or operational intensity in the use phase. For a SSD composed of flash which has been produced with controls on PFC emissions, this study cannot provide a definitive conclusion concerning the environmental superiority of either SSD or HDD in operationally intensive use cases, particularly in data center applications. A LCA for a laptop HDD produced in 2009 with a boundary equivalent to the current study which includes all direct emissions and resource demands for manufacturing, as well as the production of process chemicals, would allow a more definitive answer to these questions.

APPENDIX A
SUPPORTING INFORMATION FOR METHODOLOGY AND RESULTS

TABLE II
YIELDS AND CHIP SIZES FOR EACH TECHNOLOGY GENERATION

flash half pitch (nm)	nm	150	120	90	65	45
gross yield	(die/wafer)	557	445	433	469	469
net yield	(die/wafer)	418	334	325	352	352
capacity	GB	0.512	1	2	4	8
die size	mm^2	125	135	141	131	131

TABLE III
45 NM NODE RESULTS, WITH UNCERTAINTY

Resource use per die	Primary energy MJ expected value	lower bound	upper bound	Water liters expected value	lower bound	upper bound
Transport	1.5	N/A	N/A	N/A	N/A	N/A
Electricity (Si, fab., use)	47	45	49	293	282	303
Fab. fuel	0.11	0.10	0.12	N/A	N/A	N/A
Fab. direct water use	0.16	0.15	0.18	24	21	26
Infrastructure	6.65	3.32	9.97	0.54	0.27	0.80
Chemicals	5.95	2.98	8.93	9.4	4.7	14.1
Total	61.3	51.6	67.7	326	308	344
Impacts per die	Photochemical Smog g NO_x expected value	lower bound	upper bound	Acidification mol H^+ expected value	lower bound	upper bound
Transportation	0.62	N/A	N/A	0.64	N/A	N/A
Electricity (Si, fab. and use)	0.75	0.72	0.78	0.49	0.46	0.51
Fab. direct emissions	0.25	0.13	0.51	0.18	0.09	0.37
Infrastructure	2.81	1.41	3.52	3.22	1.61	4.02
Total	4.4	2.9	5.4	4.5	2.8	5.5
	Ecotoxicity g 2,4-D expected value	lower bound	upper bound	Human Health Cancer g C_6H_6 expected value	lower bound	upper bound
Transport	0.00	N/A	N/A	0.00	N/A	N/A
Electricity (Si, fab., use)	3.70	3.62	3.77	0.00	0.00	0.00
Fab. direct emissions	0.16	0.15	0.18	0.06	0.04	0.11
Infrastructure	0.02	0.01	0.03	0.03	0.02	0.04
Total	3.9	3.8	4.0	0.10	0.06	0.15
	Human Health Criteria total DALYs expected value	lower bound	upper bound	Human Health Noncancer kg C_7H_7 expected value	lower bound	upper bound
Transport	3.3E-06	N/A	N/A	0.00	N/A	N/A
Electricity (Si, fab., use)	1.1E-05	1.1E-05	1.1E-05	0.30	0.29	0.30
Fab. direct emissions	9.0E-08	4.5E-08	1.8E-07	2.5	2.2	2.8
Infra.	4.9E-05	2.5E-05	6.2E-05	1.4	0.7	1.7
Total	6.4E-05	3.9E-05	7.6E-05	4.1	3.1	4.8
	Eutrophication, to air g N expected value	lower bound	upper bound	Eutrophication, to water g N expected value	lower bound	upper bound
Transportation	0.02	N/A	N/A	N/A	N/A	N/A
Electricity (Si, fab., use)	0.027	0.026	0.028	N/A	N/A	N/A
Fab. direct emissions	1.8E-03	9.0E-04	3.6E-03	13	0.0	26
Infrastructure	0.10	0.05	0.12	N/A	N/A	N/A
Total	0.15	0.10	0.17	13	0.0	26

TABLE IV
SUMMARY OF PROCESS TECHNOLOGIES

node (nm)	**150**	**120**	**90**	**65**	**45**
wafer (mm)	300	300	300	300	300
interconnect	4 poly layer, 1 layer Al	4 poly layer, 1 layer Al	4 poly layer, 1 layer Al	4 poly layer, 1 Al	4 poly layer, 3 Cu
starting wafer		SOI	SOI	SOI	SOI
floating gate inter-poly dielectric	ONO	ONO	ONO	ONO	Si/SiO$_2$/SiN/ /Al$_2$/O$_3$//TaN (TANOS)
dielectric	PSG PMD, USG ILD (remote clean)	PSG PMD, USG ILD (remote clean)	PSG PMD, USG ILD (remote clean)	PSG PMD, USG ILD (remote clean)	PSG PMD, USG and FSG ILD (remote cln.)
contact	tungsten silicide	tungsten silicide	tungsten silicide	tungsten silicide	tungsten silicide
strain engineering			nitride cap, spacer	nitride cap, spacer	Epi SiGe, nitride cap
gate	RTO gate oxide	RTO gate oxide	RTO gate oxide	nitridation of oxide: ONO gate stack	nitridation of oxide: ONO gate stack
other		source-drain extension implant	source-drain ext. implant	source-drain ext. implant	source-drain ext. implant
mask				phase-shift mask	phase-shift mask
PR Strip	SPM wet PR strip	SPM wet PR strip and plasma PR strip	SPM wet PR strip and plasma PR strip	SPM wet PR strip and plasma PR strip	SPM wet PR strip and plasma PR strip
wafer cleans	FEOL single wafer cleans	FEOL single wafer cleans	FEOL single wafer cleans	FEOL single wafer cleans	FEOL single wafer cleans
package	TSOP	TSOP	TSOP	TSOP	TSOP
solder	SnPb	SnPb	SnPb	SnAgCu (”SAC”)	SnAgCu (”SAC”)

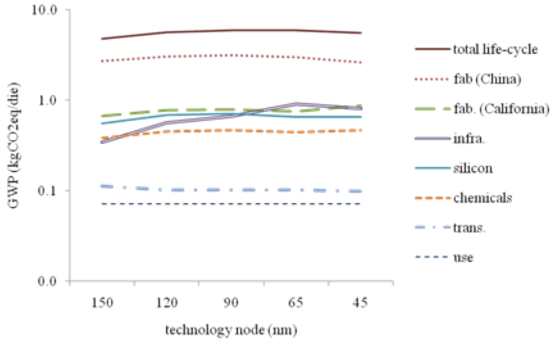


Fig. 7. GWP per die, by life-cycle stage, over five technology nodes

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REFERENCES

[1] SIA, *Annual Forecast of Global Semiconductor Sales*. Semiconductor Industry Association, November 14 2007.

[2] SIA , *Annual Forecast of Global Semiconductor Sales*. Semiconductor Industry Association, November 14 2008.

[3] K. Schischke, M. Stutz, J. Ruelle, H. Griese, and H. Reichl, "Life cycle inventory analysis and identification of environmentally significant aspects in semiconductor manufacturing," in *Proceedings of the IEEE International Symposium on Electronics and the Environment*. IEEE, 2001, pp. 145–150.

[4] F. Taiariol, P. Fea, C. Papuzza, R. Casalino, E. Galbiati, and S. Zappa, "Life cycle assessment of an integrated circuit product," in *Proceedings of the IEEE International Symposium on Electronics and the Environment*, 2001, pp. 128–133.

[5] E. D. Williams, R. U. Ayres, and M. Heller, "The 1.7 kilogram microchip: Energy and material use in the production of semiconductor devices," *Environmental Science and Technology*, vol. 36, no. 24, pp. 5504–5510, 2002.

[6] N. Krishnan, S. Boyd, A. Somani, S. Raoux, D. Clark, and D. Dornfeld, "A hybrid life cycle inventory of nano-scale semiconductor manufacturing," *Environmental Science and Technology*, vol. 42, no. 8, pp. 3069–3075, Apr. 2008. [Online]. Available: http://dx.doi.org/10.1021/es071174k

[7] CGDM, "Supporting information for nand flash lca," *Consortium on Green Design and Manufacturing*, 2010. [Online]. Available: cgdm.berkeley.edu/cgdmResearchSI.html

[8] M. O'Halloran, "Fab Utility Cost Values for Cost of Ownership (CoO) Calculations, Technology Transfer #02034260A-TR, available online: www.sematech.org/ docubase/abstracts/4260atr.htm," International Sematech, Tech. Rep. 02034260A-TR, 2002.

[9] S. Boyd, A. Horvath, and D. Dornfeld, "Life-cycle energy and global warming potential of computational logic," *Environmental Science and Technology*, vol. 43, no. 19, pp. 7303–7309, 2009. [Online]. Available: http://pubs.acs.org/doi/abs/10.1021/es901514n

[10] LBNL. (2000) Energy efficient cleanroom information site: Case studies. [Online]. Available: http://ateam.lbl.gov/cleanroom/Cases.html

[11] Carnegie Mellon University Green Design Institute, *Economic Input-Output Life Cycle Assessment (EIO-LCA), US 1997 Industry Benchmark model, Economic Input-Output Life Cycle Assessment (EIO-LCA), US 1997 Industry Benchmark model*. http://www.eiolca.net, accessed May 15, 2009. [Online]. Available: http://www.eiolca.net

[12] S. Kim and M. Overcash, "Energy in chemical manufacturing processes: gate-to-gate information for life cycle assessment," *Journal of Chemical Technology & Biotechnology*, vol. 78, no. 8, pp. 995–1005, 2003.

[13] S. Lipp, G. Pitts, and F. Cassidy, Eds., *Environmental consciousness: a strategic competitiveness issue for the electronics and computer industry*. Microelectronics and Computer Technology Corporation, 1993.

[14] J. Stokes and A. Horvath, "Life cycle energy assessment of alternative water supply systems," *The International Journal of Life Cycle Assessment*, vol. 11, no. 5, pp. 335–343, 2006. [Online]. Available: http://www.springerlink.com/index/10.1065/lca2005.06.214

[15] C. Facanha and A. Horvath, "Evaluation of life cycle air emission factors of freight transportation," *Environ. Sci. Technol.*, vol. 41, no. 20, pp. 7138–7144, 2007. [Online]. Available: http://pubs.acs.org/doi/abs/10.1021/es070989q

[16] EPA, *The Emissions & Generation Resource Integrated Database for 2007 (eGrid2007), available online: www.epa.gov/cleanenergy/energy-resources/ egrid/index.html*. U.S. Environmental Protection Agency, September 2008.

[17] C. Reich-Weiser, T. Fletcher, D. Dornfeld, and S. Horne, "Development of the supply chain optimization and planning for the environment (SCOPE) tool - applied to solar energy," in *International Symposium on Electronics and the Environment*. IEEE, 2008.

[18] C. W. King and M. E. Webber, "The water intensity of the Plugged-In automotive economy," *Environmental Science & Technology*, vol. 42, no. 12, pp. 4305–4311, Jun. 2008. [Online]. Available: http://pubs.acs.org/doi/abs/10.1021/es0716195

[19] Samsung, *Samsung 4G x 8 Bit NAND Flash Memory Datasheet, Samsung 16M x 8 Bit NAND Flash Memory Datasheet*. Samsung, 2002.

[20] Micron, *2Gb NAND Flash Replacement for Toshiba Devices*. Micron, 2004.

[21] ——, *DDR2 Power Calc 16.XLS, Available online: download.micron.com*. Micron Semiconductor Products, 2007.

[22] P. Schmid and A. Roos, *Spring 2010 Solid State Drive Roundup*. Tom's Hardware, Bestof Media, available online: http://www.tomshardware.com/reviews/6gb-s-ssd-hdd,2603.html, 2010.

[23] T. Hardware, *2.5 Mobile Hard Drive Charts*. Bestof Media, available online: http://www.tomshardware.com/charts/2.5-hard-drive-charts-2008/benchmarks,25.html, 2008.

[24] IPCC, *Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007, susan Solomon, Dahe Qin, Martin Manning, Melinda Marquis, Kristen Averyt, Melinda Tignor, Henry LeRoy Miller and Zhenlin Chen.

[25] G. A. Norris, "Impact characterization in the tool for the reduction and assesment of chemical and other environmental impacts." *J. Ind. Ecol.*, vol. 6, no. 3-4, pp. 79–99, 2003.

[26] S. C. Bartos, N. Kshetry, and C. S. Burton, "Modeling China's semiconductor industry fluorinated compound emissions and drafting a roadmap for climate protection," *International Journal of Greenhouse Gas Control*, vol. 2, no. 4, pp. 665–676, Oct 2008. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S1750583608000078

[27] W. Digital, *2009 Annual Report and Form 10-K*. Western Digital, available online: www.westerndigital.com, 2009.

[28] ——, *Environmental Report, Fiscal Year 2009*. Western Digital, available online: www.westerndigital.com, 2010.

[29] Y. Chen and R. Liu, "Future trend of flash memories," in *Memory Technology, Design and Testing, 2007. MTDT 2007. IEEE International Workshop on*, 2007, pp. 17–18.

[30] E. Pinheiro, W.-D. Weber, and L. A. Barroso, "Failure trends in a large disk drive population," in *Proceedings of the 5th USENIX Conference on File and Storage Technologies*, 2007.

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