Supporting Information for *"Life-cycle Energy Demand and Global Warming Potential of Computational Logic"*

Sarah B. Boyd,*,† Arpad Horvath,‡ and David Dornfeld†

Department of Mechanical Engineering, University of California at Berkeley, Berkeley, CA, and Department of Civil and Environmental Engineering, University of California at Berkeley, Berkeley, CA

Methodological Details, Data Sources and Uncertainty

Chemicals

In this study's method for chemicals LCA data collection, data based on process descriptions are used where available, and data from the Carnegie Mellon EIO-LCA database are used where costs are known. The method is the same as that used in a preceding paper (*1*), with some small modifications. When no process LCA data and no cost information is known, an estimate for the energy intensity of chemicals manufacturing developed by Kim and Overcash is used (*2*). 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 ma-

†Mechanical Engineering, University of California at Berkeley
‡Civil and Environmental Engineering, University of California at Berkeley

terials 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.

EIO-LCA energy consumption and GWG emissions has an assumed uncertainty range of +/-10% which arises largely from the chronological incongruity of data. Data for the energy generation sector do not suffer significant error due to aggregation, and while CMU EIO-LCA results for toxic releases for example would have a lower precision due to the errors associated with the survey procedures for the Toxics Release Inventory, CMU EIO-LCA results for energy and GWP of emissions are based on census data and EPA emissions factors, which have a higher degree of accuracy. 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. A table of the data sources and impact values for all materials using process data is given in the in Table S1. Chemicals using EIO-LCA data are given in Table S2. Data from the Kim/Overcash study has an uncertainty of +25%/-75% as described in their analysis (*2*). The chemicals based on these common impact values are given in Table S3.

Table S1: Chemicals LCA Data Sources, part 1: Process data

	energy intensity MJ/kg	carbon intensity gCO_2eq/g	
Al	260	22	(*3*)
Ar	3.6	0.31	(*3*)
C_2F_4	20	1.7	(*4*)
CH_4	38	3.3	(*5*)
CO	0.52	0.04	(*6*)
Cu	4.7	0.40	(*7*)
F_2	61	5.3	(*8*)
H_2			(*3*)
H_2O_2	12	1.0	(*3*)
H_2SO_4	0.040	0.00	(*9*)
HCl	0.91	0.08	(*10*)
He	0.83	0.07	(*11*)
HF (gas)	18	1.5	(*12*)
HF (liquid)	18	1.5	(*3*)
N_2	0.66	0.06	(*13*)
NF_3	40	3.4	(*14*)
NH_3	31	2.7	(*15*)
NH_4OH			(*15*)
O_2	1.8	0.15	(*13*)
Pb	2.0	0.2	(*16*)
polyamides	115.0	9.9	(*16*)
Pt	270	23	(*17*)
SiH_4	2321	200	(*18*)
Sn	122	11	(*16*)
Ti	140	12	(*15*)
utility N_2	0.02	0.06	(*13*)

Table S2: Chemicals LCA Data Sources, part 2: EIO-LCA data

	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
H_2	1.8E+02	16
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 S3: Chemicals LCA Data Sources, part 3: Process-based common value(*2*)

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

Silicon

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 LCA data used in the current study is based on a study from Williams (*19*) and is duplicated for clarity in Table S4.

Table S4: 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 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 (*20*). (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 resulting global warming emissions per liter of water provided in Santa Clara is 0.6 gCO_2eq and the energy intensity and percent contribution of each source is presented in Table S5.

Table S5: Global Warming Intensity of Santa Clara Water

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

GWP of Electricity

The electricity mix for Santa Clara in 2008 and the GWP intensity of each generation type is presented in Table S6. The GWP intensity of electricity in Santa Clara is found as 280 gCO_2eq/kWh.

Table S6: GWP Intensity of Electricity

Electricity Mix		GWP Intensity gCO_2eq/kWh	Source
Coal	4%	811	Horvath, Pacca (*21*)
Nat Gas	47%	450	Horvath, Pacca
Nuclear	23%	25	Fthenakis (*22*)
Large Hydro	13%	41	Horvath, Pacca
Biomass/waste	4%	0	EPA (*23*)
Geothermal	4%	35	EPA
Small Hydro	3%	41	Horvath, Pacca
Wind	2%	7	Horvath, Pacca
Solar	0.1%	90	Horvath, Pacca

Primary Energy Use in Electricity Generation

In order to allow easier comparison with preceding studies, 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. 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 this worldwide average. In actuality, the primary energy intensity of Santa Clara electricity is almost certainly lower than the world average. A comparison of the contribution of each generation type is given in Table S7. 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.

Table S7: Electricity Generation by Type, World Average vs. California

	conventional thermal	hydroelectric	nuclear	geothermal, solar, wind, and waste/biomass
world average	69%	19%	9%	3%
California (PG&E)	52%	16%	23%	10%

Infrastructure and Equipment

The energy and global warming impacts for infrastructure and equipment are evaluated with EIO-LCA using the industrial construction (NAICS #230210) and semiconductor manufacturing equipment (NAICS #333295) Sectors. Rock's Law is used to estimate the total cost of the fabrication facility (*24*) 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 S8.

Table S8: 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

Semiconductor Fabrication

Yields

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 S9)(*25*).

Table S9: 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

Facility and Process Equipment Energy Demand

In industry, operational and technological changes have been made to the energy efficiency of nearly all of the major fab systems: water cooling, exhaust, water flow, clean room airflow, clean dry air (CDA) and facility nitrogen delivery systems, and chamber vacuum pumps. 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. Fab energy efficiency has also been assisted by technological developments such as higher efficiency pumps and fans, variable speed drives and improvements in ducting and clean room airflow arrangement such as mini-environments. The model accounts for these changes, with adjustments appearing at each technology generation as they would in a typical fab (Table S10). 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 (*25*, *26*).

Table S10: 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

Power data for process tools are based on previously published measurements taken using three phase power measurement equipment, which have a maximum error of +/- 2.6% (*1*).

Process Emissions

The mass flows of GWG emissions from each process step have been determined, pre- and post-abatement, using in-situ mass spectrometry and Fourier Transform Infrared (FT-IR) spectroscopy by a procedure which requires mass balance to be closed within 10% of chamber inputs (*1*). Each of these measurements thus has a maximum uncertainty of +/- 10% for each chemical. Each process flow is specific to its technology generation. For more details concerning the process flow and wafer processing technologies assumed in this study see (*27*) and (*28*), which provide information concerning the process steps used at the 130 nm and 45 nm technology nodes. Global warming potentials for PFC emissions are the latest values defined by the IPCC (*29*).

Transportation

Semiconductor assembly and test sites are clustered in Vietnam, Malaysia, Costa Rica, Puerto Rico, China and the Philippines. Costa Rica is the closest location to Santa Clara and is the assumed location of assembly 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 (*30*). Each travel leg and its corresponding GWP impact and energy intensity is given in Table S11.

Table S11: GWP Intensity of Transportation

	Distance, wafer 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

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. It is assumed that the mass to volume ratio is within the range typical for truck and air freight, so that the emission factor may be applied on the basis of ton-miles rather than m^3-miles. The total energy and GWP intensity of transport for each technology node is presented in Table S12.

Table S12: Transportation Energy and CO_2 Emissions by Technology Node

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

Use phase

The average power requirements for logic chips are taken from the 2001-2007 International Semiconductor Manufacturing Roadmap reports (*25*) and, for years previous, from manufacturer's specifications (Table S13)

Table S13: Use phase power by technology node

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

In order to compare impacts on the basis of operational performance, we use millions of instructions per second (MIPS) as a metric of computational capacity. Though instruction rate falls short of providing a complete 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 (*31*).

Additional Results

Over successive technology nodes, life-cycle energy use and GWP have increased per wafer and per die but decreased when normalized by computational power. Figure S1 shows total life-cycle energy demands per wafer, per die and per 1000 MIPS.

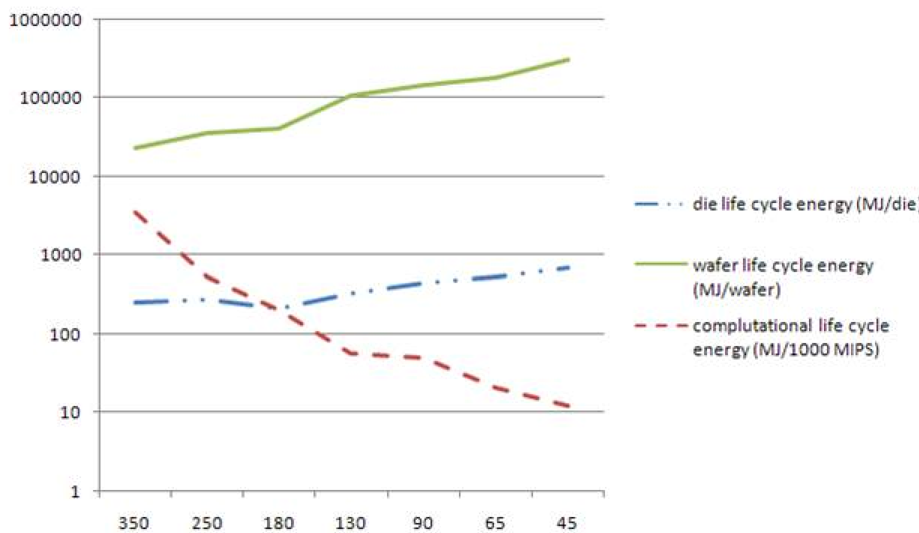

Figure S1: Energy use per die, per 300mm wafer equivalent and per 1000 MIPS

The switch to 300 mm wafers at the 130 nm node resulted in a notable increase in energy efficiency. Since then, equipment energy has increased continuously on a per-wafer basis, while facilities energy demands have advanced and receded at a modest pace owing to facility efficiency measures.

In terms of energy consumption, dominance of the use phase has increased over time, with use consuming about 79% of total life-cycle energy per die at the 350 nm node, and almost 99% per die at the 45 nm node. If it weren't for the increasing operational power demand of chips, total

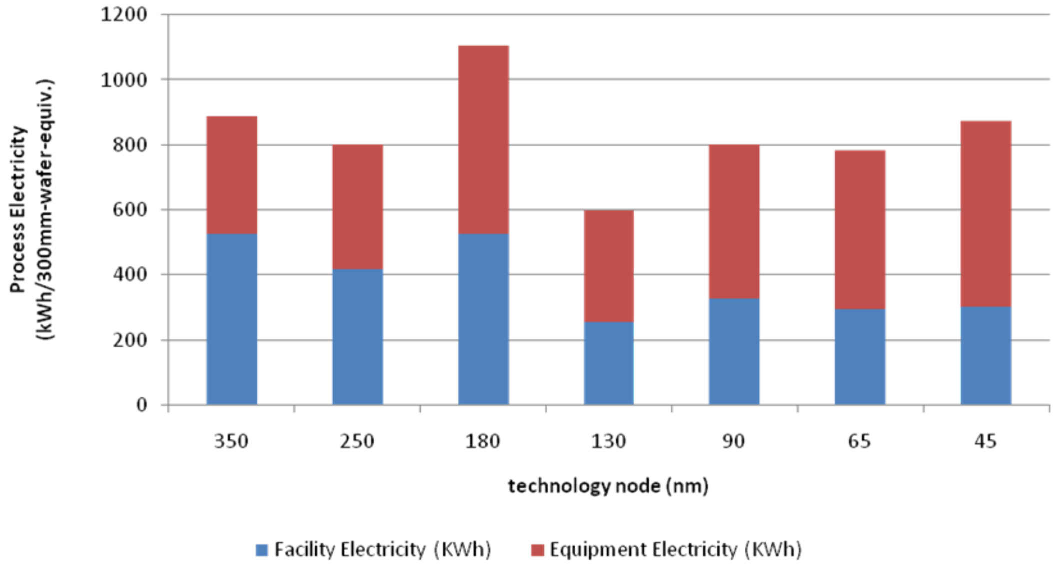

Figure S2: Facility and process equipment energy use per 300 mm wafer equivalent, over seven technology nodes

life-cycle energy and GWP of emissions per die would be decreasing, as illustrated in Figure S3.

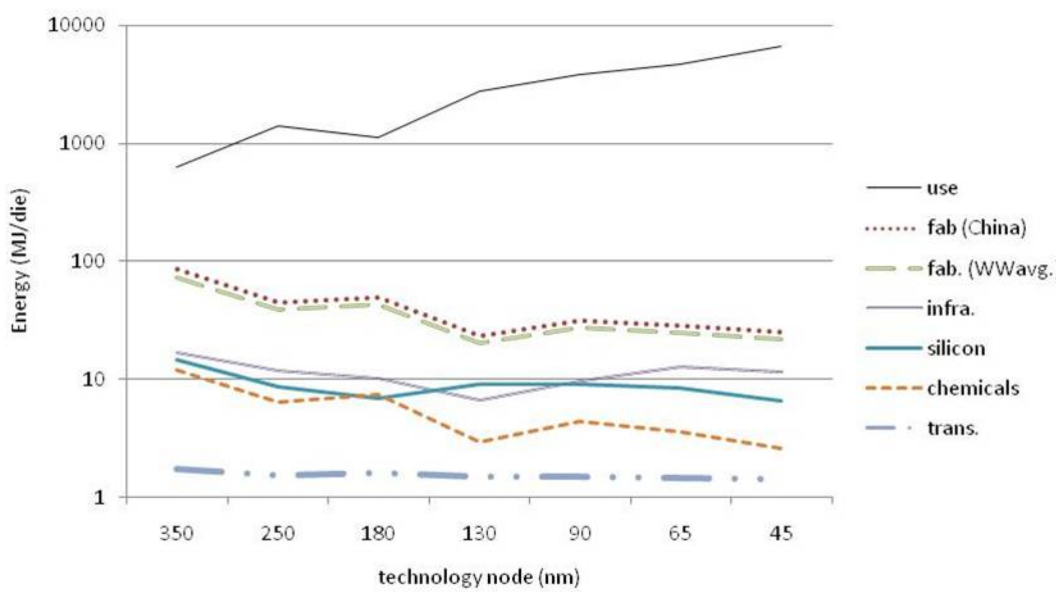

Figure S3: Energy use per die, by life-cycle stage, over seven technology nodes

As with GWP, energy use falls dramatically when normalized to computational power (Figure S4).

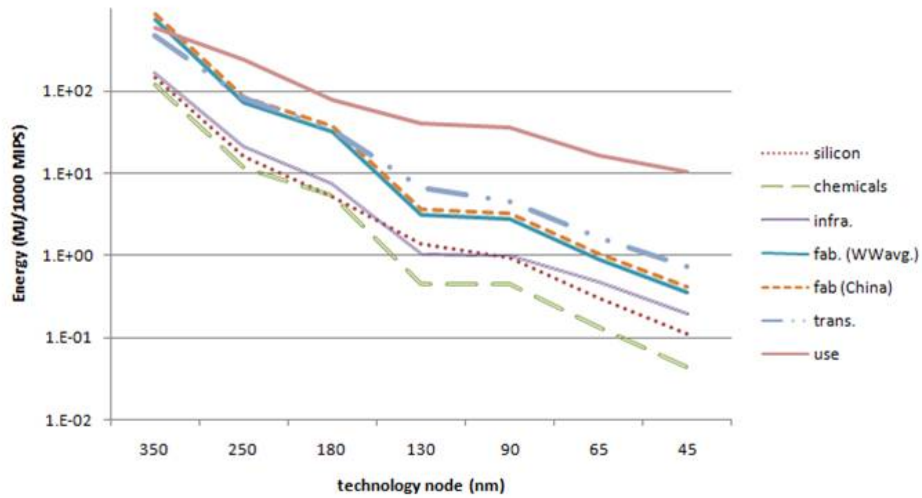

Figure S4: Life-cycle energy use per computational power

Energy use and GWP data per die are provided for each life cycle stage in Table S14 and Table S15. To determine impact values for a specific logic chip, use the appropriate technology generation (e.g. 65 nm). If the chip size is different from the average value used in this study (see Table S9), account for the difference in chip size. (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 the most important variable in determining life-cycle energy demand.

Table S14: Energy consumption per die by life cycle stage

Energy (MJ/die)							
year	1995	1998	1999	2001	2004	2007	2010
technology node (nm)	350	250	180	130	90	65	45
use	1,272	1,975	1,594	3,916	5,393	6,677	9,373
fab (China)	76	44	35	30	28	32	30
fab. (WWavg.)	65	38	30	26	24	27	26
infra.	15	12	10	7	12	16	19
silicon	15	8.5	6.8	8.9	8.9	8.3	6.5
chemicals	12	7.8	5.9	4.6	5.0	4.6	5.5
trans.	1.8	1.6	1.6	1.5	1.5	1.5	1.4
life cycle energy (MJ/die)	1,457	2,087	1,684	3,994	5,473	6,766	9,462

Table S15: GWP per die by life cycle stage

GWP ($kgCO_2eq$/die)							
year	1995	1998	1999	2001	2004	2007	2010
technology node (nm)	350	250	180	130	90	65	45
use	17	38	30	74	102	127	178
fab (China)	7.5	4.5	3.0	2.6	2.4	2.8	2.1
fab. (California)	1.9	1.0	0.8	0.7	0.7	0.7	0.7
infra.	1.3	1.0	0.8	0.5	1.0	1.3	1.5
silicon	1.2	0.68	0.55	0.72	0.72	0.67	0.52
chemicals	1.0	0.64	0.49	0.38	0.41	0.38	0.57
trans.	0.12	0.11	0.11	0.10	0.10	0.10	0.10
total life-cycle	30	45	36	79	108	133	184

Uncertainty

Energy consumption and GWP of emissions at each life-cycle stage are presented with uncertainty for the most recent technology node, 45 nm, in Figure S5 and Figure S6.

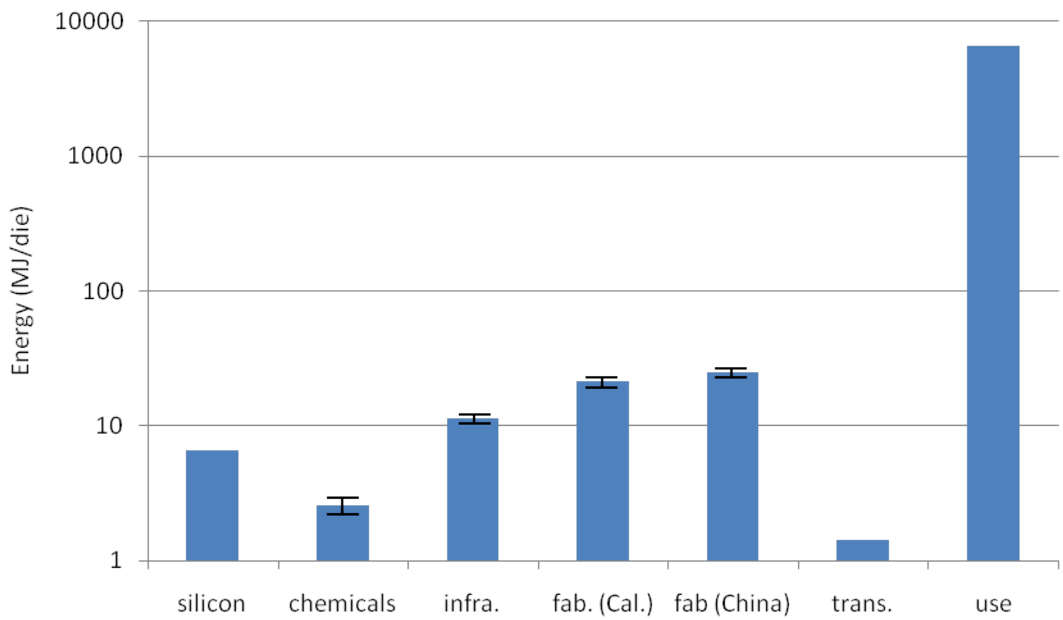

Figure S5: Energy use per die by life-cycle stage, 45 nm node
Note: log scale attenuates appearance of uncertainty

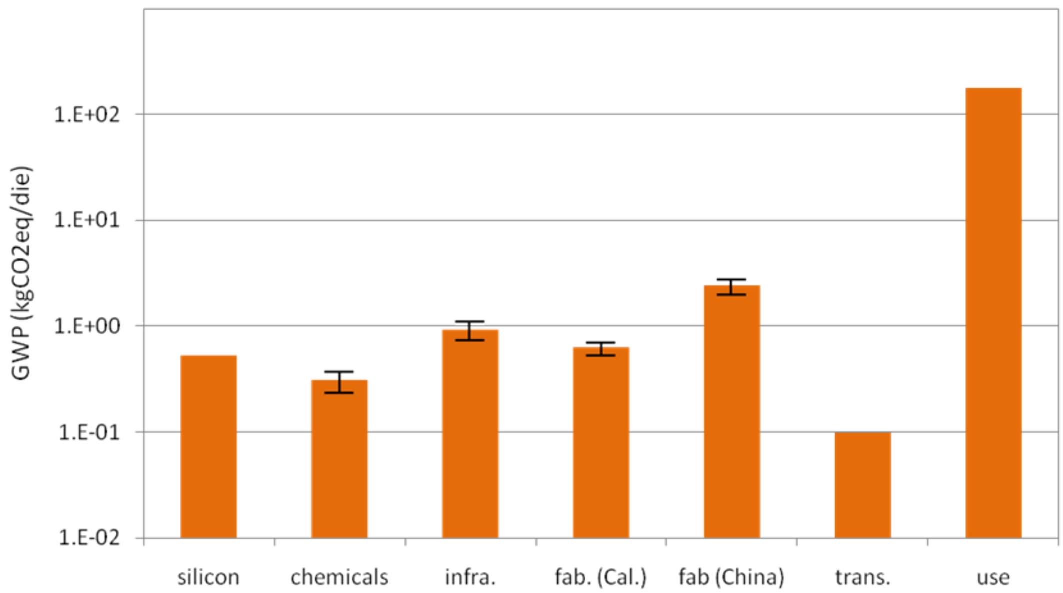

Figure S6: GWP of emissions per die by life-cycle phase, 45 nm node
Note: log scale attenuates appearance of uncertainty

Data Quality

A data quality assessment following the template of Weidema and Wesnaes is provided in Table S16 (*32*). The quality of data is high: all of the LCA data, with the exception of chemicals and infrastructure data, come from sources that are specific to the process, geographical location and time period of the study.

Table S16: Data quality assessment

	Reliability	Completeness correlation	Temporal correlation	Geographical correlation	Tech.
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: atm. 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	
Transportation	2-3	1	1	2	2
Use (chip power, performance)	1	2	1	1	1

Indicator score	1	2	3	4	5
Reliability	Verified[a] data based on measurements[b]	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation	Less than three years of difference to year of study	Less than six years difference	Less than 10 years difference	Less than 15 years difference	Age of data unknown or more than 15 years of difference
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

Figure S7: Data quality scoring rubric

This table is a reproduction from (*32*).

References

(1) Krishnan, N.; Boyd, S.; Somani, A.; Raoux, S.; Clark, D.; Dornfeld, D. A Hybrid Life Cycle Inventory of Nano-Scale Semiconductor Manufacturing. *Environ. Sci. Technol.* **2008**, *42*, 3069–3075.

(2) Kim, S.; Overcash, M. Energy in chemical manufacturing processes: gate-to-gate information for life cycle assessment. *Journal of Chemical Technology & Biotechnology* **2003**, *78*, 995–1005.

(3) *Ullmann's Encyclopedia of Industrial Chemistry, 7th Edition*; John Wiley & Sons, 2009.

(4) Webster, J. L. *Preparation of tetrafluoroethylene*; United States Patent No. 5684218, 1997.

(5) Pahade, R. F.; Saunders, J. B.; Maloney, J. J. *Process for separating methane and nitrogen. United States Patent, 4592767*; 1986.

(6) Gallarda, J.; Wegrzyn, F. *Process and plant for production of carbon monoxide and hydrogen. United States Patent, 6098424.*; 2000.

(7) Beattie, M. J. V.; Bacon, W. G.; Raudsepp, R. *Hydrometallurgical copper process. United States Patent, 4632738.*; 1986.

(8) Faron, R.; Devilliers, D.; Romano, R. Fluorine, in Ullmann's Encyclopedia of Industrial Chemistry. *John Wiley & Sons* **2000**.

(9) Homme, A. C. *Contact sulfuric acid process employing double conversion/ double absorption. United States Patent, 4088742.*; 1978.

(10) Harris, W. G. *Method and apparatus for making hydrochloric acid and sodium hydroxide. United States Patent, 4749453*; 1988.

(11) Gottier, G. N. *Low pressure stripping process for production of crude helium. United States Patent, 5011521.*; 1991.

(12) Reed, R. S. *Production of high purity hydrogen fluoride from silicon tetrafluoride. United States Patent, 4036938.*; 1977.

(13) Higginbotham, P.; Agrawal, R.; Herron, D. M. *Process for the production of oxygen and nitrogen. United States Patent, 6227005.*; 2001.

(14) Coronell, D. G.; Hsiung, T. H. L.; Withers, H. P. J.; Woytek, A. J. *Process for nitrogen trifluoride syntheis. United States Patent, 5637285.*; 1997.

(15) *Kirk-Othmer Encyclopedia of Chemical Technology*; John Wiley & Sons, 2001.

(16) Andrae, A. S.; Andersson, D. R.; Liu, J. Significance of intermediate production processes in life cycle assessment of electronic products assessed using a generic compact model. *J. Cleaner Prod.* **2005**, *13*, 1269–1279.

(17) Day, J. G. *Recovery of platinum group metals, gold and silver from scrap. United States Patent, 4427442.*; 1984.

(18) Franklin, R. E.; Francis, A. W.; Tarancon, G. *Process for the production of silane. United States Patent, 4041136.*; 1977.

(19) Williams, E. D.; Ayres, R. U.; Heller, M. The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices. *Environ. Sci. Technol.* **2002**, *36*, 5504–5510.

(20) Williams, S. M. *The Santa Clara Valley Water District Fiscal Year 2007-08 Five-Year Capital Improvement Program*; Technical Report, 2007.

(21) Pacca, S.; Horvath, A. Greenhouse Gas Emissions from Building and Operating Electric Power Plants in the Upper Colorado River Basin. *Environ. Sci. Technol.* **2002**, *36*, 3194–3200.

(22) Fthenakis, V.; Kim, H. Greenhouse-gas emissions from solar electric and nuclear power: A life-cycle study. *Energy Policy* **2007**, *35*, 2549–2557.

(23) EPA, *The Emissions & Generation Resource Integrated Database for 2007 (eGrid2007) Technical Support Document*; U.S. Environmental Protection Agency, 2008.

(24) Kanellos, M. *Soaring costs of chipmaking recast industry*, 2003. `http://news.cnet.com/Semi-survival/2009-1001_3-981418.html`.

(25) Sematech, *The International Technology Roadmap For Semiconductors: 2005, 2003, 2001 and 1999 Editions*; Technical Report, 1999-2005.

(26) Hu, S. C.; Chuah, Y. K. Power consumption of semiconductor fabs in Taiwan. *Energy* **2003**, *28*, 895 – 907.

(27) Boyd, S.; Dornfeld, D.; Krishnan, N. Life Cycle Inventory of a CMOS Chip. *Proceedings of the IEEE International Symposium on Electronics and the Environment*, 2006; pp 253–257.

(28) Boyd, S.; Dornfeld, D.; Krishnan, N.; Moalem, M. Environmental Challenges for 45-nm and 32-nm node CMOS Logic. *Proceedings of the IEEE International Symposium on Electronics and the Environment*, 2007; pp 102–105.

(29) 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, UK and New York, NY, USA, 2007.

(30) Facanha, C.; Horvath, A. Evaluation of Life Cycle Air Emission Factors of Freight Transportation. *Environ. Sci. Technol.* **2007**, *41*, 7138–7144.

(31) Wikipedia, *Moore's law*, 2009. `http://en.wikipedia.org/wiki/Moore's_law`.

(32) Weidema, B. P.; Wesnaes, M. S. Data quality management for life cycle inventories–an example of using data quality indicators. *J. Cleaner Prod.* **1996**, *4*, 167–174.