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EPA's PFC Emissions Vintage Model (PEVM) v.2.14: Description and Documentation

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Prepared for

Mr. Scott Bartos
U.S. Environmental Protection Agency
Global Programs Division
1200 Pennsylvania Avenue NW (6205J0
Washington, DC 20460

Prepared by

C. Shepherd Burton
Consultant
2047 Huckleberry Road
San Rafael, CA 94903

Ramin Beizaie
ICF Consulting
60 Broadway
San Francisco, CA 94111

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1. INTRODUCING EPA'S PFC EMISSIONS VINTAGE MODEL (PEVM)

This report describes and documents the U. S. Environmental Protection Agency's top-down PFC Emissions Vintage Model (PEVM), v2.14. The PEVM endeavors to describe the "average" or general vicissitudes of the semiconductor manufacturing industry that influence the emissions of perfluorinated compounds (PFCs). PEVM manifests itself in an application of Microsoft® Excel 97 that requires publicly available input information from the PFC Emission Reduction Partnership for the Semiconductor Industry, International Technology Roadmap for Semiconductors (ITRS), World Fab Watch (WFW) fab database, VLSI Research Incorporated and numerous published as well as some unpublished reports. The Partnership is a voluntary program between the EPA and industry to reduce PFC emissions. This report also presents some results of applying the PEVM—first to demonstrate its use and second to help readers gauge its efficacy to capture the realities of the production and reduction of PFC emissions from semiconductor manufacturing. Completeness and accuracy were among the goals that we pursued in preparing the report.

The term completeness needs further explanation. By completeness, we mean including everything to support and describe the PEVM as currently implemented, without going too deep into the manufacturing processes and jargon of semiconductor manufacturing. It is our intention to proceed at a level and speed that permits "hydroplaning" on the world semiconductor industry, which we acknowledge presents some risk.

PFC gases are vital to the semiconductor industry in the manufacture of microchips (or integrated circuits, ICs) and will remain so for the foreseeable future *[ITRS 2000]*. During IC manufacturing, atmospheric emissions result from unused PFCs (or from PFCs formed) during manufacturing. The industry currently uses six fully fluorinated compounds and one hydrofluorocarbon: tetrafluormethane (CF_4), hexafluorethane (C_2F_6), octafluorpropane (C_3F_8), cyclo-octafluorbutane (c-C_4F_8 or simply C_4F_8), sulfur hexafluoroide (SF_6), nitrogen trifluoride (NF_3) and trifluoromethane (CHF_3). The combination of their long atmospheric lifetimes and strong absorption of infrared radiation produces global warming potentials (GWPs) that exceed CO_2 by roughly six thousand to 24 thousand times.

Reducing PFC emissions—and the emissions of other greenhouse gases (GHG) with high global warming potentials (GWPs)—is a key element of a global strategy to reduce the threats of climate change. The PFC Emission Reduction Partnership for the Semiconductor Industry exemplifies a key component of EPA's contribution to this global strategy. In a Memorandum of Understanding, the partners express, among other things, their shared commitment "to work toward reducing PFC emissions and, if possible, toward replacing PFCs with compounds that do not trigger global warming or other potential adverse effects."

Partners, working closely with equipment manufacturers and suppliers, have demonstrated a continuous record of progress since its formation in 1995. *[MOU 1995, MOU 2000, Bartos 2000, Rand 2000]* Partners have:

- Developed reliable analytical methods and standard protocols for measuring PFC emissions and PFC utilization under manufacturing conditions *[Myers 1998, 2000]*.
- Implemented a practice of annually reporting PFC emissions *[MOU 1995, MOU 2000]*.
- Identified and evaluated technologies for reducing PFC emissions *[SEMATECH 1998, Worth 2000]*.
- Established, under the auspices of the IPCC, good practices in emissions estimation and inventory management *[IPCC 2000]*.
- Mobilized global action through the World Semiconductor Council to establish an aggressive emission-reduction target for 2010 *[MOU 2000]*.

This report uses information provided by the Partnership and aims to contribute to the Partnership's growing accomplishments. Using best available information, version 2.14 of PEVM develops and employs for the first time a new emissions factor to forecast PFC emissions for business-as-usual (BAU) scenarios and emission reduction strategies. The report also provides a summary of the PEVM's limitations as well the results of an initial evaluation using independent estimates of PFC emissions.

1.1. Purposes of PFC Emissions Vintage Model

In developing this version of the PEVM, the EPA had three main purposes:

- Facilitate understanding of the industry's diverse and dynamic manufacturing technologies, especially the characteristics that affect PFC emissions growth trends.
- Provide projections of US PFC emissions under BAU conditions to 2010.
- Identify opportunities to introduce emission reduction technologies.

1.2. Initial Considerations for PEVM

Our modeling philosophy is captured by the epigram "as simple as possible but not one bit simpler." This epigram, in our modeling experience, joins modeling idealism to modeling pragmatism, while facilitating alignment of mathematical abstraction and reality.

From the outset, we intuitively favored a top-down rather than a bottom-up approach for PEVM. We believed that a top-down model of PFC emissions could best capture the industry's collective manufacturing practices and trends that explicitly and implicitly affect PFC emissions.

It is these practices, which seem to sprout from the industry's adherence to Moore's law, that we believed would reflect prevailing and foreseeable business and technical innovations, as presented in the ITRS.[1] We also decided to adopt a deterministic instead of a stochastic description of the factors that govern emissions. In choosing a deterministic description, we were mindful of the consequential trade-off: unaccounted-for randomness (i.e. uncertainty) that remains in forecasted estimates of emissions as well as the relative conceptual simplicity of formulation, input gathering and interpretation.

We avoided bottom-up modeling approaches because they seemed to present significant risks of becoming entangled in individual company/fab manufacturing practices. We did not consider approaches that might require accounting for the variance in PFC emissions from individual companies/fabs of similar capacities, manufacturing technologies and utilizations that manufacture ICs with similar functions. For example, an IC fabricated from 150 and 200 mm wafers may require approximately 500–600 manufacturing steps of which as many as a 100 may use PFCs *[Hutchison 1996, ICE 1997]*. Trade reports and partner accounts provide compelling evidence for a secretive kind of Darwinian-diversity of IC manufacturing practices: virtually innumerable recipes for process steps that employ a variety of PFC gases, gas mixtures and reactor conditions, each with differing PFC-gas utilizations over as many as 100 PFC-using process chambers in a fab supplied by four to five major equipment manufacturers. An emissions model that sought to account for such diversity would lack for meaningful and credible input information and would risk giving false appearances of precision in its account of details about the causes of PFC emissions and the measures to reduce them.

We also reasoned at the outset that a credible emissions model had to reflect the essential features that collectively drive the industry's technical pace (viz., Moore's law) and trends in PFC use. We learned that what governs the technical pace of the semiconductor industry is the rate at which it adopts new IC design rules. These rules require the identification of new manufacturing processes that could serendipitously increase or decrease PFC emissions. The adoption of each new design rule—a decrease in feature size or increase in IC resolution—starts a new technology cycle every two to three years *[Hutchison 1996, ITRS 2000]*.

Emissions will increase with each new cycle provided everything else that affects emissions remains unchanged. This increase occurs because, as resolution increases, the number of levels required for component connection increases, which, in turn, increases the number of PFC-using process steps. For example, according to the ITRS *[ITRS 2000]*, the number of levels increases, for logic devices, from 6 to 8 - 10 for a doubling of the resolution from 0.18 µm to 0.09 µm in 2004. As many as 12–14 levels are projected by 2010 *[ITRS 2000, Bohr 1995]*.

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[1] Moore's law originally stated, more than three decades ago, that transistor counts double every two years. Since then the industry has achieved even more by extending Moore's law to include transistor speed, power consumption, among others.

Another factor that lowers IC manufacturing cost and increases emissions is wafer size: larger wafers result in more ICs per wafer and more PFC usage. In 2000 for example, approximately 93 percent of silicon demand used in IC manufacturing had diameters of 125, 150 and 200 mm *[VLSI Research, Inc. 2001]*. Emissions from ICs manufactured using 200 mm wafers are approximately 1.8 times greater than the identical ICs made using a 150 mm wafer and the identical PFC-using processes. Projections by VLSI Research indicate that by 2005 approximately 35% of silicon demand will be met by 300 mm diameter wafers *[VLSI Research, Inc. 2001]*.

From principally the foregoing reasoning, we concluded at this time that the design of a PFC emissions model would be strongly constrained by the availability of self-consistent and credible information. While we believed we could design and develop a model that, in principle, could mathematically describe most if not all of the details that govern PFC emissions from production fabs within the U. S., we also recognized that we could not obtain most of the information for a specific recent year without making speculative and questionable assumptions or resorting to sophistic mathematical methods; and for future years the situation appeared hopelessly complex and not cost-effective.

It is from these considerations that we designed and developed the top-down model named PEVM, which is described in the remainder of this report.

1.3. Report Structure

Chapter 2 presents a relatively brief review of the sources of PFC emissions and methods for estimating those emissions. The perspective of Chapter 2 is projecting emissions or emissions modeling, but the information comes from the context of emission inventory development and maintenance. Chapter 3 presents PEVM’s mathematical formulation, in which assumptions, approximations, uncertainties and limitations become evident. However, Chapter 3 is not burdened with the explicit mention of assumptions and uncertainties. Those are gathered and summarized in Chapter 6, the last chapter. After describing the mathematical formulation of PEVM, Chapter 4 presents the operationalization of that formulation. This is accomplished via a description of a detailed flowchart of PEVM. Results from PEVM are presented in Chapter 5, which includes charts and tables of emissions, including a comparison of the results of PEVM with results produced using PFC-sales and projections of PFC-usage to 2010. The report concludes, as mentioned earlier, with a summary of assumptions, uncertainties and limitations. At the end of Chapter 6, we provide our overall evaluation of the current reliability of PEVM, v2.14.

2. SOURCES AND ESTIMATION OF PFC EMISSIONS

Industry reports indicate that PFC emissions originate from two processes, dry etching and cleaning plasma enhanced chemical vapor deposition (PECVD) chambers[2] *[Worth 2000]*. The emitted PFCs are either unused gas during the etching and cleaning process or are formed during etching and cleaning. The proportion of PFC gas emitted from chemical vapor deposition (CVD) and etch processes varies by manufacturing technology and practice. Several reports indicate that emissions from cleaning range between 60–90 percent and that emissions from etching range between 40–10 percent from etching, on a carbon equivalent basis *[Worth 2000, Beu and Brown 1998, Elder et al. 2001, Alaoui et al. 2001]*.

When estimating air emissions from any source, it is customary practice to express the emissions as a product of two factors: an emissions factor, expressed as emissions per unit of activity, and an activity factor, expressed as a quantity of activity *[EPA 2001]*. For estimating PFC emissions from the semiconductor industry, there are two broad methodological alternatives. The first and generally accepted approach takes PFC gas usage as the unit of activity. The second approach, used by the PEVM, takes silicon consumption as the unit of activity. The first approach then requires explicit knowledge of gas consumption and an emissions factor that accounts for utilization of PFC gases and formation of PFC gases during IC manufacture. The second approach requires explicit knowledge of silicon consumption and an emissions factor that accounts for PFC emissions per unit of silicon consumed during IC manufacture. Either method can be gas specific average across all PFC gases. Also, either method can express the emissions for specific cleaning and etch processes or as an average over all cleaning and etch processes.[3]

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[2] CF_4, a specific PFC, is also used in ashing, which is a method of stripping photoresists by a plasma. The ashing process uses a mixture of oxygen and CF_4. Ashing accounts for but a few percent of CF_4 usage and emissions, which both account for approximately 25% of all PFCs purchased during the period 1992–1996 or emitted during the period 1995 to 1999. It appears, therefore, that CF_4 emissions from ashing contribute less than 1% to all PFC emissions on an MMTCE basis.

[3] Because the report is about PFC emissions modeling, the report excludes discussion of measuring PFC emissions. However, it is important to note that Partner emission reports, which serve as the source of all emissions used in this report, originate from measurements of actual gas-specific utilizations/formation made during process-specific conditions. See Myers, 1998, "Process Tool Emissions Measurements Standardization," presented at *A Partnership for PFC Emission Reduction,* Semicon Southwest, October 19, 1998.

2.1. Nature, Magnitude and Distribution of Source

As a whole, the determinants of PFC usage by and emissions from the semiconductor industry are fab capacity, fab utilization, wafer size and IC complexity as well as the total number of fabs. Another important contributor is the industry's relatively rapid growth, in terms of both its size and manufacturing complexity.[4]

Approximately 190 production and 80 R&D and pilot fabs were operating in the U.S. in the year 2000. Combined, these facilities had the design capacity to process 1,200 million square inches of silicon per year, using wafers with diameters of 25, 50, 75 mm, 125 mm, 175 mm and 200 mm. The U. S. share of world fab capacity in 2000 was approximately 25%. No U. S. production fabs in 2000 (or in 2001) used 300 mm diameter wafers—one R&D fab does. The design capacities of modern production fabs vary between 420 wafer starts per month to 44,000 wafer starts per month *[World Fab Watch 2000]*. Over the period from 1988 to 2000, industry average fab utilization increased from approximately 50% to as high as approximately 87% with year to year fluctuations that change by as much as 15 percentage points, but usually considerably less *[ICE 2000, VLSI Research, Inc. 2001]*. Since 1988, the compound average growth rate of silicon consumption in the U. S. has been approximately 8.4%, with growth rates that vary in any year between – 4.5% ('90/'91) and +25% ('94/'95) over the same period *[VLSI Research, Inc. 2001]*. Wafer capacity (200 mm equivalents) has increased at an average annual rate of 10% *[McClean 2000]*. Qualitatively, PFC usage increases as silicon consumption increases. However, as discussed later, PFC usage increases at a rate that exceeds the rate of silicon consumption.

2.1.1. Description of PFC Use

PFCs usage is vital in many process steps during IC manufacture. IC manufacture begins with a semi-conductive crystalline wafer, usually made of silicon. A wafer passes through a dust and particle-free production area called a clean room, during which time it cycles through various pieces of manufacturing equipment or "tools." The function of many of these tools, which may use one or more process chambers, is to deposit thin layers of insulating and conductive materials (thin-films) and to etch intricate patterns into the successive layers of insulating films and metal. The patterned metal layers act to connect (i.e., to wire together or integrate) the active elements that prescribe the function of the IC. The insulating (or dielectric) layers isolate

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[4] The term complexity carries special meaning in the semiconductor industry, which will become clearer later. For now, the term refers to both the expanded functionality of and the exponentially increasing number of circuit elements—transistors, resistors and capacitors— on a silicon chip, which require increasingly elaborate methods to connect the elements in order to achieve the expanded functionality.

the active elements. A single wafer, from start to finish, may require as many as 100 distinct PFC-using process steps, and up to 3 months of process time *[Van Zant 2000, ICE 1997]*.

PFC usage occurs during both plasma cleaning of plasma enhanced chemical vapor deposition (PECVD) chambers and plasma (dry) etching of the thin insulating and metal layers. During cleaning, the plasma dissociates the PFC cleaning gas into reactive constituents that react chemically with (and dislodge) materials that inadvertently had deposited on the chamber walls during film deposition on the wafer. The fluorine—principally fluorine atoms formed within the plasma—serves as the principal cleaning agent. The reacted/removed materials and any unused PFC (or newly formed PFC) gases are pumped into highly diluted fab waste streams for removal (in the case of toxic substances) or release into the air (in the case of non-toxic and inert materials, like PFCs) *[Van Zant 2000]*.

When placed in a plasma reactor, PFCs serve as etchants that can create intricate sub-micron patterns on metal and insulating layers. These patterns consist of vias and trenches that ultimately form the connections to the active components formed on the silicon wafer. Etching requires both F and C, as F serves as the etchant and C, after reacting with the available F, forms polymeric layers that deposit a film, causing the etching to stop. It is the F:C ratio that, among other things, governs the balance between etch and deposition *[Van Zant 2000]*.

In a modern fab that processes 200 mm wafers and uses 0.18 µm feature sizes, there can be as many as 105 to 200 PECVD and etch chambers in the approximate ratio of 3:4 to 3:5 CVD to etch chambers *[Pang, T. 2000, Beu and Brown 1998]*.

Utilization of PFCs during chamber cleaning and etch varies widely by gas and process. For both etch and CVD cleaning, PFC utilizations vary roughly between 20 and 80 % and CF_4 formation can range between 10–20%, depending on the gas and whether the process is cleaning or etching *[IPCC 2001]*

2.1.2. Magnitude of PFC Usage and Emissions

The magnitude of emissions for a particular PFC, a particular process or particular fab varies widely. As annual fab and utilization increases—measured by increases in surface area of silicon consumed during IC manufacture—PFC usage (and concurrently emissions) increases. In addition, as IC manufacturers increase the density of chip components, uncontrolled "complexity." In fact, without increasing an IC's surface area, the only means to connect the more densely packed components is to manufacture new layers of "wires" and insulators. It is the total area of silicon and number of layers (i.e., complexity) that determine gas usage, utilization and emissions.

Total annual PFC gas usage by the U. S. semiconductor industry for the period 1992 to 1996 increased by approximately a factor of 3.3, to approximately 2 million pounds. Roughly, except for C_3F_8, each of the PFC gases increased by the same multiple over this 5-year period. Over the same period, we estimate that total U. S. PFC emissions grew by approximately the same multiple, to approximately 1.6 MMTCE in 1996. Of the 1.6 MMTCE of emissions in 1996, 50% of the emissions were from C_2F_6 (the predominant PFC for chamber cleaning), with the gases CF_4, SF_6, CHF_3, NF_3 and C_3F_8 accounting for, respectively, 25, 18, 6, 1 and <1% of the remaining emissions *[Burton 1997, Burton 2001]*. The 50% industry-wide fraction for C_2F_6 usage compares favorably with information published by Beau and Brown for a typical 1997 vintage fab *[Beu and Brown 1998]*. For comparison with other sources of GHG, the1.6 MMTCE emitted from semiconductor manufacturing in 1996 represented approximately 0.1% of all U. S. GHG emissions, an increase of approximately 2.5 times the corresponding share in 1990 *[EPA 2001]*

The magnitude of PFC emissions for a given process (step) is a function of the gas, chamber, film, plasma power, pressure, flow, concentration, time to clean/etch, and more. The magnitude of the annual emissions from that process step depends on the utilization of the process during a year. For example, cleaning a chamber after deposition of a plasma-enhanced TEOS-formed SiO_2 film on a single wafer takes 1–1.5 minutes. There are approximately 5×10^{-9} MMTCE of unused C_2F_6 and formed CF_4 emitted during cleaning *[Vrtis 2001]*. The annual PFC emissions from such a process step will be determined by the annual number of wafers processed and the annual number of times that process is used per wafer. For a high-capacity fab operated at historical utilizations, the annual PFC emissions would be of order 0.015 MMTCE for a deep-submicron IC logic device that employs 5 metal layers (roughly two-thirds of the emissions from all cleaning processes).

The magnitude of the annual PFC emissions from a single “typical” large fab from all cleaning and etching is approximately 0.04 MMTCE, of which approximately 0.01 MMTCE (approximately 25%) originate from etch processes and 0.03 MMTCE from cleaning process *[Beu and Brown 1998]*.

2.1.3. Distribution of Semiconductor Industry Sources

In the U.S. in 2000, fewer than half of the (roughly 100) organizations operated fewer than three-quarters of U. S. fabs (roughly 190) and accounted for 90% of the total design capacity (1.8 million wafer starts per month (200 mm equivalents)). The range in the 200 mm equivalent capacities of fabs operated in 2000 was broad—from as few as a few hundred wafer starts per month to as many as 50,000 wafer starts per month. Of the total 1.8 million wafer design capacity of the industry in 2000, approximately 19% of the companies managed two-thirds of that capacity (and operated 46% of the fabs), while 44% of the companies managed 90% of the design capacity (and operated 72% of the fabs). In addition, 94% of the U. S. design capacity in 2000 was used to manufacture logic units (e.g. multiprocessor units) and memory units (e.g., DRAM) *[Burton and Beizaie 2001]*. Logic and memory ICs are, generally, the most complex devices made in volume *[ICE 2000]*.

2.2. Methods for Estimating PFC Emissions

All methods for modeling uncontrolled emissions from any source are conceptually simple and similar: they employ some form of mass balance around the materials used in the processes that produce the emissions for a specified operating period. Emissions are modeled as the product of two factors that are representative of the period, location and process: one factor expresses the activity that produces the emissions and the second factor defines the emissions per unit of that activity. Other factors may also be used to account for post-process control.

Modeling PFC emissions from semiconductor manufacturing then is similarly simple. Complications may arise depending on the availability of suitably representative data and the intended use of the result. As noted at the beginning of this chapter, two broadly conceived methods may be used to model PFC emissions from semiconductor manufacturing. They differ in their unit of activity, which in turn requires different emission factors.

The first method takes the unit of activity as PFC-gas usage during the process and expresses the emission factor as the utilization (and formation) of PFCs during the process, expressed as either a mass or mole percent of the incoming PFC gas. The unutilized and formed PFCs in the process comprise the uncontrolled emissions.

The second method takes the unit of activity as silicon consumption and expresses the emission factor as the PFCs emitted (both unused and formed) during the use (or consumption) of silicon. More specifically, in this method, it is the “effective” silicon used during IC manufacture that governs PFC emissions. This effective silicon exceeds the total silicon output (working and defective ICs) because, as mentioned previously, as the density of IC components increases, so generally does emissions due to the increase in the number of wiring levels.

The first method was first outlined by Worth *[Worth 1996]*, and also expanded on by Beu *[Beu 1996]* and Burton, Vranka and Steiner *[Burton et al. 1996]*. Further, the first method has received extensive consideration *[Beu and Brown 1998, Beu et al. 2000, IPCC 2001]*. The second—the silicon consumption method—is presented in this report for the first time.

2.2.1. PFC Usage Method

The PFC usage method, provided the information is available, can account for each PFC used and PFC formed by etch and CVD cleaning process type. This method is named Tier 2A and is described in detail in the Revised IPCC Guidelines for National Greenhouse Gas Inventories (Ref. 5). For PFC gas i, process p, used at facility k under company operation, the mathematical representation of the Tier 2A method is expressed in equations 1 and 2:

$$\text{Emissions of PFC}_{i,,j,k} = (1 - h_{i,k}) \sum_{p=1}^{NP} [\text{PFC}_{i,p,k}\ (1 - C_{i,p,k})\ (1 - a_{i,p,j,k}\ d_{i,p,j,k})] \qquad (1)$$

where

p	denotes the process or process type, viz., etching or PECVD cleaning and *NP* denotes the total number of such processes.
$PFC_{i,p,k}$	denotes mass of gas i fed into process/process type p (for all gases) at facility k under company operation.
$h_{i,k}$	denotes the fraction of gas i that remains in the shipping container (the heel) after use a facility k under company operation.
$C_{i,p,k}$	denotes the mass use rate (fraction destroyed or transformed) of gas i and process p at facility k under company operation.
$a_{i,p,j,k}$	denotes the fraction of gas volume i used in processes that control emissions using technology type j, which includes no control, at facility k under company operation.
$d_{i,p,j,k}$	denotes the fraction of gas i destroyed the application of emission control technology j, which includes no control, from process p at facility k under company operation.

$$\text{Emissions of } PFC_{CF4,,j,k} = (1 - h_{i,k}) \sum_{p=1}^{NP} [B_{i,p,k}\ PFC_{i,p}\ (1 - a_{i,p,j,k}\ d_{CF4,p,j,k})] \qquad (2)$$

where, in addition to the previous definitions of symbols,

$B_{i,p,k}$	denotes the fraction of gas i transformed into CF_4 for each process/process type p at facility k under company operation.
$d_{CF4,p,j,k}$	denotes the fraction of CF_4 by-product destroyed by the emissions control technology.

In this description, it is assumed that only CF_4 can be formed during the process, although this “simplification” could be removed if necessary. The total PFC emissions from facilities under company operations is summed over the all facilities PFCs i, all k facilities and all applicable control technologies j.

Under simplifying assumptions, the information and resource requirements needed for using equations (1) and (2) may be reduced. For example, if one assumes that the indexed parameters can be replaced with appropriate averages, equations (1) and (2) could be simplified to

$$\langle PFC \rangle = (1 - \langle h \rangle)\ [\langle PFC\text{-input} \rangle\ (1 - \langle c \rangle)\ (1 - \langle a \rangle \langle d \rangle)] \qquad (3)$$

$$\langle PFC_{(CF4)} \rangle = (1 - \langle h \rangle)\ \langle B \rangle\ \langle PFC\text{-input} \rangle \qquad (4)$$

where the brackets <x> denote appropriate population averaging for the parameters, $h_{i,k}$, $PFC_{i,p,k}$, $C_{i,p,k}$, $a_{i,p,k,j}$, $d_{i,p,k,j}$ and $B_{i,p,k}$. In principle, equations (3) and (4) might be used at the company or country level, provided suitable averages can be formed for each of the variables.

In practice, the IPCC does not support such a simple approach, i.e., averaging over all PFC gases. The IPCC does support, however, forming process average emission factors.

This method defined by equations (1) and (2) requires considerable specific knowledge about PFC usage and process effects on PFC utilization and formation. This method and its simplifications appear, by virtue of IPCC adoption, sufficiently reliable and useful for estimating annual PFC emissions from the semiconductor industry *[Beu 2000]*.

The IPCC methods (and its simplifications) did not seem suitable for the PEVM, principally because the PEVM is intended for projecting emissions. Adoption of the IPCC methodology for the PEVM requires routinely available third-party estimates of contemporary and projected PFC usage. While worldwide PFC-use surveys have been performed (at least for the period 1992–1996), we learned from the Semiconductor Industry Association (SIA) that such surveys were no longer conducted. In researching this topic, we also learned that projections of PFC use for semiconductor manufacturing were not publicly available, even if they were made. The absence, therefore, of point estimates, trends and projections of PFC usage information prompted us to develop the second-silicon consumption-method for estimating and projecting PFC emissions, which is introduced next.

2.2.2. Silicon Demand/Consumption Method

The PFC silicon demand/consumption method for modeling emissions, as defined and used in this report, does not distinguish between specific PFC gases and specific processes, viz., etching and CVD cleaning. The mathematical representation of PFC emissions used in the PEVM is

$$\mathrm{PFC}(y) = \sum_{t(y)}^{\mathrm{T}(y)} \langle e_{t(y)} \rangle\, S_{t(y)} \qquad (5)$$

where

PFC(y) denotes the U. S. total PFC emissions (including PFC formation) for year y for all PFCs from all processes in year y.

$\langle e_{t(y)} \rangle$ denotes a PFC-process population average emissions factor for linewidth technology t in year y.

$S_{t(y)}$ denotes the silicon consumed that used linewidth technology t in the U. S. in year y.

The sum in equation (5) is taken over all linewidth technologies that were either used to manufacture ICs in a historical year or are projected to be used in some future year, and denoted as T(y). For any future year, the ITRS provides the projected years for which IC production will begin using each linewidth technology. For a contemporary year, SEMI's WFW database provides the linewidth technology employed by each fab in the world.

The emissions factor, $<e_{t(y)}>$, has units of average PFC emissions per unit of silicon consumed at linewidth technology `t.` The formation and estimation of $<e_{t(y)}>$ is defined mathematically in the next chapter and operationally in Chapter 4. Suffice it to say here that $<e_{t(y)}>$ is formed from the aggregate of PFC emissions reported by partners and the corresponding aggregate estimate of partner silicon consumption for year y.

3. MODEL FORMULATION

The design of the PEVM starts from the accepted idea that annual PFC emissions is a function of annual silicon consumption during IC manufacture. Continuous innovations in manufacturing processes—motivated, guided and sustained by the industry's adherence to Moore's Law—drives growth in annual silicon consumption. More than the change in silicon consumption, however, contributes to the change in PFC emissions.

Important to the design of the PEVM is that PFC emissions, without the application of emission control measures, will likely grow faster than the rate of silicon consumption alone, albeit at a monotonically decreasing annual rate. The increased rate of PFC emissions can exceed the rate of silicon demand because a major target of manufacturing innovation is shrinking the size—increasing the density— of the active elements on the chip. Each increase in density, in turn, necessitates the manufacture of a more complex framework above the more densely "packed" active circuit elements in order to connect the active elements of the IC. With increasing complexity there are more levels on the chip. For each new level, more thin films are deposited and etched, which serve as insulators and "wires" and which require more PFCs. But the quantity of silicon consumed does not increase with increasing complexity, at least not proportionally to the increase in component density.

An example illustrates the relationship between silicon consumption, number of levels and PFC emissions. In going from 5 to 6 levels, PFC emissions would increase by 1/5th(20%) assuming PFC-use per unit area of consumed silicon per average level (or layer) does not change. So, in this example, even if the silicon demand did not increase, PFC emissions could increase by 20%. If, in addition to increasing the number of levels by 20%, silicon consumption increased by 10% over the previous year—the long-term compound average growth rate (CAGR) for worldwide silicon consumption—the increase in PFC emissions from the combined effects would be 32% (= [1.1 x 1.2] - 1).

Another effect on PFC emissions from shrinking feature sizes is that, for a uniform rate of growth in silicon, the *rate* at which PFC emissions increases, due to increasing numbers of levels, decreases. Returning to the previous example, extension of the number of levels from 6 to 7 and under the assumption of a 10% growth in silicon consumption, the yearly increase in PFC emissions would then be 28% (= [1.1 x {1 + 1/6}] - 1), somewhat slower than the 32% increase for the change from 5 to 6 levels. The formulation of the PEVM accounts for the combined effects of increasing silicon demand and the number of device levels.

The formulation of the PEVM rests on two interlocking, equiponderant notions. The first is that annual PFC emissions from IC manufacture should be proportional to the annual silicon demand (consumed) for *each* manufacturing (linewidth or "shrink") technology used during a specific year. The second is that a suitable emissions factor can be formed from available year-specific Partner reports of PFC-process average emissions and from appropriately developed estimates of silicon consumption (by linewidth technology) for that year. The PEVM uses such an emissions factor together with corresponding estimates of silicon consumption (weighted by the effective number of layers associated with each linewidth technology) to obtain an estimate of the linewidth-specific U. S. PFC-process average emissions. The PEVM produces an estimate of the total PFC-process average emissions for year y by summing over all linewidth technologies used in IC manufacturing.

3.1 Overview of Model and Its Structure

Version 2.14 of the PEVM merges, uses and manages information from four major sources in three basic steps. Information comes from Partners, Semiconductor Equipment Manufacturers International (SEMI), VLSI Research Incorporated, and the International Technology Roadmap for Semiconductors. The three steps are: (1) formation of PFC-process average emission factors, (2) projection of silicon consumption to 2010, and (3) projection of emissions to 2010 under alternative assumptions with respect to manufacturing methods and measures for reducing emissions. This section describes each of these steps, with emphasis on the sources of information. Chapter 4 provides more operational details about these steps, after we develop the PEVM's mathematical formulation in the next section, Section 3.2.

3.1.1. Formation of PFC-Silicon Consumption Emission Factors

The PEVM uses PFC emissions and silicon consumption information for the period 1995–1999 to form the emissions factors. For each year, the PEVM develops an emission factor in three steps, which is required by virtue of the silicon consumption data that VLSI Research publishes. These three steps are:

1. Divide Partner reports of PFC-process aggregated emissions by estimates of silicon consumed by Partners, a factor that expresses emissions per unit of area silicon consumed.
2. Recast the emissions factor formed in Step 1 into one that expresses Partner emissions per unit area of Partner-consumed silicon per *average* layer of Partner-manufactured IC.
3. Form a linewidth-technology-specific emissions factor by multiplying the result from Step 2 by the effective number of layers used by Partners in IC manufacture.

The formulation of the PEVM assumes that the result of Step 2, after some averaging, is typical and applicable to the entire semiconductor industry that uses PFCs. It follows then the linewidth-technology-specific emissions factor formed in Step 3 is similarly typical of the entire semiconductor industry.

Latham & Watkins, the law firm that administers and maintains files of Partner-submitted emissions for the Partnership, provides the aggregate Partner PFC-process average emissions for each year. VLSI Research publishes worldwide silicon consumption data for different years by various categories (wafer size, number of wafers, product types, and wafer starts by linewidth technology), which the PEVM uses to obtain estimates of linewidth-specific silicon consumption. The PEVM also uses information from SEMI's World Fab Watch database to produce estimates of U. S. and Partner shares of world linewidth-specific IC production. Finally, the PEVM uses the latest published version of the ITRS to obtain figures for the number of layers associated with each technology node (linewidth technology) and allows for that number to vary by IC according to the nominal values provided in the latest ITRS, viz., whether the IC is a logic, memory or application-specific device.

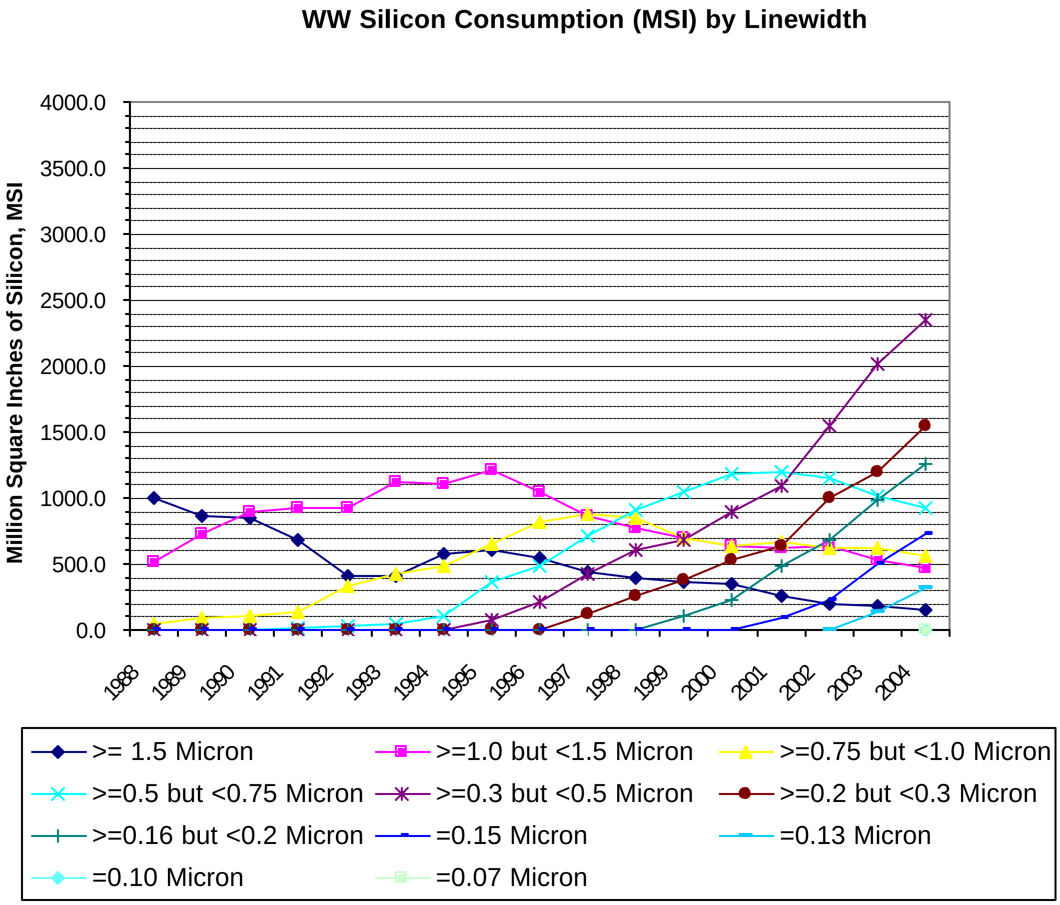
3.1.2. Projection of Silicon Consumption to 2010

VLSI Research also publishes projections of *world* silicon consumption used to manufacture ICs that can be recast in terms of silicon consumed by linewidth technologies. However, the PEVM recasts these figures by making three adjustments. First, the PEVM extends the VLSI's projections to 2010, beyond the five-year projection horizon published by VLSI. For example, projections published in calendar year 1999, extend only to 2004. Second, the PEVM adjusts the 2010 projections to reflect on the silicon that encounters PFC. The base silicon consumption figures published by VLSI include *all* wafers used to manufacture ICs, which includes test wafers, of which some portion do not encounter PFCs. Third, the PEVM uses estimates of U. S. shares of world layer-weighted estimates of silicon consumption to estimate the corresponding U. S. layer-weighted silicon consumption.

To project silicon demand by linewidth technology to 2010, the PEVM needs information about future technology cycles—their onset, adoption/penetration/expansion rates, maximum consumption of silicon and decay rates/lifetimes—as well as the growth rate in aggregate silicon demand (i.e., over all linewidth technologies). VLSI Research provides information about aggregate silicon growth, which we confirmed separately using reports published by ICE, Inc and IC Insights. The ITRS provides information about nominal technology cycles, which we confirmed using reports published by ICE, Inc., equipment manufacturers and several financial analysts who closely track and write succinctly about the industry (e.g., SG Cowen and Deutsche Bank Alex Brown). The remainder of this section provides a description of approaches we implemented and evaluated, and the approach eventually implemented in the PEVM.

Our analysis of the historical data for the period 1983 to 1998 revealed consistent patterns for silicon demand by each technology cycle—defined as the onset, rise and decay of each major manufacturing (or process technology) advance and marked by a 30% reduction in feature size every 3 years (for example, from feature sizes of 0.35 um in 1995 to 0.25 um in 1998). The nominal start of each cycle is specified in the ITRS *[ITRS 2000]*. Each cycle for the period 1983 to 1998—which covers feature size reductions from 1.5 µm to 0.25 µm—showed a consistent pattern: a 10-year expansion phase with slightly increasing penetration rates followed by a decay in silicon consumption. (See Figure 3-1).

Figure 3-1.
VLSI Published Silicon Consumption by Linewidth, 1998–2004



To reflect these cycles, we examined two approaches—one mathematically compact and elegant and the other brute-force-simple. The first entailed using a mathematical model to quantitatively reproduce and project the observed patterns. The second relied on qualitative, “hand-drawn” renditions of the observed patterns. For reasons that we describe next, we chose the latter for the PEVM.

We discovered that a four-parameter function could reliably reproduce the observed patterns. We defined and obtained that function by convolution of the symmetric Gaussian distribution, which describes the probability of penetration of a linewidth technology, with a triangular function, which describes the end of the penetration some period after the start of a cycle and, going forward therefrom, at a constant yearly decay rate to 2010. The area encompassed by the function represents the total silicon consumed for that linewidth technology over the period 1995 to 2010.

It turned out that the implementation of the a four-parameter model within the PEVM proved somewhat unreliable and too complex—less simple than necessary. For example, each technology cycle for each start year required estimation and projection of four parameters as functions of the overall and technology-specific silicon demand, which would then have to be constrained by overall silicon demand as it changed over time.[5]

We chose not to adopt the four-parameter model for the PEVM. We had neither the resources nor credible insights to evaluate and test such a "business model;" the challenges increased rapidly in light of requirements to extrapolate/project/estimate the (four technologically- and business-determined) parameters.

Instead, we adopted the next simplest approach: project consumption in a way that qualitatively preserves the "shape" of the historical curves, which implicitly account for start, penetration/expansion and decay. With this conceptually simple but brute-force method, we could also qualitatively adjust cyclic profiles for each technology, guided by available trade and analyst reports about business and technological innovations/challenges. We could also scale up or down all or portions of the profile for each technology cycle according to consensus estimates of the penetration of each technology, the fraction of total silicon demand that the technology might command and factors that influence faster adoption, penetration and/or decay of any specific cycle.

It might be argued that using "hand-drawn" renditions of historical patterns of projected silicon are objectionably subjective and that projections from a mathematical model are advantageously objective. We would argue, at this time, that the objectivity of such model-derived projections is a mathematical illusion—engendered by misconstruing parameter selection to be objective instead of the subjective procedure it really is.

Finally, the projected silicon demand described thus far includes *all* silicon wafers—the wafers that form ICs and the test wafers that assure process quality. This projected silicon demand overstates the silicon that is processed with PFCs. The PEVM corrects this projected silicon by first removing just the portion attributed to test wafers, which we obtain from VLSI. The total amount of test wafers is then reduced to account for just the portion that encounters PFC during etch, cleaning and ashing processes. This reduced amount of test wafers is then added to the total silicon used to form ICs to give the total silicon demand, including a portion for processed with PFCs.

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[5] We also tried well-known distributions used to describe time-dependent stochastic processes, viz., the Poisson, Gamma, Weibull, and log-normal distributions. None of these alternative, simpler distributions could reliably and consistently reproduce the patterns observed over the historical period.

3.1.3. Projection of U. S. PFC Emissions to 2010

The PEVM projects U. S. PFC emissions to 2010 by multiplying the projected linewidth-specific silicon consumption figures by the corresponding linewidth-specific emissions factors. As described in the previous sections, technological and business factors affect silicon projections. Other factors affect linewidth-specific emissions factors. The PEVM is configured to explore projected emissions under a variety of situations that affect emissions.

EPA intends to use the PEVM to project PFC emissions to 2010 for two categories of scenarios. The categories are:

1. Business-as-usual (BAU) scenarios, which include technological advances not explicitly intended to reduce PFC emissions but which may serendipitously do so. There are at least two examples. First, the industry's switch from aluminum to copper for connecting active elements reduces the number wiring levels (by as much as 50% although this large a reduction has not been reported) and therefore PFC emissions. Second, with the use of copper comes the requirement to use of low-K and ultra-low-K dielectric thin films at and below the 0.13 μm technology node. Spin-on rather than CVD technology is an apparently attractive process for applying these films, which does not require PFC use.

2. Alternative emission control scenarios, which include the application of combinations of technologies to reduce emissions from CVD-cleaning or etching processes, alternative schedules for applying emission reduction measures (which for the most part are determined by schedules for the technology nodes) and alternative assumptions about silicon growth. The PEVM permits examination of these scenarios to attain and maintain (or exceed) the industry's 2010 emissions target.

3.1. Mathematical Formulation

The formulation presented in this section uses conventional mathematical methods, although the notation may first appear somewhat cumbersome. In the next chapter, the report presents the implementation of this formulation as an Excel application, using a detailed flowchart as an organizing device.

3.2.1. Estimation of Year-Specific Linewidth-Specific U.S. PFC-Process Average Emissions

Version 2.14 of the PEVM estimates U. S. PFC-Process linewidth-specific emissions from the corresponding world estimate, PFC_w (y). The PEVM obtains PFC_w (y) by summing over world estimates of emissions for each linewidth technology (node) t (y) for year y, i.e.,

$$\mathrm{PFC}_w(y) = \sum_{t(y)=1}^{T(y)} \mathrm{PFC}_{w,\,t}(y) \qquad (6)$$

where t is a function of the year. For any year, y, there are T manufacturing technologies in use. For example, in 1995, there were 6 processes that used PFCs, i.e., T (1995) = 6 for the six linewidth intervals: >=1.5 m m; >=1.0 m m to <1.5 m m; >=0.75 m m to <1.0 m m; >=0.5 m m to <0.75 m m; >=0.3 m m to <0.5 m m; and <0.3 m m.

The PEVM estimates U. S. emissions for year y by multiplying quantities $\mathrm{PFC}_{w,\,t}(y)$ by the U. S. share of world silicon consumption for each linewidth technology, denoted by g (C(y), t (y)), where C denotes fab capacity. The PEVM then estimates the PFC-process average U. S. emissions for year y from equation (7), viz.,

$$\mathrm{PFC}_{US}(y) = \sum_{t(y)=1}^{T(y)} \mathrm{PFC}_{US,\,t}(y) = \sum_{t(y)=1}^{T(y)} g\,(C(y),\, t\,(y))\, \mathrm{PFC}_{US,\,t}(y), \qquad (7)$$

where once again the summation is taken over all T (y).

The yearly shares, g (C(y), t (y)), are defined (and obtained) for year y using the formula

$$g\,(C(y),\, t\,(y)) = \left\{u_{US} \sum_{i=1}^{NUS} C_{US,i}(y)\ l_i(p(y),\, t\,(y))\right\} \Big/ \left\{u_W \sum_{i=1}^{NW} C_{W,i}(y)\ l_i(p(y),\, t\,(y))\right\}, \qquad (8)$$

where the summations are taken over all U. S. and World (production, R&D and pilot) fabs, designated NUS and NW, respectively. $u_{US,\,\tau(y)}$ and $u_{W,\,\tau(y)}$ denote, respectively, the average utilization of US and world fab capacity. $C_i(y)$ denotes the capacity of each fab (in units of million square inches of capacity in year y). l_i(p(y), t (y)) denotes the number of layers associated with product type p(y) and linewidth technology t (y) for year y at the i^{th} US or World fab. In this formulation, there are three product types: logic, memory and application-specific ICs. Nominal values of l for each product type are provided in the ITRS.[6] The WFW denotes products manufactured at each fab.

PEVM uses estimates of the quantities $C_i(y)$ and the corresponding technologies t (y) from the WFW database for year y for all US and World fabs.

Because it turns out that publicly available figures for U.S. and world fab average capacity utilizations are not generally available and both industry experts and industry-analysts report that, for this global industry, U.S, and world figures are practically indistinguishable, we rewrite equation (8) somewhat more simply as,

$$\gamma_{\tau(y)} = \left\{ \sum_{i=1}^{NUS} C_{US,i}(y)\ l_{i}(p(y),\ t\ (y)) \right\} / \left\{ \sum_{i=1}^{NW} C_{W,i}(y)\ l_{i}(p(y),\ t\ (y)) \right\}, \qquad (9)$$

We now turn to a discussion of our formulation for forming and estimating linewidth-specific emissions factors, which the PEVM needs to calculate world PFC emissions.

3.2.2. Formation of Linewidth-Specific PFC-Process Average Emission Factor

As we described previously in Chapter 2, we estimate PFC-Process average emissions using

$$PFC(y) = \sum_{t(y)=1}^{T(y)} \langle e_{t(y)} \rangle\ S_{t(y)} \qquad (5)$$

where $\langle e_{t(y)} \rangle$ denotes a PFC-process population average emissions factor for linewidth technology t (y) in year y, and

$S_{t(y)}$ denotes the silicon consumed that used linewidth technology t (y) in the U. S. in year y.

The sum in equation (5) is taken over all linewidth technologies that were used to manufacture ICs in a historical year or are projected to be used in some future year.

We form the set of emissions factors given by $\langle e_{t(y)} \rangle$ in three steps:

Step 1: Form an aggregate emissions factor, $\langle E_y \rangle$, that expresses the PFC-process average emissions per unit of silicon consumed, which does not explicitly account for the linewidth technology used during IC manufacture.

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[6] Version 2.14 of PEVM uses only a single value for ?. It was only with publication of the 2000 update of the ITRS in 2001 that the three product distinctions were made in the ITRS, after v2.14 was completed.

Step 2: Form a per average layer emissions factor, $<e_y>$, which expresses the PFC-process average emissions per unit of silicon consumed per *average* layer manufactured for all linewidth technologies and only implicitly reflects linewidth technology during IC manufacture.

Step 3: Form $<e_{t(y)}>$, the PFC-process average linewidth-technology-specific emissions factor.

A discussion of each step follows.

Step 1 consists simply of dividing the aggregate partner emissions by the quantity of silicon consumed by Partners in year y, $S_{P(y)}$. We obtain $S_{P(y)}$ from the WFW database for year y using an expression similar to equation (9), which reflects the Partner share, $\gamma_{P(y),\tau(y)}$ of world silicon consumption for year y, i.e.,

$$<E_y> = PFC_{P(y)} / S_{P(y)} \tag{10}$$

where

$$S_{P(y)} = \sum_{t(y)=1}^{T(y)} g'(C(y), t(y))\, S_{w(y)}. \tag{11}$$

The PEVM uses the WFW database for year y to obtain $S_{w(y)}$ and to estimate $g'(C(y), t(y))$, Partner shares (designated by the prime) of world silicon consumed for each year y.

Step 2 consists of disaggregating $<E_y>$ into the components that reflect the emissions per unit of silicon consumed for the linewidth technologies used by all Partners, $S_{P(y)}$, to manufacture ICs in year y. The PEVM accomplishes this by performing a PFC emissions mass balance defined by equation (12), viz.,

$$<E_y>\, S_{P(y)} = PFC_{P\,(y)} = \sum_{t(y)=1}^{T(y)} \sum_{p=1}^{3} \sum_{P=1}^{NP} <e_y>\, l_{\tau(y),\, p(c)}\, S_{p(c),t(y),P(y)}$$

$$= <e_y> \sum_{t(y)=1}^{T(y)} \sum_{p(c)=1}^{3} l_{\tau(y),\, p(c)}\, S'_{p(c),t(y)} \tag{12}$$

where $l_{\tau(y),\, p(c)}$ denotes the number of layers associated with each linewidth technology and product class (logic, memory and application-specific ICs) *p(c)* used by Partners in year y, which is obtained from the ITRS and WFW database, $S'_{p(c),t(y)}$ is the silicon consumed by Partners for each product class and linewidth technology, which is obtained using the WFW database for year y and extracting only Partner fabs operated in year y noting the product class and linewidth technology used at those fabs.

Equation (12) can be solved for $<e_y>$ to give

$$<e_y> = <E_y>\, S_{P(y)} \Big/ \sum_{t(y)=1}^{T(y)} \sum_{p(c)=1}^{3} l_{\tau(y),\, p(c)}\, S'_{p(c),t(y)} \quad . \tag{13}$$

The *per average-layer* emissions factor represents then the aggregate Partner emissions divided by the average number of layers, $< l_{\tau(y),\, p(c)} >$ for applicable product class and linewidth technologies used during IC manufacture by the Partners in year y, where $< l_{\tau(y),\, p(c)} >$

$$< l_{\tau(y),\, p(c)} > \equiv (1/\, S_{P(y)}) \sum_{t(y)=1}^{T(y)} \sum_{p(c)=1}^{3} l_{\tau(y),\, p(c)}\, S'_{p(c),t(y)} \, . \tag{14}$$

Step 3, formation of the linewidth-specific emissions factors $<e_{t(y)}>$ using equation (15).

$$<e_{t(y)}> = <e_y> \sum_{p(c)=1}^{3} l_{\tau(y),\, p(c)} \quad \omega_{p(c)}(\tau(y)) \tag{15}$$

Equation (15) reflects the multiplication of the *per average-layer* emissions factor by the product-class-weighted average number of layers for technology τ for year y. The weights, $\omega_{p(c)}(\tau(y))$, represent the fraction of layer-weighted capacities by the Partners for each linewidth technology and each of the three product classes in year y, which is published by VLSI. In equation form, $\omega_{p(c)}(\tau(y))$ is defined by equation (16), viz.,

$$\omega_{p(c)}(\tau(y)) = S'_{p(c),t(y)} \,/\, S_{P(y)} \tag{16}$$

Before concluding this section, we wish to present a practically useful observation, which we anticipated and which prompted us to consider our three-step approach for developing silicon-consumption-based emission factors. We expected $<E_y>$ to show significant yearly variation because, as noted previously, changes in emissions should be influenced by changes in both silicon consumption and the number of layers added to that silicon during IC manufacture. Importantly however, we expected to observe little or no trend in the *per average-layer* emissions factor, $<e_y>$, over some reasonably long period, say 5 years, provided a significant share of Partners did not adopt major manufacturing changes that influence PFC use or did not implement, in a major way, measures to reduce PFC emissions. If the estimates of $<e_y>$ show only random variations, then we could justify averaging them to form a relatively robust, yearly invariant *per average-layer*, $<e>$. This factor, we could then use in BAU projections.

Table 3-1 presents the results for $<E_y>$ and $<e_y>$, over the period 1995 to 1999, a period when Partner emission reports indicate no substantial, if any, application of emission control measures.[7] Industry reports indicate no major penetration of any new manufacturing methods. The results in Table 3-1 support averaging the yearly values of $<e_y>$ to form $<e>$.[8] We exclude 1995, the first for which SIA published the WFW (then called the Fabs On Disk database) because it contained an unusually large fraction of missing information, which in subsequent years was substantially reduced.

The average value, $<e>$, and standard deviation for the 1996 to 1999 period are, respectively, 0.60 and ±0.03 MMTCE/BSI-layer. That the value for $<e_{1995}>$ lies outside the 90% confidence interval of ±0.06 for the average of values for the 1996–1999 period supports excluding the $<e_{1995}>$ in estimating $<e>$.

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[7] Partner emission for 2000 appear to reveal the effect of employing emission reduction measures, which is why we exclude 2000 for the purpose of estimating this BAU per average-layer emissions factor.

[8] The only reported manufacturing change that effects PFC emissions is the use of copper interconnects in late 1998. Using copper reduces the number of interconnect layers by as much as 50% although its effect on PFC use is less. By 2001, copper-interconnect technology accounted for between 3–5% of logic IC manufacture *[Yanamandra 2001]*. We interpret this to mean that copper use had no substantive effect on Partner emissions in 1998 and 1999.

Table 3-1.
Silicon Normalized Emission Factors Formed Using Partner Reported Emissions and PEVM Estimates of Silicon and Layer-Weighted Silicon Consumption for Years 1995–1999

Emissions and Emissions Factor Metric	1995	1996	1997	1998	1999
Partner emissions, MMTCE	0.85	1.02	1.17	1.28	1.38
Per unit area emission factor, $<E_y>$,g/in2 Si (Note 1)	0.98	0.76	0.83	0.95	1.05
Per unit area emission factor, $<E_y>$, MMTCE/billion in^2 (BSI) Si	2.49	1.93	2.1	2.42	2.67
Per average layer emission factor, $<e_y>$, g/(in^2 Si)(layer) (Note 1)	0.31	0.23	0.23	0.24	0.25
Per average layer emission factor, $<e_y>$, MMTCE/(billion in^2[BSI] Si,)(layer)	0.79	0.58	0.57	0.62	0.64

Note 1. To convert Partner MMTCE emissions to grams, we used the weighted average global warming potential (GWP) of 9300 MMTCE based on 1996 world gas-specific sales ($) and market prices, $/lbs *[Burton 1997]*.

3.2.3. Formation of Emissions Matrices: BAU, Process- and Gas-Specific and Controlled Emissions Matrices

As noted at the outset of Section 3.2.1, the PEVM estimates U. S. PFC-Process average emissions, $PFC_{US(y),\ \tau(y)}$, as a function of year and linewidth technology. The values for $PFC_{US(y),\ \tau(y)}$ may express BAU, process-specific, gas-specific and controlled emissions. Each alternative set of emission values is estimated under an alternative assumption about future technology and business conditions.

To generate the alternative emission values, it is convenient to express the BAU process- and gas-specific emission values as elements of a matrix, E_{BAU}. E_{BAU} is an n x m matrix, where n denotes the number of years (1995, 1996, …, 2010) and m denotes the technology nodes ($T_{1.5\mu m}$, $T_{1.0\mu m}$, $T_{0.75\mu m}$ ... , $T_{\leq 0.07\mu m}$) implemented over the same period. E_{BAU} , then, has the form

$$E_{BAU}[(n = 16) \times (m = 10)] = \begin{bmatrix} a & b & ... & 0 \\ k & l & ... & 0 \\ . & . & ... & . \\ ff & gg & ... & hh \end{bmatrix} \tag{17}$$

where the zeroes in the (1,10) and (2,10) positions denotes that in the years 1995 and 1996 technology node $T_{\leq 0.07\mu m}$ was not being used and hh in the (16,10) position denotes the PFC process- and gas-specific average emissions in 2010 from ICs produced using manufacturing technology that corresponds to $T_{\leq 0.07\mu m}$.

In the remainder of this section, we describe the generation of the BAU, the process-specific, gas-specific, and the controlled emission matrices, conventionally denoted, respectively, as E_{BAU}, E_{PS}, E_{GS} and $E_{C(i)}$. Because there are alternative control matrices, we index them with i.

Business-As-Usual Matrix: PFC-Process Average Emissions

We generate U.S. year- and technology-specific emissions for the BAU matrix, E_{BAU}, from our estimates of world PFC emissions, as noted previously. Specifically, the elements of E_{BAU} are developed from scaled estimates of $PFC_{W(y),\tau(y)}$, according to the equations that follow.

$$PFC_{W(y),\tau(y)} = PW_{i,j} \equiv \langle e_{\tau(y)} \rangle \, S_{W(y),\tau(y)}, \tag{18}$$

where $\langle e_{\tau(y)} \rangle$ denotes the average technology-node-specific emission factor for a business as usual scenario and $S_{W(y),\tau(y)}$ denotes the projection of silicon demand for the same business as usual scenario. For example, if one assumes that a future business-as-usual scenario should include the use of copper interconnects, then the effective number of layers used for each linewidth technology would be reduced appropriately, which would be reflected in lower values for the corresponding emission factors, $\langle e_{\tau(y)} \rangle$. Analogously, adjustments could be made to account for use of CMP and/or spin on dielectrics, which would reduce the emissions factor, respectively, for etch and CVD components. We do not consider such adjustments in this version of PEVM.

The corresponding emissions for the US are obtained by scaling the world estimate using an estimate of the U. S. technology-weighted share of world silicon capacity, $\gamma_{\tau(y)}$, i.e.,

$$PFC_{US(y),\tau(y)} = \gamma_{\tau(y)} \, PFC_{W(y),\tau(y)}.$$

Therefore,

$$E_{BAU} = [\, PFC_{US(y),\tau(y)} \,]. \tag{19a}$$

The emissions for each year can be projected from E_{BAU} by using the vector/operator I, to give,

$$E¢_{BAU(y)} = E_{BAU} \times I, \tag{19b}$$

where

$$\mathrm{I} = \begin{bmatrix}1\\1\\...\\1\end{bmatrix}. \tag{19c}$$

The (16,1) component of $\text{E¢}_{\text{BAU(y)}}$ (viz., $\text{E¢}_{\text{BAU(2010)}}$), then, is the BAU PFC-process average emissions for 2010, i.e., the emissions summed over all technology nodes τ used to manufacture ICs in 2010. The industry aims to reduce these emissions to 0.9 $\text{E¢}_{\text{BAU(1995)}}$, to which we will return at the end of this section.

Business-As-Usual Matrix: Process-Specific PFC-Average Emissions

For any business-as-usual emissions matrix, we can extract the process-specific PFC average emissions using two process-specific vectors we denote as $\mathrm{F}_{\mathbf{CVD},\tau}$ and $\mathrm{F}_{\mathbf{etch},\tau}$. Each vector has m x 1 dimensions such that each component equals the fraction of PFC emissions for technology τ, which is taken to be the same for each year, i.e., for any given technology τ, there is no (or at most an inconsequentially important) yearly variation in the fraction of the process-specific PFC-average emissions.

We then conveniently express the fraction of process-specific PFC-average emissions as

$$\mathrm{E}_{\text{CVD(y)}} = \mathrm{E}_{\text{BAU}}\ \mathrm{F}_{\text{CVD},\tau}\ , \tag{20a}$$

where the elements of the vector denoted as $\mathrm{F}_{\text{CVD},\tau(\text{T(i)})}$ and are the fractions of PFC emissions from CVD processes for technology τ, i.e., $\tau = \mathrm{T}_{1.5\mu\text{m}},\ \mathrm{T}_{1.0\mu\text{m}},\ \mathrm{T}_{0.75\mu\text{m}}\ ...,\ \mathrm{T}_{\le 0.07\mu\text{m}}$. As noted previously, we assume no significant yearly variation in the fractions, $[\phi_{1,\tau}]$, for each technology, $\tau = \mathrm{T}_{1.5\mu\text{m}},\ \mathrm{T}_{1.0\mu\text{m}},\ \mathrm{T}_{0.75\mu\text{m}}\ ...,\ \mathrm{T}_{\le 0.07\mu\text{m}}$]. As a review of matrix multiplication, equation (20a) can be rewritten symbolically as

$$\mathrm{E}_{\text{CVD(y)}} = \begin{bmatrix} a & b & ... & 0 \\ k & l & ... & 0 \\ . & . & ... & . \\ ff & gg & ... & hh \end{bmatrix} \times \begin{bmatrix} a \\ b \\ . \\ z \end{bmatrix} = \begin{bmatrix} aa + bb + ... + 0z \\ ka + lb + ... + 0z \\ . \\ ffa + ggb + ... + hhz \end{bmatrix} \tag{20b}$$

The vector $\mathrm{F}_{\text{CVD},\tau}$, then, acts as an operator the result of which is to project from E_{BAU} the vector $\mathrm{E}_{\text{CVD(y)}}$, the PFC-average emissions from CVD cleaning processes for each of the years 1995–2010.

Similarly, the emissions from etch are obtained using

$$\mathrm{E}_{\text{etch(y)}} = \mathrm{E}_{\text{BAU}}\ \mathrm{F}_{\text{etch},\tau}\ , \tag{21a}$$

where $\mathrm{F}_{\text{etch},\tau} = \mathrm{I} - \mathrm{F}_{\text{CVD},\tau}$ and I is defined by equation (19c). The vector $\mathrm{F}_{\text{etch},\tau}$, then, is the complement of $\mathrm{F}_{\text{CVD},\tau}$. $\mathrm{E}_{\text{etch(y)}}$ is a vector of which each element/component estimates the PFC-average emissions for years 1995–2010 for etch processes.

Another option is to assume that the fraction of emissions from CVD and etch processes do not vary by technology. In this alternative, F becomes $\mathrm{F}¢$, which we represent as $\mathrm{F}¢_{\text{CVD}}$ and $\mathrm{F}¢_{\text{Etch}}$ for, respectively CVD and etch processes. In these cases, the vectors $\mathrm{F}¢_{\text{CVD},\tau'}$ and $\mathrm{F}¢_{\text{Etch},\tau'}$ contain m constant fractions, $\phi_{\tau'}$ and $1 - \phi_{\tau'}$, respectively. Then, equations (20a) and (21a) become

$$\mathrm{E}_{\text{CVD(y)}} = \mathrm{E}_{\text{BAU}}\ \mathrm{F}'_{\text{CVD},\tau'} \tag{20b}$$

$$\mathrm{E}_{\text{etch(y)}} = \mathrm{E}_{\text{BAU}}\ \mathrm{F}'_{\text{etch},\tau'} \tag{21b}$$

where, as in equation (21a), $\mathrm{F}¢_{\text{etch},\tau'} = \mathrm{I} - \mathrm{F}¢_{\text{CVD},\tau'}$, ισ the complement of the vector $\mathrm{F}¢_{\text{CVD},\tau'}$. Version 2.14 follows the approach represented by equations (20b) and (21b). We have not performed sufficient research yet to support the use of (20a) and (20b).

Business-As-Usual Matrix: Gas-Specific Process-Average Emissions

By analogy to the methods used to extract estimates of the process-specific PFC-average emissions from E_{BAU}, we can also extract gas-specific estimates of process-average PFC emissions for each year. However, we do not develop the formulas for performing such an extraction at this time because, at this time, we do not have the evidence of the required information.

Business-As-Usual Matrix: Controlled PFC-Process Average Emissions

Using E_{BAU}, we can also project controlled emissions for pre-defined emission reduction control scenarios by defining an m x 1 control technology vector, $\mathbf{CT}_\tau$. Multiplication of E_{BAU} by $\mathbf{CT}_\tau$ gives an m x 1 vector whose components denote the controlled PFC-Process average emissions for each year, i.e.,

$$\mathrm{E}_{\text{CT-BAU(y)}} = \mathrm{E}_{\text{BAU}}\ \mathbf{CT}_\tau. \tag{22}$$

Each of the m components of the vector $\mathbf{CT}_\tau$ denote the net amount by which PFC-average emissions would be reduced by applying different or similar emission reduction technologies to CVD and/or etch processes for presumed penetration rates for each process and technology. Thus, the τ^{th} component of $\mathbf{CT}_\tau$ that uses control technology j to control CVD emissions with reduction efficiency ρ_j and penetration rate π_j and uses control technology i to control etch emissions with reduction efficiency ρ_i and penetration rate π_i is given by

$$\mathrm{CT}_\tau(j,i) = \{[f_{\text{CVD},\tau}\ (1 - \rho_{\text{CVD(j)},\tau})\ (1 - \pi_{\text{CVD(j)},\tau})] + [(1 - f_{\text{CVD},\tau})\ (1 - \rho_{\text{etch(i)},\tau})\ (1 - \pi_{\text{etch(i)},\tau})]\}. \tag{23}$$

PEVM can then examine alternative control strategies using alternative control measures applied to CVD and etch processes, each process and linewidth technology having its own reduction effectiveness and separate penetration rate.

Equations (22) and (23) can be solved, for all τ and control technologies applied to CVD and etch processes for each τ, to estimate, for example, the minimum amount of control needed to attain the WSC goal in 2010, viz., 0.9 $E¢_{BAU(2010)}$, the last component of the business-as-usual vector of emissions, $E¢_{BAU(y)}$, equation (19b). Because the solutions to these equation lay outside the scope of this version of the PEVM, we do not pursue them further here. Suffice it to say, however, that minimum amounts of control and/or control-costs are subject to the availability of knowledge about projected business conditions and costs of control, which appear to vary by company and fab. If available, such knowledge may be used to form constraints, which, when combined with established linear programming methods, can lead to estimates of optimum level(s) of control. This capability could be added to PEVM using Microsoft Excel®, which has the capability to solve such a linear programming problem.

4. FLOWCHART OF PEVM

This chapter, with the accompanying flow chart (Figure 4-1), describes the operation of PEVM (v. 2.14). The chart schematically shows the logical relationships between input data, input parameters and intermediate and major results. The organization of this chapter parallels the major portions of the flow chart. The flow chart contains five pictorial devices: arrows to denote operations, ovals to denote input parameters, single-lined boxes to denote intermediate results, and double-lined boxes to denote outputs. Boxes also contain bracketed italicized numbers of the *(x.y)*, where *x* denotes a major portion of the flow chart and *y* denotes a result within that portion. Text in this chapter uses these italicized references to guide readers to the relevant portions of this relatively complex chart.

The PEVM consist of 4 major portions, which are identified along the top of the flow chart and are distinguished by left-to-right shading:

1. Sources and types of information.
2. Development of PFC-process average emission factors.
3. Projection of silicon consumption to 2010.
4. Projection of emissions (MMTCE) to 2010.

In Section 3.1, the report identifies sources of information. The remaining portions of the PEVM, items 2–4 are described in the following sections.

4.1. Development of PFC-Process Average Emission Factors

The PEVM develops three sets of emission factors:

1. Per unit area emission factors (MMTCE/in^{2}Si consumed), a set consisting of one factor for each year 1995-2000
2. Per average layer emission factors (MMTCE/in^{2}Si*layers), a set consisting of one factor for each year 1995-2000
3. Linewidth-specific emission factors (MMTCE/in^{2}Si), a set consisting of one factor for each linewidth technology for each year 1995-2000.

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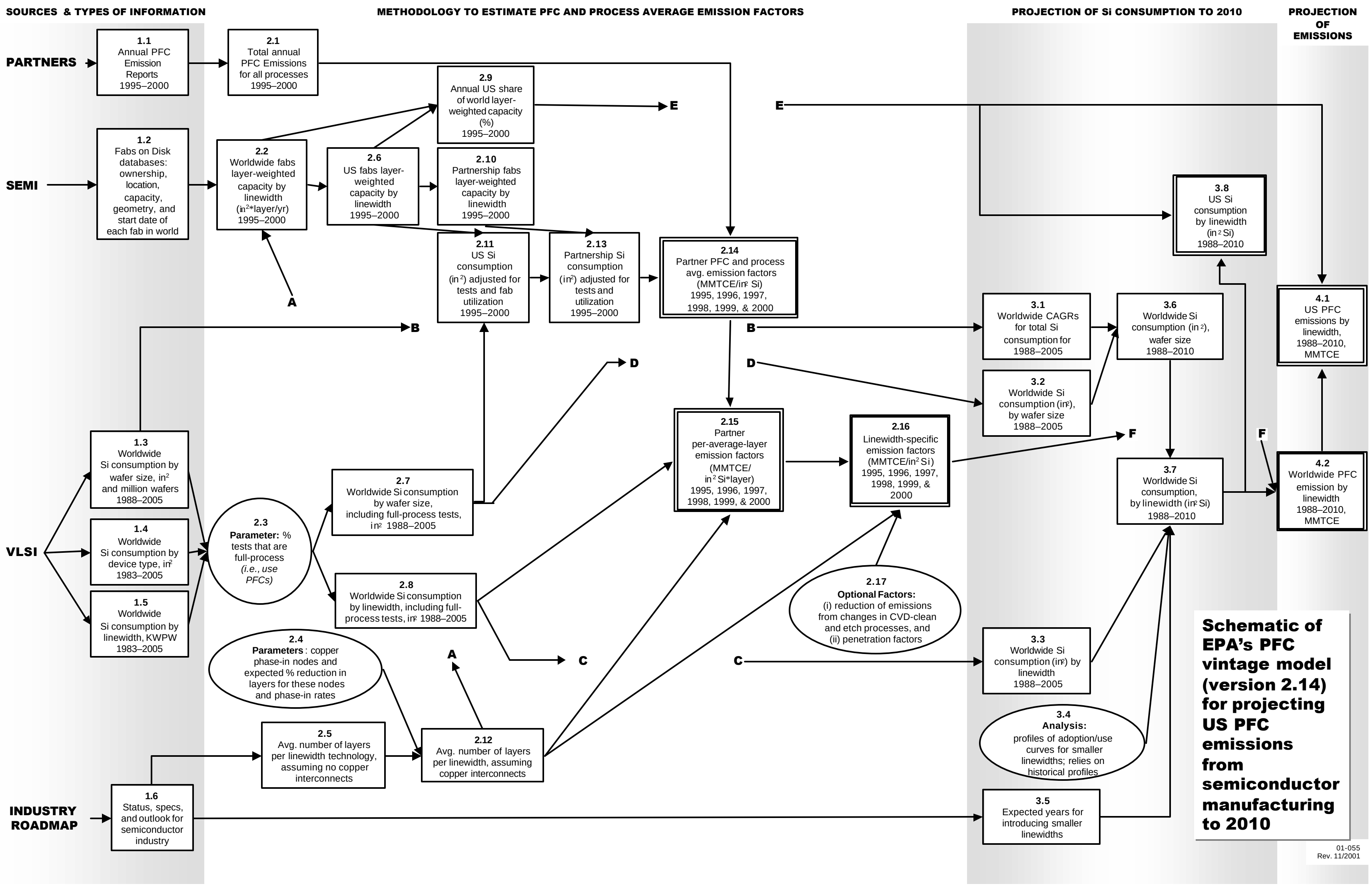
Figure 4-1
Model Flow Chart



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These three types of emission factors must be calculated in order, as each set of emission factors is a refinement of the previous set. Each factor is an estimate of the PFC-process average emissions per unit of activity that is directly related to IC manufacture. These factors do not account for emissions of specific PFCs or emissions from specific processes.

4.1.1. Per unit area emission factors

PEVM forms a per unit area emission factor for each year of the period 1995-2000. This emission factor estimates the amount of PFC emissions (MMTCE) per unit area (in^2) of silicon consumed, accounting for all silicon that encounters PFCs during manufacturing. Inputs required for the per unit area emission factors for each year are:

1. Total annual PFC emissions across all processes and gases. From the annual Partner submittals to Latham and Watkins *(2.1).*
2. Layer-weighted fab capacities (in^2Si-layers) for worldwide *(2.2)*, US *(2.6)*, and Partner *(2.10)* fabs. Capacity estimates come from year-appropriate SEMI World Fab Watch databases for the period 1995-2000. Information for layer-weighting comes from the ITRS.[9]
3. Worldwide silicon consumption data for 1995-2000, by wafer size *(1.3)* (which includes all test wafers used during IC manufacture) and by product (called device-type in the flow chart, which does not include test wafers) *(1.4)*, from VLSI Research.
4. User-prescribed parameter that reflects the percentage of test wafers that encounter PFCs, called the full-process test silicon *(2.3)*.

PEVM estimates the amount of worldwide full-process tests by applying a full-process parameter *(2.3)* to VLSI worldwide by product silicon-consumption data *(1.4)*. The full-process parameter is a user-prescribed input that corresponds to the test wafers that go through the entire manufacturing process (and thus encounter PFCs during IC manufacture), expressed as a percentage of all test wafers. The full-process test-consumption figure is added to VLSI's worldwide by-wafer-size-silicon-consumption figures *(1.3)* to arrive at worldwide silicon consumption by wafer size, including full-process tests, for each year 1995-2000 *(2.7)*.

PEVM compares the layer-weighted worldwide *capacity* figures to the test-adjusted worldwide *consumption* figures to estimate an industry average utilization rate. This utilization rate is then multiplied by the layer-weighted Partnership capacity (with tests) to calculate the Partners'

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[9] In version 2.14, PEVM uses a single estimate for the effective number of layers associated with each technology node, τ. When version 2.14 was completed, the ITRS had not yet presented nominal values for the number of metal layers for the major product classes. ITRS first published these values in the 2000 Update, too late to be included in version 2.14.

silicon consumption (in^2), adjusted for tests and utilization, for each year 1995-2000 *(2.13)*.[10] Finally, the Partners' submitted emissions (MMTCE) are divided by their adjusted annual consumption numbers to arrive at the Partner per unit area emission factors (MMTCE/in^{2}Si) for each year 1995-2000 *(2.14)*. PEVM assumes these Partner-derived emission factors apply worldwide.

4.1.2. Per average layer emission factors

PEVM then refines the per unit area emission factors by estimating the emissions associated with each layer of each unit area of silicon consumed. This follows from the recognition that emissions per unit of silicon depends on the complexity (number of layers) of the chip being manufactured. Specifically, production using smaller linewidth technologies (many layers) will result in higher emissions per unit area than production at larger linewidth technologies (fewer layers).

PEVM *(2.15)* first derives annual in^2 silicon consumed by linewidth by:

1. Calculating a weighted average wafer diameter for each year of the by-wafer-size-consumption data provided by VLSI, and
2. Applying those averages to the VLSI by-linewidth data, which are provided in units of KWPW (thousand wafer starts per week).

The PEVM then assigns a number of layers to each linewidth technology by using:

1. The ITRS *(1.6)*, and, optionally,
2. A set of reduction factors for the smaller linewidth technologies to account for the reduction of layers due to the use of copper interconnects *(2.4)*.

PEVM then apportions the total emissions for each year 1995-2000 into linewidth bins, which are weighted for consumption as well as the number of layers *(2.12)*. The annual values in each bin are then divided by the per unit area emission factor for that year, and the results are summed to achieve a per average layer emission factor (MMTCE/in^2-layer) for each year 1995-2000. *(2.15)* (See equation (13) in Section 3.2.2)

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[10] PEVM's estimate of capacity utilization is not the same utilization published by SIA and others. SIA estimates represent the fraction of a fab's design capacity that is utilized, which excludes test wafers. PEVM's estimate of fab "utilization" is a smaller number, typically 10 percentage points or so. PEVM's estimate is lower because it includes silicon used in testing , which does not actually find its way directly into product.

4.1.3. Linewidth-specific emission factors

The third and final set of emission factors is specific to each linewidth technology for each year 1995-2000. *(2.16)* For 1995-*1999*, the PEVM calculates these factors by simply multiplying the per average layer emission factor *(2.15)* for each year by the average number of layers (per SIA Roadmap) for each specific linewidth technology *(2.12)*.[11]

The year 2000 is done differently because unspecified abatement measures appear to have reduced Partner emissions. Because we do not know to which linewidth technologies the measures were applied, we cannot derive the 2000 linewidth-specific emission factors from the per average layer emission factors for 2000. Instead, we designed the PEVM to average the per-layer factors for the 1996–1999 period, which, as we described in Chapter 3, show little and random variation over this period. The 1995 emission factor is excluded from this averaging because we suspect it is overstated. 1995 was the first year SIA published the WFW database (then called the Fabs on Disk database) and we observed considerable amounts of missing entries, which we believe caused estimates of world capacity and partner capacity to be understated. This, in turn, would lead to overstated estimates of emission factors for 1995. (See Table 1, Chapter 3, where the entry for the per-layer emission factor exceeds the average by a factor of 1.3).

In the linewidth-specific emission factor calculations, PEFVM can accept emission reduction and penetration factors as well as a factor to account for copper use (and phase-in or penetration). In forming these factors, PEVM forms reduced-case emission factors. *(2.4, 2.17 and 2.16)* (Cf. Section 3.2.3, specifically text that follows Equation (18) for a discussion of this feature.)

4.2. Projection of Si Demand to 2010

This portion of PEVM calculates *worldwide* silicon consumption (in^2), by linewidth technology, to 2010. [*(3.1), (3.6), (3.7)*] For years up to 2005, the PEVM estimates the average wafer diameter of consumed silicon for each year. Each average diameter is then used to estimate annual silicon consumption for each linewidth technology, in in^2 of silicon. For the years 2006-2010, growth or decay curves are input to PEVM for each linewidth technology, as described in Section 3.1.2.

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[11] PEVM adds 1 to the nominal number of metal layers for each technology node. Additionally, in version 2.14, PEVM uses a single nominal values for each technology node—the value for IC logic devices—instead of a value weighted by product class. The distinction by the three product classes presented in Section 3.2.2 (Cf. Equation (13) was not included in pre-2000 versions of the ITRS.

4.3. Projection of US Emissions of PFCs (MMTCE) to 2010

PEVM calculates linewidth-specific *worldwide* emissions for each linewidth and each year to 2010 by multiplying the projected consumption figures by the linewidth-specific emission factors. Years prior to 1995 use the 1995 emission factors, while years following 2000 use the 2000 emission factors, as described above in Section 4.1.3.

PEVM calculates U.S. PFC emissions as a share of worldwide PFC emissions. The U.S. share of the worldwide emissions at each linewidth technology for each year is calculated by multiplying each worldwide figure by the layer-weighted share of US capacity at that linewidth for that year. 1995 shares are applied to all years prior to 1995, and 2000 shares are applied to all years after 2000.

5. APPLICATION OF PEVM: RESULTS AND THEIR REASONABLENESS

While PEVM may appear somewhat abstruse in its formulation (Chapter 3) and involved in its implementation (Chapter 4), its output is clear and simple. We illustrate PEVM outputs in this chapter.

In its simplest form, PEVM's output consists of a stacked column over the period 1995 to 2010 for a prescribed set of inputs and assumptions; each segment of a stack represents the emissions from IC manufacture for each linewidth technology. Additional outputs include charts and tables of emissions and silicon consumption.

We present the results of two BAU projections—one with and one without the use of copper—and another projection that illustrates attainment of the WCS goal in 2010 for partner fabs. We also compare the BAU results for version 2.14 with results obtained using an alternative method for projecting emissions—one based on projecting PFC usage from sales trends for the period 1992–1996.

5.1. Business As Usual Projections of Emissions: 1995 to 2010

Figure 5-1 shows the essential output of PEVM (v. 2.14). The chart depicts the emissions (MMTCE) for each linewidth technology for each year from 1995 to 2010. PEVM identifies the pertinent assumptions for these BAU projections in a text box, which in Figure 5-1 indicates (a) copper use with a 30% reduction in the number of layers and (b) no adoption of measures to reduce emissions. In addition, Figure 5-1 also indicates the WSC goal (= 0.9 x 1995 emissions = 1.7 MMTCE) by a horizontal line. In this example, U.S. emissions would be reduced by 88% from the 1995 BAU baseline projection to achieve the WSC goal in 2010, from 14.6 to 1.7 MMTCE.

Figure 5-1.
Projected US Business As Usual PFC Emissions from PEVM v2.14.

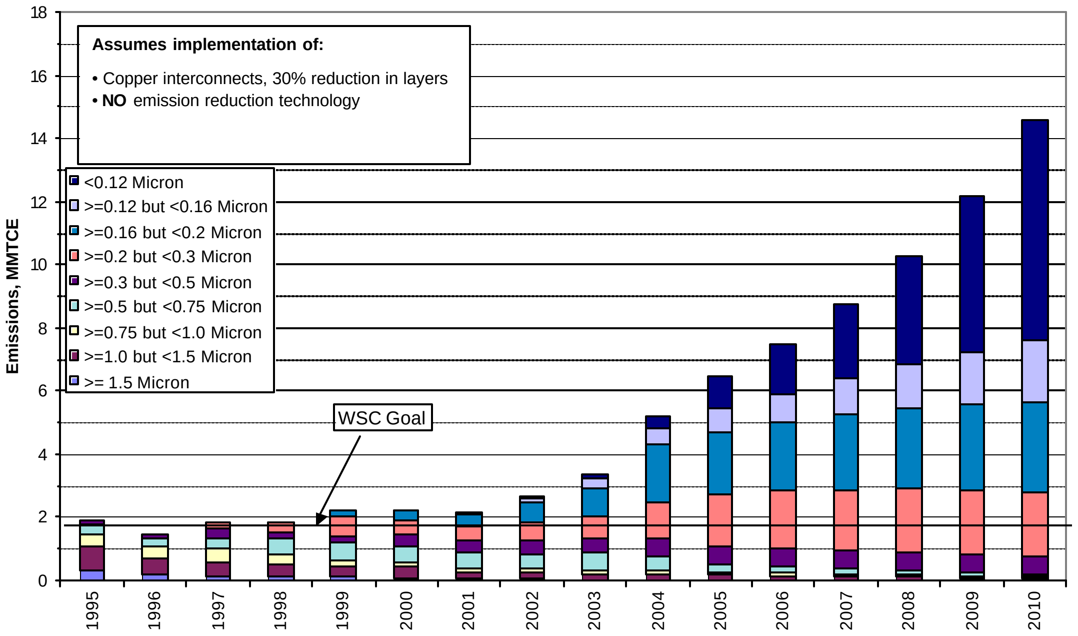


Table 5-1 contains the same emissions as in Figure 5-1. In both the figure and the table, the effect of IC complexity (increasing metal layers) is evident.

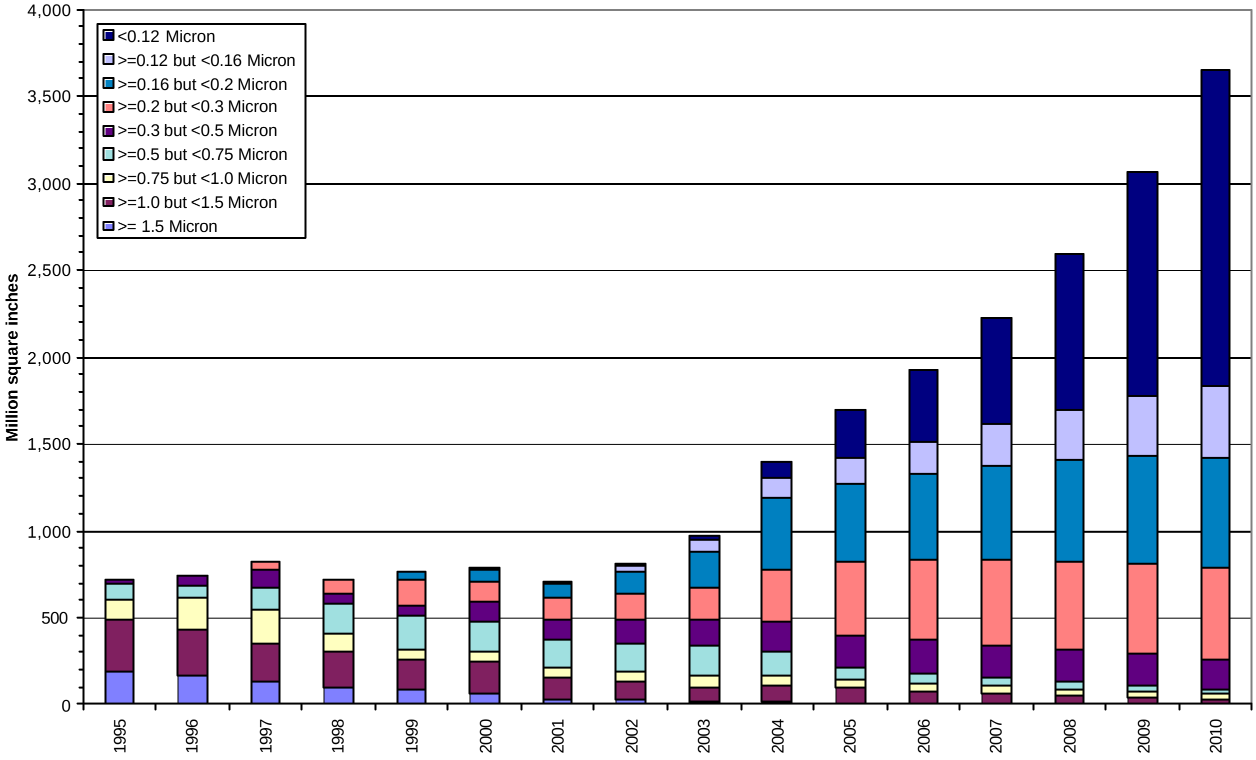
Table 5-1.
PFC U.S. Emissions: Total and by Linewidth, MMTCE for 1995–2010.

	>= 1.5 mm	>=1.0 but <1.5 mm	>=0.75 but <1.0 mm	>=0.5 but <0.75 mm	>=0.3 but <0.5 mm	>=0.2 but <0.3 mm	>=0.16 but <0.2 mm	>=0.12 but <0.16 mm	<0.12 mm	Total
1995	0.33	0.75	0.36	0.36	0.08	0.00	0.00	0.00	0.00	1.88
1996	0.20	0.51	0.39	0.22	0.15	0.00	0.00	0.00	0.00	1.47
1997	0.16	0.40	0.42	0.37	0.30	0.17	0.00	0.00	0.00	1.82
1998	0.13	0.41	0.25	0.52	0.19	0.31	0.00	0.00	0.00	1.82
1999	0.12	0.35	0.15	0.59	0.21	0.61	0.19	0.00	0.00	2.22
2000	0.09	0.34	0.14	0.52	0.36	0.46	0.30	0.02	0.00	2.22
2001	0.04	0.23	0.13	0.47	0.38	0.47	0.37	0.08	0.00	2.18
2002	0.04	0.21	0.12	0.48	0.43	0.57	0.60	0.16	0.04	2.65
2003	0.03	0.15	0.14	0.53	0.47	0.74	0.88	0.33	0.11	3.37
2004	0.03	0.17	0.14	0.40	0.57	1.17	1.82	0.52	0.37	5.18
2005	0.01	0.16	0.10	0.22	0.59	1.66	1.97	0.72	1.05	6.48
2006	0.01	0.14	0.10	0.18	0.61	1.79	2.19	0.92	1.59	7.51
2007	0.01	0.12	0.09	0.15	0.61	1.89	2.39	1.14	2.36	8.75
2008	0.00	0.10	0.08	0.12	0.61	1.97	2.57	1.39	3.44	10.29
2009	0.00	0.08	0.07	0.09	0.60	2.02	2.71	1.67	4.95	12.20
2010	0.00	0.06	0.06	0.07	0.58	2.03	2.81	1.97	6.97	14.56

It also interesting to note the changing contribution to emissions made by increasing IC complexity. For example, using the information in Table 5-1 it is evident that in 2000, the contribution to the total emissions from ICs with 0.2µm to 0.3µm features sizes is estimated by PEVM to be approximately 21%, while the contribution from ICs manufactured with feature sizes < 0.16µm is just less than 0.1%. In 2010, however, the corresponding figures projected by PEVM are about equal, 13% and 14%, respectively.

Figure 5-2 depicts silicon consumption, also over the period 1995–2010. A quantitative comparisons of Figures 5-1 and 5-2 reveals that the growth rate of emissions exceeds the growth rate of silicon consumption. For example, PEVM estimates that emissions increase by a factor of 6.6 over the period 2000 to 2010, while silicon consumption increase by a factor of 5 over the same period. The increase in IC complexity over the period 2000–2010 quantitatively accounts for the difference in the two growth rates. It should also be noted that the silicon consumption for the period 1988–2005 comes directly from VLSI Research Incorporated. Silicon consumption from 2006–2010 are from PEVM.

Figure 5-2.
U.S. Silicon consumption, 1995–2010
(Source VLSI Research, Inc. to 2005, PEVM to 2006 to 2010.



5.2. Comparison of PFC Emissions Using PEVM and Gas Usage

The results presented in Figure 5-1 can also be compared with estimates of PFC emissions using projected US PFC gas usage, Figure 5-3. The emission estimates displayed in Figure 5-3 were developed following a procedure developed in late 1997 and early 1998.

The procedure relies on PFC-specific gas sales—obtained from DataQuest—for the period 1992–1996.[12] Gas-specific sales were converted to gas-specific mass using gas-specific market prices provided by confidential industry sources and confirmed for reasonableness by gas suppliers, who wished to remain confidential. Gas-specific usages (mass basis) were

projected using estimates of the corresponding compound average growth rates, assuming that, on average, 10% of the gas is returned to the gas supplier unused (the so-called heel of the cylinder). Gas-specific emissions factors, obtained from the IPCC Inventory Report *[IPCC ????]*. and expressed as emissions out per unit of gas in, were used to convert usage into emissions, MMTCE. These gas-specific emissions were then summed and graphed as shown in Figure 5-3.

Each method for estimating and projecting emissions compares favorably with the other. For example, the projected values for 2010 for gas-usage and silicon-consumption methods are 15.6 MMTCE and 14.6 MMTCE, respectively—a fractional difference of 7.9%. The corresponding fractional difference for 2000 is 16%. Figure 5-4 shows the correlation between both methods, in which the r^2 is 0.97. The results in Figure 5-4 also show that gas-sales method overstates emissions relative to PEVM, on average, by approximately 8%.

The gas-sales method did not account for the reduction in projected omissions associated with the use of copper interconnects, which is explicitly treated in the PEVM. This difference could be offered as a partial explanation for why the gas-sales methods produces, on average, higher estimates than the silicon-consumption method of PEVM.

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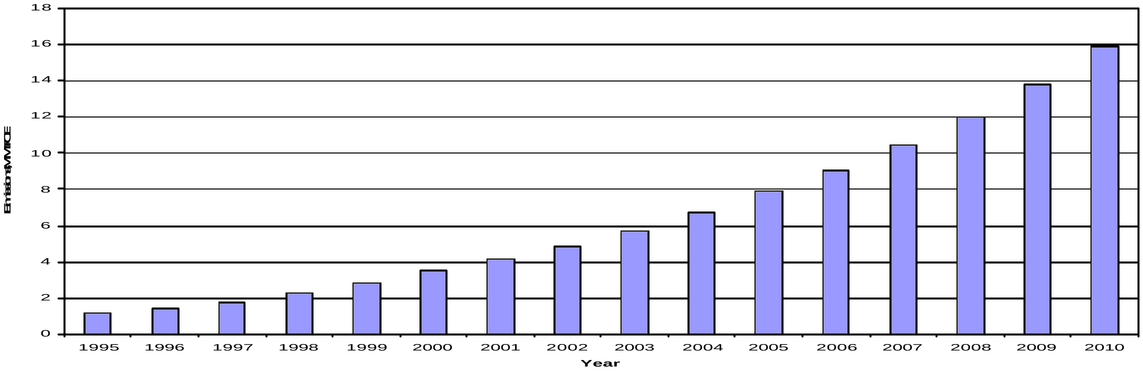
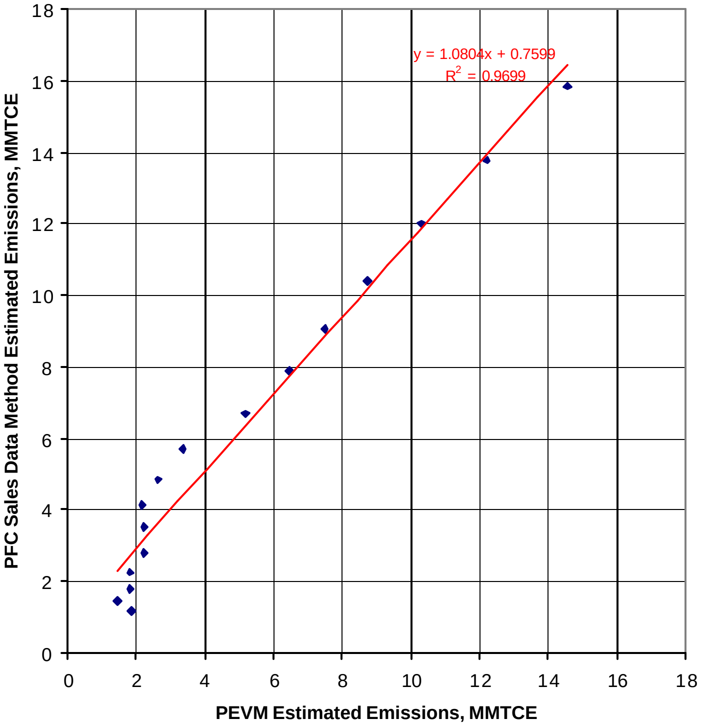
[12] DataQuest ceased publishing gas sales data in 1997.

Figure 5-3.
Projected U.S. PFC Emissions Using Gas-Sales Method, 1995–2010



The agreement indicates that both methods are consistent and probably of equal validity. However, for the reasons presented in Chapter 2, repeated in part here, we believe that the silicon-consumption method is preferable to the gas-sales method because, even if gas sales information were available, it is layer-weighted silicon consumption that best indicates the effects of industry manufacturing practices on emissions of PFCs.

Figure 5-4.
Correlation of Emissions Obtained using PEVM (Figure 5-1) and Gas-Sales (Figure 5-34).

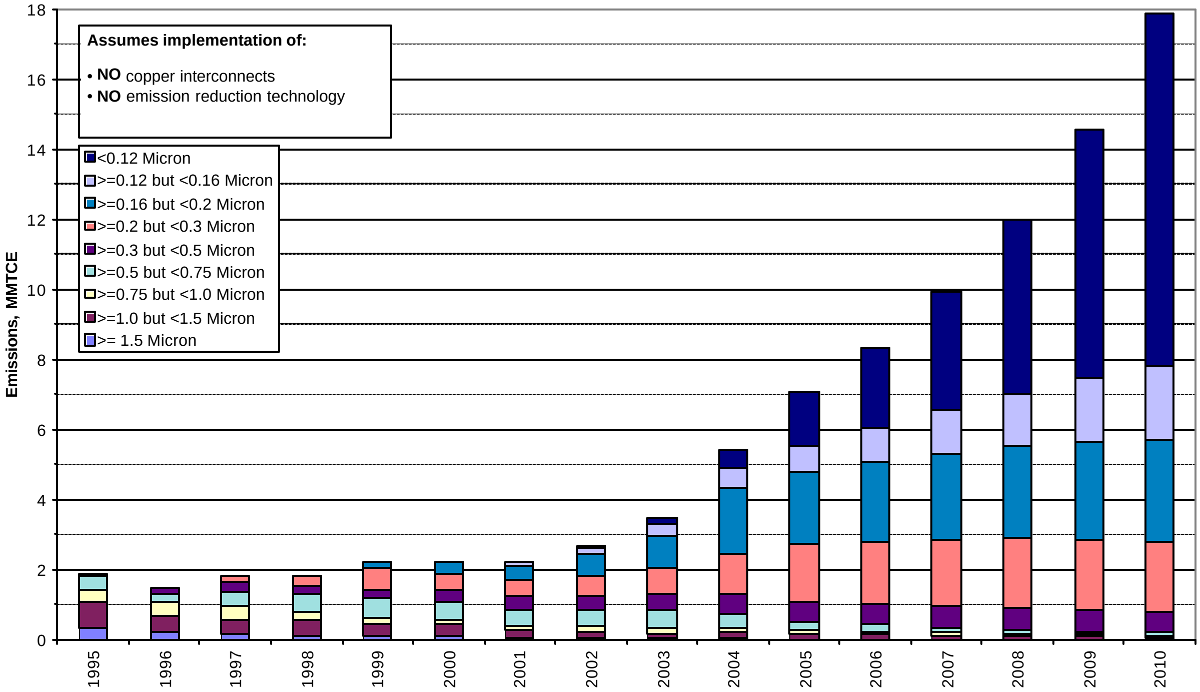


5.3. The Effect of Using Copper on Projected PFC Emissions

Qualitatively, as described in Chapter 3 and Section 4.1.3, the use of copper reduces the number of metal layers and, in turn, emissions. The PEVM BAU results presented in this section reflect this effect.

Comparing the results in Figure 5-5 with those in Figure 5-1 shows that, in 2010, PEVM results without copper are 22% higher than those with copper. If the results in Figure 5-5 were assumed to represent the 1995 baseline emissions, the reduction needed to achieve the WSC goal increases to 90%, up from 89% when copper is assumed and the number of metal layers is reduced by 30%.

Figure 5-5.
US.. PFC Emissions: BAU Without Copper Interconnects, 1995–2010, MMTCE



5.4. An Emission Reduction Path for Partners to Achieve the WSC Goal

We close this chapter by illustrating how PEVM can be used to examine emission reduction strategies. We choose an example in which emission reduction is accomplished by applying control measures to fabs operated by Partners (using SIA's WFW database) to both CVD and etch processes, which begin in 1999.

Tables 5-2 and 5-3 present the specific assumptions used by PEVM to obtain the results presented in Figure 5-6. Table 5-2 specifies the expected (assumed) emissions reductions for each linewidth technology and the assumed distribution of emissions between etch and CVD processes. Table 5-3 provides the penetration rates by year. It is evident from Tables 5-2 and 5-3 that controls are assumed to begin in 1999 and the assumed emission reductions range between 50% and 100%. The greatest reductions are associated with the manufacture of features sizes ≤ 0.3 μm.

Table 5-2.
Hypothetical PEVM Assumed Reductions and CVD: Etch Proportions of Emissions, by Technology, to Achieve WSC Goal

Technology	Emission Reductions from Control Measures		Distribution of Emissions Between Clean and Etch Processes:	
	Etch	Clean	Etch	Clean
>= 1.5 Micron	0%	0%	50%	50%
>=1.0 but <1.5 Micron	0%	0%	50%	50%
>=0.75 but <1.0 Micron	0%	0%	50%	50%
>=0.5 but <0.75 Micron	50%	50%	50%	50%
>=0.3 but <0.5 Micron	85%	90%	40%	60%
>=0.2 but <0.3 Micron	90%	95%	30%	70%
>=0.16 but <0.2 Micron	90%	99%	30%	70%
=0.15 Micron	95%	99%	20%	80%
=0.13 Micron	95%	99%	20%	80%
=0.10 Micron	95%	99%	20%	80%
=0.07 Micron	100%	100%	20%	80%

Among the items to note when examining Figure 5-6, is (a) the scale change and (b) the projected emissions in 2010 equals 1.04 MMTCE (= 0.9 x Partner emissions for 1995 [=1.84 MMTCE], the WSC target.[13] The relatively rapid drop in emissions that begins after 2005 is due to the assumed levels of control applied to linewidth technologies <0.2 µm, which represents a growing fraction of emissions beginning in 2004.

Figure 5-6.
Illustration of Hypothetical Control Strategy for Achieving WSC Goal by Partners (for assumed emission reductions and penetration rates, see Tables 5-2 and 5-3).

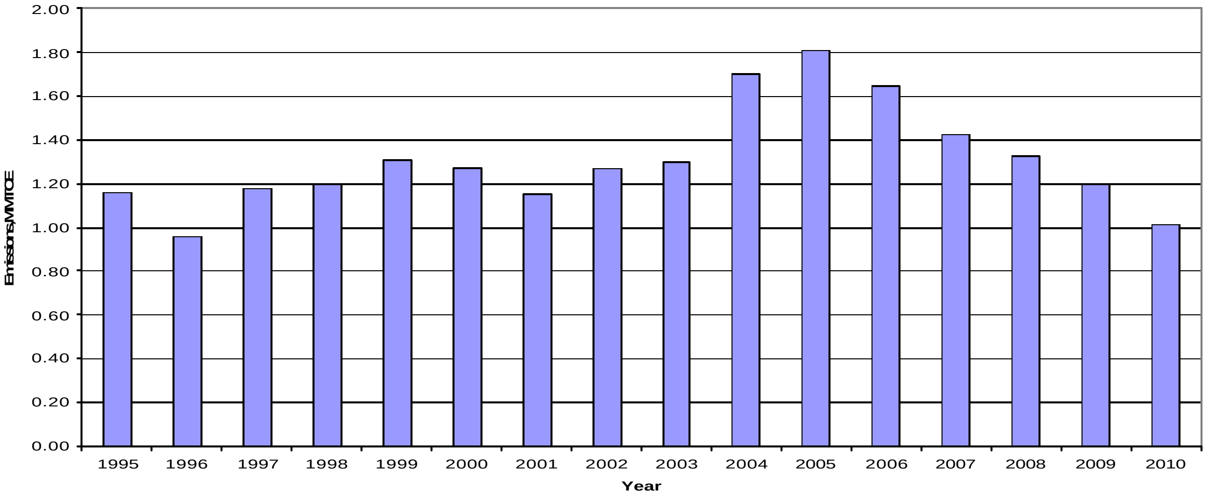


Table 5-3.
Penetration Rates for Control Technologies Shown in Table 5-2.

Year	Technology Penetration Rates
1995	0%
1996	0%
1997	0%
1998	0%
1999	10%
2000	25%
2001	30%
2002	35%

Year	Technology Penetration Rates
2003	50%
2004	55%
2005	60%
2006	70%
2007	80%
2008	85%
2009	90%
2010	95%

---

[13] The Partners emissions, 1.84 MMTCE for 1995, are obtained using PEVM (v2.10). This estimate is slightly lower than the corresponding value presented in Table 5-1 (1.88 MTCE) because the emissions in Table 5-1 were obtained using v2.14. Version 2.14 uses layer-weighted Partner shares to extract emissions from world totals, while version 2.10 uses unweighted capacities to extract Partner emissions.

6. SUMMARY OF KEY ASSUMPTIONS, UNCERTAINTIES AND LIMITATIONS OF PEVM

The applicability, uncertainties and credibility of any new model originate principally from the physical and mathematical assumptions that form its foundation and from the efficacy of input data. In this chapter we identify those assumptions and their consequential uncertainties and limitations.[14]

Mathematically, PEVM is a simple linear model; PEVM requires no linearization and all operations are linear. PEVM, in fact, is a definitional model that follows directly from the definition of new emission factors (see Chapters 2 and 3), where the unit of activity is silicon consumption. This definition, while a departure from IPCC methods, follows directly from PEVM's principal intended use—U.S. emission projections from 1995 to 2010—and the judgment that projecting emissions should rest on key manufacturing drivers that influence emissions—silicon consumption and manufacturing technology. However, this definition carries limitations because, as implemented in PEVM, it is an average over all PFCs—all PFC-using manufacturing processes and over all complexities used to manufacture many, many ICs. When examining emission reduction strategies, PEVM uses, for example, factors to "decompose" these averages into its process-specific components.

PEVM allots considerable resources to assure the available information suits PEVM. The procedures to do this introduce complexities. As described in detail in Chapter 4, PEVM incorporates adjustment procedures to account for tests, to estimate US and Partner shares of world capacities, and others. PEVM also makes adjustments to convert published silicon consumption figures into silicon-by-linewidth consumption figures.

The most challenging part of PEVM is projecting silicon consumption. In part to avoid unjustifiable complexity, an illusion of objectivity and false precision, and the risks associated with numerable undesirable contentious assumptions, we adopted the subjective approach described in Chapter 3. In this way, PEVM can easily accommodate other projections of silicon consumption.

Table 6-1 details the assumptions that we believe PEVM now contains, although there may be one or two others. With these assumptions comes uncertainty as well as consequences that includes limitations. Table 6-1 provides all of this.

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[14] We acknowledge that unintended and unknown correctable errors produced during implementation also affect a model's applicability and credibility. We cannot discuss them here because, if they exist, they are unknown.

It is our opinion at this time that these assumptions and uncertainties do not lead to biased emission projections. In other words, we believe that PEVM's projections, on average, neither overstate or understate U.S. PFC emissions. During the design and development of PEVM, our aim was to develop best point estimates of inputs regardless of the uncertainty we faced in the process. At no point did we use so-called "conservative" or "non-conservative" thinking to decide on a procedure or a result to use/adopt.

We wish to make a concluding comment about the reliability and utility of PEVM's projections. As described in Chapter 5, the only other projections of PFC emissions of which we are aware—those based on projected gas-usage—compared favorably with those from the PEVM. We warn, however, that too much should not be made of their comparability because both methods depend on some similar information. For example, PEVM relies on Partner emissions and the gas-sale method relies on gas-usage emission factors, which Partners use when estimating and reporting their emissions to Latham & Watkins. PEVM uses the same Partner emissions to form its emission factors. Nevertheless, we are encouraged and pleased with the relative agreement, which we provisionally interpret as PEVM offering a useful framework for projecting PFC emissions using consensus information about the expected PFC emission futures for this distinguished, innovative industry.

Table 6-1.
Summary of PEVM's Key Assumptions, Uncertainties, Likely Consequences and Limitations

Model Element	Key Assumption(s) and Source(s) of Uncertainty	Likely Key Consequence(s)	Limitation(s) and Caveats
Emissions factors	• Use of Partner aggregate emissions. • Estimates of Partner share of world silicon consumption. • Use of nominal ITRS values for number of metal layers. • Method for accounting for test wafers in consumption figures. • Application of Partner-derived emission factors to world fabs. • Use of SIA's World Fab Watch databases over a period when these databases were still very new.	• Emission factors may be overstated or understated by an unknown amount at this time.	• Use of these emission factors outside of the PEVM may not be appropriate. • Use of these emission factors should note their indeterminate accuracy.
Silicon projections	• Adoption, penetration, and decay rates for linewidth-specific silicon consumption. • Aggregate growth rates of total silicon for partners and apportionment of that rate into the linewidth-specific components. • Emissions from silicon manufacturing only; no accounting before 2010 for emission from wider use of other semiconductor materials, such as GeSi, GaAs, C-nanotubes, or nanotubes Si, nanowires, and other materials before 2010.	• Emissions may be overstated or understated by an unknown amount at this time. • Risks appearance of unjustified precision in projected emissions.	• Use of silicon projections outside of the PEVM may not be appropriate, although an independent assessment, while subject to change, could be useful. • Use of these Si projections should note their indeterminate accuracy.
Extracting process-specific estimate of emissions	• Separation of process and gas usage into simple fractions. • Selection and usage of average proportions of emissions from CVD and etch processes that vary by linewidth technology. • Neglecting portion of emissions from ashing.	• Process-specific emissions may be overstated or understated by an unknown amount at this time. • Risks appearance of unjustified precision in process-specific emissions.	• Use cautiously until industry consensus is reached.
Extracting gas-specific estimates of emissions	• Usage and application of Partner information (and/or older gas-sales information) as estimate of proportions of gas-specific usages. • Accounting for PFC formation as a simple fraction, for example, of C_2F_6 usage.	• Gas-specific emission may be overstated or understated by an unknown amount at this time. • Risks appearance of unjustified precision in projected emissions.	• Use cautiously until industry consensus is reached.
Investigation of alternative control strategies	• Selection of penetration rates of emission control measures that apply to the entire industry. • Disregard of emissions from ashing.	• Emissions may be overstated or understated by an unknown amount at this time.	• Use cautiously until industry consensus is reached.
Estimation of U.S> share of world emissions	• Usage of the ration of U.S.-to-world technology-weighted silicon capacity as a surrogate for the ration of U.S.-to-world emissions.	• Emissions may be overstated or understated by an unknown amount at this time.	• Use of this share outside of the PEVM may not be appropriate.

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