Global Production Chains and Sustainability:

The case of high-purity silicon and its applications in IT and renewable energy

Eric Williams

The United Nations University

UNU/IAS

Institute of Advanced Studies

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United Nations University/Institute of Advanced Studies
53-67 Jingumae 5-chome, Tokyo 150-8304, Japan
Tel: 81-3-5467-2323
Fax: 81-3-5467-2324
URL: www.ias.unu.edu

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Executive Summary

Societies face complex choices in the pursuit of sustainable industrial development. The global production system of goods and services becomes more extensive under the influence of globalization and technological change. Sustainable development sets forth an agenda including economic, environmental and social objectives, which are often difficult to satisfy simultaneously. Considering these points, it is clear that analysis of and information systems for industrial activities must evolve in order to constructively inform decision-making. This report investigates *systems analysis* of global production chains and the status and appropriate form of the *sector-level knowledge system*. Systems analysis and the sector-level knowledge system are addressed through a case study of a particular global production chain: the linked network of industrial sectors producing high-purity silicon from raw materials and the related microchip, solar cell, and optical fiber industries.

The systems analysis includes estimations of production levels, materials flows, trends, and future projections for the global production chain. Two points from this analysis are:

- Though the knowledge economy is often described as “weightless”, the material component of the underlying IT infrastructure is not trivial. Large quantities of energy and chemicals are consumed in production, though not directly contained in final products. Projections indicate that high-tech sectors will represent a significant share of the demand of primary materials. Overall the new economy could indeed lead to significant dematerialization, however these results emphasize the need for careful analysis.
- The geographic distribution of activities in the production chain for high-purity silicon does not indicate a tendency for environmentally damaging stages to be located in developing countries. The opposite has perhaps been true, with the riskier chemical industries and semiconductor fabrication mainly located in developed countries, though such production is increasingly shifting to East Asia. This is however, a result for only one production chain, which could easily be an exception to the situation for the overall production system.

The status of publicly available information on economics, environment, and technology at the sector level was surveyed and recommendations made for improving availability and organization of knowledge. Two main points are:

- In general, information on emissions and environmental impacts for industrial sectors is insufficient to answer many key questions. It is suggested that this lack of information has important ramifications for the overall system by which societies respond to environmental issues. Institutional change is needed to address this issue. Such reform involves rethinking the role of governments, sector level industry organizations, and other institutions in organizing and disseminating environmental information.
- Very little knowledge on industry is integrated to combine economic, environmental, social, and/or technological information. It is reasonable to assert that an integrated knowledge system underpins implementation of a multi-issue agenda such as sustainable development. Useful formats for an industry knowledge system are suggested, which include a reformulation of the Geographical Information System methodology towards application to networks of industrial sectors.

Section I:
Introduction

I.1 Background

Decision-making for industrial activities, both in terms of government policy and the decisions of firms, faces an increasingly challenging climate in recent decades. On one hand, production systems become more complex in response to rapid globalization and advancing process and management technologies. Also, societies are placing an increasing priority on sustainable development, which encompasses environmental and social issues as well as economic growth [1,2]. A broader scope of factors considered naturally results in greater difficulties in resolving courses of action. Information systems for and analysis of production activities must evolve to constructively inform decision-makers in this new climate. To address the increasing complexity of production activities, this study investigates systems analysis of global production chains. To respond to a broadened development agenda, the status of the current industrial knowledge system is surveyed and means of developing integrated information systems are considered.

The above issues are investigated in the context of a case study of a particular global production chain: the network of industrial sectors involved in producing high-purity silicon from raw materials to its application in microchips, solar cells, and optical fiber. The motivation for this choice of case study is rooted in the observation that Information Technology and renewable energy are keystones in the future of human societies.

I.2 Systems analysis and global production chains

In its most general sense, systems analysis could be described as a holistic approach to understanding a given phenomenon. A global production chain is a network of global industrial sectors that produce a given product or service starting from raw materials. The rationale for and approach taken to systems analysis of global production chains will be discussed in this section, beginning with a summary of the resulting targets and methodology of the current work.

In overall terms the goal is to progress towards understanding global production activities on a system basis, rather than sector-by-sector. As any given industrial activity is highly dependent on sectors up and downstream, in broad terms this is obviously a highly relevant issue for industrial development policy. More specifically, particular types of systems analysis of global production chains are undertaken with related objectives in mind. One major category is quantitative analysis of material and economic status of and flows between sectors in a production chain. This is intended to characterize the physical scale, trends, and interdependencies between industrial sectors. One purpose of such analysis is to identify areas of particular economic and environmental significance, as well as to project future shifts in structure. This analysis also serves as an important consistency check between economic census, business intelligence, and technological process data. Another area of analysis the assessment of the evolving roles of developed and less developed countries in different stages of a production chain. Understanding the changing geographical patterns of production is important with respect to economic development and environment. Another area of interest is to take a systems perspective on the development and adoption of process technologies. Links between sectors, either direct (e.g. material requirement) or indirect (e.g. overlapping physical basis of technology), can play a important role in what process technology succeeds in a given industry.

The above summarizes the approach taken; the remainder of this section is devoted to providing more background on systems analysis and the choice of global production chains as the object of study.

Systems approaches

One of the major shifts in recent decades with respect to analysis and response to environmental issues is an increasing recognition of the importance of a systems perspective. Expressed roughly, a systems perspective endeavors to understand the behavior of groups of related activities and phenomena instead of dealing with the components piecemeal. One example of where a systems perspective is important is in the reduction of environmental impacts associated with a given product or service. Environmental impacts arise at all phases of the life cycle of the product: manufacture, use and disposal. Given the finiteness of resources available to address environmental issues, the question of how to allocate those resources efficiently clearly requires a systems analysis of the life cycle. Also, a well-intentioned change in process at one stage can have unforeseen negative environmental implications up or down stream from that activity.

Industrial ecology/metabolism

Industrial Ecology/Metabolism is an "approach" that explicitly incorporates the systems perspective. Indeed, one definition of Industrial Ecology describes it as "an integrated systems approach to managing the environmental effects of energy, materials and capital in industrial ecosystems." [3]. A broad variety of research and activities could be categorized as falling under the umbrella of Industrial Ecology: methodologies such as Materials Flows Analysis (MFA) of regions, strategies aiming at dematerialization such as product-to-service transformation and particular technologies for recycling [4,5]. A general theme that underlies Industrial Ecology is a vision of a cyclic and highly efficient production/consumption system that emulates natural eco-systems. Industrial Metabolism is an approach related to Industrial Ecology that emphasizes an analogy between industrial systems and the metabolism of organisms [6].

Life Cycle Assessment

A more specific set of activities taking up systems analysis from an environmental perspective fall under the field of Life Cycle Assessment (LCA). LCA could be described as a set of methodologies and practice aimed at evaluating the environmental impacts associated with a given product or service. Usually the evaluation is quantitative and detailed process databases have been developed to facilitate calculation. An emphasis is placed on a "cradle-to-grave" or "cradle-to-cradle" approach, which entails a priority to address as much of the life cycle of the product or service as possible. LCA has gained a certain degree of popularity in the private sector, many large firms have established sub-groups in their environmental divisions devoted to LCA. Also, a group of LCA consulting companies has arisen, which produce software and databases as well as carrying out contracted projects for firms. Many LCA studies of products and services have been carried out, with a general trend towards addressing greenhouse emissions associated with durable goods. Discussions of general LCA methodologies can be found in [7], while [8] contains many short reviews of case studies and development of methodologies and databases.

Global production chains

Given that the goal is to explore the applications of systems analysis to industrial policy relevant to sustainability, what object is appropriate to study? The system chosen here is the global production chain, which is a connected set of industrial sectors that follows the processing of materials from extraction of raw materials through production of finished goods. Global refers to the fact that each sector is considered as the collection of world production activities. A specific example is the chain to produce an aluminum object, which involves mining and processing of bauxite ore, production of raw aluminum metal, and casting of the part.

Why choose a production chain? While it is a simple matter to agree in principle that a systems understanding of production activities is desirable, the extreme large scale and complexity of the network of industrial sectors make it clear that quite finite boundaries must be set in order to make practical progress. Thus a production chain, or limited sub-network of connected sectors, is an appropriate object to deal with.

Why choose a *global* production chain? The basic root is the increasingly globalized character of the production system insists a trans-boundary treatment. Indeed, for most sectors dealing with international commodities, competition on global markets is a primary driver of industrial practice. Globalization also spills over into environmental issues. Free trade acts as a constraint on pollution control as there is a diversity of environmental regulation regimes (various national and local governments), and one economic regime, the international market. From a macro standpoint, globalization makes the problem of understanding the overall trends in progress on environmental issues considerably more challenging. While there has apparently been a great deal of success in developed countries in dealing with environmental problems, much of the effort to improve domestic practice has also been accompanied by a general shift of manufacturing to developing countries. It is important to understand the extent to which problems have been squarely addressed and the extent to which they have simply shifted location, akin to a bubble under wallpaper. A study of the geographical evolution of production patterns in a global production chains can provide a useful perspective on this issue.

There is to date little work on multi-issue treatments of global production chains, though the work on Industrial Ecology and LCA substantially informs directions such a study can take. The study of Ayres et. Al. on the high-purity silicon production chain represents a step in the direction being suggested here [9]. To frame the approach here in the language of LCA, this represents a study with fairly restricted boundaries, considering relatively few sectors in production stages. However, the scope is substantially expanded to encompass the economic and technological context of the sectors considered.

Let us assume that the above argument regarding the need for studies of global production chains is in principle correct. It is a crucial question whether such studies are feasible in practice or not. Analysts and researchers are acutely aware of the obstacles arising from data availability: the existing data system only supports application of a small fraction of possible analytic approaches. International data are still often scarce and unreliable, and we shall see that sector data on environmental, economics and technology has many gaps, an issue to be discussed in more depth later. Here, the central point to be stressed is that the Information Technology revolution has a profound effect on information dissemination, and thus on what types of analyses can feasibly be conducted. Twenty, even ten years ago the type of study being suggested here would have been exceedingly costly in terms of the amount of resources required to gather data. However, the Internet has a huge effect in making the world smaller, allowing information to travel cheaply and efficiently across borders and disciplines. It is important to identify the possibilities opened up through IT and the Internet to arrive at new syntheses of knowledge.

I.3 Sector-level knowledge system

The sector-level knowledge system is the second general theme addressed by this study. The term *sector-level knowledge system* is used to refer to the set of economic, technological and environmental information related to a given industrial sector that is available to civil, government, *and* private sectors of society. Two aspects of knowledge systems are investigated in this work: the status and availability of knowledge and the organization of such knowledge. The status of knowledge is related to the question of whether there is sufficient information in inform analysis and response for decision-making related to industrial activities. The question of organization has to do whether information is integrated to support a multi-issue agenda such as sustainable development.

Societal response system

To begin with, it is appropriate to discuss the role of knowledge in sustainable development. Figure I.1 shows a graphical depiction of the interaction of phenomena and activities that lead to societal responses to environmental, economic, and social issues. As the most basic level one has a set of human activities such as production and use of goods and services. These activities interact with the societal- and eco-systems through drawing on human and natural capital and inducing various changes or impacts on the environment. Above this complex interacting system lies a set of activities designed to observe and measure data relevant to sustainability and pass this information on to appropriate societal actors for analysis. Specific examples of such data are emissions of pollutants, changes in ecosystem parameters such as water quality, health effects on workers, as well as a whole set of economic information related to development. In the analysis stage, this information is used to study various issues of concern, examples of environmental issues are global warming and human toxicity and examples of social examples are poverty and equity. Finally, analyses serve to inform decision making for corrective actions of various forms such as implementing governmental policies or changing industrial processes and personal lifestyles. These corrective actions lead to some change in behavior and thus in environmental impacts. This whole system forms an interconnected feedback loop determining societal response. It is clearly important to have all phases of the response cycle functioning well to formulate and effect change, any weak link undermining the whole process. Also, it is important to note that the different phases are interlinked. For example, what analyses are undertaken depends on what data is available and likewise data collection systems evolve to respond to demand for certain kinds of analysis.

The main focus of this work will be on the observation phase, specifically on the question whether or not there is sufficient information available on industrial activities to inform analysis, particularly in the field of environment issues. Narrowing the field considered to impacts of production is not an assertion that there are not serious issues associated with consumption and society's responses to it. There has been a strong tendency for industry to be regarded as the sole culprit in environmental issues, while in fact consumption patterns also play a large role. With this caveat and the excuse that resources to undertake analysis are limited, only production activities will be considered at this point.

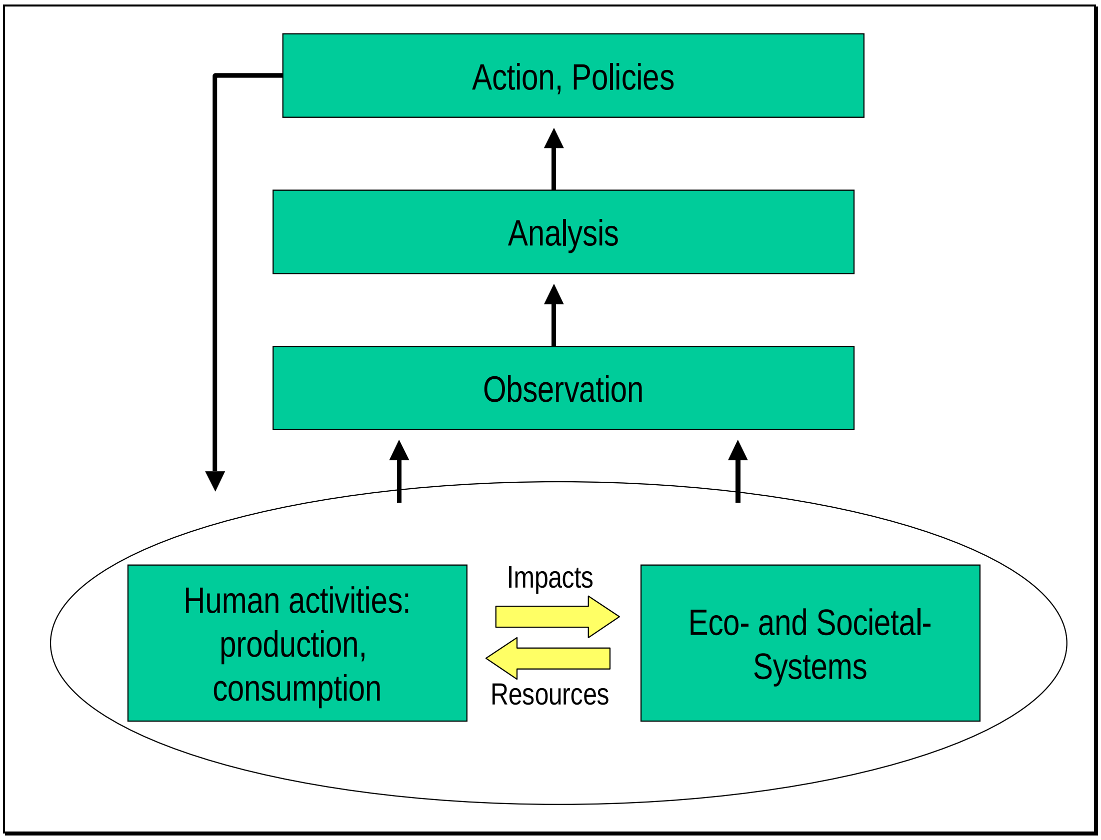


Figure I.1: The system for societal response to environmental, economic, and social issues

Societal actors

A key issue in the functioning of the response system is the relative role of different sectors of society at different stages. One common way of distinguishing different actors is to consider society as three sectors: government, industry and civil sectors. Civil actors here are considered as general society including organizations such as academia, international organizations, and Non-Governmental Organizations (NGOs). The roles of these actors in the societal response system are quite different. For example, with respect to the environment, governments have been principal agents in formulating and implementing policies in response to environmental issues. Government agencies have also been quite important in disseminating results of observation to civil sectors. With the proliferation of multilateral environmental agreements such as the Kyoto Protocol, international organizations are taking a larger role in policy formulation. Firms in industry no doubt have the most detailed knowledge of their own process and emissions, and have a and engage in process changes to respond to government or internal policies. Civil sectors of society are very active in the analysis stage as well in influencing political processes.

What should the appropriate roles of different actors in society to maximize the effectiveness of the response system? Do those actors have enough access to information and resources to fulfill that role? These are complex questions and will not be discussed in any thoroughness here. However, one aspect will be considered: the level and role of environmental information available to civil sectors of society. This is argued to be a critical area, mainly due to the increasing role of civil society in world affairs. The existence of conflicts of interest between government, private, and civil society has been substantially internalized in many parts of the world in recent decades. Part of this shift is reflected by the fact that civil society in many nations is far less trusting of government and industry than it once was, and has become far more vocal and active. This issue is part of the larger debate in social science circles that goes under the term Ecological Modernization [10]. At any rate, it can be strongly argued that sustainability will only be possible through active interaction of all three sectors of society: government, private, and civil, as only through this interaction can different interests be balanced. Given this context, it is clear that the issue of access to environmental information is a crucial element for a meaningful participation of civil society in environmental affairs.

Presuming that the level of publicly available environmental information is an important issue, are there indications of shortcomings in the current system? The answer is an overwhelming yes. There are extreme data shortages in many areas, especially on emissions of pollutants and possible impacts of those emissions. This issue will be discussed in much detail, as part of this study will be a survey of publicly available knowledge.

It is important to recognize the barriers towards making information available, for these must be considered carefully for reforming the system. At the firm level, aside from concern over public reaction to emissions data, the market system imposes a serious constraint. Detailed emissions data contain information about the underlying production process used, which is often knowledge relevant to competitiveness. Concern over leaking valuable information to competitors is thus an inhibiting factor in the release of firm level data.

Developing countries

The response system to address environmental, economic and social issues tends to be far more developed in industrialized nations than in developing ones. One can consider a number of factors to account for this, but perhaps the primary reason is the institutional and financial overhead required by such a system. It is through wealth that the luxury of introspection becomes possible. The ability for introspection and response is also a key to greater wealth as well as for dealing with environmental and social problems.

One shortcut for improvement of response systems in developing and developed countries is through increased international communication. Though the challenges encountered vary nation by nation, there are many common issues to industrial activities anywhere. Thus, increased dissemination and availability at the observation stage, for instance, serves the dual purpose of enhancing the domestic response system as well as those abroad.

Industrial sectors

In order to progress on the issue on availability of information, it is necessary make the discussion more concrete. In this section, it will be argued that a key object for closer consideration is the industrial sector.

Up to this point, industrial activities have been referred to as an aggregate object. This is too general and complex a system to be able to discuss usefully. It is natural to shift the focus to global industrial sectors as the objects of primary interest. Why? The industrial system is a highly interconnected network of industrial activities, of which the industrial sector is a “fundamental” building block or atom in some sense. Given sufficient knowledge of each sector and how the sectors are connected, the behavior of the overall industrial system can be most faithfully represented.

It is appropriate to do clarify what is meant by industrial sector, as it is a word used in many contexts to refer to differing degrees of aggregation of activities. A model of an economy broken in into twelve production sectors is considered detailed for certain purposes in economic, and at the most aggregated level, all production can be considered as one sector. Here the focus is on far more disaggregated sectors such as production of raw aluminum or mining of iron ore. The reason for this is that environmental issues arising from an activity are intimately related to process or technology. It is only at a relatively detailed level of process can the connection between technology and environmental impacts be understood in a meaningful way.

The relevance of publicly available environmental information is taken up again in the context of industrial sectors. Three specific areas are discussed: addressing global environmental issues, the environmental performance of firms, and implementation of general strategies for sustainable industry.

Global environmental issues

Consider a global environmental issue such as global warming or ozone depletion. They affect a global public good and such problems are increasingly being addressed through international treaties such as the Kyoto protocol for global warming and the Montreal protocol for ozone depleting gases. Such treaties involve laborious negotiations to arrive at targets and mechanisms to see that targets are met. For example, in the Kyoto protocol, reductions of greenhouse gas emissions averaging around 5% of 1990 levels were negotiated [11].

All such emission target approaches depend on having a reasonably reliable figure for national emissions. However, consider that a calculation of the cumulative national greenhouse gases is quite non-trivial, involving summation of emissions over hundreds of individual industry and societal sectors. The dependability of this calculation depends crucially on the status of sector level knowledge. Current national emissions inventories are typically produced by national environment agencies in respective countries. The inventory produced for the US by USEPA, and it is clear from the discussion that even in the US there are large margins of uncertainty in emissions data [12]. Aside from the question of uncertainty and errors in emission estimations, the issues of transparency and verifiability are probably more crucial. The emissions reductions being discussed are likely to have serious economic and social implications for countries implementing the protocol. This creates a palpable danger of "creative emissions accounting", through which targets are reached through announcement of initiatives and sleight-of–hand alterations in the measurement and calculation of emissions. An improved system for observation and dissemination of sector level emissions is probably the most effective counter to this problem. Thus, it is asserted that the sector level knowledge system is an important component in the meaningful implementation of emission reduction treaties.

Firm-level environmental performance

Environmental performance is increasingly becoming an issue relevant to the competitiveness of firms. In response, companies are becoming more active and vocal regarding their environmental activities. This is a development with great potential. The market system has proved an extremely effective force to realize efficient production, and there is much to be gained if it can be harnessed to address environmental issues as well. However, as currently there is almost no means to evaluate the environmental performance of firms, there is a danger that the competition could easily become one of environmental image over substance. This concern is exacerbated by the content of the environmental reports of firms: such reports often appear to be advertisements asserting environmental friendliness, with little substantial information on the emissions and impacts of production activities.

There are some developments towards external certification of the environmental activities of firms. The ISO14,000 series of environmental management standards has come to be perceived as a seal of good environmental performance. No doubt there is a correlation in many cases, but it is worthwhile to emphasize that ISO14,000 prescribes a management system to respond to environmental issues, the actual targets for emissions are determined and evaluated internally [13]. There also are a number of initiatives for certifying that manufacturing activities meet certain standards of environmental performance in the form of ecolabel initiatives [14]. In Europe, a number a domestic ecolabel programs are already underway, such as "the Blue Angel" in Germany and the Swan in Sweden.

The question of what system should be implemented to ensure a meaningful competition between firms is complex and goes far beyond the scope of this work. However, the degree of publicly available information at the sector level is clearly a key issue in whatever system is developed. It is thus important to understand the current level of environmental knowledge and the institutional arrangements that lead to this situation.

Implementation of general strategies for sustainable industry

Many general approaches to progress towards sustainable industry have been developed, such as Pollution Prevention, Zero Emissions, and Product-to-Service Transformation. Pollution Prevention emphasizes redesigning processes such that less pollution is generated, thus reducing the need for end-of-pipe treatment [15]. A main theme of Zero Emissions the realization of industrial networks such that the process wastes are used as an input materials for other processes [16]. Product-to-Service transformation involves an extension of the producer's role such that post-consumption re-use/treatment becomes the responsibility of the supplying firm [17]. The consumer thus increasingly leases services rather than owns products. There are many other approaches as well, with their respective advantages and disadvantages, how and which can be applied in practice depends very much on the sector/product involved.

On one hand, these strategies can simply be communicated to individual firms to help strategize improvement in environmental performance. But from the perspective of the overall societal response system, this is probably not enough. For the most part, the literature regarding such strategies amounts to a series of success stories. But this leaves open the question of what is happening at the macro-level, what is the overall effect of various strategies for a sector? Without organized knowledge of what worked and where, it is difficult to judge effectiveness and strategize further progress. Another obstacle is the tendency for such strategies to become viewed as name-brands, whose activities are accounted for by organizations who align themselves with particular approaches. In fact, there is a huge amount of informal activity in areas such as process redesign (Pollution Prevention) and process symbiosis (Zero Emissions) that never comes to light because it is not identified.

From the above discussion, it is clear that the level of sector information regarding environmental strategies taken is very relevant for the macro-analysis and thus development of approaches to environmentally friendly industry.

Focus of survey of sector-level knowledge system

The overall conclusion of the above discussion is an assertion that the level of publicly available information at the level of the industrial sectors is an important issue for sustainable development. It has also been suggested that the current system needs improvement. It seems an appropriate first task to characterize and understand the structure of the existing system. To this end, a survey of publicly available knowledge at the sector level will be undertaken. Also, the question of how an information system may be improved, through methodological and institutional change, will be considered.

I.4 Case study: the global production chain for high-purity silicon

The two main topics, global production chains and the sector-level knowledge system, will be investigated through undertaking a case study of a particular global production chain. This section will discuss the choice of case study and the methodology used to investigate it. The production chain studied is that producing high purity silicon and its use in three high-tech products: microchips, solar cells, and optical fiber. These three products are key ingredients in information technology and renewable energy, thus the relevance of these industries to the future of human societies is apparent.

Information Technology and renewable energy

The industrial trade system that yields microchips, solar cells, and optical fiber has many implications for sustainable development, both in terms of the benefits bestowed from its products as well as in the environmental impacts resulting from associated production processes. Microchips and optical fiber are basic ingredients in the physical infrastructure of information technology, which has a key role in the function of what is sometimes called the "knowledge-based economy" [18]. Information Technology also continues to transform society in a manifold of ways. There are direct environmental benefits as well, as optical fiber provides far more information transmission capacity per environmental load than copper cable, thus its substitution is environmentally favorable [19]. Power from photovoltaic solar cells are potentially an important source of renewable energy, and thus could have a major role to play in realizing sustainable economic activities. Converse to these benefits, there are also environmental impacts associated with the production system that yields these products, both in terms of resource use and emissions. These environmental implications are slated to increase as all three manufacturing sectors continue to experience growth rates far above the global GNP, and demand is apparently far from bottoming out in the near decades. It is clearly desirable that the system evolves to produce all three products more economically, but at the same time follow an environmentally friendly development path.

There are ten global industrial sectors considered in the production chain, those producing quartz/silica, coal, charcoal, silicon metal, chlorosilane compounds (intermediate chemicals used in purifying silicon), polysilicon, semiconductor devices (microchips), solar cells, and optical fiber. A diagram of the sectors and their relationships appears in Figure I.2. The functional roles of different sectors in the production chain will be briefly explained. Processing begins with the extraction and preparation of raw materials, quartz, charcoal and coal. Silicon "metal" is produced from these materials through reduction in an electric furnace. The purity of this silicon is around 99%, unsuitable for the demands of high-tech industries, thus the next step is conversion to chlorine compounds such as trichlorosilane ($HSiCl_3$) and silicon tetrachloride ($SiCl_4$) and purification via distillation. Silicon tetrachloride is a primary ingredient in producing the pure glass cores of optical fibers. For microchips and solar cells, trichlorosilane is converted into a valuable commodity known as polysilicon, which is extremely pure silicon with impurity levels in the parts per *billion*. This polysilicon is used in the production of silicon wafers, thin discs of pure silicon. These silicon wafers form the base onto which microchips, certain solar cells, and other semiconductor devices are fabricated.

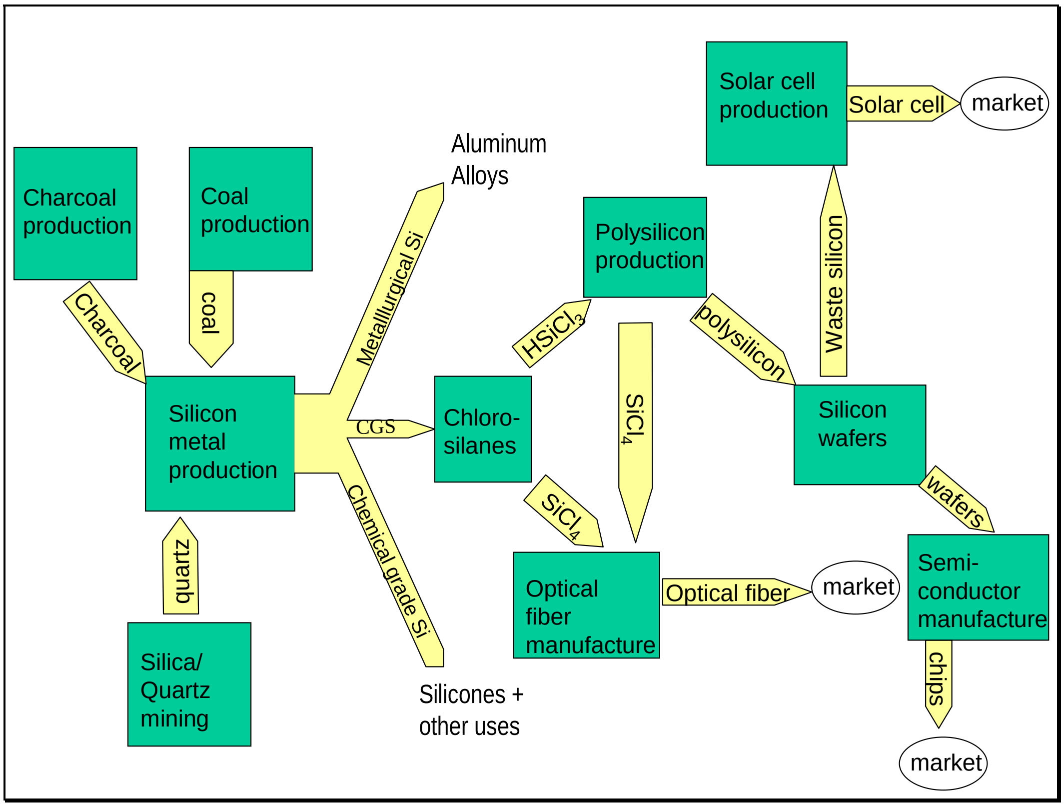


Figure I.2: The production chain for high-purity silicon and its use in semiconductors, solar cells, and optical fiber

Methodology

The next question is what form of study is appropriate to address the two objectives: undertaking systems analysis of a production chain and evaluation of the environmental knowledge system. For both subjects the basic object is the global industrial sector, thus a main task will be to develop a profile of each industrial sector in the production chain. Each profile is intended to provide a survey of available knowledge of the global sector concerning economics, technology and environment. The profiles serve three purposes: by themselves they are intended to provide a useful reference for practitioners involved in studying or implementing sustainability in the case study sectors. Second, the data in the profiles is the basis for systems analysis of the production chain, including estimations of global flows of materials, capital and energy. The process of collecting the information for the profiles serves as a survey of the status of publicly available knowledge at the sector level.

Sector profiles

In order to decide what information should be collected for each it is useful to start off with a set of core questions to guide the work. Some questions framed for this purpose were:

1. What is the economic and physical scale of the sector? What have the growth rates been in the short and long term?

2. Does this sector produce a locally or internationally traded commodity? Is competition on international markets between similar firms? What are the environmental issues related to this trade?
3. What is the geographic distribution of production activities in the sector? How is this related to the geographic distribution of firms? What are relative roles of developed and developing countries with respect to the previous two questions?
4. What are the amounts of emissions of environmental relevance of a given sector? How are these emissions connected with production technology? What are the possible impacts of these emissions?
5. Is the technology of a given sector rapidly evolving or more or less stable? Are the technologies implemented on similar level across different countries/firms, or are there high-tech/low-tech divisions?

These questions touch on many issues related to the sustainable development of the sector. Of course providing satisfactory and illuminating answers to all the above questions is well beyond the scope of available data. The intent here is to partially address them and contribute to developing a knowledge system that allows them to be answered in the future.

Considering the questions above, the types of information to be gathered for a profile are:

1. Definition and role of the sector
    - Description of the good produced and its role in the larger industrial system
    - Quantitative data on its connections to other industrial sectors.
2. Economics
    - World production, production trends, prices
    - Geographical distribution of production, firms
    - Extent of international trade
3. Technology
    - Description of process technologies
    - Process input/outputs of materials and energy
    - Discussion of technological trends, rate of technological change
4. Environment
    - Survey of environmental impacts of the industry
    - Use levels and efficiency of energy and resources

The profiles obtained appear in Section II of this report. The methodologies and results for systems analysis and the environmental knowledge system appear in Section III.

Section II: Industrial Sector Profiles

II.1 Silica/Quartz

II.1.1 Overview of the material and its applications

Silica and quartz are related terms referring to substances primarily composed of silicon dioxide (SiO_2). Silica is a general term for silicon dioxide, both natural and man-made, while quartz refers to certain crystalline forms of silica. Quartz is a very common mineral, occurring in abundance in the earth's crust. Silica and quartz are used extensively in many industries, from low to high-tech and the grade and type of silica used depends very much on the application. Low grade silica, essentially sand and gravel, is extracted on a huge scale for use as an aggregate in road construction, cement production, and as filler. 1992 world production of construction sand and gravel in was estimated at 10 billion metric tons [1]. Purer material, generally over 95% silicon dioxide, is known as industrial silica, major applications are in glassmaking, foundry sands, abrasives, and hydraulic fracturing of oil wells. Other uses include as abrasives, fillers for paints and other chemicals, filtration, ceramics, and in silicon metal production.

This report is primarily concerned with quartz used in production of silicon metal, but two other specialized silica sectors are of particular relevance to the production chain of interest: fused silica and quartz crystal. Fused silica is glass nearly 100% silicon dioxide (typical window glass, for instance, is only around 70% SiO_2), and can be produced from high purity raw silica, or if higher quality is desired, from chemically purified forms of silicon such as silicon tetrachloride. Very pure fused silica, many orders of magnitude more transparent than ordinary glass, is the base material for transmission of light in optical fibers. Also, fused silica is used to make specialty glassware for processing semiconductors and solar cells. Ordinary glassware contains impurities that would soon contaminate materials used in manufacturing microchips, thus fused silica glassware plays an important role in the production process. Quartz crystal of high purity and good crystal structure is highly prized for its piezoelectric properties. This property is utilized to make quartz resonators, filters, and tranducers. Quartz crystal resonators have a very stable and reproducible frequency, which has lead to them becoming the standard in devices such as timing chips used in computers, and of course, wristwatches. Though some naturally occurring quartz is suitable for resonator applications, most quartz crystal is synthetically cultured, grown around chips of natural quartz crystal known as lascas.

Quartz used to produce silicon metal must satisfy moderate requirements in terms of particle size and purity. Feed chip sizes ranging from 10-100 mm insure appropriate gas permeability in the electric furnaces used for silicon reduction. In terms of purity, a typical composition for quartz used for silicon metal production is: SiO_2 content > 98.0%, Al_2O_3 1.0% max, Fe_2O_3 1.5% max, CaO .2% max, and MgO .2% max [2].

II.1.2 Economy/Trade

Production/prices

World production of industrial silica was estimated at 110 million metric tons in 1998, down 13% from 1997, and down 10% in total over the interval 1988-1988 [3]. It is interesting that the industry to extract such a basic raw commodity is shrinking. The total value of 1998 silica production can be roughly estimated at $US 2.0 billion, by taking the US average price of all industrial silicas, $18.17 per metric ton [3], as the world average.

Consumption

Table II.1.1 shows the shares of certain end-use world markets for industrial silica [1]. Data on the first four sectors comes from a report by Roskill Information Services, the

Table II.1.1: Consumption of silica according to end-use sector

End-use	Share
Glass Making	40%
Foundry Sands	25%
Abrasives	10%
Hydraulic fracturing (of oil wells)	5%
Silicon metal production	2%

last share is estimated as discussed below. The above end-use markets account for 82% of total production, accounting for the remaining 18% will not be addressed in this report.

While there are no readily available statistics for the amount of silica used to produce silicon metal, world consumption can be reasonably estimated using input requirements of the silicon production process. Assuming 2.85 tons of silica is required for each ton of silicon metal produced [4], 1998 consumption of silica for silicon production is calculated to be 2.7 million tons, or 2.4% of 1998 world production. The 1997 US price of silica used in silicon reduction was US$16.64 per ton [3]. Taking this to represent the average world price, the estimated world market of silica for silicon metal is US $45 million.

1992 world production of fused silica was estimated to be 20,000 tons, with 20% of this production destined for semiconductor manufacturing equipment [1]. 1990 extraction of quartz lascas for culturing piezoelectric crystals was estimated at 2,800 tons [1]. At about $900 per metric ton, lascas command a much higher price than many other forms of natural quartz. The total 1990 market value for the lascas sector was about $2.5 million.

Geographical distribution of production/trade

The 1997 output of the eight largest production of industrial silica is shown in Table II.1.2 [3], the total of these eight represents around 70% of world extraction. It should be noted however that these figures do not include data for Chinese production.

Table II.1.2: 1997 production of industrial silica according to region (source: USGS [3])

Country	Production (millions of metric tons)	Country	Production (millions of metric tons)
United States	28.7	Paraguay	5.0
Netherlands	24.0	UK	4.8
Austria	6.5	Japan	3.3
Germany	6.5	Italy	3.3

The data indicates that industrialized countries dominate production, perhaps reflecting the higher scales of demand from the silica end-use industries, e.g. glass and metal foundries. As industrial silica is a fairly abundant resource, the distribution of production is more dependent on local demand than on the scarcity of deposits. With respect to the sub-sector of silica used for silicon metal production, silica extraction is apparently located in the same region as silicon production facilities in most cases.

Trade

Although worldwide trade data for industrial silica were not available, most industrial silica is a "regional commodity", meaning that production and consumption generally occur in the same region, with limited international trade. For example, of the 1997 US industrial silica production of 28.5 million tons, only 1.4 million tons was exported, and 1.05 million tons of those exports was to neighbors Canada and Mexico [3]. Thus only 1.2% percent of silica is exported beyond neighboring counties. This local nature of silica production and consumption is likely due to the fact that most grades are relatively abundant and inexpensive.

II.1.3 Technology

Extraction process

Extraction of quartz for metallic silicon production is similar to other methods for mining industrial silica. The description that follows is mainly based on reference [5], in which the reader can find a more detailed treatment. The rock material is typically mined from open pits containing quartz-rich sand and sandstone, though extraction is also carried out from streams or even the sea (widely practiced in the Netherlands). Depending on the cementation of the deposit, blasting may be required to loosen the rock for collection. The material is collected and transported to a processing site, where it is crushed and size sorted. After separating sizes, the material is washed with water to remove dirt and other debris. It is then dried, cooled and prepared for shipment. Depending on the plant, the different chip sizes obtained in the crushing sequence are packaged separately and sold for other uses. For instance, very fine sand-like particles may be sold as construction material.

Process inputs/outputs

Silica extraction is one of the simplest of mining processes, as the material does not require refining, resulting in relatively small amounts of overburden. According to one estimation of Brazilian production practices, 3.3 tons of extracted material is from the ground and 1.3 tons of water is used to produce 1 ton of silicon grade quartz [6]. According to 1992 US Census data, the total energy consumed to produce 1 ton of silica is 126 kWh, 21 kWh of which was electrical energy, the remainder coming mainly from fossil fuels [7].

II.1.4 Environment

Process emissions/impacts

Compared to other process to extract metallic ores of industrial minerals, the environmental impacts due to silica extraction are relatively low. The content of the desired substance, silicon dioxide, in the extracted rock is high, leading to small overburden levels. The main process chemical is ordinary water used in moderate amounts. The main process emissions are silica dust, spent water, and emissions from the machinery used to collect process the ore [5]. Silica dust does represent a potential occupational risk. Inhalation of silica dust can lead to a serious lung condition known as silicosis, and is also a suspected carcinogen [8]. During the mining and other “dusty” stages appropriate precautions need be taken to prevent exposure. At many later process stages, the risk level is substantially mitigated by the wet state of the material, which reduces amounts of airborne dust.

Resource use/efficiency

As a sector directly involved in extraction of a natural resource, it is appropriate to comment on the long-term availability of that resource. Although deposits of industrial silica are scarcer than those of ordinary construction sand and gravel, still reserves for future use are apparently quite abundant [9]. Minerals contains high percentages of silica occur are quite common and occur in many areas in the world.

However, reserves of lascas suitable for quartz crystal culturing are quite limited, and could be used up in the next 20 years [8]. Recycling rates at the industry level are likely high, as low-grade material can always be used as a construction aggregate. Post consumer level recycling varies according to the application, but at least for the largest sector, glass, recycling programs have been implemented on a wide scale.

Energy – Taken the process data estimated from US Census statistics as the world average, the total energy consumed by the world silica industry is estimated to be 13.8 billion kWh. Electricity use represents 2.3 billion kWh of this total, the remainder composing of fossil fuels.

II.2 Charcoal Production

II.2.1 Overview of the material and its applications

Charcoal is vegetable matter that has undergone a pyrolysis reaction (heating with limited contact with oxygen) such that the resulting material is composed primarily of fixed carbon. Most any type of plant matter can be converted into charcoal, but wood is the primary material used. As a fuel, charcoal is valued for its high energy and low ash content, and is widely used in cooking and heating. Woodfuels are an important energy source in the developing world, supplying 15% of energy demand on average, with the figure exceeding 70% for many countries [1]. Charcoal represents 8% of the woodfuel energy supply on average [1], with the share reaching 30-50% in countries such as Malaysia and Thailand [2].

Charcoal also has a great variety of industrial applications. In the metallurgical sector, it is primarily used in the iron and steel industry, and also in the production of ferrosilicon and silicon metal. There are also many chemical applications, the largest of which is conversion to activated charcoal, which with its extreme porosity is a widely used absorber and purifier [3].

Charcoal is a porous, crumbly material with a bulk density varying from .2-.4 g/cm^3. The energy content of charcoal is around 30 MJ/kg, equivalent to high quality coal. A representative composition of good quality charcoal for metallurgical use has about 75-80% fixed carbon, 20-25% volatile components, and 3-4% ash [4]. The composition of ash varies considerably according to the type of plant material used, typical figures for temperate zone hardwood are about 50% CaO, 20% K_2O, with smaller amounts of Na_2O, MgO, SiO_2, Fe_2O_3, and P_2O_5 [5]. Charcoal for silicon reduction and other metallurgical uses is sized in chunks from 10-100 mm.

II.2.2 Economics

Production/prices

FAO estimated the 1998 total world production of to be around 21.6 million tons, up .5% from 1997, and with overall 7.7% growth over the decade [6]. The price of charcoal in developing countries the price reportedly varies from $90-$180 per metric ton [7]. Taking an average world price of $100 per ton, the scale of the world charcoal market is estimated to be $22 billion.

Consumption/End-use

More than 90% of charcoal produced is used as fuel. It is difficult to arrive at an accurate estimate of the amount of charcoal used for silicon production, as a mixture of charcoal, coal and coke are used, and this mix varies according to the manufacturer. This issue is addressed in section II.4.2, and according to the calculations and data found there, the total amount of charcoal used in silicon metal production in 1997 is estimated at 642,000 metric tons, around 2.3% of world consumption. The price of charcoal for silicon reduction varies according to locale, but in Brazil a sample spot price for charcoal for silicon reduction was $80 per ton, and typically stays between

$70-100 per ton [8]. Taking $100 per ton as the average world price, this leads to an estimated world market value of $64 million dollars.

Geographical distribution of production/trade

The top eight producers of charcoal are listed below in Table II.2.1. From this table it

Table II.2.1: 1998 production of charcoal of top eight producing countries (source: FAOSTAT [6])

Country	Production (metric tons)	Country	Production (metric tons)
Brazil	3,600,000	Sudan	1,143,000
India	2,208,000	Zambia	1,041,000
Kenya	2,187,000	USA	853,000
Nigeria	1,633,000	Thailand	656,000

is evident that charcoal production is overwhelmingly centered in developing countries., which reflects the high usage of woodfuels in those areas. In Brazil, charcoal is also used on a large scale as a reductant in the steel industry.

Trade

A total of 689,000 tons of charcoal was exported to international markets in 1998, accounting for about 3.2% of production [6]. This rather low figure reflects that charcoal is mainly a regional commodity, partly due to its bulkiness and fragility

II.2.3 Technology

Production processes

Producing charcoal involves heating cut wood or other vegetable matter in limited contact with oxygen. The basic process goes through three stages: heating, carbonization (pyrolysis), and cooling. The material to be converted is placed in some semi-closed structure and heated to around 500 C. Carbonization reactions decompose the vegetable material, in which many organic vapors and tars are formed and emitted, the solid product being charcoal. The material must then be cooled to a point where it can be handled, which can take from hours to several days depending on the technology implemented. For a more complete description of pyrolysis chemistry, the reader is referred to [5].

There are many processes for charcoal production and the equipment, labor requirements, process efficiency and environmental emissions vary considerably with implementation. The main batch type processes can be categorized into three groups: earth pit/mound, brick kilns, and metal kilns. An earth mound/pit involves where covering the material to be converted with earth, except for a few openings, and then applying heat to initiate the reactions. Brick kilns are simple permanent structures composed mostly of clay with some small amount of steel. Reasonable efficiency and performance is possible with relatively small investment. The beehive kiln, a particular design of brick kiln, is the mainstay of production of the world largest producer, Brazil. Portable steel kilns are fairly small vessels designed to be easily transportable to the area near wood extraction. On the higher end of investment and technology scales, there are larger steel furnaces with retorts that burn volatile wastes. Continuous multiple hearth furnaces implement a continuous, rather than batch process, are most suitable for pyrolysis of smaller chunks of wood. Such furnaces are used widely in developed countries, especially the United States. Table II.2.2 shows a profile of some of the main characteristics of the different production processes.

Table II.2.2: Profile of different charcoal production processes
(sources: Smil [9], FAO [3,4])

Process	Efficiency	Time	Life expectancy of facility (years)
Earth	10-22%	30-60 days	.1
Brick kiln	22-27%	9-13 days	5
Portable steel	20-25%	2-3 days	3
Waggon Retort	30-33%	3 days	30
Continuous hearth (input is waste wood)	25%	continuous	30

The above efficiencies are measured by dividing weight of charcoal by weight of input "dry" wood. As the extent of drying possible varies with the wood type and drying process used, the efficiency figures should be viewed as rough estimates. Because charcoal crumbles easily, handling and transport generally leads to 10-20% of the material sloughing off as small charcoal particles called fines. One option to avoid this waste is to produce charcoal briquettes, which are denser and sturdier than charcoal. In the briquette production process, fines are sized through a 3mm screen, and mixed with a binder solution and sometimes sawdust or other materials to alter burning properties. Typical binders are plant starches, such as cornstarch, milostarch, or cornstarch, in an 8-10% solution. This mix of fines, binder, water and fillers is pressed into briquettes and dried at about 375 C for 3-4 hours [10]. Briquettes have similar performance to raw charcoal in terms of fuel use, but unfortunately are not economically feasible in general, due to the extra cost of the briquetting process. Charcoal briquetting has been quite successful in the United States, where household charcoal markets allow a relatively high price. Continuous multiple hearth furnaces are used to carbonize sawdust and bark to yield fine charcoal, which are then formed into briquettes.

For more complete descriptions of charcoal production processes, the reader is referred to References [3] and [4].

Process inputs/outputs

As the input vegetable matter contains far larger quantities of such elements such as oxygen and hydrogen than charcoal, the production process naturally results in emissions of large amounts of other substances. For processes without output-burning "retorts", a great variety of organic compounds, from tars to organic acids and other substances, are emitted. With retorts, the main outputs are carbon dioxide and water. Given an input of dry wood of approximately 3000-4000 kg, the outputs of a typical kiln charcoal production process are shown in Table II.2.3.

Table II.2.3: Average outputs of batch kiln charcoal production process (sources: USEPA [10] and Smith[11])

Substance	Amount	Substance	Amount
Charcoal	1000 kg	Methanol	75 kg
Brands†	150 kg	Methane	55 kg
CO_2	550 kg	Ethane	26 kg
CO	145 kg	Particulate matter (includes condensable tars and oils)	176 kg
NO_x	12 kg		

†Brands are partially converted charcoal.

In most cases the non-charcoal products are emitted into the atmosphere.

Technological trends

The technologies to produce charcoal have remained more or less stable for many years, though researchers and industry continue to work to develop improvements. A group at the Latvian State Institute of Wood Technology has developed a kiln-retort system wherein combustion of the off-gases is used to dry the input wood, which speeds and improves process performance [12]. A group at the University of Hawaii pioneered a high-pressure process with extremely high efficiency, realizing yields near the theoretical maximum of 42-62% [7]. What new technologies are appropriate for the variety of local economic conditions for charcoal production is however unclear.

II.2.4 Environment

Environmental impacts of emissions

Charcoal production and use, as with any biomass based product, can in principle be greenhouse effect neutral, presuming nearly all carbon in the material ends up as carbon dioxide which is taken up by the next generation of biomass. However, this is not generally the case under current practice, as much of the carbon contained in the wood input is emitted as methane, a potent greenhouse gas. Assuming that the CO_2 equivalence multiplier of methane is 11 [global], the process data in Table II.2.3 suggest that the combined cycle of carbon absorption due to growth of biomass input and production of 1000 kg of charcoal yields a net emission of around 500 kg of CO_2 equivalent greenhouse gases. This result assumes that the carbon in all outputs other than methane are eventually converted to carbon dioxide. Thus, methane emissions substantially shift the carbon balance of charcoal production towards net emissions. This highlights the importance of combustion of methane emissions if carbon neutrality is to be achieved. Another important issue is whether the forest resources consumed in charcoal production are being managed in a sustainable manner.

Charcoal production is also related to deforestation. Using an optimistic estimated yield of 10 tons of charcoal per hectare of forest cleared (this assumes all charcoal is produced from mature tropical forests [4]), current production levels represents a yearly clearing of 2.1 million hectares of forest. Thus, charcoal production is involved in at least 20% of deforestation (the average yearly deforestation rate in the period 1990-1995 was 10 million hectares/year [1]). However, it cannot be said that this deforestation is necessarily *caused* by charcoal. In many areas charcoal production is secondary to the objective of clearing the land for agricultural use. With regard to the sub-sector of charcoal for silicon metal, much of the production is based from Eucalyptus plantations (Australia and Brazil), some portion comes from native woods, such as from Cerrados Savannah forests in Minas Gerais, Brazil.

With respect to impacts of process emissions, charcoal kilns without retorts emit fair quantitative of a number of organic substances of potential concern to human health and eco-systems. However, there would seem to be little readily available literature discussing the situation.

Resource utilization/efficiency

By and large the production of charcoal represents a rather inefficient use of resources. In typical cases, 60% or more of the input mass and around 50% of energy is unutilized. The continuous hearth kiln-electricity generation combination probably represents best practice, but its implementation requires considerable investment and appropriate market conditions. It is worth noting that there are many useful by-products contained in the emissions, in fact charcoal production used to be implemented so as to yield co-products such as methanol, acetic acid, acetone and specialty tars [3]. However, such production practices have dwindled out with the development of the petrochemicals industry.

II.3 Coal Production

II.3.1 Overview of the material and its applications

Coal is a black sedimentary rock that formed due to the geological transformation of ancient plant material. Known as "the rock that burns", coal's high-energy content and abundance of deposits have given it an important role in the global energy supply. The classification and properties of different types of coals is related to the geological processes that form it. Coal begins as peat, partially decomposed plant material composed mainly of cellulose and lignins. As sedimentary deposits settle over the material, the temperature and pressure increase, setting off coalification, a combination of physical and chemical processes in which water and various gases are driven from the material, and carbon content is increased [1]. As coalification proceeds over longer periods, some tens to hundreds of millions of year, the rank of the coal increases, starting from lignite, subbituminous (brown coal), moving on to bituminous, and finally anthracite. Some basic properties of these categories appear in Table II.3.1:

Table II.3.1: Characteristics of different classes of coal
(adapted from Kesler [1], Coal Week International [2], and Kirk-Othmer [3])

Type	%Fixed carbon	%Volatile matter	%Ash	%Sulfur	Calorific value (MJ/kg)
Lignite	50-55	45-50	-	-	<19.31
Subbituminous	55-60	40-45	-	-	19-26
Bituminous	60-85	14-40	5-14%	.5-5%	27-36
Anthracite	85-98	2-14	8-15%	.3-.9%	36-37

The main use of coal is as a fuel for power and heat stations, where fuel-grade bituminous (steam coal), sub-bituminous, and lignite coals are used. Coal also plays an important role in the metallurgical sector, where it is primarily used in its pyrolized form, coke. Blast furnaces using coke and coal account for around 70% of world steel production [4]. Sub-bituminous and steam coals are also used as a main source of heat in cement manufacture. Anthracite coal is mainly used for domestic heating, and on a smaller scale in industrial applications, such as in purifying and filtering agents.

A typical low-ash coal used in silicon metal production has 55-70% fixed carbon and less than 4% ash [5]. High purity anthracite coal is also used as the main ingredient in amorphous carbon electrodes used in electric furnaces for silicon metal reduction.

II.3.2 Economy

Production

World production of coal in 1998 was 4.54 billion metric tons, down 2.5% from the previous year with an overall 3.8% decrease since 1988 [4]. This is clearly a huge scale of extraction, and in fact among commodities, coal is second only to sand and gravel aggregrates in terms of annual weight of production. Production levels have been more or less stable since the late 80’s, with a slight overall decline. Table II.3.2 shows a breakdown of 1995 production according to the different types of coal [6]:

Table II.3.2: Breakdown and value of 1995 world coal production
(source: US DOE [6])

	Anthracite	Bituminous (steam)	Bituminous (coking)	Brown coal/ lignite	total
Production (million MT)	386	2670	600	895	
Price (per ton)	$50	$35	$45	$12	
Value (billion $)	19.3	93.4	27	10.7	$150

Total world production is valued at around $150 billion. This estimate is rather crude, however, as the prices reported above are rough guesses at average world prices. At any rate, the world coal market is among the largest of primary commodity sectors.

End-uses/consumption

Some 58% of hard coal production (above sub-bituminous) is consumed in power and heat stations [4]. Coal based energy represents 26% of world energy production and is used in generating 38% of the world’s electricity [7]. 16%, or 600 million metric tons, of hard coal is used in steel production. About 630 kg of coal is required for each 1000 kg of steel produced [4]. Around 12% is consumed in other industrial applications, with around half of this used in cement production. Residential use a heating fuel, largely filled by anthracite coal due to its low smoke outputs, accounts for around 5% of consumption. Most brown coals and lignite are consumed in power and heat stations. Roughly 260,000 tons of high grade bituminous coal is estimated to be consumed in the production of silicon metal (see section III.1 for calculation)

Geographical distribution of production

The top eight bituminous coal producers and production levels in 1998 are shown in Table II.3.3. [4], whose output accounts for 89% of world production. Up to the

Table II.3.3: 1998 Production of Bituminous Coal by country
(source: World Coal Institute [4])

Country	Production (10^6 tons)	Country	Production (10^6 tons)
China	1,236	Australia	219
USA	939	Russia	149
India	303	Poland	117
S. Africa	223	Ukraine	75

1950's, the US and the EU were the main producers of coal. Chinese and USSR production grew through the 1960's and 1970's, both coming to match US production in the late 70's. European production has been steadily declining since the 1950's.

Trade

The total amount of coal exported to international markets in 1997 was 494 million tons [6]. This corresponds to around 10% of total world production, indicating that most coal is locally consumed. However, given the massive overall scale of the coal industry, the amount of coal internationally traded is quite large. Coal is one of the most inexpensive of bulk commodities exported on a large scale. Australia, the US, and Indonesia are the largest exporters of coal, the three countries combined accounting for around 50% of total world exports. Japan is by far the largest importer of coal, importing 129 million metric tons in 1997 [6].

II.3.3 Technology

Extraction process

Coal is extracted from both surface and underground mines, the two processes will be described separately. Surface, or strip mines are used when the coal deposit is sufficiently close to the ground, typically some tens of meters. Extraction methods vary according to the extent that land reclamation is practiced, the process representing good practice will be described here [1],[8]. Depending on the scope and configuration of the underlying coal seams, the mining is carried out in a sequence such that the materials of a current extraction area are used to rebuild the landscape of a previously mined site. For a given site in this sequence, the initial step is to remove topsoil and subsoil with large scrapers. The topsoil is placed on a previously mined area prepared for reclamation. The next stage is removal of the overburden down to the coal seam using drills and blasting. This material is collected into piles with shovels and trucks for later use to fill a previously mined site. The coal in the seam is drilled, blasted, and transported to a processing area. After the coal has been exhausted, overburden is replaced and graded using bulldozers. Subsoil and topsoil is placed on top of this graded area, which is then limed and cultivated with new vegetation

Underground mines typically some hundreds of meters under the surface [9]. There is range of techniques for mining, ranging from manual blasting of tunnels and collection of ore to nearly fully mechanized extraction. One major distinction made in mining techniques deals with the configuration in which tunnels are cut. In the *room-and-pillar* configuration, deposits are mined through cutting a network of rooms, leaving behind a set of pillars that support the roof of the mine. This limits the amount of coal that can initially be extracted from the mine to around 60%, though some of this material can be removed at a later stage. In *longwall* mines, coal is extracted perpendicular to a long narrow tunnel, which is being temporarily supported. As the extraction proceeds inwards, the supports are moved and the previously mined section is allowed to collapse in a controlled manner. Some 70% or more of the coal deposit is extractable via longwall mining [4]. Coal extraction has been evolving more and more towards mechanized extraction, fully mechanized longwall mines account for 25% of world coal production [9]. But still, very labor intensive methods are still in practice, for example some 55% of Chinese underground mines are hand blasted and drilled [9].

Post extraction processing

Typical material extracted from coal seams contains about 25% mineral matter [10]. Also, there are various qualities of coal within the same seam, thus separation systems are often implemented to improve quality. These are also often referred to as coal washing and coal cleaning. To give an indication of the extent of implementation of coal washing, note that the two major coal producing countries, China and the US, wash 25% and 55% of coal production respectively [11]. Typically, the coal is crushed into smaller pieces and then separated by some mechanical method according to density (coal has a density of 1.1-1.5 g/cm3, much lighter than typical minerals). The most widely used method is jig washing [5], which involves applying alternating upward and downward streams of water to a tilted bed of coal particles. Lighter coal particles are pushed to the top, while heavier waste particles go to the bottom. The resulting improved coal is then dried using vibrating screens, centrifuges, or even ovens in the case that extremely low moisture contents is required.

Process inputs/outputs

From 1992 US Census data on aggregate sector energy use, the average energy consumption for coal mining is estimated at 50 kWh per metric ton of coal produced [12]. From the same report, electricity consumption is estimated at 13 kWh per metric ton of coal extracted. Underground mining is much more electricity intensive that surface mining, 64% of energy consumed in underground mines was electrical as opposed to 14% for surface mines.

Methane output from surface mining estimated at 10 kg per metric ton of coal extracted [13].

II.3.4 Environment

Environmental impacts

Emissions – the main emissions from coalmines are methane gas, dust, and waste rock material. The methane emissions are considerable, coal mining activities were believed to account for emission of 46.3 million metric of methane in 1994, which represents around 12% of total anthropogenic methane emissions [13].

Landscape impacts - surface mining of coal can have substantial impacts on the environmental system where it is carried out. Large tracts of soil and rock are removed, leaving the area subject to new weathering mechanisms. Overburden, even if carefully replaced, is generally more porous than the original material, thus many minerals in the rock, including heavy metals, are more easily released. In cases where minerals that dissolve into acids are present, such as pyrites, acid mine drainage can occur, affecting local water quality [14]. Often lime and other acid neutralizing materials are applied at reclamation sites to mitigate this. Also, if the mine area is not re-planted with vegetation, chronic erosion will occur. However, if reclamation practices are properly implemented, the impacts of surface mining are perhaps more or less temporary. The extent to which land reclamation is practiced worldwide will not be addressed here, but it will be noted that it represents a substantial added expense to the operation. In the US at any rate, compulsory reclamation was legislated by a law in 1977, which is apparently fairly well enforced.

Underground coal mining poses many potential occupational safety and health risks. Prolonged exposure to coal dust in mines leads to a condition known as pneumoconiosis, or “black lung disease”. Though modern preventive measures can seriously reduces incidence of the condition, black lung disease continues to be a serious problem. In China, for instance, the death toll of the disease is estimated to be around 2,500 persons annually [15]. Explosion of released methane and cave-ins are additional occupation risks in underground coal mining, such contributed to 54 mine deaths in the US in 1992, where safety regulations are well above the international average [1]. In China, there were an estimated 5,000 deaths due to coal mining accidents in 1995 [16]. Thus as a global industry, there tremendous problems remain in terms of occupational health and safety in coal extraction.

Materials utilization/efficiency

Energy – taking the process energy figures in section II.3.3 as the world average, the total energy consumed by the world coal-mining sector is estimated at 227 billion kWh, 26% of which is electrical energy. This is likely an overestimate, as less mechanized production practices in China and other less-developed countries likely have lower energy consumption.

II.4. Silicon metal

II.4.1 Overview of the material and its applications

The term silicon metal is used to refer to elemental silicon with purity around 95-99%, though "metal" is something of a misnomer as in terms of electrical behavior, silicon is a semiconductor rather than a metal. Elemental silicon is a gray, brittle material, and while not useful for its mechanical properties, has many valuable applications as an alloying agent with various metals. Approximately 54% of the world production of silicon metal is consumed in aluminum-silicon alloys, which have silicon concentrations typically about 6% silicon. Such alloys have improved properties with respect to casting and welding, and are used widely in the automobile industry. The average content of Al-Si in a 1995 automobile was reportedly 945 kg [1].

Silicon is also used extensively the production of many kinds of iron and steel. Silicon metal itself is only used in small amounts; rather a related commodity, ferrosilicon, is the main form used in the iron and steel industry. Ferrosilicon is a mixture of iron and silicon containing typically 50% or 75% silicon, and is produced on a much larger scale than silicon metal. 1995 production of ferrosilicon exceeded production of silicon metal by a factor of 9 [2]. The cast iron industry accounts for about half of ferrosilicon consumption, where it is used to soften and improve the machinability of iron. Ferrosilicon is used in the steel industry as a deoxidiser in the production of killed steels, as a reducing agent removing metal oxides for recovery from slag, and as an alloying element. Controlling silicon content of steels (typically between .5-5.0%) allows fine-tuning of mechanical and electrical properties.

A typical composition of silicon metal for metallurgical applications is 98.5% Si, and .5% max of Al, .5% max of Fe, and .3% max for Ca.

Roughly 43% of silicon metal production was used in chemical applications, and this proportion continues to grow [3]. The largest chemical use of silicon metal is in making silicones, a class of silicon-containing polymer compounds used in sealants, greases, resins, and rubbers. Also, silicon metal in used in the production of chlorosilanes, which includes precursors for the production of high-purity silicon for electronics, fumed silica for epoxies, and high purity fused silica used in optical fibers and specialty glasses. These applications will be discussed further in the section describing the chlorosilanes sector. A typical composition of silicon metal for chemical uses is 99.0% Si, and .4% max of Al, .2% max of Fe, and .1% max for Ca.

II.4.2 Economy

Production

1998 production of silicon metal of all substantial producers excluding China was an estimated 653,000 metric tons, down 1.6% from 1997 and up an overall 6.7% since 1988 [2]. Though perhaps the world's largest producer, Chinese production is excluded due to lack of data sources. Exports of Chinese silicon totaled 290,000 tons in 1997, an increase of 5% over the previous year [2]. A crude estimation of 1998 world production can be made by assuming that all Chinese silicon produced is exported, which yields a figure of 958,000 tons. Assuming a 5% annual growth of Chinese production yields an average overall yearly growth rate 2% in the decade 1988-1998.

1997 prices for silicon metal ranged from about $1,000-$1,800 per metric ton depending on grade and location of production and destination market [3]. For example, chinese metallurgical grade silicon metal exports to Japan had an average 1997 price of $1,050 per ton, while Brazilian exports to Japan of chemical grade material averaged $1,700 per ton. An average price of $1,300 per ton was calculated by averaging typical prices of major markets.

Consumption/end-uses

In the Western world, around 54% of silicon metal production by weight was consumed by the aluminum alloy sector in 1995 [3]. Excluding use in semiconductors, roughly 38% of production was used by the chemical industry, the vast bulk of this going to silicone production. The remaining few percent was consumed in steel and other sectors, including various specialty alloys. For the interval between 1989 and 1995, the average annual growth in demand for silicon by the Western economies was an average 3%, with sector demand changing at rates of 1.4% for aluminum alloys, 5.6% for chemicals (mainly silicones), and 8.0% for semiconductor applications [3]. This estimation is rather uncertain as it depends very much on the silicon consumption of the polysilicon industry, for which little data was available.

This section will address the quantity of silicon metal consumed to produce semiconductors. In a report by Roskill Information Services, 24,600 tons of silicon metal was listed as having been in the production of semiconductors in 1995. It is worth comparing the results of consulting company data such as the above with results derived from those derived from process technology. The silicon demand for semiconductors should be dominated by the production of polysilicon, a precursor for silicon wafers. The world demand for polysilicon in 1995 was reportedly 11,300 tons. According to process data in sections II.6 and II.7, the amount of silicon required for such production is calculated to be 30,000 tons compared to the figure of 24,600 tons above. Thus the various data sets are consistent to within around 20%. Using process data to estimate the amount of silicon consumed in manufacture of semiconductors in 1998 yields a result of 53,000 tons, or 5.7% of total 1998 production.

Geographical distribution of production

Table II.4.1 lists the world's eight largest silicon metal producers by country, which account for 91% of world production [3].

Table II.4.1: Top eight silicon metal producers in 1995 (source: Roskill [3] except Chinese figure)

Country	Production (10^3 tons)	Country	Production (10^3 tons)
China	249	France	71
USA	163	Russia	60
Brazil	116	Australia	30
Norway	101	South Africa	30
		World	779

The level of Chinese production is, as mentioned before, quite uncertain. In terms of export destinations, the bulk of Chinese silicon is exported to Japan and to a lesser extent other Asian countries. The United States is nominally the second world's largest producer, but must import an additional 80,000 tons to meet domestic demand. Brazil's exports are mainly to Japan, the Netherlands, and the US. Norway is the primary supplier for Germany, though also has substantial exports to Japan and the UK. With shipments reaching 190,000 tons in 1996, Japan is the world's major importer of silicon metal. There has been no domestic production in Japan since 1982, mainly due to the high energy costs associated with production.

Firm structure

As with any globalized industrial sector, location of production does not necessarily reflect the character of international production. Around 20-30% of US production, for example, is carried out by US branches of the Norwegian firm Elkem AC. Nearly all of Australian production is under Simcoa, which is wholly owned by the Japanese conglomerate Shin-Etsu. Chinese and Brazilian producers, on the other hand, are for the most part domestically owned.

Trade

Silicon metal is a highly traded commodity, with 86% of 1995 world production exported to international markets [3]. The trade patterns of silicon metal are heavily influenced by the imposition of anti-dumping duties by the United States and Europe. The United States applies substantial duties on imports from Argentina, Brazil, and China. The EU has placed duties on imports from Brazil and China, some of which have been removed at the time of writing of this report.

II.4.3 Technology

Silicon metal is produced using an open electric furnace, wherein an AC electric current is passed through graphite electrodes into a mixture of quartz and carbon sources such as charcoal, low ash coal, and/or petroleum coke [1]. The overall chemical reaction is:

$$SiO_2 + 2C \rightarrow Si + 2CO.$$

Most of the resulting carbon monoxide later combines with oxygen outside the furnace to yield carbon dioxide: $2CO + O_2 \rightarrow 2CO_2$. The actual sequence of reactions is however, more complex, with SiC and SiO forming as intermediate products in temperature zones of the furnace [4]. Molten silicon metal is poured off from the bottom of the furnace and then refined by passing nitrogen and oxygen through the containing vessel. These gases react with impurity metals such as calcium and aluminum to form oxides, which float to the top to form an impurity rich layer. After solidification, this layer (called dross) is removed and the silicon metal is packaged for shipping.

A typical unit of production is a 24 MW furnace capable of producing 10,000 tons/year, is 3 meters deep, with three amorphous carbon electrodes each measuring 1.2 meters in diameter. The temperature at the bottom of the furnace is 1800-2000 C, naturally well above the 1700 C melting point of silicon.

Process inputs/outputs

A sample input/output table for production appears in Table II.4.2 [5]. In order to attain a favorable gas permeability of the melt, the input materials are sized to around 10-100mm. In practice the mix of carbon sources varies considerably according to the producer, for example Brazilian and Australian producers reportedly use no coal or coke, only charcoal and wood chips. Chinese firms apparently use mixes of 1151-1154 kg of charcoal, 266-498 kg of petroleum coke, and 37-46 kg of bituminous coal to produce 1000 kg of silicon [6]. Charcoal is a preferred reducing agent, due to its high reactivity with silica and high electrical resitivity, but is expensive and not always available, so petroleum coke and low-ash coal are often used. Silicon reduction is supposed to be a nearly slag-free process, so carbon inputs should be chosen for minimal ash content. For the purposes of understanding the scales of the industries supplying reductants for silicon metal production, it would be useful to know the global average mix of carbon sources. While it is difficult to estimate accurately without a global survey of manufacturing firms, using a variety of regional data this mix is estimated to be 1.07 tons wood chips, .35 tons petroleum coke, .27 tons coal, and .67 tons charcoal per metric ton of silicon metal produced.

Table II.4.2: Input/Output table for production of silicon metal (source: Phylipsen and Alsema [5])

Input	**Amount**	Output	**Amount**
Quartz	2,850 kg	Silicon metal	1,000 kg
Charcoal	370 kg	CO_2	4,500 kg
Low ash coal	560 kg	SiO_2	10 kg
Petroleum coke	370 kg	H_2O	1,100 kg
Wood scrap	1,320 kg	SO_2	20 kg
Electricity	13.0 MWh		
Electrode material	100 kg		

Technological trends

Overall, the technology for silicon metal production has not undergone substantial change in the last two decades, though a number of refinements have taken place. These include introduction of self-baking composite electrodes, computer process control technology, and optimization of electrode spacing [1]. On a more fundamental level, a recent initiative of the Silicon Technology Competitive Cooperative (STCC) in the US could lead to substantial improvements. The main focus of the project is to develop a direct current closed furnace, which is expected to have lower energy consumption and be relatively insensitive to the sizes of input silica and carbon sources [7].

II.4.4 Environment

Environmental impacts of emissions

The main process inputs (quartz, carbon sources, and water) and outputs (silicon metal and exhaust gases) apparently non-toxic for the most part. While the carbon sources do contain substantial amounts of organic volatiles, these are decomposed in the high-temperature environment in the furnace. The main environmental emissions of possible concern are carbon dioxide and sulfur dioxide. There are both direct and indirect emissions of carbon dioxide. The direct emissions are, according to Table II.4.2, 4.5 tons of CO_2 per ton of silicon metal yielded, thus 1998 world production resulted in 4.3 million tons of emissions. The indirect emissions resulting from production of the electricity required for reduction vary widely according to the power source used. For each kilowatt-hour of electricity generated via a “typical” coal plant, 97 kg of CO_2 are emitted, while for hydropower the emissions are .004 kg [9]. Thus the indirect emissions range between 52 and 1261 kg depending on input power mix. As hydropower is used in much of silicon production, the indirect emissions are likely to on the low end of the previous range.

Using the data from Table II.4.2 as an average for the world industry, 1997 production resulted in an emission of 16 million kg of sulfur dioxide. This is likely an overestimate, as sulfur dioxide emissions are tied to the sulfur content of the input materials. Table II.4.2 reflects European practice, where more fossil fuel sources, which have higher sulfur contents, are used instead of biomass.

Resource utilization/efficiency

Silicon - Roughly 80-85% of input silicon ends up in the final product [1]. Most of this waste silicon ends up as small particles of amorphous silica dust, which is emitted into the air. Though not a hazardous substance, it does represent a nuisance and substantial amount of unutilized material. However, such amorphous silica, also known as fumed silica, has been found to be an excellent additive for concrete of exceptional strength and durability. Many silicon metal manufacturers have implemented systems to bag and sell fumed silica to concrete producers. Depending on the locale, such silica fume can be in such demand that silicon manufacturers opt to maximize for fume production over silicon metal. However, the markets remain sporadic and this practice has yet to become universal.
Energy- 13 kWh/kg, the energy requirements to produce silicon metal are comparable to that for primary aluminum, setting it as one of the most energy intensive of mass-produced metals. Only 31% of the electrical energy input through the electrodes and chemical energy of reductants is utilized in the reduction of quartz, the remaining 69% is lost, mostly in the process off-gases [1]. Clearly this represents a need for improvement, highlighting the importance of developing closed furnaces.

Material Inputs - the size requirements for silica and charcoal mentioned earlier results in a substantial amount of rejected input material. Small quartz particles can be sold to cement manufacturers, if conveniently located, but generally small particles of charcoal, known as charcoal fines, are discarded unused. From production to use in reduction, roughly 25% of the original charcoal ends up as charcoal fines and thus is not utilized [8]. Redesign of furnaces to accept smaller particles, or realization of fines collection and briquetting represent means to utilize these materials.

II.5 Chlorosilane Production

II.5.1 Overview of the materials and their applications

Crude metallic silicon must undergo rigorous purification to reach a purity level suitable for use in high-tech applications. Two chlorosilane compounds, trichlorosilane ($HSiCl_3$) and silicon tetrachloride ($SiCl_4$) are key intermediate chemicals in the production of semiconductors, solar cells, and optical fibers.

Trichlorosilane is the main feedstock chemical for production of polysilicon, the precursor for silicon wafers. Silicon wafers are the base on which semiconductor devices are fabricated. With a boiling point of 31.9 C, the high volatility of trichlorosilane is key in being able to distill in it pure form. Also, it reacts explosively with water yielding hydrochloric acid, thus must be handled with extreme caution. Trichlorosilane is also used is for conversion to organosilanes used as adhesion promoters and as an intermediate product in the production of certain pharmaceuticals. Table II.5.1 details the qualities of trichlorosilane suitable for use in producing polysilicon.

Table II.5.1: Composition of purified trichlorosilane for semiconductor manufacture (source: Jackson et Al [1])

Substance	Amount	Substance	Amount
$SiHCl_3$	99.9%min	Fe	<5 ppba
SiH_2Cl_2	<.2%max	Ca	<1 ppba
$SiCl_4$	.01% max	Al	<1 ppba
Carbon	<.5ppma	Mg	<.02 pppa

Silicon tetrachloride is the main silicon feedstock in optical fiber manufacture. It is a colorless, corrosive liquid with a boiling point of 57.6 C. High purity silicon tetrachloride is also an important raw material for the semiconductor industry in production of high-purity glassware, photomasks for photolithography, and in deposition of epitaxial silicon films. Fair amounts of lower purity silicon tetrachloride (80-95%) are consumed in the production of silica fume, which small particles of amorphous silicon dioxide used as an additive in adhesives and sealants [2]. Silicon tetrachloride used in optical fiber production has metal impurities in the parts per million and other chlorosilanes in the parts per thousand [3].

It is also worth mentioning that two other silanes, dichlorosilane (SiH_2Cl_2) and silane (SiH_4) are used in the deposition of thin films of silicon in the semiconductor and solar cell industries.

II.5.2 Economy

Production

Publicly available data on world or even national production and trade of chlorosilanes is quite scarce. 60-65% of trichlorosilane production is reportedly consumed in the semiconductor sector [2], thus an estimate of world production can be obtained through knowledge of the amount used in semiconductors. The total amount of silicon metal used in the semiconductor sector in 1998 is estimated at 53,000 tons (see section II.4.2). Using production data on the production process, one can estimate that 228,000 metric tons of trichlorosilane was from this input. From this, world production of trichlorosilane is perhaps 350,000-380,000 tons per annum.

The US Department of Commerce reports 1997 domestic production of “100%” silicon tetrachloride at 48,500 tons [4]. World production is not likely to exceed 3-5 times this figure. Using the input/output table in section in section II.9.3, the amount of silicon tetrachloride consumed in worldwide optical fiber manufacture is estimated to be 16,300 tons.

The price of trichlorosilane is from $2-10/kg, depending on grade and packaging [2]. The price of silicon tetrachlororide ranges from $1-25/kg, depending on grade and container [2]. The price for optical fiber grade product is on the high end of this range.

Trade statistics were not available, so it is not clear to what extent chlorosilanes are internationally traded.

Geographical/firm structure

The largest producers of trichlorosilane are Wacker and Dow Corning, which are based in Germany and the US respectively. In Japan, the three major producers are Tokuyama Corp., Mitsubishi Materials, and Osaka Titanium [2].

The US is apparently the largest producer of silicon tetrachloride, with the two main manufacturers being Dow Corning and General Electric. Japan has the second largest production level, with leading firms being Shin-Etsu, Tokuyama Corp., and Mitsubishi Materials. In Europe, the largest producers are Wacher and Huls AG (the latter now Degussa-Huls AG) [2].

II.5.3 Process/technology

Powdered metallic silicon is mixed with anhydrous hydrogen chloride gas over a fluidized bed at 575 C [5]. The main two reactions that occur are:

$$Si + 3HCl \rightarrow HSiCl_3 + H_2, \text{ and}$$
$$Si + 4HCl \rightarrow SiCl_4 + 2\ H_2,$$

though other products are also formed. Approximately 90% of the yield of this reaction is trichlorosilane, with 2-3% silicon tetrachloride. Hydrogen, other chlorosilanes, silane, and other impurity chlorides are also formed. Small particles that arose of impurities in the silicon metal, such as $AlCl_3$, are removed using a filter, and the gas stream is passed on to a fractional distillation unit. As trichlorosilane has a lower boiling point than chlorides of the principal impurities, distillation yields a significantly purified product. Silicon tetrachloride is also separated, and either processed for sale as a co-product, or converted to trichlorosilane via another reaction. Waste products include other chlorosilanes, silane, and various chlorides of impurities present in metallic silicon [6]. The by-product silicon tetrachloride is sold to other industries.

Process inputs/outputs

A partial list of process inputs and outputs appears in Table II.5.2. The data here corresponds with relative yields of trichlorosilane and silicon tetrachloride as 90% and 3% respectively. For comparison, a report from engineers at Advanced Silicon Materials (ASM) indicates the yields at 80% for $HSiCl_3$ and 20% $SiCl_4$ [7]. Since there are obviously other reaction products that these two compounds, it is assumed that the report is implicitly asserting these products account for less than 1% of input silicon. The reason for the difference in data sets is not readily determinable.

Table II.5.2: Inputs/outputs for fluidized bed trichlorosilane production process
(source: Ayres [6])

Inputs	**Amount**	Outputs	**Amount**
Metallic silicon	232 g	Trichlorosilane	1000 g
Hydrochloric Acid	918 g	Silicon tetrachloride	42 g
		Hydrogen	17 g
		Metal Chlorides	107 g

II.5.4 Environment

Environment impacts of emissions

No data on emissions from the process and possible impacts of those emissions was available for this report. Looking at the input/output data in Table II.5.2, the main emissions from the process are likely metal chlorides and some amount of "un-desired" chlorine-silicon compounds. Trichlorosilane and silicon tetrachloride react explosively with water to form HCl and thus must be handled very carefully for occupational health and safety reasons.

Materials utilization/efficiency:

Silicon - According to the data in Table II.5.2, at least 92% of silicon input into the process ends up in a final product. It is not clear to what extent reclamation systems to transform other products into useful outputs are implemented.

II.6 Polycrystalline Silicon

II.6.1 Overview of the material and its applications

Polysilicon, a term used to refer to extremely pure polycrystalline silicon, is a key precursor in the production of semiconductors. It is the primary ingredient in producing silicon wafers, which are the base onto which microcircuits are fabricated. Polycrystalline refers to the fact that the material is divided into domains (or regions) in which the atomic alignment is the same. This is in contrast with a monocrystalline substance, in which atoms are aligned throughout the entire object (as in a gem), or an amorphous substance like glass that has no long-range arrangement of atoms. The purity of electronics grade polysilicon is known as 11/9 (eleven nine), denoting that metallic impurities are in the parts per billion level. A typical impurity profile of such is: Carbon <<.5 ppma, Fe<.4 ppba, Cr <.05 ppba, Zr < .2 ppba, and other metals less than .02 ppba [1]. Polysilicon is the purest substance among materials produced on an industrial scale.

Polysilicon is also a major feedstock for solar cell production, though the purity requirements are far less stringent, 5/9 or 6/9 is apparently acceptable. Nearly all silicon for solar cell production is supplied from the scrap silicon from the semiconductor industry that arises from production of polysilicon and ingots of single crystal silicon (see section II.8).

Polysilicon is a highly specialized commodity, and essentially its only application is in making silicon wafers for semiconductors and solar cells

II.6.2 Economy

Production

1998 world production of polysilicon was reported at 20,000 metric tons, which includes “captive” production capacities of wafer makers [2]. Production was up 18% from 16,950 tons in 1997 [3] and increase of 204% from 6,581 tons in 1988 [4]. This reflects a long period of strong growth for the polysilicon sector. The price of polycrystalline silicon for use in the microchip industry in 1998 was reportedly from $50/kg, down from $60-$70/kg in 1996 [3]. This puts the value of 1998 world production of polysilicon at around $1 billion. The fact that such a small volume of production represents a market scale equivalent to for all silicon metal reflects the high-value added of the product.

An additional 2,100 kg of “rejected” silicon reportedly supplied the 1997 needs of the world industry for photovoltaics [5]. The price of this “waste” material was around $25/kg.

Trade

Japan reportedly imported 3,533 tons of polysilicon in 1997 [6]. Though data on imports and exports from other countries were not available, the figure for Japan suggests that polysilicon is a highly traded international commodity.

Geographic/ firm distribution

The regional and firm structure of production of polysilicon is displayed in Table II.6.1 [6].

Table II.6.1 1997 Production of polysilicon: regional and firm structure (source: New Metals Databook [6])

Region	Firm	1997 Production (metric tons)	Remarks
Japan	Mitsubishi Material Polysilicon	1,600	
	Sumitomo Sitix	700	
	Tokuyama	3,300	
	total	5,600	
USA	Hemlock Semiconductor Corporation	4,200	Jointly owned by: Dow Corning (63%), Shin Etsu (25%), Mitsubishi Materials (12%)
	Advanced Silicon Materials	2,100	Subsidiary of Komatsu
	MEMC	1,400	
	Total	7,700	
Europe	Wacher Chemie	2,800	
	MEMC	850	
	total	3,650	
	Total	16,950	

According to this data, developed countries are the only producers, though in fact there are a few small-scale firms in developing countries not listed, such as Metkem in India. Japan has the largest share of production in terms of firm ownership, while domestically located production is highest in the United States.

II.6.3 Process/technology

In this report only the Siemens process using trichlorosilane for producing polycrystalline silicon will be discussed, as it accounts for around 80% of world production [6]. A description of the main alternative, which is a similar process using silane as an input, can be found in references [1] and [7]. The basic reaction underlying the Siemens process for polysilicon production is the catalytic decomposition of trichlorosilane with hydrogen

$$HSiCl_3 + H_2 \rightarrow Si + HCl \text{ (1100-1150 C)},$$

though many other reactions also occur including those resulting in the formation of silicon tetrachloride and other compounds, include oily silicones [7]. The reactants are passed into an evacuated bell jar made of pure fused silica. Bell jar dimensions typically range from .46-3m in diameter and.45-3m in height. The chamber is heated via electric current passed through a slim rod of substrate silicon, which is generally U-shaped to minimize size of the bell jar. Reagents passed into the bottom of the chamber disassociate and the silicon formed deposits onto the substrate. Single pass conversion efficiencies are quite low, from 8-25% depending on reactor conditions and the stage of deposition. Recovery systems to process the waste chemical vapor are generally implemented, and are quite important for economic operation of the plant. There are many designs for recovery systems, the basic goal of such is the separation of trichlorosilane and silicon tetrachloride from HCl and hydrogen gases, to re-purify trichlorosilane for re-use in silicon deposition. The silicon tetrachloride can be converted to trichlorosilane and used as feedstock, or separated and sold to other industries. Recovered HCl can be sold to other industries, such as for swimming pool or plating applications, or converted with silicon metal to silicon tetrachloride for use as feedstock for polysilicon. The hydrogen is purified and re-used for polysilicon deposition [7].

Process inputs/outputs

The efficiency and outputs of a polysilicon plant depend on the design of recovery system installed. Smaller plants apparently tend to favor production of silicon tetrachloride, while larger ones tend to favor conversion of "waste" vapors to trichlorosilane for re-use as feedstock [7]. A plant with the capacity to produce 10 metric tons/year of polysilicon requires 113 metric tons of trichlorosilane input. 113 metric tons of trichlorosilane contains 23.7 metric tons of elemental silicon, thus around 42% of silicon input ends up in polysilicon. In addition to 10 metric tons of polysilicon output, around 58 metric tons of silicon tetrachloride is reportedly produced and sold to other industries. Thus 9.28 metric tons of input silicon, or 39% of the total, ends up in silicon tetrachloride as a co-product. This leaves 4.4 metric tons, or 18% of silicon input unaccounted for. The fate of this 4.4 metric tons is not known, though some fraction of it apparently ends up as other silicon-chlorine compounds, including more complex ones such as oily silanes. The above discussion is based entirely on data from reference [7], another other sources indicate that 20-23% (as opposed to 42%) of input silicon materials end up in the final polysilicon product [4]. The reasons for the wide variation in data is not clear.

In terms of energy consumption, the requirements of the process are apparently quite high, reportedly around 250 kWh per kilogram of polysilicon produced [5]. Reference [8] lists a figure of 300 kWh per kilogram.

II.6.4 Environment

Environmental impacts of emissions

According to a report on the environmental issues encountered in decommissioning a polysilicon plant, "When the system was operating properly, trichlorosilane was conserved, silicon tetrachloride was produced for sale, hydrogen was produced, and only a limited amount of material was discharged to the environment" [9]. However, no quantitative data was available documenting emissions at polysilicon plants. Given the relatively small scale of world production and assuming an 80% raw materials utilization rate, total tonnage of emitted waste is expected to be small. In terms of occupational safety and health, polysilicon production involves a number of hazardous materials and must be handled with great caution. This risk is illustrated by the occurrence of an explosion at a polysilicon plant in Washington that led to the death of one worker, and injuries to three others [10].

Materials utilization/efficiency

Though data is quite scarce on material use in polysilicon production, apparently the reclamation systems are perhaps effective at reprocessing the waste stream for reuse and production of value-added co-products. The ultimate fate of the unaccounted 18% of silicon input discussed section II.6.3 is an interesting question. The energy intensity of the industry is quite high, some 5 billion kWh are consumed in world production. It is interesting to note that the amount of coal required this amount of electricity is around 1.8 million tons. This is an order of magnitude greater that the input of trichlorosilane into the global industry, reflecting a general point that for energy intensive industries, indirect material flows for energy can easily exceed the direct flows of input materials.

II.7 Silicon Wafers

II.7.1 Overview of the object and its applications

Silicon wafers are extremely pure, smooth, thin discs of monocrystalline silicon. They are a key element in the production of microchips, providing the base on top of which integrated circuits are laid. In order to achieve good yields in microcircuit fabrication, silicon wafers must satisfy very strict requirements for size, flatness, crystal structure, and impurity levels. Table II.7.1 shows a set of specifications for a typical 200-mm wafer [1].

Table II.7.1: 200-mm Wafer Specifications (source: Van Zant [1])

Property	Specification
Diameter tolerance	±.25mm
Crystal orientation	<100> ±1 degree
Resistivity	2.7-4 ohm-cm
Resitivity gradient	10%
Oxygen	25-29 ppma
Oxygen gradient	5%
Carbon	.3 ppma
Heavy metal impurities	< 1 ppba

Conditions on the resitivity and oxygen gradients reflect requirements that the properties of the wafer be spatially uniform.

Wafers are produced in a number of discrete diameters: 100 mm, 125 mm, 150 mm, 200 mm, and 300 mm. Wafer thickness ranges from .5mm-.75mm, with .725 mm being typical. Using the fact that silicon has a density of 2.329 g/cm^3, the mass of 725 mm thick, 200-mm diameter wafer is calculated to be 53 g. There has been a continuing shift to larger radii, due to favorable economies of scale at the semiconductor production stage: a larger radius means more chips in one fabrication batch and less wasted space at the boundary. 150-mm and 200-mm are currently the standard sizes, and the industry is currently in transition to 300-mm wafers, though this process has been impeded by the recent slump in the global semiconductor industry.

The bulk of wafers produced are called polished wafers, reflecting that the silicon surface has been polished to a mirror-like finish. Another important type of wafer is the epitaxial wafer, which has a thin layer of chemically deposited silicon on the surface. This epitaxial layer has properties important for later fabrication of dense circuits, thus epitaxial wafers are the main choice for production of high value logic circuits such as microprocessors.

Silicon wafers are produced from polysilicon by first creating a cylindrical ingot of monocrystalline ingot of silicon, which is then sliced into wafers who surfaces are processed for suitability in semiconductor fabrication. To a certain extent monocrystalline ingots can be considered to be a separate commodity, however for the purposes of this report the two production steps will be lumped into one sector.

II.7.2 Economy

Production

World production of silicon wafers in 1998 reportedly totaled 3.8 billion square inches (24.5 billion square centimeters), valued at $5.6 billion [2]. Production was up 5% from 1997, but total market value was down from $6.35 billion, due to plummeting prices. Over the period 1988-1998, the wafer market showed an average growth of 9% per year in terms of total square inches produced [3].

In 1999, price of a 200-mm epitaxial wafer was about $130, down from $180-$200 in 1997 [4]. 200 mm polished wafers cost about $75-$90 in 1999, down from $105-$140 in 1997. It is interesting to note that $80 for a 200-mm wafer corresponds to $1500 per kg in terms of weight, an indicator of the extremely high value-added in the product.

Geographical distribution/firm structure

In terms of share of 1996 market value, Japan is the largest wafer producing country accounting for 38% of world production, followed by the US with 27%, Europe with 14%, and non-Japanese Asia accounting for 20% [3]. In terms of firm structure, the major seven wafer producing companies and country of origin are shown in Table II.7.2 [5]. These seven companies represent 92% of 1997 world production, Japan-based firms account for at least 61%. Comparing this data with the regional production figures, it becomes evident that much of the domestic production in Asia and the USA is being carried out by subsidiaries of Japanese firms.

Trade

Though full international data on silicon wafer trade were not available for this report, partial evidence indicates that wafers are a heavily traded international commodity. In Japan, for example, 37% of domestically produced wafers were exported in 1998 [6].

Table II.7.2: Top Wafer Producing Companies in 1997 (source: Chemical Week[5])

Company	Country of Headquarters	Market Share
Shin-Etsu Semiconductor	Japan	25%
MEMC Electronic Materials	USA	15%
Sumitomo Sitix	Japan	14%
Wacher Siltronic	Germany	14%
Mitsubishi Materials	Japan	10%
Komatsu Electronic Metals	Japan	7%
Toshiba Ceramics	Japan	5%

II.7.3 Technology

The production process starting from polysilicon consists of two distinct steps: casting of a single crystal ingot and then preparation of wafers from this ingot. The fabrication of circuits is quite sensitive to the crystal structure, impurities, and surface characteristics of the underlying wafer, thus the production process is exacting.

Casting of single crystal ingot

The dominant industrial process for casting single crystal ingots is the Czochralski (CZ) method [1]. In this method, polysilicon is first melted at around 1400 C in a fused silica crucible, surrounded by an inert atmosphere of pure argon. The melt is cooled to a precise temperature, at which point a single crystal seed is dipped in the melt, and then pulled out slowly while rotating. Melted silicon crystallizes onto the seed, and an ingot of pure silicon slowly forms. The diameter of the rod is determined by the temperature and rotation speed.

The resulting ingot is cylindrical with tapered ends. After cutting the tops and bottoms of the ingots and machining them to a more precise circular shape, these cylinders of single crystal silicon, typically 1-2m in height with radii of 100mm, 150mm, or 200mm, are passed on to the wafer preparation process.

An alternative process for creating a single crystal ingot is the Floating Zone (FZ) method, which accounts for about 5% of total ingot production [7]. This method does not require a crucible, rather the starting point is a polysilicon rod with a single crystal seed attached to one end. An RF coil moves along the rod, melting a small section of the interior at a time. The heated sections solidify with the crystal structure of the seed, and with sufficient passes, a uniform ingot is obtained. The main advantage of this method is that there is no contamination of oxygen from the crucible (almost immeasurable as compared to a level of 10^{16}-10^{18} atoms/cm^3 with the CZ method). However, the level of crystalline defects is higher and the process is more expensive to implement, especially for larger ingot radii. The FZ process is mainly used to produce wafers for specialized application such as high power and high voltage diodes.

Wafer preparation

To yield a product that satisfies the rather stringent standards outlined in II.7.1, the wafer preparation process is quite elaborate and involves use of many chemicals. The preparation process proceeds along the following steps:

1. Wafer slicing – The cylindrical monocrystalline ingot is cut into wafers using diamond coated, inside diameter saws.
2. Wafer lapping – The wafer surface is rather rough after slicing, so wafers are furthered flattened and smoothed using an abrasive slurry (typically silicon carbide).
3. Wafer etching – A solution of nitric acid/acetic acid or sodium hydroxide is applied to remove microscopic cracks and surface damage. This acidic or caustic solution is cleaned from the wafer using series of water purified via Reverse Osmosis/De-Ionization (RO/DI water).

4. Chemical-mechanical polishing – Wafers are mounted on a holder and lowered onto a rotating pad surface typically composed of polyurethane. A slurry of silica, RO/DI water, and alkali (e.g. potassium or ammonium hydroxide) is applied and this alkaline slurry induces growth of silicon dioxide layer, which is removed by the pad. The polishing process is generally repeated 2-3 times with progressively finer slurries, with intermediate cleanings using RO/DI water.
5. Wafer Cleaning – First, a solution of ammonia, hydrogen peroxide, RO/DI water is applied to remove organic impurities and particles from surface. Next, natural oxides and metallic impurities are removed with hydrofluoric acid. Finally, application of hydrochloric acid and hydrogen peroxide solution causes a new layer of pure natural oxides to grow on surface. This layer protects the wafer from contamination.

Process inputs/outputs

Published quantitative data on inputs and outputs of wafer processing are scarce, thus the following discussion is limited. A partial input/output table for the monocrystalline ingot step is shown in Table II.7.3 below.

Table II.7.3: Inputs/outputs for monocrytalline ingot production

Input	Amount	Output	Amount
Polysilicon	2 kg	Single crystal ingot	1 kg
argon	ND	Waste silicon for solar cell industry	.2 kg
Quartz crucible	ND		
Electricity	250 kWh		

Data indicating that around 50% of polysilicon input into the process ends up as single crystal ingots is based on a unpublished report from the New Metals Society of Japan. Rejected silicon material includes the tops and bottoms of the ingots, leftovers in the crucible, and material ground off in the shaping of ingots. Quartz crucibles are listed as an expendable input rather than as equipment because apparently they require frequent changing, only after 3-4 uses [8]. The figure for energy consumption is from reference [9].

For the preparation of silicon wafers, a list of input materials is shown in Table II.7.4.

Table II.7.4: Inputs to wafer processing

Input	Input
Single crystal silicon	RO/DI water
Electricity	KOH
Slurry: typically alumina	Ammonia
Nitric acid	Hydrogen peroxide
Acetic acid	Hydrochloric acid
NaOH	Hydrofluoric acid

This is only a partial list and data on quantities was only available for the first two items. Regarding the silicon efficiency of the process, unpublished data from the New

Metals Society indicates that roughly 56% of input silicon monocrystalline ingots up in the final wafers. The remaining 46% is lost in cutting and polishing: a section of silicon at least as thick as the saw blade is ground to silicon dust, and small silicon particles are also ground and washed away with the slurry in the polishing stage. In terms of electrical energy requirements, wafer processing reportedly uses 7 kWh per 150 mm wafer, or about .04 kWh per square centimeter [9].

To discuss in more detail the silicon efficiency of both stages of the process, first note that using the above data, the overall conversion efficiency from polysilicon to wafers is around 30%.   This compares reasonably well with a report to the effect that 17% (30%) of polysilicon ends up in 200mm (150mm) wafers [10]. Another check on the overall efficiency is possible through comparing the total tonnage of polysilicon production with the total tonnage of wafers produced. To minimize error due to year to year variation in ingot stocks, a three-year interval of polysilicon and wafer production is used. The total wafer production from 1996-1998 was about 72 billion square cm, and assuming the average thickness of a finished wafer to be 750 um, this corresponds to around 12,500 tons of silicon. Considering that polysilicon production from 1996-1998 was about 48,750 tons, this yields a rough conversion efficiency of about 25%, in rough agreement with the other results.

II.7.4 Environment

Environmental impacts of emissions

Given that that many liquid chemicals are used in fair quantities, it seems reasonable to assume that the main possible environmental concerns would be related to water pollution.   Without quantitative data on emissions, however, the extent of impacts is difficult to characterize.

Resource utilization/efficiency

From the data and estimations on silicon efficiency discussed in II.7.3, roughly 30% of silicon input into the two-stage process ends up in silicon wafers, and perhaps another 10% or so is utilized in the production of solar cells. Perhaps half of more of the 60% of waste silicon is kerf, or silicon dust, resulting from the slicing process.

Given the process energies per wafer from Section II.7.3, the total electrical energy consumed by the world industry in the ingot stage is 5 billion kWh, and nearly 1 billion for the wafer processing stage.

II.8 Semiconductors

II.8.1 Overview of the object and its applications

Semiconductor here refers to electronic devices whose function derives from semiconductor properties of materials. Many materials display semiconducting properties, but the dominant material used in the devices of today is silicon, and to a lesser extent gallium arsenide. The electrical properties of semiconductors change greatly with addition of small amounts of certain materials known as dopants (typically boron or phosphorus). Interfaces between regions of different doping (p-n junctions) have special electrical properties that allow construction of solid state diodes, transistors and other components that are far smaller and consume far less power than for instance, equivalent vacuum tube devices. Since the invention of the solid-state transistor in 1965, it has since been understood how to fit complex arrays of electronic components into a small space, giving rise to the microchip. The heart of a microchip is a stack of extremely thin pattered layers of doped silicon, silicon dioxide, and conducting metals such as aluminum.

The variety and applications of such devices is immense, here only a brief explanation will be given. For a more thorough treatment, the reader is referred to the book by Van Zant [1]. Semiconductor products are often divided into the groupings [2]:

a) MOS (metal oxide semiconductor) micro devices - includes microprocessors and other control devices, which broadly speaking function for computation and management of data.
b) MOS memory – includes DRAM (dynamic random access memory) and SRAM (static random access memory), and various ROM (read-only-memory) devices, whose purpose is the storage of information
c) MOS logic - include devices such as ASICs (Application Specific Integrated Circuits) and systems-on-a-chip, are used in special purpose electronics markets. Video games, telecommunications, and networking products are frequent applications.
d) digital bipolar – represents a design concept distinct from MOS, and traditionally are faster, but with higher power requirement.
e) analog devices - designed to process analog signals. Often used in telecommunications and computer networks.
f) discrete devices - unlike all the above, do not combine different circuit functions into one package. Diodes for voltage regulators and transistors specialized for small signals or high power represent main.
g) Optoelectronics – includes devices such as LED’s, semiconductor lasers, and CCD sensors. Such devices are usually based on gallium arsenide rather than silicon. Two major applications are in telecommunications and optical sensors used as in storage devices such as CD-ROM drives.

The panoply of the above devices is used in a number of markets. Table II.8.1 shows consumption of semiconductors according to different end-use markets [3]:

Table II.8.1: Share of semiconductor markets for various end-uses (source: [3] reporting Dataquest data)

Market	1990	1995	2000 (estimated)
Computer Products	37.5%	49.0%	49.3%
Telecommunications equipment	15.8%	17.1%	19.2%
Consumer electronics	24.6%	17.3%	15.7%
Industrial	11.0%	10.0%	10.2%
Automotive and aerospace	11.0%	6.6%	5.5%
All markets	100.0%	100.0%	100.0%

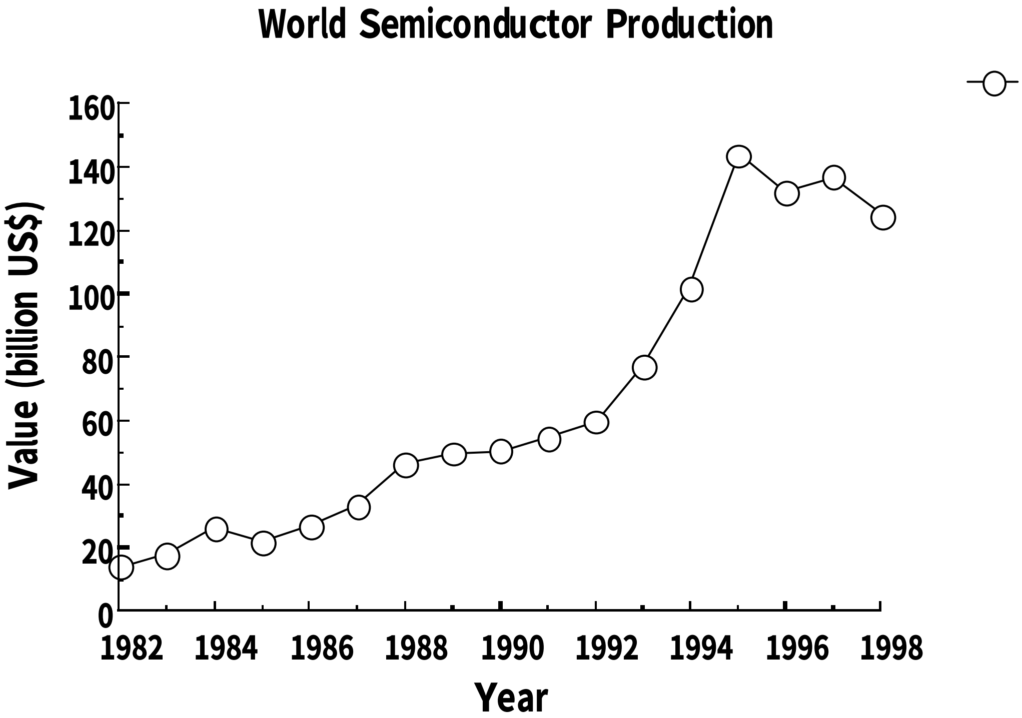
Microchips for computers stand out as a dominant and growing sector for the overall semiconductor business. It needs to be noted, however, that the data above and much to follow excludes *captive consumption*, which are semiconductor products are produced by a company for use in their own products, and so never directly enter markets.

II.8.2 Economy

Production/prices

According the World Semiconductor Trade Statistics (WSTS) organization, 1998 world shipments of semiconductors totaled $125 billion in receipts for 257 billion units [2]. This represented an 8.8% decline from the previous year, continuing the slump in the global semiconductor industry that began in 1996. The causes of the slump are thought to be a combination of an overcapacity in DRAM production that led to price collapse, and depressed demand from end-markets due to the Asian financial crisis and downturn of Japanese economy [4]. However, Jan.-Jun. sales in 1999 are up 9.3% from 1998 [5], so the industry could well by on the road to recovery. Figure II.8.1 shows a chart of the historical production figures for the semiconductor industry:

Figure II.8.1: World Semiconductor Production 1982-1998
(source: Semiconductor Industry Association [5])



It should be noted however, that all the above figures are based on surveys of inter-firm sales, and thus do not take into account captive production, which is the direct use of semiconductor in the product of the same company. Thus, while the WSTS figures are a commonly used measure of the size of the semiconductor industry, they are an underestimate of total economic activity.

Looking at the trends in growth over the decade 1988-1998, the industry grew an average of 10% per year in terms of economic value.

Given the different types of semiconductors and the rapid change in products, a comprehensive discussion of prices and trends is quite beyond the scope of this report. However, it will be noted that the price indexes for memory and microprocessors fell respectively, an average of 20% and 35% per annum over the period 1985-1996 [6].

Markets

Table II.8.2 indicates the relative sizes of the different semiconductor markets in 1998, from which it is evident that microprocessors and memory are the largest markets [2]. It is interesting to note that the market with the largest value has the highest value/unit (microprocessors), while the market with the largest number of units has the lowest value/unit (discrete devices).

Table II.8.2: 1998 World Sales of Semiconductors broken down according to category of device [2]

Category	# of Units (billion)	Value (billion US$)
MOS micro (microprocessors, etc.)	6.3	$47.3
MOS memory (DRAM, SRAM,etc.)	8.6	$23.0
MOS logic	14	$18.6
Digital bipolar	2.5	$1.01
Analog (amplifiers, voltage regulators, comparators)	26.7	$19.1
Discrete devices (power transistors, rectifiers, thyristors, etc.)	180	$11.9
Optoelectronics (LED's, solid state lasers, CCD sensors, etc.)	18	$4.62
Total	256.1	125.5

The distribution of end-use markets by industrial sector was shown in Table II.8.1. To partially indicate the scale of the market for products that incorporate semiconductors, note that the top 250 consumer electronics and computer companies had revenues from electronics sales totaling $1.36 trillion dollars in 1998 [7].

Geographic distribution of production

As the semiconductor production system is highly globalized, it is rather difficult to accurately characterize the geographic distribution of activities. The main "overseers" of production are multinational corporations (MNCs), primarily headquartered in the US and Japan, and to a lesser extent Europe and East-Asia. The production activities of large semiconductor firms are in general geographically distributed over many countries. In many cases, certain phases of the production process are contracted out to smaller companies. The activities of these contracting companies are a "service" in some sense, and as their products do not enter markets, often are not properly accounted for in statistics. However, cumulatively their role in the industry is significant. A thorough analysis of the geographical distribution of semiconductors is beyond the scope of this report, however a rough discussion follows. One measure is the value of production according to the final location of manufacturing. One Dataquest report indicates shares of 1997 production by this measure to be: 40.8% for the Americas, 32.2% for Japan, 15.5% share for Europe, and an 11.5% share for Asia/Pacific. Another measure comes from organizing the value of sales of the 60 top semiconductor firms according to location of world headquarters. Table II.8.3 shows a partial listing of these top semiconductor firms. The top 60 firms account for 98% of world production. The share of sales according to location of world headquarters yields: 46% for the US, 33% for Japan, 9% for Europe, and 8% for East-Asia. Although it is difficult to draw conclusions from these two measures, they suggest that greater than 5% of US final production is located abroad and that a substantial share of European production is foreign-owned.

Table II.8.3: Major[*] semiconductor firms according to location of headquarters (source: Cahners-InStat [8])

Region	Major Firms	1997 sales million US$	1996 sales million US$	change
USA	Intel	$21,120	$17,496	20.70%
	Motorola	$8,034	$7,858	2.20%
	Texas-Instruments	$7,560	$7,357	2.80%
	IBM	$3,310	$3,146	5.20%
	Lucent-Technologies	$2,760	$2,332	18.40%
	National-Semiconductor	$2,521	$2,440	3.30%
	AMD	$2,356	$1,953	20.60%
Japan	NEC	$9,249	$9,036	2.40%
	Hitachi	$7,586	$7,868	-3.60%
	Toshiba	$7,392	$8,029	-7.90%
	Mitsubishi	$4,100	$4,268	-3.90%
	Fujitsu	$3,867	$3,825	1.10%
	Matsushita	$2,876	$2,856	0.70%
	Sharp	$2,099	$2,257	-7.00%
EU	Philips (The Netherlands)	$4,451	$4,237	5.10%
	SGS-Thomson (France)	$3,970	$4,078	-2.60%
	Siemens (Germany)	$3,475	$3,048	14.00%
East Asia	Samsung (Korea)	$5,933	$6,196	-4.20%
	LG-Semicon (Korea)	$2,370	$2,756	-14.00%
	Hyundai (Korea)	$2,015	$2,317	-13.00%
	Mosel-Vitelic (Taiwan)	$414	$396	4.50%
	Winbond (Taiwan)	$371	$350	6.00%
	Macronix (Taiwan)	$314	$266	18.00%
Total Sales of listed firms		$108,143		

[*]Major defined as firms with over $2 billion yearly sales (excepting Taiwan)

US firms have been leading semiconductor production in the last few years, though from 1986-1992, the value of production of Japanese companies exceeded that of US ones. US firms overwhelmingly dominate microprocessor production with some 98% share of the market [8]. Only one firm, Intel, has an 80% share of the world MPU market. Semiconductor production of larger US firms is generally quite distributed globally, with many subsidiaries in East Asia and Europe. Also, most "fabless" semiconductor firms are located in the United States, though there are some companies following this model in Europe and Japan. A fabless semiconductor firm is one that contracts out all manufacturing phases, only handling the design phase. The total value of 1997 semiconductor production of the US is reported by the US Census at $64.7 billion [9].

Japanese semiconductor firms traditionally dominated the memory market, though this situation has changed substantially with the development of the Korean semiconductor industry, which became the world leader in DRAM production in the mid 1990's. All major Japanese companies that produce semiconductors are also major producers of consumer electronics and computers, reflecting the trend towards vertical integration in Japanese industry. This fact also suggests that captive production in Japan of semiconductors is perhaps quite large. Major Japanese semiconductor producers have subsidiaries in East Asia, Europe, and the United States. Official Japanese production statistics reported the 1996 production of semiconductors at $43.7 billion [10].

Three European producers remain major players in the semiconductor industry, Phillips, SGS-Thompson, and Siemens. The share of European based production has been slowly declining since the late 1980's [11]. Certain areas in Europe, however, especially Great Britain and Ireland, have been attracting investments of US and Japanese semiconductor companies to build local subsidiaries.

The semiconductor industry in East Asia is quite varied in structure. Korea, through leveraging the financial muscle of its industrial groups, chaebols, established a domestic industry focusing on the mass production of DRAM chips. Korea's 1997 production of semiconductors was valued at $9.7 billion, 74% of this value was due to DRAM [12]. Taiwan has quite a different industrial structure, its semiconductor industry is mainly composed of smaller companies and MNC subsidiaries. Value of 1998 Taiwanese semiconductor production was $8.4 billion, with shares of design, fabrication, and packaging 15%, 61%, and 20% respectively [13]. Taiwan is a key player in the semiconductor foundry business. Foundries, fabrication plants set up to flexibly manufacture specialized chips by contract, are the production counterpart to fabless firms. Singapore's semiconductor industry, which was largely built through attracting subsidiaries of foreign multinationals, is substantially involved in all phases of production [14]. Semiconductor production in Malaysia totaled $8.3 billion in 1996 [14]. Malaysian semiconductor manufacturing activities are specialized in testing, assembly, and packaging phases, which are carried out both through MNC subsidiaries and some domestic firms. Apparently only one facility carries out fabrication in Malaysia, an Intel subsidiary, though this situation is changing [15]. The structure of the semiconductor industry in the Philippines is quite similar to Malaysia, 1995 exports were reportedly $6.05 billion [16].

Trade

The value of all world exports of semiconductors is estimated at $105 billion in 1995 [17]. Comparing with the total sales in that year of $144 billion, thus some 73% of semiconductor produced entered international markets. Thus, not unexpectedly, the data indicates that semiconductor devices are a highly traded international commodity.

II.8.3 Technology

II.8.3.1 Overview of manufacturing processes

The manufacture of semiconductor devices can be broken into three stages: design, wafer fabrication, and assembly.

Design

Design involves coming up with the specifications of the desired product and determining what configuration of circuits is needed to meet those specifications. This often involves sophisticated computer modeling. From the design, a set of masks that contain the patterns of the desired chip are determined.

Wafer fabrication

This stage involves laying patterned layers of silicon, silicon oxides/nitrides, and metals on top of a silicon wafer in order to realize the circuit network as specified by the design. The process of fabrication is extremely complex, involving hundreds of steps. A brief summary of fabrication follows the review of the overall process, for a more detailed description the reader is referred to [1,18,19]. An excellent web-based overview of the process can be found at http://www.fullman.com/semiconductors.

Assembly

Assembly can be broken into four substages: probe test, die cut, wire bonding, and packaging. The end result of wafer fabrication is a rectangular lattice of dies on top of a wafer; each die is the functional unit of a single microchip. At this point, a **probe test** is carried out, whose function is to identify and mark functional dies. The fraction of non-functional dies can be quite high, thus it is very important for efficiency to prevent defects from being committed to the next production stage. In the die cut stage, the wafer is cut to separate each individual die. In wire bonding, dies are mounted onto a metallic attach pad, and the electrical contacts of the die are connected to a larger framework, the lead frame, with ultra-thin wires (e.g. 1/3 diameter of human hair). The lead frame has metal legs, which are ultimately connected to a printed circuit board. In the packaging stage, the die, die attach pad, and part of the lead frame are encased in a protective material, typically ceramic or some moldable plastic.

Wafer fabrication (reprise)

As it is one of the most technically challenging and resource intensive stages of semiconductor production, the wafer fabrication stage will be discussed in somewhat more depth.

The basic elements of the wafer fabrication process are layering, patterning, and doping. As mentioned before, the goal of fabrication is the creation of a stack of patterned layers.

1. Layering – involves depositing a thin layer, typically ranging from .5-5 µm in thickness, typically of polysilicon, silicon dioxide, silicon nitride, or conductive metals. Polysilicon layers are usually doped to create p-n junctions, silicon dioxide and silicon nitride act as crucial insulating layers between sections that need to be electrically isolated, and layers of conductive metals (aluminum, aluminum-silicon, and tungsten often used) electrically connect different components. Layers are deposited through a variety of methods depending on the material. Oxidation

(nitradation) involves heating the wafer in the presence of oxygen (nitrogen) and causes the growth of a layer of silicon dioxide (silicon nitride). Chemical vapor deposition involves controlling vapor phase chemical reactions above the wafer to yield a layer of desired material. For a layer of polysilicon, trichlorosilane or a related compound may be reacted with hydrogen as described for polysilicon production in section II.7.3. Evaporation or sputtering are common methods for depositing metallic layers. Evaporation simply involves heating a metal past its boiling point, after which the vaporized metal collects on the wafer. In sputtering, a target made from the metal to be deposited is bombarded by a beam of neutral atoms such as argon. Atoms are "kicked" off the target and collect on the surface of the wafer.

2. Patterning – involves "carving" a very dense pattern into the layer deposited in the above step. This is done through a process known as photolithography, which bears many similarities to photography. The first step of photolithography is to deposit a layer of photoresist on top of the wafer. A photoresist is a substance that becomes either more or less dissolvable with respect to a given solvent when exposed to light. Next, ultraviolet light is shone onto the wafer through a photomask, which is a glass sheet with the maze-like pattern intended for the chip etched onto the surface. This pattern is transferred to the wafer in the form of a pattern of exposed and unexposed regions. Next, the pattern is **developed**, applying special solvents that specifically dissolve only exposed (or unexposed) photoresist. Up to this stage, the layer underneath the photoresist has not been altered, this is done in the next step, known as **etching**. There are two main categories of etching techniques: wet and dry. Wet etching involves using a special solvent that selectively removes the material below the photoresist, but not the photoresist itself. Dry etching involves ion bombardment which eats away both photoresist and the material below, but presuming the photoresist layer is thick enough, it is sufficient to protect the pattern. The final step is **stripping** – is the removal of the now unneeded photoresist, through bath in a solvent that dissolves photoresist but not other layers on the wafer.
3. Doping – is the addition of a very controlled amount of impurities, typically boron or phosphorous onto a silicon layer. One technique, known as the diffusion method involves baking the wafer in a chamber containing the impurity gas. The Ion Implantation method utilizes a precise ion gun to shoot impurities into the semiconductor surface.

In between steps, wafers are frequently cleaned using de-ionized water and detergents, solvents, acids, and/or caustic solutions. Layering, patterning, doping, and cleaning steps are repeated using different types of materials until the desired pattern of layers is achieved. 10-24 "layers", each requiring different patterning using photolithography, is typical.

One defining characteristic of wafer fabrication is its strict requirements on quality and purity control, particle contamination accounts for 80% of defects. In addition to silicon wafers, all chemicals and tools that are used in the process must satisfy severe purity standards. Dust particles in usual atmospheric air contaminate the wafer, so fabrication is carried out in strict clean rooms. Workers in clean rooms wear special "bunny" suits to prevent skin and hair particles from contaminating the wafers.

II.8.3.2 Process inputs/outputs:

The inputs to the semiconductor manufacturing process(es) can be grouped into the categories of wafers, chemicals, water, and energy.

Wafers

The silicon wafer is a key ingredient in the semiconductor fabrication process. They are also expensive, accounting for about half of total fab material costs [20]. As there are many types of semiconductor devices and the wafer requirements depends on the device, a thorough discussion of what area of wafer is required for a given functional unit of microchip is quite beyond the scope of this report. It will be mentioned however, that to produce the microchips in one workstation, approximately one 150-mm wafer is required [21]. The remainder of this discussion on wafer will focus on yields in the different manufacturing stages.

The yield of silicon wafers that make it through the manufacturing process has many implications for the ultimate materials usage and profitability of the industry. As semiconductor manufacturing has many process steps, typically 100-200, achieving good overall yields is a technical challenge. Table II.8.4 shows a breakdown of process yields for different products and process phases in semiconductor manufacturing [1]. A note regarding terms used in the table: ULSI stands for Ultra

Table II.8.4: Typical yields from Wafer Fabrication stages (source: Van Zant[1])

Technology	Product Maturity	Fab yield (%)	Sort yield (%)	Assembly & Final test (%)	Overall yield (%)
ULSI	Mature	95	85	97	78
ULSI	mid	88	65	92	53
ULSI	Introduction	65	35	70	16
LSI	Mature	98	95	98	91
discrete	Mature	99	97	98	94

Large Scale Integration, which is for a technology to produce denser patterns on wafers and larger chips. LSI stands for Large Scale Integration, which is an older technology. Here the overall process has been broken down into three phases: fab, sort, and assembly & final test. “Sort” here refers to a testing process to identify the non-functioning dies on a fabricated wafer, which reflects on the cumulative result of the fabrication process. Overall yield is obtained through multiplication of the yields of the three phases.

From this data, it is apparent that the yield depends very much on the complexity of the device to be manufactured and the maturity of the technology. With respect to the above discussion, it is important however to note that the above yields refer to the fraction of wafers *committed to the manufacturing process*. A large fraction of wafers are used as control wafers or “dummies” simply to test equipment. In this test, the dummy wafers generally become unusable, through it is possible to reprocess them for re-use [22]. According to one report, about half of 200 mm wafers are used to test equipment [23].

Chemicals

Hundreds, even thousands of different chemicals are used in semiconductor manufacturing and full input/output tables are generally not available. An indicator of overall amount of chemicals used is indicated in a classic 1993 LCA study by Microelectronics Computer Corporation which states that the fabrication of integrated circuits on one 150 mm wafer generates 40.5 kg of waste chemicals [21]. 11.4 kg of this total is reportedly sodium hydroxide used in wastewater neutralization. The study defines waste material is process materials not ending up in the final product, and as the weight of the fabricated wafer is small (well under 100g), the above figures can also be considered as representing the material input requirement of the manufacturing process.

A more detailed, though still aggregate picture of chemical use appears in Table II.8.5, which displays chemical consumption of the Japanese semiconductor industry in 1996 [10]. As Japan consumed 1.5 billion square inches of silicon wafers in 1996 [24], about 40% of the world wafer market, the consumption of the global semiconductor industry of chemicals is perhaps 2-3 times the above amounts.

Table II.8.5: Chemical inputs of Japanese semiconductor industry (1996 data) (source: IC Handbook of the Electronics Industry Association of Japan [10])

Process	Substance	Amount (tons/year)
Washing	Acids (e.g. sulfuric, hydrofluoric, nitric)	34,000-50,000
	Alkali (e.g. NaOH, KOH)	1,400-2,000
	Organic solvents	16,000-25,000
Lithography	Photoresists (e.g. ortho-diazoketone, isoprene)	2,700-3,500
	Developing agents (e.g. xylene, isopropyl alcohol, ethylene glycol)	9,400-12,000
CVD	Silicon containing gases (e.g. monosilane, silicon tetrachloride)	45-60
	Boron, phosphorous compounds (e.g. diborane, phosphine)	8-10
Etching (dry)	fluorine compounds (e.g. HF, NH_4F)	290-380
Assembly	Resin	10,000-15,000

To attempt to roughly check the consistency of the two sets of data, note that the upper limit of total chemical consumption indicated in Table 8.5 is around 108,000 tons/year. 1.5 billion square inches of wafers were used by Japanese industry, but statistics on wafer utilization rates were not available. Assuming for the moment an unrealistic 100% utilization rate, this corresponds to a chemical usage of .073 kg per square inch. The MCC figure of 40.5 kg per wafer corresponds to 1.5 kg per square inch. There are many possible explanations for the factor of 20 difference between the two figures. One possible factor is that the EIAJ figure reflects aggregate Japanese production of all types of semiconductors, while the MCC figure reflects only chips used in personal computers, which are the most complex and thus may require larger amounts of chemicals. However, there is not sufficient information in the studies to judge which factors were most relevant.

A detailed breakdown of chemical inputs according to process step is published in a 1993 UNIDO/UNEP report on environmental management in the electronics industry [25]. The tables display flow rates and time for inputs of most chemicals for fabrications of circuits on a 100-mm diameter wafer. Summing the mass of chemical inputs (other than water) listed results in a total consumption of 4.0 kg per square inch, significantly higher than the MCC and EIAJ results.

Water

The semiconductor manufacturing process also requires large amounts of high purity water. Generally each etching or cleaning step is followed by rinsing with water, and throughout the entire fabrication process, the wafer may spend a total of several hours in water rinse systems [1]. Water is generally purified on site, in order remove contaminants such as dissolved minerals, particulates, bacteria, organics, dissolved gases, and silica. A typical purification system will generally take municipal water with impurity levels in the parts per hundred or parts per thousand to the few parts per billion level [26]. The purification system is quite complex, including application of reverse osmosis, a vacuum degasifer to remove gases such as O_2 and CO_2, ion exchange treatment, UV treatment to remove organics, and filtration [19]. Such high purity water used is often referred to as DI (De-Ionized) water or RO/DI (Reverse Osmosis/De-Ionized) water.

Regarding quantities of water used, the 1993 MCC LCA study indicates that 10,600 liters of water are used in fabrication of integrated circuits on one 150 mm wafer, 80% of which is DI water [21]. This corresponds to a requirement of 392 liters per square inch (314 liters of DI water) per wafer processed, clearly an impressive amount. Results of a 1996 SEMATECH study indicated that water usage at US chip manufacturing facilities varied from 40-180 liters per square inch, with a typical figure being 120 liters per square inch [26]. It is not clear whether the difference in usage rates is due to efficiency gains made from 1993 to 1996 or to differences in study methodology and/or subject group.

Energy

A substantial amount of electricity is consumed in semiconductor manufacturing. Cleanroom heating, ventilation, and air conditioning are apparently major energy consuming facilities, accounting for around 50% of use, while wafer processing tools account for 30-40% of consumption [27]. According the 1997 National Technology Roadmap for Semiconductors, average energy consumption was 9 kWh per square inch of silicon wafer processed [27]. While efficiency has reportedly been increasing in the last decade, this trend may be leveling off. The 1993 MCC life cycle study reports that fabrication of semiconductor circuits on one 150-mm wafer takes 285 kWh of electricity, which corresponds to 10.6 kWh per square inch, rather close to the Roadmap result.

Output/waste stream

Limited data prohibit a thorough characterization of the waste stream, but some hints may be gleaned through publicly available studies. Table II.8.6 presents results of a

Table II.8.6: 1997 Aggregate waste quantities of Japanese semiconductor industry (source: EIAJ [29])

Waste stream	Main source Processes	Amount (tons)	Share	Treatment method
Sludge	Water treatment	64,989	25%	Landfill or use as cement ingredient
Oil	Vacuum pumps	41,844	16%	Incineration or purify for reuse
Acids	Etching	68,668	26%	Neutralization, precipitation, landfill
Alkali	Lithography	41,111	16%	Microorganisms
Plastic	Assembly, Packaging	22,495	9%	Conversion to Fuel or landfill
Metal	Lead frame, soldering	16,352	6%	Reuse
Ceramics, glass	Various (quartz vessels)	2,720	1%	Crush, then landfill
Other		5,396	2%	
Total		263,576		

nationwide survey of Japanese semiconductor manufacturers carried out by the Electronic Industries Association of Japan (EIAJ) [29]. The survey covered 23 semiconductor firms, which in total represent 98% of Japanese production. The sludge indicated in the first column was generated through treatment of wastewater streams that contain panoply of developing and etching agents, acids, bases, metals, etc. An interesting note about the glass waste is that as the containers and instruments used in wafer processing must satisfy strict purity standards, they soon become contaminated with use and need to be replaced.

Another source of data on outputs of waste of the semiconductor industry is the Toxics Release Inventory (TRI) collected by the United States Environmental Protection Agency [30]. This is a national survey of waste outputs of national manufacturers in many industrial sectors, including self-reported facility release and transfer of over 600 toxic chemicals. The total tonnage of reported TRI releases and transfers of waste chemicals by the semiconductor industry in 1993 was 7,000 tons. Given that the semiconductor production capacity of the US and Japan are comparable, the factor of 40 difference between this figure and that for Japanese emissions in Table II.8.6 may seem surprising. However, it is important to note that only a small fraction of semiconductor firms reported to TRI. 439 semiconductor firms reported to the US Census, while between 1 and 125 facilities submitted TRI data, depending on the chemical. Thus is it not clear what fraction of US emissions is represented in TRI.

II.8.3.3 Technological trends

The rapid advances in semiconductor technology and resulting dramatic increased performance of computers and other devices has been startling. That this breathtaking pace has continued for decades is even more surprising, there seems to be continual revolution with regards to computer and communications systems performance. The technological advance in semiconductor performance has been quantified in the form of an observation known as Moore’s Law. Moore’s Law, formulated in 1964, is the observation that the number of transistors and producers could put on a chip was doubling every year [31]. This pace has slowed to doubling every 18 months since the late 1970’s, but the latter pace of advance has continued to today.

Fitting more transistors on a chips is driven by two factors: decreasing feature size (thus increasing density of circuits) and increasing the size of a die. Decreasing feature size has been a more important factor, also has been a main driver in the increased speed of microprocessors. Smaller feature size means shorter distances for signals to travel, thus faster performance. A typical feature size in 1980 was 2.0 µm in 1980, this decreased to about .20 µm by 1999. The Semiconductor Industry Association, an organization of mainly US semiconductor manufacturers, publishes National Technology Roadmaps outlining the technological challenges facing the industry. In the 1997 Technology Roadmap, a feature size of .1 µm for MPU gates was set as the goal to be met to maintain current rates of progress [28].

II.8.4 Environment

Environment impacts of emissions

The large chemical use in semiconductor manufacturing represents a potential for significant impacts on air, water, and land systems as well as worker health. A survey of the different possible effects can be found in Reference [25]. The question is whether or not the treatment and handling of these chemicals is sufficiently stringent enough to avoid such problems. There is a substantial body of literature existing regarding developing recycling and treatment systems for chemicals and water, which suggests the issue is receiving a fair amount of attention. However little data exists to indicate the overall results of these efforts.

In terms of the greenhouse gas emissions, the semiconductor industry has direct and indirect emissions. The main direct emissions are of the compounds CF_4, C_2F_6, and NF_3, which are used in fabrication processes, mainly dry etching [32]. All three are all potent greenhouse gases. Table II.8.7 shows a calculation of the total estimated CO_2 equivalent greenhouse gas emissions. The world semiconductor industry emissions of CF_6 and C_2F_6 are assumed to be 5% of the global total emissions, the

Table II.8.7 Estimates of direct emissions of greenhouse gases by global semiconductor industry (source: SEMATECH [32])

Chemical	Yearly Global emissions (metric tons)	Semiconductor sector emissions (metric tons)	Global warming potential	CO_2 equivalent emissions (metric tons)
CF_6	27,000	1,350	10,900	14.7 million
C_2F_6	2,700	135	11,500	1.5 million
NF_3	45	45	24,200	1 million
			Total CO_2 equivalent:	17 million

low end of the estimations of reference [32]. The result of 17 million tons of CO_2 equivalent gases emitted should however be treated as a very rough estimate. In terms of indirect emissions due to energy consumption, using the estimate that the world semiconductor industry consumes about 34 billion kWh of electricity, the indirect emissions of the world semiconductor industry is roughly 12 million tons of CO_2. This was calculated using a rather conservative estimate of the emissions of a mix of power sources as being .35 kg of CO_2 per kWh generated. The above calculations indicate that the scale of direct and indirect emissions are similar, and that the total sector results in emissions of 29 million tons of CO_2 equivalent, which corresponds to about .1% of total world carbon dioxide emissions [33].

Historically, environmental impacts of semiconductor industry chemical wastes on water systems have been considerable. In many sites in “Silicon Valley”, California, groundwater has shown concentrations of toxic semiconductor manufacturing chemicals exceeding safe limits. Chemicals found in water tables include trichloroethylene, 1,1,1 trichloroethane, dichloroethane, toluene, and xylene [34]. Also, 24 of the 29 Superfund sites in Silicon Valley are electronics companies [35].

In Japan, groundwater near electronics plants of Matsushita and Toshiba were found to contain concentrations of tetrachloroethylene and trichloroethylene far exceeding regulated standards [36,37]. Semiconductor manufacturers have made considerable efforts to reduce groundwater pollution, and through chemical substitution and treatment technologies the situation has probably improved greatly. However, as the amount of publicly available data is scarce, it is difficult to judge the current situation.

The issue of occupational health and safety in the semiconductor industry has become more controversial in recent years. On one hand, labor statistics on occupational injury and illnesses do not indicate semiconductor as a high-risk sector. According to 1996 data of the US OSHA, the incidence rate of injury and illness in the US semiconductor sector was 3.3 cases per 100 full-time workers, which compares well to the manufacturing sector average of 10.6 cases [38]. However, while the figure for number of incidents is low, such aggregate data does not reflect the seriousness of incidences, and also does not address the issue of subtler long-term health effects of working in an industry. Given that hundreds of chemicals are used in large amounts in semiconductor manufacture, effects of chemical exposure on workers naturally arise as a concern. Several epidemiological studies indicated that female fabrication workers displayed an elevated incidence of miscarriage [39]. This increased miscarriage rate was correlated, though not conclusively, with exposure to ethylene glycol compounds (which are used as a photoresist solvent) [39]. Increased miscarriage rates are of serious concern, and can also be associated with birth defects and increased cancer rates. A group of around 100 former IBM employees is suing the firm, alleging that increased cancer rates and birth rates in fabrication workers was caused by chemical exposure [40]. Anecdotal reports of increased cancer rates in Scottish semiconductor workers appeared in the Wall Street Journal [41]. These incidents suggest a need for clarification of the long-term health effects on fabrication workers. However, the situation remains very uncertain and there is little evidence either way in terms of a link between semiconductor fabrication and worker illness. There are apparently very few epidemiological studies addressing the issue [42]. Establishing causal links between particular exposure and illness is likely quite difficult due to the rapid evolution of the industry, processes and chemicals used change frequently. However, it should be possible to establish whether or not semiconductor workers experience higher incidence rates of cancers and birth defects compared to other manufacturing sectors.

Resource utilization/efficiency

There are certainly many efforts being made worldwide by the semiconductor industry to improve materials and energy efficiency in production processes. Materials and waste processing costs are substantial so there exists many opportunities for double dividends, technological and process change that is beneficial both environmentally and economically.

Wafers – As discussed in section II.8.3, many wafers are used simply to test equipment. In the past, such wafers were typically discarded, but recently companies have sprung up to reprocess these wafers for reuse. This processing involves shaving some tens of microns from the surface and then repolishing for use [43]. While this is quite a positive development in terms of materials use, in the short term overall efficiency in the use of silicon wafers is likely to decrease as the industry retools for a transition to 300-mm wafers.

Chemicals – there is apparently a fair amount of activity towards developing chemical recycling/reclaiming systems. For example, processes for reusing sulfuric and hydrochloric acid and N-butyl-acetate are discussed in references [44] and [45] respectively. The recycling systems reviewed had investment payback times of 21 months for hydrochloric acid and 6 months for N-butyl-acetate, suggesting that reuse is in many cases economically favorable, though capital costs can be high. There are very few analyses of historical trends for particular processes or the industry as a whole. An exception is the "Implementing Reuse" program of the Electronic Industries Association of Japan, which surveys aggregate recycling/reuse rates of Japanese semiconductor companies. The results of this survey for waste acids and bases is shown in Table II.8.8. [29]. Note that the total amounts of wastes remain

Table II.8.8: Tonnage and recycling rates for chemical wastes from Japanese semiconductor industry (source: Electronic Industries Association of Japan [28])

Year	Acid waste (tons)	Share recycled	Alkali waste (tons)	Share recycled
1990	59,232	16.1%	44,881	.2%
1991	62,650	19.6%	52,368	.4%
1992	68,535	21.8%	51,339	.5%
1993	63,180	28.0%	60,669	2.9%
1994	65,784	29.8%	56,836	4.0%
1995	61,724	36.4%	37,655	14.4%
1996	69,838	36.6%	45,338	18.0%
1997	68,668	43.0%	41,111	24.4%

relatively stable, suggesting that the rapidly increasing recycling rates result in net reductions in discharged wastes. Another indicator of chemical usage trends comes from analysis of markets for semiconductor chemicals. A recent articles states that in a year where the overall semiconductor market grows at 15%, markets for wet process chemicals grow at 8% [46]. The difference in growth rates is explained as being due to the reduced chemical requirements of improved technologies.

Water – along with chemicals, the extremely large consumption of water in semiconductor manufacture sets increased reuse and usage efficiency as important targets. Rinse water reduction strategies include redesigning the geometry of rinse tanks for improved flow around the wafers and increasing the temperature of the water [47]. Water recycling strategies include feeding waste water back into the purification process and using waste water from one process directly for another that has less stringent purity requirements. An article describing two pilot water conservation projects at a Motorola facility in Arizona reports a 3% reduction in the facility's annual water consumption of 6.2 billion liters [48]. No reports were found that described overall trends in water usage in semiconductor manufacturing. It should be noted that fabrication facilities handling the new 300-mm wafers are expected to have 1.5-2.5 times the water consumption of a 200-mm wafer fab [27]. As larger wafers also yield more functional "units", it is not obvious whether the shift to larger wafers represents an increase or decrease in water consumption per chip.

Energy – Assuming the 9 kWh/square inch figure is roughly representative of average world practice, the total energy consumption of the world semiconductor industry can be estimated at 34 billion kWh. Electricity costs represent 25-40% of the operating budget of a fabrication plant [28], thus energy conservation is economically as well as environmentally relevant. Efforts towards reducing electricity consumption include the redesign of equipment such as using smaller motors for air recirculation [27]. The transition to handling larger wafers also should reduce energy consumption, as more significantly more dies can be made with little increase in power [28].

To sum up, there are trends towards both increasing and decreasing resource efficiency in the semiconductor industry. Effort being made towards refining existing processes and implementing conservation reduces material and energy requirements. The trend towards increasing wafer size probably has a net effect of increasing efficiency, due to favorable relative scaling. On the other hand, achieving smaller feature size and denser patterns of circuits implies stricter process and purity control [19], which can lead to increased demand of materials and energy. Also, newer technologies are earlier in the "learning curve", implying that optimization of yield and resource use must begin again to a certain extent.

II.9 Solar cells

II.9.1 Overview of the object and its uses

Solar cells (or photovoltaic cells) are semiconductor devices that directly convert incident light into electricity. A proper discussion of how such devices generate electricity from light would delve into solid-state physics quite beyond the scope of this report. Here it will simply be mentioned that the function of a photovoltaic cell depends on the behavior of a p-n junction when exposed to light. The area around the junction has a non-zero voltage that transports nearby charge carriers excited by light through the cell, creating a current. Readers interested in the physical functioning of photovoltaic (PV) cells are referred to references [1] and [2].

Solar power from photovoltaic cells represents an important potential source for renewable energy. To illustrate the possible energy generation capacity of solar power, note that a typical yearly incident solar energy on a flat plate solar system is around 1800 kWh/m^2 [2], though this figure varies from region to region. Assuming an array of solar cells with 15% conversion efficiency (consistent with currently produced commercial systems), generation to match the 1996 global electricity demand of 13,600 TWh [3] would require photovoltaic arrays with total surface area of 51,000 km^2. This corresponds to around .3% of the land area of the earth, a requirement within reasonable limits. Land requirement is naturally only a preliminary constraint, a key question for any energy source is its economic performance compared to other sources. Photovoltaic electricity remains more expensive than many other means of generation, with unsubsidized solar electricity costs at least $.20 per kWh in 1999, in comparison to fossil fuel electricity which costs as little as $.03 per kWh in favorable conditions [4]. However, photovoltaic systems continue to fall in price, and in many niche markets based on demand for energy in remote locations, solar power is already quite competitive.

Solar cells, modules, and systems

Cells

Solar cell refers to the basic “element” of a photovoltaic system. Photovoltaic cells can be made from various types of materials. Table II.9.1 shows the main types of commercial solar cells and their 1998 share of production:

Table II.9.1: Types of solar cells and production levels (source: IEEE Spectrum [5])

Class	Type of cell	1998 production share (MW)
Wafer	Multicrytalline silicon	46%
	Single crystal silicon	40%
	Gallium Arsenide	<.5%
Thin Film	Amorphous silicon	13%
	Thin layer silicon	.6%
	Cadmium Telluride	.6%
	Copper Indium Diselenide	<.5%

Note that silicon-based cells represent around 99% of recent commercial production. Solar cells can be broadly classified into wafer based and thin film types. Wafer based cells are, as the name implies, manufactured starting from a single or multicrystalline wafer, which generally serves as the p-half of the p-n junction. Cells made from a multicrystalline silicon wafer have been the most produced type for many years: while generally their efficiency is somewhat less than single-crystal cells, they are simpler to produce and thus manufacturing costs are lower. Gallium Arsenide has advantages over silicon as a photovoltaic material and can yield extremely efficient cells, but remains quite expensive. Thin film cells are manufactured through deposition of very thin layers, typically a few microns in thickness, of photovoltaic materials on top of a substrate such as metal, plastic, or glass. Thin-film cells have been viewed by many in the industry as being the future technology for producing low cost solar cells [6]. The two main reasons for this belief are lower material costs and the possibility of implementing a continuous manufacturing process for thin film cells. For now, however, the efficiencies of commercial thin film cells remains low, thus increasing array area and the associated costs of encapsulation and module formation. Amorphous silicon has been the most commercially successful of thin film cells, and is widely used in handheld electronic devices. There are hopes that more exotic photovoltaic materials such as Cadmium Telluride and Copper Indium Diselenide can lead to efficient, low cost cells. Much progress has been made and the performance/cost gap between thin film and wafer-based cells has been shrinking.

The structure of a polycrystalline cell, the type most produced currently, will be discussed in some detail. Single crystal cells are quite similar in most respects. A typical cell is square shaped, 12.5cm x 12.5cm, with a wafer thickness of 200 μm [7]. The layer structure of a cell is as follows: on the back side, the silicon wafer is bonded to a 10-20 μm layer of aluminum and silver, which forms the rear electrical contact. The top of the wafer has typically been treated to yield a layer of n-type semiconductor less than 1 μm thick. A finger-like network of silver and aluminum lies above this to form the front contact, the coverage of metal on the front side is some 7% of the surface area. Above the front contact there is a layer of antireflective coating, typically TiO_2.

Modules

Module refers to a collection of cells that are laid out in a matrix, connected together and encapsulated for protection against mechanical stress and chemical exposure. A polycrystalline module typically is a matrix 4 by 9 of cells. The front and back are encapsulated with a substance that seals the inside from chemical contact from the outside, is transparent to light, durable, and bonds to glass. A typical encapsulent is Ethylene Vinyl Acetate (EVA), with front and back layers .5 mm thick each. On the backside, a 100-200 µm layer of aluminum or aluminum and Tedlar (a high-strength polymer) provides structural support. For the front, a 3 mm layer of chemically hardened glass is used.

Systems

To form a power generating system for general use, modules are encased in a frame, usually aluminum, and are combined with a set of batteries and an inverter to convert DC to AC for home use. Such a complete power generating system is called Balance of System (BOS).

Applications/end-uses

The various energy niches in which PV cells are applied evolve as the industry develops. Historically, the use of PV began in the 1960's for powering space satellites. The next major application developed was providing electricity to remote industrial and military equipment such as telecommunications repeaters and navigation buoys. In the early 80's, the use of solar cells in consumer electronics goods such as calculators and wristwatches became ubiquitous. As costs decreased and efficiencies increased, photovoltaics increasingly penetrated the market for supplying power to homes in remote areas. Currently, for a single residence located more than a kilometer from a power grid, installation of a PV system is often more economical than extension of the grid [5]. While there is certainly room for the PV industry to continue to grow expanding the above applications, a main target is to economically provide power to electrical grids. Promoted through various subsidy and incentive programs, grid applications have in recent years become the largest end-use of solar cells. Still, the total amount of world installed solar power in 1998 is around 1000 MW, an indicator that solar power represents a rather small fraction of total energy production. A breakdown of trends in aggregate end-use markets is shown in Table II.9.2.

Table II.9.2 Breakdown of solar cell end-use markets (source: World Bank website [8])

Application	1994 share	1997 share
Remote Industrial Use	38%	28%
Remote Residential Use	28%	27%
Grid Connected Systems	20%	36%
Small device power	14%	9%

II.9.2 Economy

Production

World production of solar cells in 1998 was estimated at 151 MWp[1] [9]. The estimated values of module and cell shipments were $846 million and $590 million respectively [10]. These figures reflect an average price for modules of $5.60 per Wp and a price of cell of $3.90 per Wp. The total market for photovoltaic systems in 1997 was estimated at around $1.2 billion [11]. The industry grew 26% from 1997 [11], and the average annual growth rate from the interval 1988-1998 in terms of watt power produced is 16% [9]. Future growth rates are predicted to grow an average of 22% per year until 2003 [10].

Geographical distribution of production

The regional distribution of the production of solar cells appears below in Table II.9.3

Table II.9.3 Regional distribution of production of photovoltaic modules (source: PV News, February, 1999 [9])

Region	1997 Production		1998 Production		Yearly change	
	MWp	%	MWp	%	MWp	%
US	51	40.5	53.7	35.4	2.7	5.3
Japan	35	27.8	49.2	32.4	14.2	40.6
Europe	30.4	24.2	30.1	19.9	-0.3	-1
Rest of World	9.4	7.5	18.7	12.3	9.3	98.9
Total	125.8	100	151.7	100	25.9	20.6

[9]. This data apparently reflects domestic production figures. The Japanese solar cell industry has been increasing in leap and bounds in recent years and seems set to become the leading producer. While there are no doubt many factors contributing to this, one of these is substantial (about $140 million in 1998) government subsidies of residential PV systems implemented under the New Sunshine Project.

Firm structure

To understand better the geographical patterns of production, it is useful to look into the major producing firms and their geographical characteristics. Table II.9.4 shows the 1998 production of the leading photovoltaic cell firms [9]. The top 10 firms accounted for about 80% of 1998 world production. The location of headquarters of a

[1] Wp is a measure of generating capacity of a solar cell. One Wp means the cell generates one Watt in “standard” sunlight (1000 Watts/square meter)

Table II.9.4: 1998 Production of leading PV firms
(Source: PV News, Feb 1999 [9])

Company	Location of headquarters	Share (of 151 MW)
Kyocera	Japan	16.2%
Siemens Solar	Germany	13.2%
Solarex	US	10.5%
Sharp	Japan	9.2%
BP Solar International	UK	8.8%
PhotoWatt	France	7.9%
Astropower	US	4.6%
Sanyo	Japan	4.3%
ASE	Germany	4.0%
Solec Intl	US	2.6%
Remaining firms		18.7%

firm is only a partial indication of geographical distribution of activities. Siemens Solar, for instance, is headquartered in Germany, but most production takes place in the US. This is counted as US production in Table II.9.3.1, which reflects domestic production rather than company ownership. Also, Solarex was purchased by BP in early 1999 and Solec is co-owned by two Japanese companies, Sanyo and Sumitomo Corporation [12]. Thus nearly all US production is owned by foreign firms.

Trade

Though world trade figures for solar cells were not available for this report, the US reportedly exported 73% of its 1997 production [13], which is an indicator that solar cells are an international commodity with large demand outside of the main production regions of the US and Japan.

II.9.3 Technology

II.9.3.1 Manufacturing technology for silicon wafer-based photovoltaic modules

In this report only the production technologies for polycrystalline and single crystal wafer cells will be discussed, according to Table II.9.1 the two types account for around 86% of current production. The primary source for this discussion is the life cycle study of Phylipsen and Alsema [7].

The manufacturing process of polycrystalline and single crystal solar cells can be broken into the following stages: wafer preparation, creation of p-n junction, contact formation, and application of antireflective coating. At this point, the cell is complete, the next step is combining the cells into a module. For module production, the key steps are assembly and encapsulation.

Wafer preparation

In the case of single crystal cell, wafers are prepared much the same in the semiconductor industry, using CZ or float zone growth methods. The CZ process is described in Section II.7.3. In the case of multicrystalline cells, wafers are made from rectangular cast ingots. Silicon feedstock is melted in a graphite crucible in inert atmosphere (e.g. argon) and allowed to solidify under controlled thermal conditions. Impurity levels are higher in outer portions of ingot, which are contoured off, leading to a 15% loss of material. It is also possible to produce ingot via electromagnetic casting, in which the melt is contained through electromagnetic confinement. By preventing contact of melt with container, contamination is reduced.

Next, ingots are sliced into wafers of 200-300 µm thickness, using multiple wire saws and abrasive slurry. A typical slurry is SiC and mineral-oil. Loss of silicon as kerf, silicon dust arising from the slicing process, is about 50%. After slicing, the surface of the wafer is smoothed and textured to increase light absorption. This is typically done through etching using sodium hydroxide and/or potassium hydroxide. After this the wafer is rinsed with water and sulfuric or nitric acid.

Creation of p-n junction

The starting wafer is typically a p-type semiconductor doped with boron. To create the p-n junction, a layer of n-type is formed through introducing phosphorous impurities. This is done by baking the wafer in an oven at around 800-900 C in the presence of $POCl_3$ and oxygen. According to the reaction

$$4POCl_3 + 3O_2 \rightarrow 2P_2O_5 + 6\,Cl_2,$$

phosphorus pentoxide forms a phosphorous-silica layer on the wafers, from which phosphorus atoms diffuse into the wafer. This layer is later removed by etching with flouric acid (HF), according to:

$$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2\,H_2O.$$

Contact formation

Electrical contacts must be applied so as to efficiently transport the generated electricity away from the cell. The back contact is generally a uniform layer of silver and aluminum, the front contract a very fine fingerlike network that allows conduction of electricity while leaving most of the surface area open for exposure to light. The formation of such contacts is called metallization.

The backside layer is a mixture of silver and aluminum, often around 80% silver but aluminum only layers are also possible. This metal layer serves the function of a back contact as well as improving the efficiency of the cell. Efficiency is increased through two effects: the creation of a “back surface field” that prevents recombination of electrons and holes and the layer can also have a gettering effect to neutralize the effects of impurities. The back layer is formed by applying a metal containing paste to the bottom of the wafer, and then baking the paste. The paste is made up of silver and/or aluminum, solvents, resins, fillers and glass fritt. The solvents adjust the viscosity of paste to keep it printable, resins keep metal particles in emulsion, and glass fritt increases cohesion between metal particles and metal-wafer adhesion. The paste is screenprinted onto back of wafer, then the wafers are baked at 120-150, then 300-400 C, and finally above 600 C to sinter the fritt.

The front layer is generally silver, screenprinted in a similar fashion as above. A typical finger width is 120 µm, and the contact network covers around 7% of the surface of the cell.

Antireflective coating

To increase the efficiency of the cell, it is important to minimize reflection from the surface. This is achieved through applying a coating of an antireflective substance, typically TiO_2 or Ta_2O_5 are used. This layer is applied using chemical vapor deposition according titanium isopropoxide according to the chemical reactions:

$$Ti[(CH_3)_2CHO]_4 + 4\ H_2O \rightarrow 4\ (CH_3)_2CHOH\ (g) + Ti(OH)_4,$$
$$Ti(OH)_4 \rightarrow TiO_2 + 2\ H_2O.$$

It should be mentioned that in addition to the production step being described here, in some cases the cell undergoes a process known as passivation prior to the application of the antireflective coating. Passivation involves introducing hydrogen atoms into the wafer so as to mitigate the effect that impurities, crystal defects, and grain boundaries have to reduce the efficiency of the cell. For further discussion of this process, see [7]. If the quality of the silicon wafer is sufficiently high, for instance in the case of a high-purity single-crystal wafer, passivation is unnecessary.

Module assembly

In this step, functional cells from the preceding step are arranged in a matrix, typically 4 cells by 9 cells or 4 cells by 10 cells in the polycrystalline case, and interconnected via copper strips (coated with tin).

Module encapsulation

At this point, the “cell” is complete, but is encapsulated in protective materials and connected together into a frame in the module assembly phase. The purpose of encapsulation is to chemically and physically insulate the cells from the outside environment. In the first step, the cell matrix is sandwiched between .5 mm layers of a substance known as Ethylene Vinyl Acetate (EVA). EVA is a durable transparent polymer that serves the purpose of chemically insulating the cell and also allows good bonding with subsequent encapsulation layers. Next, a 3 mm layer of glass is applied to the top and a 125 µm Tedlar/Al/Tedlar layer is deposited on the bottom. Tedlar is a polyvinyl flouride film known for ruggedness and resistance to chemical agents.

At this point the module is complete, for practical use it is generally placed in an aluminum frame.

II.9.3.2 Process inputs/outputs

Inputs

The material inputs for the production of one 12.5 cm by 12.5 cm polycrystalline solar cell in Table II.9.5 [7]. Assuming 14% efficiency, such a cell generates 2.34 Watts when exposed to "standard" sunlight (2.34 Wp). It is interesting to note that the primary materials used in terms of weight are, in descending order: glass, aluminum, EVA, and silicon. To indicate variances in input/output data, it is useful to compare the data with different studies. According to data from a NEDO report detailing inputs for production of polycrystalline solar cells, the material inputs to produce a cell with the same capacity are 54 g of SiC, 5.2 g of KOH, and .14 g of $POCl_3$ [14]. The two data sets are consistent within an order of magnitude, the large differences that appear are possibly due to different process implementation.

Table II.9.5 Material Inputs per 12.5 cm x 12.5 cm polycrystalline solar cell (source: base case in [7])

Production Stage	Material	Input Amount (grams)
Wafer preparation	High purity silicon	16.0
	Argon gas	5.75
	Mineral oil	15.5
	Silicon carbide (SiC)	20.0
	Cleaning fluids	5.3
	KOH	13.0
	HNO_3	.60
Emitter Formation	$POCl_3$	.09
	HF	1.10
	CF_4	.08
Contact Formation	Ag/Al paste	.78
	Ag paste	.1
Antireflective coating	titanium isopropoxide	.20
Module production[2]	EVA	18
	Glass	131
	Tedlar	2.5
	Aluminum (frame)	33

With respect to energy consumption, the study of Phylipsen and Alsema indicates that the total energy requirements to produce one cell are 312 Wh for wafer preparation and 546 Wh for cell processing. [7]. According to Yoshioka et. Al., who report data from the New Energy Development Organization (NEDO), the energy requirements for wafer preparation and cell processing of 959 Wh and 605 Wh respectively [14]. As a final note, the NEDO data also indicates that de-ionized water requirements for wafer preparation and cell processing are 1.7 liters and .8 liters respectively [14].

[2] One module here is assumed to consist of 36 cells. The numbers in Table 9.5 are the materials inputs for one module divided by 36.

Outputs

A summary of the main outputs of the solar cell production process appears in Table II.9.6 [7]. The column indicating estimation of the emissions of the world industry was calculated assuming that the output amount per cell represents average world practice and a 130 MWp production of polycrystalline and single crystal cells (see Table II.9.1). Emissions from the 21 MW of production of other types of solar cells are not included. Especially given the variation in process data as discussed above, these figures should be treated only as very rough indicators. Possible implications of these emission figures are discussed in Section II.9.4.

Table II.9.5 Material Outputs per 12.5 cm x 12.5 cm polycrystalline solar cell (source for output amounts: base case in [7])

Production Stage	Material	Output Amount (per cell)	Estimated emissions of world industry
Wafer preparation	waste silicon (kerf, contaminated)	8.8 g	484 tons
	argon gas	5.74 g	315 tons
	mineral oil	15.5 g	853 tons
	Silicon carbide (SiC)	12.8 g	704 tons
	Cleaning fluids/solvents	3.4 g	187 tons
	KCl	11.4 g	627 tons
	$NaNO_3$	.8 g	44 tons
Emitter Formation	$NaHPO_3$	.06 g	3.3 tons
	NaF	.24 g	13.2 tons
	CaF_2	2.10 g	116 tons
Contact Formation	Evaporated solvents	.21 g	11.6 tons
Antireflective coating	isopropanol	.16 g	8.8 tons
Module production	Rejected cells	5.5%	N/A
	EVA cutting losses	.8 g	44 tons

II.9.3.3 Technological trends

Two main metrics to measure technological progress in the PV industry are module price and efficiency. Table II.9.7 shows progress of actual module prices and

Table II.9.7: PV module historical prices and Laboratory cell efficiencies

Year	Average module price (1993 US$)	Single crystal Si efficiency	Thin-film efficiency
1975	76.12	-	-
1980	21.06	17.5%	7.0%
1985	8.04	20.4%	11.1%
1990	5.67	23.1%	14.9%
1994	4.00	23.1%	16.4%

laboratory cell efficiencies over selected years starting from 1975. It should be emphasized that the data on efficiencies is for laboratory cells, commercial cells generally have lower values. While there is some correlation between efficiencies of laboratory and commercial cells, it is not exact. This caveat aside, it is evident that there has been substantial progress in lowering module costs and improving efficiencies. However, the reduction in module prices is apparently slowing down, which naturally leads to the question of whether the technology is reaching a plateau. One factor that is important to emphasize, however, is that while a particular technological path, such as silicon-wafer based cells, may reach a plateau, other directions such as exotic thin-film materials are on at an earlier stage in the technology life-cycle.

R&D efforts continue into both improving existing technologies and in developing new photovoltaic materials. Thin film cells are often perceived as the technology that has the most promise of providing economic solar power. This is because the production process for thin film cells has two large advantages: the materials requirements are less and the production process can be made continuous. However, commercial thin film cells have been plagued with low efficiencies, current typical cells run around 7-9% vs. 12-13% for single crystal and polycrystalline. As forming the module represents a significant portion of manufacturing costs (about 40% for polycrystalline cells [1]), lower efficiency cells result in larger area for equivalent power outage, thus increasing production costs. Thus increasing efficiency is a major target for thin film cells.

II.9.4 Environment

Environmental impacts of emissions

Some of the substances emitted from solar cell manufacturing with possible environmental relevance are fluorine and chlorine containing compounds, solvents, and isopropanol. From the estimations of emission amounts in Table 9.6, total chemical emissions of the world industry for polycrystalline and single crystal solar cells is in the hundred of tons per annum. This figure is three orders of magnitude less than the hundreds of thousands of tons of estimated emissions for the world semiconductor industry. The much smaller overall scale of the solar cell sector is certainly an important factor accounting for this difference, but also the amount of materials and energy used "per unit" of production is much less. This is because the photovoltaic cell is a far simpler device than an integrated circuit, having but one uniform p-n layer, and thus only some basic wafer preparation and one doping step is required. Similarly, energy and water use are small compared to the semiconductor industry.

Relatively small chemical and resource use is an indicator that the environmental impacts of the industry may be small, but effective environmental burden is as much dependent on waste treatment and industry location as on size. The fact that most solar cell production is carried out by larger firms in developed countries suggests that reasonable waste treatment systems are in place, however little data was available to support or contradict this supposition.

For a more detailed discussion of the environmental impacts of emissions of multicrystalline, as well as those associated with amorphous silicon, CIS, and CdTe solar cells, the reader is referred the report of E.K. Alsema [15]

Resource utilization/efficiency

Silicon – According to Table II.9.5, the silicon requirement to produce a 2.3Wp multicrystalline cell is 16 grams. For a single crystal cell, this figure should be near 32 grams, as the single crystal ingot formation step has a silicon efficiency of around 50% (Table 7.3). Thus, the total silicon used in 1998 world production of multicrystalline and single crystal cells can be estimated from process data to be 1,300 tons. This estimate is lower, but of the same order of magnitude as the total estimated 2,000 ton input of waste polysilicon into the solar cell industry [16]. The main losses in silicon occur in the preparation of wafers.

Glass - An estimated 7,200 tons of glass was used in 1998 world production of multicrystalline and single crystal solar cells. Given that the world glass production is around 80 million tons annually, the current use of glass for silicon cells represents a rather small sub-market. Glass is produced primarily from silica sand (section II.1), a rather abundant material thus there are no resource availability problems foreseeable future.

Energy – Averaging the process data from references [7] and [14], the average electricity requirement to produce one 2.3 Wp cell is estimated at 1.211 kWh (see section II.9.3). The total electricity consumption for 1998 world production of 130 million Wp of multicrystal and single crystal cells is estimated at 68 million kWh. This is rather minimal compared to many other sectors in the production chain.

II.10. Optical Fiber

II.10.1 Overview of the object and its applications

Optical fibers are strands of material especially designed to carry light signals. The basic design for any optical fiber is that the core of the fiber is surrounded by an outside tube (cladding) of a material with a lower index of refraction [1]. Due to an optical phenomena known as "total internal reflection", the cladding acts as a flexible and nearly perfect cylindrical mirror, preventing light from escaping the core. Many materials can be used to construct an optical fiber, but the primary material used in practice is very pure glass (amorphous silicon dioxide) doped with germanium to alter the index of refraction. Modern manufacturing methods enable the manufacture of glass many orders of magnitude more transparent that air, which can carry light signals for extremely long distances.

While optical fibers have important uses as imaging devices such as medical endoscopes and optical sensors, by far the main application is as a media to transmit information in telecommunications. Optical fiber has come to play a central role in telephone, fax, computer networking, and cable television services. Its superior bandwidth and performance have made it the standard for long distance, high volume portions of telecommunication networks. For example, nearly all international telephone traffic travels through undersea optical fiber cables. Optical fiber remains somewhat expensive and inconvenient for low-bandwidth, short distance links, such as from a local phone switching box to a residence. Because of this most people rarely encounter optical fiber cable in their day-to-day lives, but this could change in the future. The prices of optical fiber and related equipment continues to fall while the demand for bandwidth continues to rise, thus optical fiber is increasingly adopted in areas where copper cabling was traditionally used.

Fiber

A single strand of optical fiber functioning as part of current commercial systems typically carries data at a capacity of 2.5 Gbits/s, which corresponds to around 40,000 phone calls simultaneously travelling through the fiber. Optical fibers used for communication today are divided into two main types: single and multi-mode fiber. Single-mode fiber, with its extremely narrow core, allows only one component of incident light to pass through the fiber, and is most suitable for long distance transmission. Multi-mode fiber allows many more components of light, and are generally used for shorter distance communication. Both types of fiber have an inner core of germanium dioxide-doped silicon dioxide, with the cladding being pure silicon dioxide. Typical overall composition of a fiber is 96% silicon dioxide, 4% germanium dioxide, with impurity levels in the parts per billion [2]. Such low impurities and other optimizations in the manufacturing process have led to extremely small attenuation levels, with .25 dB/km typical for commercial single mode fiber, and 2.5 dB/km representative of multi-mode fiber use [1]. In the single mode case, such a low attenuation level implies that a signal can travel around 100 km before requiring boosting with an amplifier. Typical dimensions for a current fiber are an 8 µm core and 125 µm cladding diameter for single mode fiber and 62.5 µm core and 125 µm cladding diameter for multi-mode fibers. Given that the density of glass is around 2.2 g per cm^3, the total amount of active material in a fiber is only around 30 grams per kilometer. The fiber is generally coated with materials such as a silicone and/or nylon to protect it from scratches and breakage.

Cable and systems

Strands of optical fiber are incorporated into a plastic cable before application in communication. The number of fibers per cable typically ranges from 4-36, depending on the application. The total fiber communication system consists of the components: transmitters, receivers, and repeaters (amplifiers). Transmitters are generally semiconductor lasers or LED's that convert a given electrical signal into a light signal, which is piped into the fiber. The repeater is a device to boost a signal that has degraded over distance. Repeater design has taken a great leap forward in recent years with the advent of the optical amplifier, which directly boosts optical signals without intermediate conversion to electrical pulses. A receiver is generally a photodiode that converts the incoming light signal back into an electrical pulse.

II.10.2 Economy

Production

According to Kessler Marketing Intelligence (KMI) data, 1998 world production of bare optical fiber was 48.9 million km, up 14% from 1997 [3]. The average growth in production for the period 1993-1998 was 23% per annum. The total value of 1998 production was $2.59 billion, down 8.8% from 1997 [3]. The fall in market value was due to plummeting prices of single-mode optical fiber, which declined from 5.3 cents per meter to 3.5 cents per meter from 1997 to 1998.

The total value of 1997 optical fiber *cable* production is estimated to be $5.0-7.2 billion. This value is indicated as a range because the figure varies widely according to source. For instance, KMI data indicates US production of cable at $1 billion higher than US census data. At any rate, the above range indicates that fiber represents a significant portion of cable costs. Considering the subcategories in the cable market, single-mode cable accounted for 92% of total volume but only 50% of market value. Multi-mode cable was 10% of the market, and 6% of volume, and submarine cable was only 2% of value, but 35% of the market [3].

The total 1997 market for optical fiber communications systems is estimated at $8.6-12.4 billion, with 58% of market value in optical fiber cable, 25% in amplifiers, 12% in transmitters, 4% in receivers, and 1% in wavelength division multiplexers [4]. Although cable represents the bulk of the costs of a fiber optic system, the components also represent a significant expense. These high component costs explain why fiber has not expanded for local uses, local networks contain use a significantly higher proportion of connecting devices.

Geographical distribution of production/trade

In 1998, 41% of optical fiber was produced in North America, 28% in the Asia-Pacific, 27% in Western Europe, and the remaining 4% of production took place in other parts of the world [4]. North America, Western Europe, and Japan account for around 82% of world production, reflecting that the developed countries are the primary parties involved. Also, a large share of fiber production in developing countries uses preforms imported from Europe or Japan.

The regional distribution of fiber consumption does not differ substantially from the distribution of production, reflecting the fact that optical fiber trade is dominated by domestic markets. Telecommunication systems have traditionally been under the jurisdiction of state-controlled monopolies, which tend to favor domestic producers for equipment. However, the trade patterns of optical fiber and related systems have been rapidly internationalizing over the last few years. For example, for the leading exporter of fiber, the United States, the ratio of fiber exported over total domestic production rose from 12.7% in 1992 to 44% in 1997 [5]. Similarly, total imports/domestic production of fiber rose from 2.4% in 1992 to 14.7% in 1997. Such changes likely reflect the effect of recent agreements regarding the liberalization of telecommunication markets. The WTO Agreement on Basic Telecommunications Services, negotiated from 1994-1997 and in effect since 1998, promises to greatly facilitate liberalization of trade.

Firm structure

While there are around 800 companies worldwide involved in optical cable manufacture, the bulk of fiber production is under a very few firms, as shown in Table II.10.1 [6]. The top 6 firms account for 76% of world fiber production. Different companies handle different segments of the cable production chain, for example Wacker in Germany and Shin-Etsu in Japan produce preforms that are sold to other companies for drawing of fiber. Many companies are involved only in cabling of fiber, while some firms such as Lucent, are quite integrated and handle all phases on a substantial scale.

Table II.10.1 Top Firms producing optical fiber in 1997
(source: Fiber Optics News [6])

Firm	Location of Headquarters	Market share
Corning	Corning, New York, USA	32%
Lucent	Murray Hill, New Jersey, USA	18%
Alcatel	Paris, France	9%
Sumitomo	Osaka, Japan	7%
Fujikura	Tokyo, Japan	5%
Pirelli	Milan, Italy	5%

II.10.3 Technology

II.10.3.1 Production processes

The optical fiber cable production process has the following stages:

1. Manufacture of preform,
2. Drawing of optical,
3. Cabling of optical fibers.

A preform is a cylinder of pure silicon dioxide with the desired profile of index of refraction. A typical preform size is 5 cm in radius and 1 meter in height, which yields about 120 km of optical fiber. Optical fiber is drawn from the preform using controlled melting: the bottom of the preform is heated and melted glass is pulled from the bottom as a thread, which solidifies into optical fiber. After solidification the fiber is coated with plastics and/or silicones and wound onto large drums. The fiber is later incorporated into a plastic cable. Only the preform step will be reviewed in any depth here, for information on other production steps or more details on preform fabrication, the reader is referred to references [1,7,8].

There are a number of technologies to produce preforms, the three main ones presently implemented are Modified Chemical Vapor Deposition (MVCD), Outside Vapor Deposition (OVD) and Axial Vapor Deposition (AVD). There are also two production processes involving plasma, Plasma CVD (PCVD) and Plasma Enhanced CVD (PMCVD), but these are implemented on a rather small scale [9].

The basic chemical reactions utilized in MCVD are

$$SiCl_4 + O_2 \rightarrow SiO_2 + 2Cl_2 \text{ and}$$

$$GeCl_4 + O_2 \rightarrow GeO_2 + 2Cl_2.$$

$SiCl_4$ and $GeCl_4$ are bubbled through argon and/or oxygen and passed into a hollow tube of high purity silica. A hydrogen/oxygen torch applied from outside heats a section of the pipe to around 1500 C. SiO_2 and GeO_2 particles are formed, which accumulate and sinter into a glass layer on the inside of the tube. The torch passes back and forth to form new layers, and the tube is continuously rotated to insure even deposition. Varying the concentration of $GeCl_4$ input into the chamber controls the concentration of deposited GeO_2, and thus the index of refraction. Eventually the entire interior is nearly filled but for a narrow hole through the center. The tube is then thermally collapsed to yield an optical preform. An advantage of this process is that as the deposition takes place in a closed environment, it is more difficult for impurities to enter. The main disadvantage of the process is the requirement for high purity tube stock, which also limits the size of the preform. MCVD is primarily used to produce multimode fibers

In the Outside Vapor Deposition process, which was developed by Corning in the US, SiO_2 and GeO_2 particles are deposited onto a glass rod, building up to form a cylinder of soot, a porous collection of silicon dioxide particles of about .2 µm in size. The basic chemical reactions are somewhat different that in MCVD,

$$SiCl_4 + O_2 + 2H_2 \rightarrow SiO_2 + 4HCl \text{ and}$$

$$GeCl_4 + O_2 + 2H_2 \rightarrow GeO_2 + 4HCl.$$

The raw materials $SiCl_4$ and $GeCl_4$ are passed through a torch, where they are heated past vaporization point and reacted with oxygen and hydrogen. The resulting glass particles accumulate on a nearby rod substrate. The rod rotates to insure even deposition, and the torch passes back and forth depositing layer by layer. After deposition, the center rod is removed and the soot tube is collapsed into glass through consolidation. The latter is carried out by placing the soot in an electric furnace with an inert atmosphere, typically helium, and under very controlled conditions heated to 1500 C, below the glass melting point. The soot collapses, its density increasing eightfold, and yields a preform. The main disadvantage is that as reaction and deposition occur in an open space, the process is much more susceptible to contamination of impurities. Thus a clean room must be maintained. Also, removal of the central substrate rod can lead to irregularities in the fiber core. An advantage of this process is that there is no real limit on preform size, thus production of long fibers (50-100km) is possible.

Axial Vapor Deposition, developed by NTT in Japan, is similar to OVD in many respects: soot particles formed in a hydrogen/oxygen torch deposit soot particles onto a substrate. However, a distinct torch-substrate geometry leads to important differences. In AVD, the torch is configured to deposit particles on top of one end of the substrate, thus the soot tube is built up from a point, rather than rod as in OVD. The torch position is fixed, while the cylinder of soot is drawn upwards as it grows. This technique eliminates the need for a central substrate rod and also simplifies the process of making large preforms. A disadvantage is that flame control is very difficult, making the fabrication of high-bandwidth fibers a challenge.

II.10.3.2 Process inputs/outputs

Table II.10.2 shows a partial input/output table for preform production. As process

Table II.10.2: Inputs/Outputs of AVD preform fabrication process

Inputs	**Amount**	Outputs	**Amount**
$SiCl_4$	333 g	Optical fiber	1 km
$GeCl_4$	10.2 g	Silica dust	23 g
H_2	173 g	Germanica dust	1 g
O_2	1380 g	HCl	59 g
He	94.0 g	Unreacted reagents	80%

data was not available, the figures in the table were calculated using industry statistics on the usage of silicon tetrachloride by Japanese industry [10] and an unpublished report on specialty gas consumption. The average deposition efficiency obtained in this way is 20%, the output amounts were calculated this figure and the chemical reactions above. Note that this data pertains only to the fabrication of the optically active core and cladding of the fiber, the fiber coating and surrounding cable are not included.

II.10.2.3 Technological trends

The current implementation of the processes described above is roughly equal, the three processes accounting for nearly all fiber production [9]. The share of AVD has been increasing, largely at the expense of MCVD, with OVD more or less stable. The drive to realize benefits of economies of scale drives a trend towards larger production facilities. Also, there is a trend to realize larger preforms, as more fiber can be obtained from a single batch.

II.10.4 Environment

Environmental impacts of emissions

Data on emissions from the optical fiber production process were not available. Based on the input/output data of section II.10.3 and production data in II.10.2, the worldwide emissions of the optical fiber industry are estimated at in the tens of thousands of metric tons. Presuming that the unreacted reagents are either reprocessed for other uses or reacted to safer compounds for disposal, the emissions of the process are silica and germanica dust and hydrochloric acid. The fate of the hydrochloric acid is undocumented, though in some cases it is reportedly collected and resold to other industries.

It must be emphasized however, that although optical fibers are being considered here, the functional unit of application is optical fiber cable and accompanying equipment. Fiber represents only a small fraction of material requirements, impacts associated with production of cable housing are likely more significant.

Resource utilization/efficiency

Silicon - based on Table II.10.2, one can calculate that roughly 20% of silicon input into the process ends up in the final optical fiber. Most of this silicon likely ends up as silicon dioxide particles that do not deposit onto the soot tube. Even given this rather low materials efficiency, the material requirements of the sector is rather small. Assuming an average 20% deposition efficiency for the world industry, the total consumption of silicon tetrachloride is estimated at 16,300 metric tons. This corresponds to a silicon content of 2,700 tons.

Germanium - Although the annual use of germanium in optical fibers is quite small, perhaps only about 200 tons per year, it accounts for around 35% of world consumption [2]. Lucent Technologies reports that it developed a technology to recover over 70% of waste germanium (most likely unreacted germanium tetrachloride) [2].

The fiber itself represents only a small part of the overall weight of an optical fiber cable. Thus, the resource use of the object used in practice, the optical fiber cable, is dominated not by the fiber content but by other materials, mainly plastic.

The service provided per materials inputs of optical fiber is much higher that the equivalent copper cables, and could thus be viewed as more environmentally friendly.

One study indicates that the weight of an optical fiber cable is 1.6% that of an equivalent set of copper cables [11]. Less weight likely translates into smaller environmental impacts associated with manufacture. Also, energy consumption per voice channel is .4% that of copper, thus there are environmental advantages in the use phase as well [11]. As telecommunications represent a substantial use of copper (about 7.5% of the US copper market in 1997 [12]), replacement of copper based systems with optical fiber could in principle lead to a reasonable reduction in copper consumption. In practice however, the use of copper in telecommunications has been increasing, at least in the US (about 14% between 1996 and 1997). This is perhaps reflective that copper remains the economical choice for low bandwidth links (such as from telephone switch box to household), thus an overall increase in telecommunication links still implies an increase in copper use.

Section III: Results of Systems Analysis and Knowledge Survey

III.1 Systems analysis of the production chain

As mentioned in the section I.2, three types of systems analysis of the production chain are undertaken. Section III.1.1 deals with quantitative analysis of material and economic scale/flows, as well as projections of the future situation for the silicon production chain. Section III.1.2 is concerned with geographical trends in production patterns as well as in characterizing environmental impacts across the chain. Section II.1.3 contains a brief discussion on how "indirect" sector connections can affect what process technology dominates production.

III.1.1 Quantitative analysis of materials and economic flows

This section is concerned with quantitative systems analysis of the material and economic flows associated with the global production chain for silicon. The underlying idea is that of an analytical tool (with supporting databases) with which to track fundamental patterns and shifts in production systems in order to inform industrial development policy. As a given industry is highly dependent on conditions up and downstream from that sector, there is clearly a role for systems considerations at the policy level. However, while industrial economic intelligence at the sector level is fairly well developed, there is a distinct lack of explicit knowledge at the systems level. Also, there is little integration of economic, technological, and environmental intelligence. Systems analysis also has a role in environmental considerations. Clarification of the scope of environmental issues associated with different stages of production is relevant to prioritization of attention. The current study is rather exploratory in nature, the main goal is to progress in the characterization of status and evolution of a production chain. It is hoped that further development of methodologies and supporting databases can lead to a powerful tool to support policy formulation.

The current focus is the economic and material characterization of sectors and flows between sectors in the production chain. The following quantities were estimated: level of production in material and economic terms, prices, process energy, and sector growth rates. In addition, future material demands and economic scale were estimated based on economic trends and sector interdependencies assuming fixed production technologies. The results are described in detail herewith, but to qualitatively summarize some main points from the analysis:

i) Though the knowledge economy is often characterized as "weightless", the material scale associated with semiconductor production is non-trivial. The energy and chemicals are consumed just in the fabrication step is the material equivalent of thousands of times the weight of the microchip itself.

ii) High-tech sectors such as semiconductors, optical fibers, and solar cells and those that directly support them show considerably higher growth than extractive and primary commodities. Extractive sectors of coal and silica display even a slight decline over the last decade. This correlates with the observed general tendency towards increased importance for knowledge/technology intensive aspects of the world economy.

iii) Due to relatively rapid growth, high tech sectors could well demand a substantial share of the future production of basic commodities. For example, silicon destined for semiconductors and optical fiber may represent 28% of the demand for silicon metal in 2020, as opposed to 6% in 1998.

iv) With 1998 coal production at 4.5 billion metric tons, coal extraction substantially surpasses all other sectors in terms of material scale. This illustrates the "material" side of energy; the indirect material flows of fossil fuels to supply process energy are often of similar or higher order than the direct material demands of a sector. The considerable energy expended in the flow processes themselves (transport of fossil fuels, losses in transmission) represent a major inefficiency of the current energy supply system.

Methodology

The methodological tool used is described in the field of Industrial Ecology as *material flows analysis*. Materials flows analysis involves the quantitative estimation of materials, energy, and/or capital flows between units in the system of interest. Various systems can be considered, such as small regions, nations, or in this case, a global production chain. Naturally, data availability is a substantial obstacle in analyzing global industrial sectors. In some cases, primary data (such as global production of solar cells) is available but many gaps exist (such as global production of trichlorosilane). The strategy to address missing data points is based on using process input/output tables. Assuming given process input/output data represents average global practice, knowledge of one input or output generates estimates for world consumption or emission of other substances. Naturally, the assumption that a set of local process data reasonable represents global practice cannot be well justified. However, it must be emphasized that the intention here is to identify general trends, not to test numerically precise theories. For such purposes uncertainties within a few tens of percents should be sufficient.

III.1.1.1 Materials

Figure III.1 (page 114) displays estimated 1998 world material flows in the silicon production chain. The numbers appearing inside the square boxes denote world production of that commodity, the numbers appearing near arrows represent the estimated flow of the material between sectors. Units to represent physical flow vary somewhat according to the commodity, the reader is referred to the glossary to check definitions of units. The amounts of silicon metal consumed by the world aluminum and silicone industries are displayed as a reminder of the highly branched nature of flows between sectors. There are of course many more materials flowing into and out of each sector, here the focus is on silicon related materials. Estimations of world sector emissions of environmentally relevant substances can be found in some of the sector profiles (section II).

To make a few observations regarding the materials scale/flows in the production chain: Coal extraction clearly stands out by far as the largest mass of production. Although some commodities such as solar cells are not represented in mass units in the figure, conversion does not change the situation. The level of production of silicon metal is modest among metals, for sake of comparison note that the world production of aluminum is around 20 million tons per annum. The high tech industries of semiconductors, solar cells, and optical fibers do not represent a huge portion of silicon demand, only about 55,700 tons or 5.8% of total silicon production in 1998. Though world demand for polysilicon in the production of semiconductors is only 20,000 tons, it is important to note that the main materials flow into the semiconductor sector is associated with chemicals, water and energy. For instance, the annual chemical consumption of the semiconductor industry is probably in the range of 500,000-5,000,000 tons.

The determination of numerical values shown in Figure III.1 is discussed in this section. Global production data came from governmental agencies or consulting firms, the details of which appear in each sector profile respectively. Data on materials flows between global sectors is very scarce, thus these figures were generally calculated using process input/output data. Materials flows into the metallic silicon were estimated taking the world production of 958,000 tons as fixed and determining required material inputs from the input/output data in section II.4.3. The total input of 16,300 tons of silicon tetrachloride to the optical fiber industry was calculated in a similar way. The figure of 2,400 tons of waste silicon supplying the solar cell industry is from reference [1], calculating what this flow should be according to process input/output data for solar cell production yields a demand of 1,300 tons. Provisionally, the higher figure is used. The semiconductor industry is the only consumer of silicon wafers, thus that flow is simply the world production of wafers. The situation is similar for polysilicon. The total figure of 55,700 tons of silicon metal consumed to produce chlorosilanes does *not* represent total world production of chlorosilanes, rather only the portion used in semiconductor devices, solar cells, and optical fiber.

III.1.1.2 Economic flows

Figure III.2 (page 114) shows estimated economic flows in the production chain. Similar to the materials chart, the figure inside the boxes represents the value of total world production and figures next to arrows indicate inter-sector flows. The number appearing below in parentheses represents a typical price of the commodity. Monetary value of world production is reported from production figures of consulting companies and government agencies, though in some cases, the figure was calculated using average prices of the commodity. The inter-sector flows were calculated by multiplying material amount by commodity price.

Coal extraction and semiconductor manufacture stand out as by far the largest sectors economically. It is clear that the solar cell industry, for example, is quite fledgling in comparison. The silicon wafer sector presents an interesting case, considering that it is geared to produce a single specialized ingredient for a single "sector", at $5.6 billion its economic scale is tremendous.

Economic scale has many implications for the sustainability of a sector. For example, the total financial "muscle" of a sector is related to the collective capital available for environmental R&D. Also, the extent of "satellite" activities of a sector is tied to its economic scale: there are generally more consulting companies, sector-level organizations, and academic activities associated with larger industrial sectors.

It is interesting to track the value-added along the processing chain by comparing the prices of different commercial forms of silicon. Silicon metal, trichlorosilane, polysilicon, and silicon wafers sell for $1.70, $8.40, $50, and $1500 per kilogram of silicon content respectively. The dramatic differences in price reflect the increasing value-added associated with more specialized forms of materials.

A note on uncertainties: the economic scales of many sectors (namely charcoal, coal, quartz, silicon metal, and polysilicon) were calculated using average prices. In the case of coal, quartz, silicon metal and polysilicon, relatively complete price data was available, thus these estimates are probably reasonably accurate. However, for the cases of charcoal and chlorosilane, price data was quite sketchy.

III.1.1.3 Energy

Estimated process energy consumption for each global sector is mapped out in Figure III.3 (page 115). The figure appearing near arrows represents the process energy embodied in the production of the amount of material flowing between sectors. In the case of coal and quartz sectors, this energy includes both electricity and consumed fossil fuels. In all other sectors, the number represents only electrical energy, which is by far the main contributor for those processes. Obviously, full information on respective electricity and fossil fuel consumption would have been preferable, but this was limited by data availability.

Energy intensity

In terms of total use, coal extraction and semiconductor manufacture stand out as the main sectors. To gain a sense of the energy intensity of a sector, energy consumption was normalized by the overall economic output. The results appear in Table III.1 below.

Table III.1: Energy intensity according to sector (energy use/production value)

Sector	**Energy used per production value (kWh/$)**
Silicon metal	10.7
Coal Mining	6.5
Polysilicon	5.0
Quartz extraction	1.6
Silicon Wafers	.95
Semiconductor	.27
Solar cells	.12

Such figures provide a crude indicator of the importance of energy costs in the respective sectors, which has some relation to the economic potential of implementing energy efficiency initiatives. Also, for energy intensive sectors such as silicon metal, local electricity costs become a critical factor in the geographical distribution of production. For instance, the lack of Japanese silicon production is apparently due to high domestic energy prices in Japan.

Life cycle energy use

Table III.2 follows electrical energy used in processing silicon in different stages as well as in the production of semiconductor devices. The interpretation of this energy as being “for” semiconductors is complicated by the generation of co-products of silicon tetrachloride for optical fiber and other applications and waste polysilicon for use in solar cells. Subtleties of allocation aside, the figures in Table III.2 present an interesting picture: energy use increases significantly as silicon is transformed to more sophisticated forms. Considering the decreasing entropy associated with purer, more organized forms of matter, this result is not too surprising. This leads to the broader question of whether stricter requirements on materials and chemicals in general leads to larger energy consumption in order to bring “dirty” materials to the desired form. This is an important issue to clarify for the “high-tech” economy of the future.

Table III.2: Energy use along the silicon device production chain

Process stage	**Process Energy (billion kWh)**
Silicon metal	.5
Polysilicon	5
Silicon Wafers	6
Semiconductor Device	34

It should be mentioned that this analysis only follows the silicon component of inputs into semiconductor production. It was noted several times already that the material requirements of semiconductor processes is dominated by chemical inputs (and water). The amount of energy expended in the production of these input chemicals was not addressed in any study found.

Indirect material flows associated with energy

It is illuminating to examine the indirect flows of fossil fuels associated with supplying energy to processes. For instance, consider the semiconductor sector, which has world energy consumption estimated at 34 billion kWh. The world average mix of electricity generation sources is 38.4% coal, 18.4% hydro, 17.7% nuclear, 14.8% gas, 9.3% oil, and 1.4% other sources [2]. Considering only fossil fuel use and assuming an average 33% conversion efficiency of fossil fuels to electricity, it can be estimated that 8.5 million tons of coal, 1.8 million tons of natural gas, and 1.6 million tons of oil were used to produce 34 billion kWh of electricity. Considering that total silicon and chemical use is likely a few million tons, the total material use of the semiconductor sector is dominated by fossil fuels used to supply energy. This illustrates the general issue that the indirect flow of materials to supply materials and goods is often on the order of magnitude or even larger than the material flow itself. Although in general this is hardly a new observation in the field of energy analysis, it is worth mentioning in this specific context.

III.1.1.4 Growth trends

Growth trends in production for the sectors and flows between sectors are shown in Figure III.4 (page 114). The figures are for average yearly growth over the 10-year interval 1988-1998. For the most part, growth is represented in *physical* terms, e.g. tons of metal, Wp, or meters of fiber, not monetary amount, the only exception being the case of semiconductors. It was decided to measure growth for semiconductors in economic terms because the only convenient physical unit (number of units produced) is not very meaningful. There is some correlation between physical and economic growth, but for sectors such as semiconductors, optical fibers, and solar cells, rapid price declines decouples these to a large degree.

Overall, the high-tech sectors and those supplying specialized materials for those sectors had much higher growth than extractive and primary commodities. Interestingly, coal and quartz extraction levels have apparently decreased slightly over the last decade. One might expect that primary commodity production should grow in tandem with world GNP growth, but this is apparently not the case for coal, quartz or silicon. This may reflect a trend towards dematerialization of the world economy [3], though naturally one cannot draw definite conclusions from only three commodities.

The methodology behind the growth rate figures will be discussed in more detail. It is non-trivial to choose a useful figure to represent growth: yearly growth shows large fluctuations, yet extremely long time averages may represent production and consumption patterns that have long since changed. To illustrate the former fluctuations, note that the semiconductor industry grew 41% from 1994-1995, but average growth rate from 1988-1998 was only 10% per year, largely due to the industry slump from 95-98. To balance these two factors, one decade was chosen as the representative unit of time to average over growth, though this choice is admittedly arbitrary. Since yearly growth figures are more customary, average yearly growth was calculated from decade growth according to the formula

$$\text{Yearly growth} = (1+\text{Decade growth})^{.1} - 1.$$

In general the interval used was 1988-1998, though this was shifted 1-2 years for some sectors due to data availability. Growth in flows was determined from input/output data.

III.1.1.5 The production chain in 2020

It is interesting to attempt to forecast future material and economic flows in the production chain, especially given the contrasting growth rates in the high-tech sectors versus extractive ones. Prediction is always a risky venture, detailed short-term analyses of a particular sector frequently fail [4]. The approach taken here is to use aggregate times scales, which average out yearly fluctuations to reveal long-term patterns. This phenomenon is often observed and analyzed in the stock market. A "business/technology as usual" scenario will be used, where past growth is taken as an indicator of future behavior over aggregate time scales. Specifically, the 1988-1998 decade growth rates are assumed to remain unchanged for the next two decades and technology is assumed to be fixed, i.e. input/output tables do not change over time. The scenario could be much improved through incorporating the rate of past technological change as well as economic growth. However, there is not sufficient time dependent input/output data to permit such an approach, thus technology is assumed to be fixed.

Using the above scenario, materials flows for the production chain in 2020 were projected, the results are shown in Figure III.5 (page 115). The formula used in most cases was

$$\text{Production}_{2020} = \text{Production}_{1998}\,(1+\text{average yearly growth})^{22}.$$

Not unexpectedly, this formula becomes particularly inaccurate for the silicon metal sector because of the radically different growth rates of the different silicon markets (1.4% for Al alloys vs. 13% for semiconductors and optical fiber). Basically, projections based on 3% average growth diverge from those breaking down the different sub-markets because of the nonlinearity of exponential growth. Thus, silicon growth was determined by summing growth of the main sub-markets. The growth in supply flows to the silicon sector were calculated to meet the needs of silicon production input table.

To a certain extent economic scale will increase with the physical, however the solar cell and optical fiber industries in particular will probably continue to experience price reductions, which reduce the factor by which economic scale increases. Projections of future economic scale were not carried out due to limitations in available data.

It terms of future material flows, extractive and primary commodity industries will be increasingly geared to supplying demand for high-tech applications. For example, semiconductor, solar cell, and optical fiber applications would represent 28% of silicon metal demand with silicones and other chemical applications at 44%. Thus, the projections suggest is that the share of materials used for high tech products will substantially increase and reach a scale comparable or exceeding traditional heavy industries. Considering the similarly high growth for related industries such as computers, communication systems, and software, it seems very possible that these high-tech sectors will play a dominant role in the future economy.

According to the fixed technology scenario, demand of silicon for solar cells would reach 23% of the total world production of polysilicon as opposed to 10% in 1998.

While a substantial portion of this could still be satisfied by waste silicon from wafer manufacture, additional sources may be required. This would lead to establishment of a distinct, though small, industry producing solar grade silicon for the solar cell industry. However, there is a strong possibility that thin film solar cells will come to represent a larger share of production, which would substantially change the material requirements. Amorphous thin film cells require far less silicon than wafer based and other cell types such as Cadmium Telluride use no silicon at all.

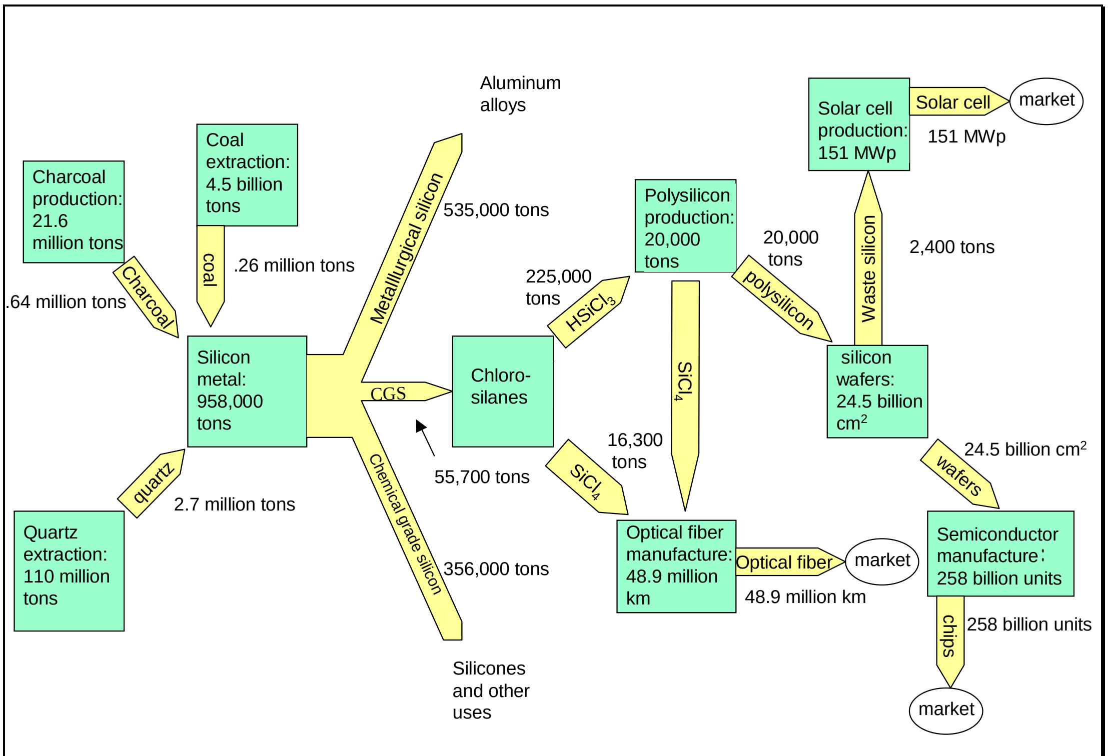


Figure III.1: 1998 World Production Levels and Material Flows

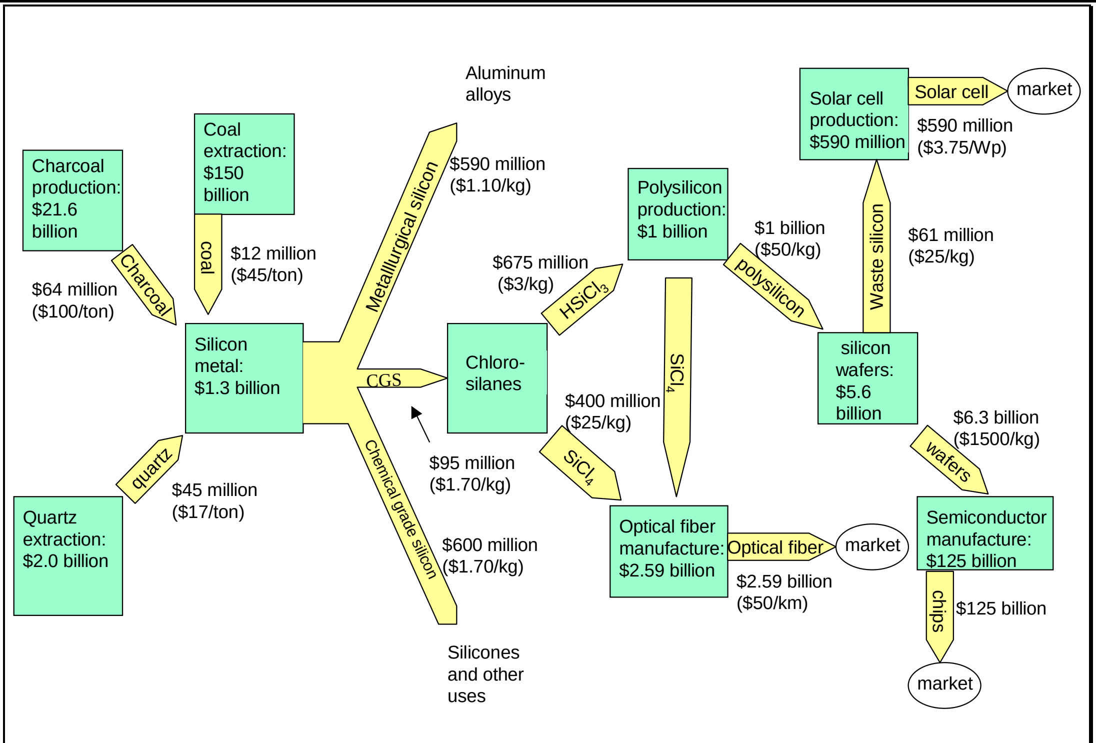


Figure III.2: 1998 World Production Values and Economic Flows

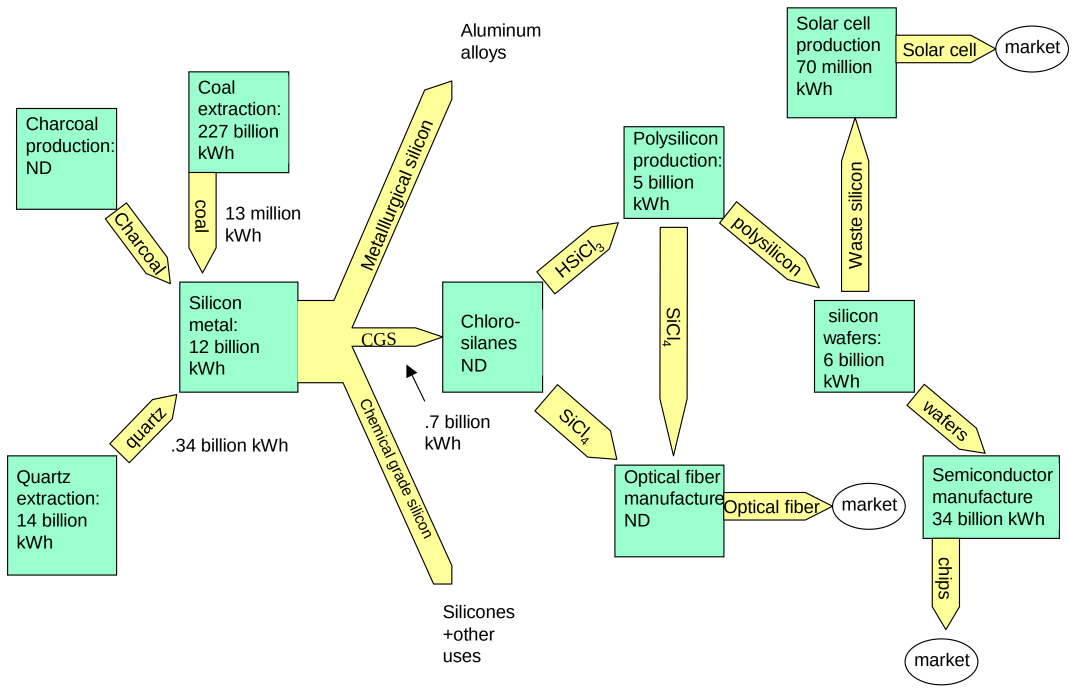


Figure III.3: 1998 Estimated World Energy Consumption by Sector

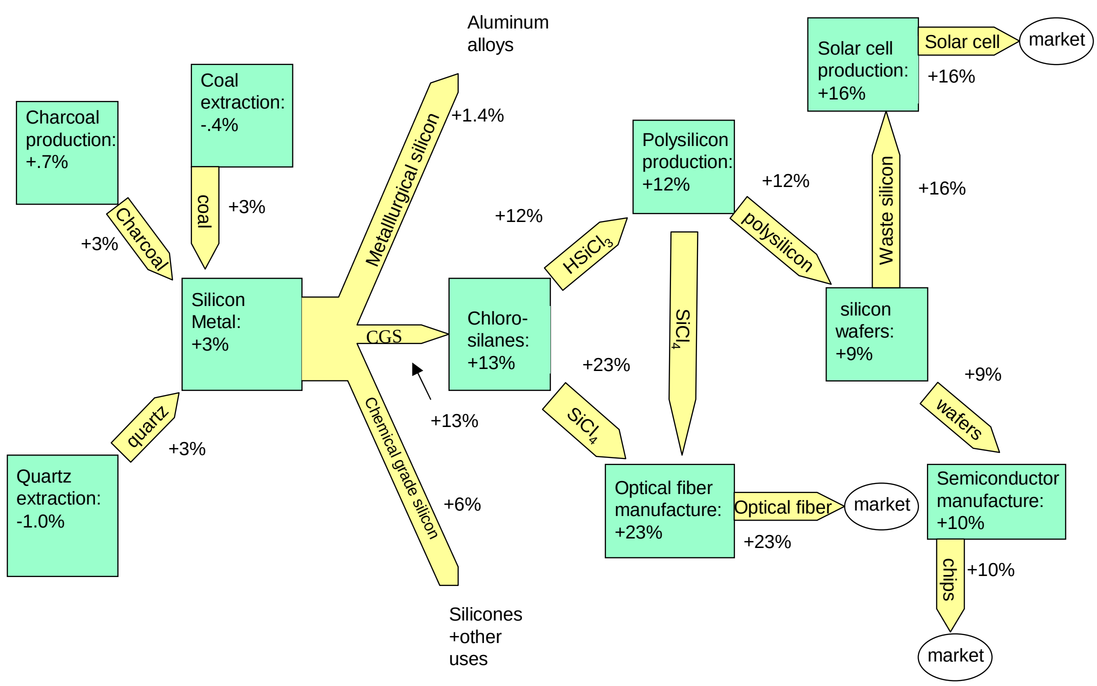


Figure III.4: Average Yearly Sectoral Growth (over period1988-1998)

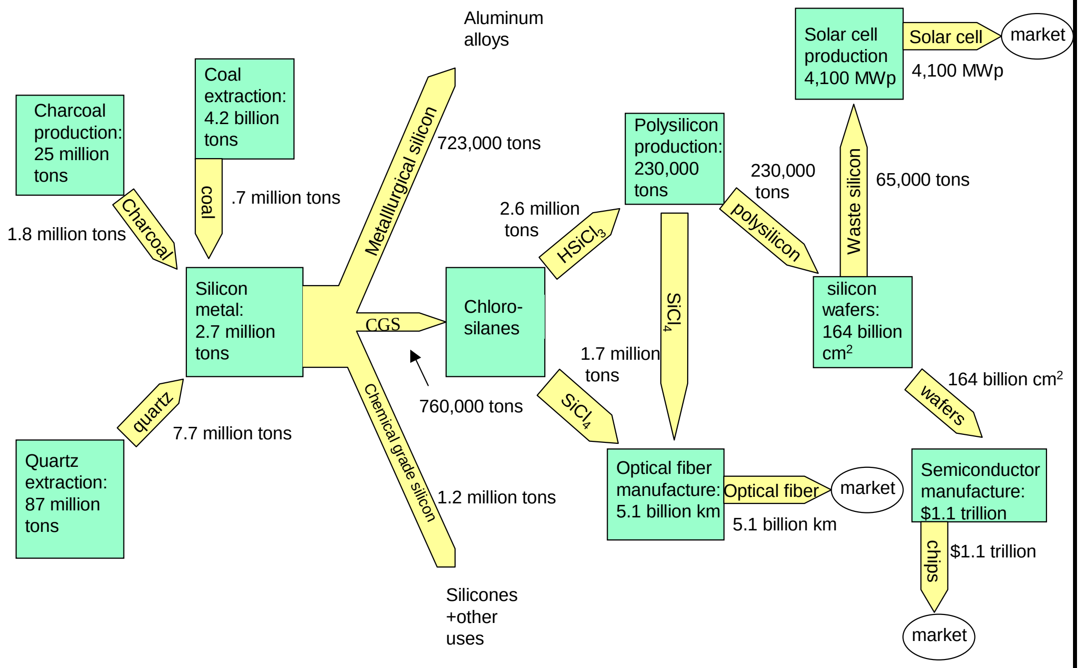


Figure III.5: World Production/Materials Flow Projections for 2020

III.1.2 Roles of developed and developing countries

This section addresses the evolving roles of developing and developed countries in industrial activities through analysis of the geographical patterns of production in the silicon production chain. The importance of the North/South dynamic is evident, it could even be considered as a key driver of the future of the global production system. As many less developed countries gain industrial capacity, the relatively low cost of many factors of production favors a major shift of manufacturing activities to Southern nations. This phenomenon has been analyzed at the sector level from various perspectives (see [5] and [6] and those referenced therein for examples). The emphasis here is on identifying major trends and driving factors for the overall global production chain.

The North/South issue is also relevant from an environmental perspective. One set of questions is related to the geographical distribution of production along different stages of production. A common perception is that developing countries are more involved in extraction and primary processing stages while the developed world manufactures products from imported materials that are exported to the developing world. To investigate this issue, the geographic distribution of environmentally significant stages is analyzed for the silicon production chain. Also, within a given sector, the issue of question of the relative environmental impact of process implementation in developed and developing countries is considered. Stricter environmental regulations and established budgets for enforcement institutions favor cleaner implementation in developed nations. Analysis is limited, however, due to a dearth of information on process implementation thus the discussion will be incomplete.

Economics

The status and trends of geographic patterns of production, as well as international trade, will be briefly reviewed sector-by-sector. Also, major factors determining geographical patterns such as resource endowments, factor prices, and technological level/rate of change are suggested. Naturally, there are many factors associated with appropriate economic conditions for a given industry, here the situation will be simplified for the sake of clarity. The sectors are grouped into extractive, primary commodities, secondary commodities, and high-tech sectors, and there are many common factors. The distinction between primary and secondary commodities can be hard to draw, here primary commodities are considered as materials made from relatively unprocessed inputs, yielding a relatively general material used in many industries. Secondary commodities are chemicals and more advanced material forms required for specific applications.

Extractive sectors

Quartz/silica is essentially a local commodity due to its abundance and low price, thus local demand is a key driver of the distribution of production. Extraction levels of developed nations are higher, likely due to the higher demand of local industries. There has been little shift in production patterns over the last decade. Differences between factor prices or endowments between North and South are not significant in determining the distribution of production.

Coal is an international commodity and is extracted substantially in both the developed and developing world, though overall, developing world extraction has been increasing with a decline in developed nations production. European production in particular has decreased, with demand being met through imports. Resource endowments are likely a dominant factor in the geographical distribution of production. Mechanization, though a costly investment, is effective at offsetting labor costs.

Primary processing sectors

Charcoal is mainly produced and locally consumed in developing countries. Compared to many other industries, the economics of charcoal production does not easily improve under mechanization or more advanced technology, thus process implementation in practice remains labor intensive and technologically simple. Being a local commodity, there is little North/South dynamic involved in the geographical pattern of production.

Silicon metal is an international commodity with developed and developed nations' products competing on international markets. Production of developed nations has grown modestly over the last decade, though the main developed world producers, Brazil and China, have grown much more rapidly. Low factor prices give an edge to developing nations, which has been partially offset by technology (and related product quality) in developed nations.

Secondary processing (chemicals/advanced materials)

Although there is little data on chlorosilane production, by and large it is probably locally consumed due to costs and difficulties associated with safe transport. Production is mainly under firms of developed nations.

Polysilicon is an international commodity, though mainly traded between developed nations and East Asia, following the demand from wafer producers. The bulk of production is under a relatively small number of US, Japanese, and European firms, probably due to the large scale and high technology required. This production is mainly domestically located, and this pattern will likely continue. The process is very technologically challenging and though high-energy costs favor a shift to counties with cheap electricity, this factor is relatively expensive in East Asia.

Silicon wafers are heavily traded internationally, mainly between developed nations and East Asia as they are the primary source of demand. Production is mainly overseen by developed world multinationals, with an increasing number of subsidiaries being opened in East Asia to serve local markets.

High-tech products

Semiconductors are very much an international commodity, with intense competition between firms for price and performance. In the past semiconductors were only fabricated in developed nations, but production is Southeast Asia has taken off in the last decade. This is partly due to the opening of subsidiaries by multinationals (according to pressures to reduce production costs), and partly due to successes of domestic firms, especially in Taiwan and South Korea. The increased production in Southeast Asia is also pulling in production of associated commodities such as wafers. Most of the investments into future fabrication facilities are going to East Asia, thus the trend is expected to continue for the time being. Some factors favoring the shift to East Asia are the labor intensity of certain phases of production and high facility costs.

Solar cells are an international commodity, with much of the demand arising from developing nations, where solar power becomes more economical due to the lesser extent of electrical grids that distribute centrally generated power. Production is mainly in developed nations, though Indian production is becoming substantial in part due to the opening of subsidiaries of BP solar. Drivers for this geographical pattern are perhaps the dominance of technological experience and innovation as factors of production and the relative small global scale of the industry.

Due to the global expansion of communication networks and free trade agreements, optical fibers are increasingly an international commodity, and much of the trade flow is from developed to developing nations. Production is almost entirely dominated by developed nations, though fiber is increasingly being drawn from imported performs in developing countries. Strict process control, rapid technological change, and a relatively small share of labor costs in production are factors favoring production remaining in developed countries

The Production chain

Synthesizing the above results to describe trends in the overall production chain, developing world production could be described as "nibbling" in at either end of the chain, with increased production in extraction, primary commodity, and high-tech sectors. Developed nations continue to dominate the production of advanced materials to supply high-tech industries. The origins of shifts in production are quite different according to the type of sector. In extraction, endowment of resources is not unexpectedly a major factor though labor and other factor prices also play a role. Mechanization, however, is an effective offset for labor for some sectors, for example coal extraction in the US and Australia remains competitive. For high-tech, the shift may be primary driven by lower factor prices in developing countries, especially labor, as later assembly stages are often labor intensive. It should be noted that a major shift in the assembly of electronic devices to East Asia preceded semiconductor fabrication. Also, wafer production and fabrication seems to be following in after microchip assembly. This strongly suggesting an inter-sector interaction in which a given industry has the effect of "pulling in" sectors earlier in the production chain.

Environment

One often expects that extraction and primary processing stages are associated with larger environmental burdens, but the silicon production chain is perhaps something of an exception. Silica/quartz is probably the cleanest of all extractive commodities, as overburden levels are very small and the only process chemical used in large quantities is water. The extraction and use of coal, of course, is of course a matter of concern both in terms of impacts on humans and ecosystems. The manufacture of semiconductor devices stands out for its large consumption of chemicals and water. It is important to emphasize that even if the semiconductor industry itself practices very strict processing of chemical wastes, there are still many possible impacts involved with upstream production of the required input chemicals. Taking the above into consideration, there does not seem to be any obvious correlation between the environmental impacts of a production stage and its geographic distribution. As a caveat however, it should be noted that it is possible that recent shifts in production of semiconductors to East Asia are partially driven by environmental considerations. There is little data to confirm or deny this hypothesis.

Within a given sector, there was in general very little information available on relative practices in developed and developed countries. The exception was the coal industry for which it is clear that low-tech extraction as carried out in China and perhaps other developing nations continues to represent a serious worker-health issue.

III.1.3 Inter-sector technology/knowledge connections

The systems analysis section will conclude with a brief discussion of how inter-sector connections can affect what technology dominates production. This issue is particularly relevant for R&D policy for subsidies to stimulate technological development. Decision-makers are often faced with the problem how to allocate research funds among a variety of technologies. It is obviously desirable, though difficult, to pick the winning technologies to the extent possible.

For photovoltaic solar cells, thin film cells have long been expected to become cheaper than their wafer based counterparts. The reason for this expectation is based on a comparison of characteristics of the two technologies: thin film cells require less materials and can be manufactured as a continuous process. However, wafer based cells continue to be more inexpensive per unit of performance. The question is why? One possible explanation is the connection between the wafer-based technology and the semiconductor industry [7]. The semiconductor sector is economically two orders of magnitude larger than the solar cell industry and thus the scale of the semiconductor equipment manufacturing and the investments in R&D are similarly larger. The wafer based solar cell industry benefits from the connection in two ways: lower equipment costs due to larger economies of scale and in gaining access to knowledge from the semiconductor industry with little investment.

What type of solar cell will dominate the industry in the future is not known. The salient point in the above example the success of a technology can be closely related to its knowledge/infrastructure connections to a larger sector. This may in fact be a general phenomenon with implications on how to approach technology forecasting. Thus, beyond comparing the characteristics of technologies from a purely engineering perspective, it is also important to consider the larger context of how each technology is applied in other established economic sectors.

III.2 The Sector-level knowledge system

This section is intended to address the fundamental issues of whether there sufficient sector-level information available to inform analysis and policy for sustainable development and whether this information organized in an appropriate form. The results of the survey of publicly available information and recommendations for organizing the sector-level knowledge system are discussed in III.2.1 and III.2.2 respectively. The word "knowledge system" is being used to denote the body of publicly available information and data regarding economics, technology, and environmental aspects of industrial sectors. Its relevance to sustainable development was discussed in section I.3.

III.2.1 Survey of available sector-level knowledge

Here the survey results will be summarized. Available knowledge was naturally highly dependent on the type of information and sector concerned. The most glaring lapses in information were in the field of environment. For some sectors, even crude quantitative estimations of emissions were not available. For those sectors for which information was available, data was generally incomplete and/or contradictory with other sources. Regarding the connection between quantitative emissions with environmental impacts (such as acid rain, water quality, etc.), very little information was readily available for any of the sectors considered.

The situation for economics-related information was much better overall. There are many reports from government Census Bureaus, consulting firms, and sector level industry organizations with sector-level economic data. Information on sector activities in developing countries, however, was often difficult to come by. The data may exist through direct personal inquiries to government agencies or firms in the country concerned, but was not readily available through standard sources of libraries and the Internet. Still, for industrial sectors not large enough to merit "big-digit" classification codes, such as chlorosilanes, production data was quite scarce.

Basic technological knowledge was accessible for all the sectors considered, largely through the body of engineering literature. More detailed information about how production is implemented and what processes are implemented where was far scarcer. In particular, in some cases descriptions of production processes were only available from developed countries. In general, little information was available on implementation in developing countries.

Recommendations

Based on the survey, a set of recommendations for the improvement of the sector-level knowledge system is made. These are summarized as:

- Sector-level industry organizations (such as the Semiconductor Industry Association) and governmental environmental agencies have excellent potential to play a larger role in the collection, aggregation and diffusion of sector-level environmental information.
- Obviously the rise of IT has played a pivotal role in making sector-level knowledge more available, yet there remains a large number of governmental, industrial, and academic organizations whose documents remain off-line. The improvement of this situation is a high priority for organizational policies.
- The knowledge base of academia in particular, remains largely fragmented in printed journals and books. It is absolutely crucial that this knowledge be re-organized into common computerized databases. Achieving this the journal industry towards IT, though in progress, needs to be stimulated as much as possible.
- There is very little readily available sector-level information from developing countries. This is probably due to the fact that the "response systems" that deal with collecting, analyzing, and distributing such knowledge represent an investment beyond the means of many nations. It is important to study how developing nations may utilize the existing knowledge system to promote development.
- There is a great need for increased awareness of the role of sector-level knowledge. Based on such awareness, communities can form to enact the above and other goals to realize a useful knowledge system that supports sustainable development.

Detailed survey description

Methodology

Availability clarified

Before reviewing what types of information are available from what sources, it is appropriate to refine the use of the word availability. Availability is considered to have aspects: existence, dissemination, and cost. Existence refers to whether the information is available at all to civil sectors. Dissemination deals with how accessible the information is. Is it fully referenced in the Internet with a downloadable report or can it be found through standard databases available in libraries? Does one need personal contacts in relevant organizations to find the information? Extent of dissemination is a fundamental issue in determining what types of analyses can be done. As researchers learn early in their experience, the search for information relevant to a given topic represents a considerable investment of time. Due to the scarcity of resources, the amount of information that can be found in a fixed amount of time has a large effect on the quality of the result. For the case of a multi-issue treatment of a global sector, the time required is multiplied due to the lack of existing institutions and communities geared in this direction. The third aspect of availability is direct economic cost. Cost varies widely according to the source of information. The ideal case for those connected to the Internet is a freely downloadable report. Articles from academic journals can be copied for minimal cost for those with access to a library. There are also many reports and databases from consulting companies or other organizations sold for profit, these can easily run from hundreds to thousands of US dollars.

Boundaries of survey

Taking the previous discussion on availability as background, it is clear that it is impossible to do a completely exhaustive survey of available knowledge: this would take time and resources valued perhaps in the millions of dollars, if possible at all. Thus, boundaries were set on what range of sources would be checked. World Wide Web websites and databases in English and Japanese were quite thoroughly searched. Among Internet resources, the ProQuest and Northern Light databases proved immensely helpful as they catalog a huge amount of commercially available literature. Relevant books journals were found through various library and bookstore computer databases. And to the extent possible, relevant companies, organizations and individuals were contacted for advice and information. Not surprisingly, these contacts proved to extremely useful sources, perhaps reflecting the extent that much knowledge remains organized tacitly rather than in computerized databases.

There is no doubt that with far more time and funding, an international team of experts in the respective industrial sectors could have been gathered and a far more complete set of information obtained. However, that would defeat the point of the exercise, which was to see what level of information was available given a reasonable amount of resources. It is hoped that the main qualitative aspects regarding the information system could be identified given the survey’s boundaries.

Also, although the questions of data quality and verifiability are extremely important, serious consideration for the most part beyond the scope of this survey. However, some attempt was made to compare consistency when multiple data sources were available.

Results

In the following a more detailed picture of the sector level knowledge availability will be described. The discussion will mainly address what types of information were available from what source: government agency, private firm, or public organization. This is done to clarify the status of available and providing social actor with the goal of formulating workable improvements to the system. Also, the results may act as a practical guide for those researching sector information.

Government sources

Environment

In terms of environmental information, the main governmental sources found were national environmental agencies. For sector emissions, the programs that exist could be divided into two categories: emissions inventories and emissions factors. Emissions Inventories involve surveying firms or measuring emissions, more often the former. The Toxic Release Inventory (TRI) of the USEPA is an archetypal example of an emission inventory program [8], which tracks toxic substances, there is also an AIRS database for atmospheric emissions [9]. In TRI, surveys are sent out every few years for firms to report quantitative amounts of emissions among a list of around 300 substances. Firms are asked to report emissions if above a threshold of 11 metric tons of annual consumption. Though the program is considered as a useful start in tracking macro emissions trends, it was not intended to be a thorough inventory of wastes from a sector. As was seen from the semiconductor profile in section II, the total emissions from TRI are an order of magnitude below those indicated from input/output data. Indeed, other studies suggest that TRI may miss 90-95% of the national flow of a material [10]. The TRI could in principle be upgraded fairly easily to yield aggregate emissions per unit output by choosing a subset of the largest firms and including aggregated production data of that group of firms. The reader is referred to [10] for a critical discussion of TRI. Government agencies of a few other nations have adopted TRI type programs as well, the UK for example runs a Chemical Release Inventory (CRI).

Another category of environmental information from governmental agencies are emissions factors programs. These give estimations of emissions per unit of production for a given sector. The USEPA runs the AP-42 program, which addresses atmospheric emissions and also contains descriptions of manufacturing processes [11].

Many government agencies publish greenhouse gas emissions inventories, the methodology for which seems to be a combination of industry surveys and estimations per unit of production. In most cases the sector data is quite aggregate.

The availability of the above types of information depends on the government agency involved. The USEPA is the most progressive in terms of dissemination and cost, with nearly all reports freely downloadable from the Internet.

Economy

Generally most national governments have an agency or division responsible for collecting statistics on industrial activities in various sectors. For example, in the United States, the Census Bureau of the Department of Commerce has this role, and in Japan it is the Statistics division of the Ministry of International Trade and Industry. The basic data is time series on production, in monetary and/or physical units. Other data includes labor and capital costs, etc. The extent to which information is available freely over the Internet depends on the agency. The US Census is by far the most available, virtually all reports are downloadable free of charge via the Internet. For example, UK and Australia's governments charge a modest fee is charged for sector level production statistics. Generally quite dis-aggregated statistics are available, but even in the case of the US, production data on chlorosilanes and polysilicon were not available.

Technology

For the most part government resources regarding production methods were scarce, with some notable exceptions. The USEPA AP-42 program has an extensive set of process description for many industrial sectors. Also, government labs dedicated to researching particular technologies, such as solar cells, often had useful information.

Industry sources

Environment

There is very little useful data in terms of a firm reporting its own emissions or environmental impacts. Some companies produce annual environmental reports, which may provide useful insight into the environmental strategies pursued, but do not contain substantial information on environmental emissions or impacts. Indirectly, anonymous emissions data from industry turns up in academic work and private databases.

Consulting firms dealing with environmental issues, in particular firms specializing in Life Cycle Assessment, do sell databases containing information on estimated emissions from various sectors. These can be quite useful, but also expensive: databases with software run from the hundreds to tens of thousands of dollars. The reliability of such data is also unknown.

An6ther source of environmental information is sector level industry organizations such as the Electronics Industry Association and the World Coal Institute. While the focus of such organizations is mostly on economics issues, there is some degree of environmental information available. The Electronics Industry Association of Japan, for instance, runs a TRI type program (though more aggregate) for the Japanese semiconductor industry that reportedly covers 98% of domestic production [12].

Economics

There are many consulting companies that produce quite excellent reports covering a range of economic issues for a given sector. They would seem to be by far the best source for economic data regarding global sector activities. Often consulting firms specialize in a given sector or group of sectors, Roskill Information Services for instance produces series of reports on primary commodities, while Dataquest mainly deals with information technology related activities. Such reports are generally quite expensive, with prices ranging from the hundreds to thousands of dollars. The coverage of sectors is uneven, for instance no reports were found that dealt with the global chlorosilane or charcoal sectors. The sector coverage is no doubt highly dependent on the demand for information. There is probably insufficient demand to address sectors below a certain threshold of economic scale and/or producing a local commodity.

Sector level industry organizations are also good sources of data on global production, trade, and trends and information is often free or of minimal cost. Such organizations would only seem to be found for rather large industrial sectors. Optical fiber and chlorosilane producers are represented in organizations representing the encompassing telecommunications and chemical industries. However, these organizations did not publish reports dealing with the production of these sub-industries.

Technology

There is some information from firms regarding production technology. Often good sources are not the manufacturers themselves, rather the producers of manufacturing equipment. Much of this information is freely available over the Internet.

Civil sources

Environment

Academia, not unexpectedly, proved to be an extremely valuable source of environmental information. Researches in the fields of Industrial Ecology and Life Cycle Analysis in particular addressed environmental impacts at the sector level. Works containing process input/output data and descriptions of sector level environmental impacts were found for some, but not all of the concerned sectors. Still, information was quite incomplete, perhaps due to two major factors: availability of data and related incentive to study the sector level. Academia generally has no direct access to process data, thus emissions are estimated through a combination of accepting anonymous information from companies and utilizing process engineering knowledge to check and supplement such data. The driving incentive for academia is production of research, and lack of data at the sector inhibits the amount of research possible.

International organizations overall had not very helpful sources on sector-level environmental information, though there were exceptions. UNEP has an Industrial Pollution Management program that produces reports on the environmental issues related to about 13 industrial sectors, which includes one on the semiconductor industry [13]. This program is quite relevant and promising, but remains small in scope: relatively few sectors are covered and reports are not regularly updated.

Environmental NGO's, despite a strong environmental agenda, did not turn out to be a substantial source of sector level data. The focus of most NGO's is seemingly more issue, rather than sector oriented. There are some exceptions to this trends however, as evidenced by the Silicon Valley Toxics Coalition, and NGO devoted especially to environmental issues related to semiconductor production.

Economics

International organizations were a good source of data in some cases. For instance, the UN Food and Agriculture Organization runs a very useful database with time series on international production and trade of agricultural and wood products. Data access is free of charge and available over the Internet. The United Nations Statistics Office produces a number of databases and reports on international trade.

Technology

The body of academic literature is perhaps the most useful resource on technology, perhaps due to the relatively large size of engineering departments and their practical need to train new engineers. Though useful, much of the literature is at a somewhat abstract level regarding how in principle a given process would be carried out. The practicalities of implementation, akin to a recipe in cooking, rarely appears, perhaps due to the economic value of this knowledge.

Observations/recommendations

The desirability of an enhanced sector-level knowledge system was briefly discussed in section I.3. The larger issue of how different sectors of society can/should participate in the overall response system is quite complex and will not be taken up in this work. It will be assumed that a maximal sector-level knowledge system is beneficial for society and this section will be devoted to discussing how that system could be improved in practice.

Application of Information Technology

The appropriate use of IT is exceedingly important in improving the sector-level knowledge system. Obviously much progress has been made and the range and quality of information available over the Internet continues to improve. Before making suggestions for improvements, it is useful to recount some success stories. The US Government has displayed a strong commitment to making information available the Internet, which has effectively been implemented by many of its sub-organizations. For example, the USEPA, Census Bureau, and Occupational Health and Safety Administration have put a large fraction of their databases and publications on the Internet for general use. In the private sector, information services like Proquest have made contracts with a large variety of publications such that their contents are searchable and readable online. Northern Light has agreements with industry intelligence firms to allow keyword searchability and the purchase of only desired pages of an expensive report.

To point out directions for future improvements, it must be noted that national governments and international organizations have not in general gone nearly as far as the US government has at making substantial amounts of data and reports available on-line. In some cases this is to be expected as the sale of the reports represents a substantial source of income, such as for the OECD. However, another common situation is that reports are sold for $10-30 (for instance production data from the Australian national government and sector reports from UNEP). Given the rather low volume of sales of such specialized documents, it seems unlikely that their sale represents appreciable income, most likely the price mainly covers cost of printing and overhead from managing sales. The rational course is such cases seems simply to put the information on-line, for which dissemination costs are virtually free. Governments and international organizations needs to be strongly encouraged to put all possible information on-line.

Opening the Ivory Tower

Despite the success stories of some modern IT-based databases of journals, there is still much progress the publishing industry can make to facilitate a knowledge system. There are a number of areas of relevance, but with respect to sector-level knowledge perhaps the most crucial is that of academic journals. There is a vast set of academic literature that continues to grow, yet it largely remains subdivided into some thousands of printed journals. There has been reasonable progress in the creation of databases of journal abstracts, but the subject areas covered are limited and they still require finding and copying the article from the physical journal. For the multidisciplinary sector knowledge being discussed here, this is a large handicap. One positive direction for the future for the sector-level knowledge system is for journals to increasingly align themselves with database services such as Proquest.

Increased role for sector-level industry organizations and government agencies

The previous points focused on how existing information may be further organized and disseminated through changes in practice. Another important aspect is expansion of the range of existing information. For the environment in particular, it has been mentioned several times already that there are severe shortages of information on sector emissions and impacts. This is not simply an issue of finding the right reference; the data simply does not exist in any public venue. As discussed in section I.3, the economic relevance of sector-level knowledge represents a major barrier to its dissemination to civil sectors. Firms are naturally loath to divulge information that might damage competitiveness, thus care is required in how possibly sensitive information is gathered and disseminated. An important point is that for many purposes, sector level information is as or more desirable than firm level. As long as some organization can act to gather firm-level data in confidentiality and perform aggregation, no individual firm need suffer. Sector-level industry organizations (such as the Semiconductor Industry Association) and governmental environmental agencies are in the best position to act as in this intermediary role. Industry organizations have both the necessary specialized expertise and close ties with member firms to be very effective at this work. They are increasingly taking a role as a representative for the industry as a whole, including environmental issues. It thus seems quite appropriate that they can act as agents to have excellent potential to play a larger role in the diffusion of sector-level environmental information. Governmental agencies are another possible agent to act as an intermediary. USEPA has begun to take on such as role with the AIRS and TRI programs. However, as clear from the previous discussion, these programs require strengthening if they are to act as reasonably reliable reporting of industry emissions. Both sector-level industry organizations and government agencies need to be strongly encouraged to take on an increasing role as intermediary in dissemination of sector-level knowledge.

The awareness issue

How can the above and other actions to improve the sector-level knowledge system be implemented in practice? A key element is the formation of communities concerned with the issue, who will communicate their needs to the concerned organizations. The current status of communities oriented to sector-level issues and sustainability is probably not strong enough to be effective at this role. Individuals at the firm level are probably most familiar and interested in sector-level issues, yet firm affiliation creates certain constraints to act at the sector level. Communities active in sustainability, such as NGOs, international organizations, and academia, rarely focus on particular industrial sectors. Thus, it is important to raise awareness of various actors to the importance of the sector-level. Based on such awareness, communities can form to enact the above and other goals to realize a useful knowledge system that supports sustainable development.

III.2.2 Information systems for industrial activities

The previous section dealt with the existence and availability of sector-level knowledge. This section addresses the question of whether this knowledge is organized in an appropriate form. The main issue to be considered with respect to organization is the integration of different types of sector knowledge: economic, environmental, technological, and social. The debate on sustainable development embodies a general trend that societies are increasingly seeking to satisfy a multi-issue agenda, one that includes economic, environmental and social issues. In decision space regions where trade-offs exist, it is not possible to maximize all factors thus some compromise must be negotiated. If the decision-making process is to occur with a strong element of rationality, it is reasonable to assert that an information base that integrates the factors of concern is necessary. In the case of the sector-level knowledge system, it is clear from the survey that information remains extremely segregated into different areas. It is thus desirable to have an integrated information system in order to inform decision-making for sustainable development.

The integration of economic, environmental, and technological information is important for another reason as well: validation of data through consistency checks. Though not generally appreciated, the issue of the validity of data is very important. It is not usually possible to directly check a given set of industrial data such as production levels or process inputs/outputs. However, by cross checking different types of information against one another it is possible to gain some confidence regarding validity. For instance, process input/output data can be extrapolated to compare with production and material flow data.

If integrated information systems at the sector-level would be useful, as is being argued, why do they not currently exist? There are many factors involved, but the issue to be focused on here is the advent of Information Technology. IT (especially the Internet) radically improves the accessibility of information and also the means of organizing and analyzing it. As IT progresses, the cost in resources to develop and maintain an industrial information system declines rapidly. We may now or soon be at a point such that the societal response system can feasibly incorporate integrated information systems.

Sector profiles

To progress towards integration of sector-level information systems, the question of format is crucial. What information should be put together in what form? Obviously formats will vary according to the specific application in mind, but it is also important to consider the value of standardization. Naturally, the construction and maintenance of information systems requires considerable investments in resources. A standardization of format leads to a strong "economies of scale" effect that reduces substantially the overall effort to construct and maintain a system. The reason for this is the multiplicity of roles that sectors generally play in the production system. If one constructs a sector profile that includes data on how it connects to other sectors enables analysis of *all* production chains containing that sector. Or in other words, one only need construct a sector profile once, after which it can be applied to many situations.

The sector profiles developed in section II represent an attempt to explore appropriate formats for an integrated information system intended to be useful in a variety of analyses.

"GIS" for industrial systems

Another aspect of the organization of an industrial information system involves making an analogy with Geographical Information Systems (GIS). Looking at the series of figures III.1-5 describing the production chain, there is an obvious analogy between the approach taken and GIS. Although the underlying object (networked sectors) is functional as opposed to geographic in nature, there are some fundamental similarities. The core idea of a GIS is to organize different types of information related to a region into distinct layers. Analysis is undertaken by utilizing data layers relevant to the issues of concern. The same strategy for the organization of data may well prove useful in the analysis of industrial systems as well. Although here only a few layers were shown, in fact the sector profiles of Section II and many other types of data could be integrated to yield a computer-based information system for industrial production chains. Naturally, the organization of information into computerized databases greatly facilitates many types of analyses.

Glossary of terms

AIRS – Aerometric Information Retrieval System, an air pollution reporting system run by USEPA
Chlorosilane – a chemical compound containing chlorine and silicon.
EIAJ – Electronics Industry Association of Japan
Fab – term used in the semiconductor industry to refer to a wafer fabrication facility
J – Joule, SI measure of energy
KWh – kilowatt-hour, equal to 3.6 x 10^6 Joules
IT – Information Technology
MCC – Microelectronics and Computer Technology Corporation
MPU – micro processing unit, microprocessor
MT – metric ton, equals 1000 kg
MJ – megajoule, equal to 10^6 Joules
NGO – Non-Governmental Organization
OECD – Organization for Economic Cooperation and Development
Ppm – parts per million, by weight
PPb – parts per billion, by weight
Polysilicon – extremely pure polycrystalline silicon, used as a raw ingredient to make silicon wafers for semiconductors.
PV –photovoltaic, refers to the direct generation of electricity from light.
Quartz – broad class of mineral forms of silicon dioxide. Used here equivalently to silica
Semiconductor – a electrical device whose function derives from semiconductor properties of materials, includes microchips, diodes, and transistors.
Silica – broad class of silicon dioxide based materials.
Silicon metal – elemental silicon with purity in the 95-99% range
Silicon wafer – a thin, extremely pure disc of monocrystalline silicon used as a base in the fabrication of semiconductor devices.
Silicon tetrachloride – the chemical compound $SiCl_4$, one use of which is as a raw material in optical fiber production.
Solar cell – a photovoltaic device that generates electricity from sunlight
Tetrachlorosilane – the chemical compound $HSiCl_3$, a major application of which is as a main ingredient in the production of polysilicon.
TRI – Toxics Release Inventory, a program run by USEPA that reports industry emissions
UNEP – United Nations Environment Programme
USEPA – United States Environmental Protection Agency
W – Watt, SI measure of power
Wp – Measure of power output of solar cell, equal to output of cell when subject to "normal sunlight", 1000 Watts per square meter
µm – micrometer, equal to 10^{-6} meters

Bibliography

Please note that the bibliography is organized into twelve different divisions. Sections I and III have one division each, while Section II is divided into ten sections, one for each industrial sector.

Section I: Introduction

1. Morita, R. et. al. "Sustainable Development: Its Definitions and Goals", *Mita Gakkai Sasshi* (Mita Journal of Economics) Vol. 4(85), 1993
2. Pearce, D. et. al., *Blueprint for a Green Economy*, Earthscan Publications Ltd.(London), 1989
3. Frosch R., "Industrial Ecology: Minimizing the Impact of Industrial Waste", Physics Today, November 1994, pp. 63-68
4. Allenby B. and Graedel, T., *Industrial Ecology*, Prentice Hall (Eaglewood Cliffs, NJ), 1995
5. Allenby, B. and Richards, D. (eds.), *The Greening of Industrial Ecosystems*, National Academy Press (Washington), 1994
6. Ayres, R. and Simonis, U. (eds.), *Industrial Metabolism: Restructuring for Sustainable Development*, United Nations University Press (Tokyo), 1994
7. Curran, M.A. (ed.), *Environmental Life Cycle Assessment*, McGraw-Hill (New York), 1996
8. *Proceedings of the Third International Conference on EcoBalance*, The Society for Non-Traditional Technology (Tokyo), 1998
9. Ayres, R.U. et. Al, "Materials-Cycle Optimisation in the Production of Major Finished Materials – Chapter 10: Electronic Grade Silicon for Semiconductors", INSEAD Working Paper 95/10/EPS, 1995
10. Hajer, M., *The Politics of Environmental Discourse: Ecological Modernization and the Policy Process*, Oxford University Press (Oxford, UK), 1995
11. Grubb, M., *The Kyoto Protocol – A Guide and Assessment*, Earthscan (London), 1999
12. Inventory of U.S. Greenhouse Gas Emissions and Sinks, United States Environmental Protection Agency, document #EPA 236-R-99-003, 1999 (available over the Internet at www.epa.gov/oppeoee1/globalwarming/publications/emissions/us1999)
13. Ritchie, I., and Hayes, W., "*A Guide to the Implementation of the ISO 14,000 Series on Environmental Management*", Prentice Hall PTR (Upper Saddle River, NJ), 1998
14. Appleton, A., *Environmental Labelling Programmes: International Trade Law Implications*, Kluwer Law (London, UK), 1997
15. Mulholland, K. and. Dyer, J., *Pollution Prevention : Methodology, Technologies and Practices*, American Institute of Chemical Engineers, 1998
16. Mshgeni, M., and Pauli, G. (eds.), "Proceedings of the Second Annual UNU World Congress on Zero Emissions", UNU/IAS publication, ISBN 4-906686-01-X, 1996 (available over the Internet at www.ias.unu.edu/research_prog/unuzeri/dissemination.html)
17. Stahel, W., "The Utilization-Focused Service Economy: Resource Efficiency and Product-Life Extension", pp. 178-190 in Reference 5
18. "The Knowledge-based economy", Organization for Economic Co-operation and Development, OECD/GD(96) 102, 1996

19. Peiter, C., "Contributions of Quartz and New Materials to Reaching the Target of Zero Emissions", in *Proceedings of the First Workshop on QITS*, UNU/IAS publication, 1998 (available over the Internet at www.ias.unu.edu/research_proj/qits/reports.html)

Section II: Industrial Sector Profiles

II.1: Silica/Quartz

1. *The Economics of Quartz*, Roskill Information Services, London, 1992
2. *The Economics of Silicon*, Roskill Information Services, London, 1997
3. Bolen, W., USGS Mineral Industry Surveys on Silica, United States Geological Survey, 1993-1997 (available over the Internet at http://minerals.usgs.gov/minerals/pubs/commodity/silica)
4. Harben, P., *The Industrial Minerals Handybook*, Industrial Minerals Information, Ltd. (Surrey, UK), 1999
5. *Compilation of Air Pollutant Emission Factors (AP-42)*, Fifth Edition, USEPA, 1995 (available over the Internet at www.epa.gov/ttn/chief/ap42.html#chapter)
6. Mathieux, F., "O ciclo integrado de producao do quartzo e o desenvolvimento sustentavel", Ph.D. thesis, University of Campinas, Brazil (in Portuguese)
7. 1992 Census of Mineral Industries, Sand and Gravel, U.S. Department of Commerce, Bureau of the Census, Document #MIC-I-14B, 1992
8. Suzuki C., University of Campinas, personal communication
9. *Ambient Levels and Noncancer Health Effects of Inhaled Crystalline and Amorphous Silica: Health Issue Assessment***,** USEPA document #EPA/600/R-95/115, 1996
10. Kesler, S., *Mineral Resources, Economics, and the Environment*, Macmillan College Publishing Co., (New York), 1994

II.2: Charcoal

1. *The State of the World's Forests 1999*, Food and Agriculture Organization of the United Nations (FAO), 1999 (available over the Internet at www.fao.org/forestry/FO/SOFO/SOFO99/sofo99-e.stm)
2. Bhattarai, T., "Charcoal and its Socio-Economic Importance in Asia: Prospects for Promotion", RWEDP Conference Paper, 1998 (available over the Internet at www.rwedp.org/p_charcsocio.html)
3. "Industrial Charcoal Making", FAO Forestry Paper 63, 1985 (available over the Internet at www.fao.org/docrep/X5555E/X5555E00.htm)
4. "Simple Technologies for Charcoal Making", FAO Forestry Paper 41, 1987, available over the Internet at www.fao.org/docrep/x5328e/x5328e00.htm
5. Deglise X., and Magne, P., "Pyrolysis and Industrial Charcoal", in *Biomass*, John Wiley & Sons Ltd. (New York), 1987, pp. 221-235
6. FAO database: FAOSTAT, available over the Internet at http://apps.fao.org/
7. Antal, M. et al., "High-Yield Biomass Charcoal: Resources, Links, Constraints", Energy & Fuels, v. 10 (3), 652-658
8. Sampaio, R., personal communication
9. Smil, V., *Biomass Energies*, Plenum Press (New York), 1983, pp. 88

10. *Compilation of Air Pollutant Emission Factors (AP-42)*, Fifth Edition, section 10.7, USEPA, 1995 (available over the Internet at www.epa.gov/ttn/chief/ap42.html#chapter)
11. Smith, K. et. Al., "Greenhouse Gases from Small-scale Combustion Devices in Developing Countries: Phase III: Charcoal Kilns in Thailand", summary of Complete Report for USEPA, 1998, available over the Internet at www.energy.demon.nl/GHG/kilns.htm
12. Zandersons, J. et. Al., "New Environmentally Friendly Process for Charcoal Production", in *Proceedings of the First Workshop on QITS*, UNU/IAS publication, 1998 (available over the Internet at www.ias.unu.edu/research_proj/qits/reports.html)

II.3: Coal

1. Kesler, S., *Mineral Resources, Economics, and the Environment*, Macmillan College Publishing Co., (New York), 1994
2. Coal Week International, v. 20 (18), 1999, p.7
3. Howe-Grant, M. and Kroschwitz, J. (eds.), *Kirk-Othmer Encyclopedia of Chemical Technology* V. 6, John Wiley & Sons (New York), 1997, p. 432
4. *Coal – Power for Progress*, 3rd Edition, World Coal Institute, 1999 (available via the Internet at http://www.wci-coal.com/)
5. Howe-Grant, M. and Kroschwitz, J. (eds.), *Kirk-Othmer Encyclopedia of Chemical Technology* V. 21, John Wiley & Sons (New York), 1997, p. 1105
6. International Energy Annual, US Department of Energy, 1998 (available via the Internet at http://www.eia.doe.gov/emeu/international/coal.html)
7. Key World Energy Statistics, International Energy Agency, 1998 (available over the Internet at http://www.iea.org/stats/files/keystats/stats_98.htm)
8. *Compilation of Air Pollutant Emission Factors (AP-42)*, Fifth Edition, section 11.9: Western Surface Coal Mining, USEPA, 1995 (available over Internet at www.epa.gov/ttn/chief/ap42.html#chapter)
9. Reid, B., "1997 International Longwall Census – Part 1", Coal Age v. 102(9), 1997, pp. 28-38
10. *Compilation of Air Pollutant Emission Factors (AP-42)*, Fifth Edition, section 11.10: Coal Cleaning, USEPA, 1995 (available over the Internet at www.epa.gov/ttn/chief/ap42.html#chapter)
11. Laurila, M., "Coal prep in the next millenium", Coal Age, Sep. 1997, pp. 47-56
12. 1992 Census of Mineral Industries, Subject series on fuel and energy consumed, US Census Bureau, document MIC92-S-2, 1992
13. Stern, D.I., and R.K. Kaufmann, 1996, "Estimates of global anthropogenic methane emissions 1860-1993", Chemosphere v. 33, pp.159-76.
14. Robb, G. and Robinson, D.F., "Acid drainage from mines", The Geographical Journal, v. 161 (1), pp. 47-55, 1995
15. Dunn, S., "King Coal's Weakening", WorldWatch, September/October, 1999, pp. 10-19
16. Hood, M. and Sweet,W., "Energy Policy and Politics in China", IEEE Spectrum, November, 1999, pp. 34-38

II.4: Silicon metal

1. Howe-Grant, M. and Kroschwitz, J. (eds.), *Kirk-Othmer Encyclopedia of Chemical Technology* V. 21, John Wiley & Sons (New York), 1997
2. Mineral Industry Surveys, Silicon 1998 Annual Review, United States Geological Service, 1998 (available over the Internet at http://minerals.er.usgs.gov/minerals)
3. *The Economics of Silicon*, Roskill Information Services, London, 1997
4. Jackson, K.A. (ed.), *Materials Science and Technology: Volume 16 Processing of Semiconductors*, VCH Press (Weinheim), 1996
5. Phylipsen G.J.M. and Alsema, E.A., "Environmental life-cycle assessment of multicrystalline silicon solar cell modules", Report #95057 of Department of Science, Technology, and Society, Utrecht University, 1995 (available over the the Internet at http://www.chem.ruu.nl/nws/www/publica/95057.htm)
6. Yunping, H. and Zhichun, Y., "40 Year History of Metal Silicon Production in China", Proceedings of INFACON 8, 1998, pp. 99-103
7. Valenti, M., "More competitive silicon smelting", Mechanical Engineering, v. 118(2), 1996, pp. 88-91
8. Godoy, P. et al, "The Process of Reducing Quartz to Silicon", in *Proceedings of the First Workshop on QITS*, UNU/IAS publication, 1998 (available over the Internet at www.ias.unu.edu/research_proj/qits/reports.html)
9. Data from SimaPro 4.0 Analyst, Life Cycle Assessment software, PRE Consultants B.V., the Netherlands

II.5: Chlorosilanes

1. Jackson, K.A. (ed.), *Materials Science and Technology: Volume 16, Processing of Semiconductors*, VCH Press (Weinheim), 1996
2. Howe-Grant, M. and Kroschwitz, J. (eds.), *Kirk-Othmer Encyclopedia of Chemical Technology* V. 22, John Wiley & Sons (New York), 1997, pp. 1-154
3. Company literature from Scott Specialty Gases (available via the Internet at www.scottgas.com/order/sicl4pur.html)
4. US Census of Manufacturers, section on Selected Inorganic Chemicals, 1997
5. O'Mara et. Al (eds.), *Handbook of Semiconductor Silicon Technology*, Noyes Publications (Park Ridge, New Jersey), 1990
6. Ayres, R.U. et. Al, "Materials-Cycle Optimisation in the Production of Major Finished Materials – Chapter 10: Electronic Grade Silicon for Semiconductors", INSEAD Working Paper 95/10/EPS, 1995
7. Breneman, W. and Dawson, H., "A comparison of the trichlorosilane and silane routes in the purifications of metallurgical grade silicon to semiconductor quality", Silicon for the Chemical Industry IV, pp. 101-112, 1998

II. 6: Polysilicon

1. Jackson, K.A. (ed.), *Materials Science and Technology: Volume 16, Processing of Semiconductors*, VCH Press (Weinheim), 1996
2. "Polysilicon: Tight Market Expected in the Next Century", Japan Chemical Week, July 28, 1998
3. Adams, J., "Polysilicon Shortfall Turns into Oversupply", Chemical Week, July 15, 1998

4. Ayres, R.U. et. Al, "Materials-Cycle Optimisation in the Production of Major Finished Materials – Chapter 10: Electronic Grade Silicon for Semiconductors", INSEAD Working Paper 95/10/EPS, 1995
5. Tsuo, Y.S. et Al, "Environmentally Benign Solar Cell Manufacturing", in 2nd World Conference on Photovoltaic Solar Energy Conversion: Proceedings of the International Conference, Vol. II, (European Commission, Italy), pp. 1199-1204, 1998
6. Yamauchi, I. (ed.), *Shinkinzoku Deetabukku (New Metals Databook)*, Homat Ad (Tokyo), 1998 (in Japanese)
7. O'Mara et. Al (eds.), *Handbook of Semiconductor Silicon Technology*, Noyes Publications (Park Ridge, New Jersey), 1990
8. Takegoshi, T., *Handoutai shiricon bijinesu no subete (All About the Semiconductor Silicon Business)*, Kougyou Chousakai (Tokyo), 1994 (in Japanese)
9. Halvorsen, F. and Sandhu, P., "Decommissioning a polysilicon plant – the safety aspects", The Safety & Health Practitioner, v. 16(8), pp. 34-39, 1998
10. Dorsch, J., "Moses Lake Blast Cause Found", Electronics News, November 9, 1998, p. 34

II.7: Silicon wafers

1. Van Zant, P., *Microchip Processing*, 3rd Edition, McGraw-Hill (New York), 1997
2. Kemezis, P., "Silicon wafer makers see recovery by 2000", Chemical Week, Nov. 11, 1998
3. Yamauchi, I. (ed.), *Shinkinzoku Deetabukku (New Metals Databook)*, Homat Ad (Tokyo), 1998 (in Japanese)
4. Wade, W., "Wafer shortage looming?", Electronic Buyers' News, Mar. 22, p. 5, 1999
5. Hunter, D., "Shin-Etsu Chemical", Chemical Week, v. 161 (14), pp. 22-24, 1999
6. Hara, Y., "Japan's wafer vendors gloomy even if ICs recover", Electronic Engineering Times, Feb. 8, p. 26, 1999
7. Korczynski, E., "Materials issues in 2000/2005", Solid State Technology, v. 41 (11), 1998
8. Torikai, D., University of Campinas, personal communication, March 1998
9. Takegoshi, T., *Handoutai shiricon bijinesu no subete (All About the Semiconductor Silicon Business)*, Kougyou Chousakai (Tokyo), 1994 (in Japanese)
10. Lammers, D. and Hara, Y., "Tight 8-in. wafer, polysilicon supply threatens growth – IC materials shortage looms", Electronic Engineering Times, Jan. 2, pp. 18, 1996

II.8: Semiconductors

1. Van Zant, P., *Microchip Processing*, 3rd Edition, McGraw-Hill (New York), 1997
2. Semiconductor Industry Blue Book, publication of World Semiconductor Trade Statistics (WSTS), December 1998
3. Stuart, A.F.H., "The Economic Significance of the Semiconductor Industry", Appendix F of "Spectator or Serious Player?: Competitiveness of Australia's Information Industries", Australian government DIST study, 1997 (available over the Internet at http://www.dist.gov.au/itt/tskforce/allen/index.html)
4. Grenier, J., "The Semiconductor Industry: Now we are in the "up" phase", PC Fab, pp. S11-15, September 1999,

5. Data from the Semiconductor Industry Association (available over the Internet at www.semichips.org)
6. Grimm, B., "Price Indexes for Selected Semiconductors, 1974-96", Survey of Current Business, February, 1998
7. "The Electronics Business: Top 250 Electronics Companies", Electronics Business magazine special report, 1999 (available over the Internet at http://www.eb-mag.com/issues/1999/9907/0799top2.asp)
8. The Electronics Industry Yearbook, Cahners-In-Stat, 1999 (available over the Internet at http://www.e-insite.net/e-insite/yearbook/0main.asp)
9. "Semiconductor and Related Device Manufacturing, report from the 1997 Economic Census Manufacturing Industry Series, US Census document #EC97M-3344C, 1997
10. *IC gaidobukku - dai 7 han (IC Guidebook – 7th Edition)*, published by the Electronic Industries Association of Japan (Tokyo), 1997 (in Japanese)
11. Macher J.T. et. Al, "Reversal of Fortune? The Recovery of the US Semiconductor Industry", California Management Review, vol. 41 (1), 1998
12. Kim, H.Y., "Korean Semiconductor Industry in 1999 Onwards", Semiconductor International, pp. 68-74, February 1999
13. Hu, G., "What you wish to know about Taiwan Semiconductor Industry (1999 Edition), Industrial Technology Research Institute publication, 1999 (available over the Internet at www.itri.org.tw)
14. Mathews, J., "A Silicon Island of the East: Creating a Semiconductor Industry in Singapore", California Management Review, vol. 41 (2), pp. 55-78, 1999
15. Bickers, C., "Sarawak Surprise: Malaysian newcomers aid to challenge Taiwan foundries' lead", Far Eastern Economic Review, pp. 13-14, October 14, 1999
16. *Nihon Handoutainenkan – 1997 nendohan (Japan Semiconductor Annual – 1997 Edition)*, Puresujaanaru (Tokyo), 1997 (in Japanese)
17. "The Globalization of the Semiconductor Industry: Executive Summary", study by DRI/McGraw Hill, 1996 (available over the Internet at www.eiaj.org/study/executive.html)
18. Sze, S.M. (ed.), VSLI Technology, McGraw-Hill (New York), 1988
19. Sze, S.M. (ed.), USLI Technology, McGraw-Hill (New York), 1996
20. Ristelhueber, R., "Wafer Vendors in Price Meltdown", Electronics News, January 18, pp. 18, 1999
21. Lipp, S. et al (eds.), *Environmental Consciousness: A Strategic Competitiveness Issue for the Electronics and Computer Industry*, published by the Microelectronics and Computer Technology Corporation, 1993
22. Dorsch, J., "Kobe ups wafer capacity", Electronic News, pp. 34-36, Nov. 23, 1998
23. Lammers, D. and Hara, Y., "Tight 8-in. wafer, polysilicon supply threatens growth – IC materials shortage looms", Electronic Engineering Times, Jan. 2, 1996
24. Yamauchi, I. (ed.), *Shinkinzoku Deetabukku (New Metals Databook)*, Homat Ad (Tokyo), 1998 (in Japanese)
25. *Environmental Management in the Electronics Industry: Semiconductor Manufacture and Assembly*, UNEP/UNIDO Technical Report 23, UN Sales #E94-III-D2, 1993
26. Genova, J. and Shadman, F., "Recovery, Reuse, and Recycle of Water in Semiconductor Wafer Fabrication Facilities", Environmental Progress, v. 16(4), 1997, pp. 263-267

27. DeJule, Ruth, "New Fab Construction", Semiconductor International, v. 21 (1), pp. 81-86, Jan 1998
28. *National Technology Roadmap for Semiconductors –1997 Edi*tion, publication of the Semiconductor Industry Association, 1997
29. *Handoutaisangyou ni okeru haikibutsushori houkokusho (Report on Waste Treatment in the Semiconductor Industry),* publication of the Electronics Industry Assocation of Japan, 1997 (in Japanese)
30. Profile of the Electronics and Computer Industry, US Environmental Protection Agency document # EPA/310-R-95-002, 1995
31. Hutcheson, G., and Hutcheson, J., "Technology and Economics in the Semiconductor Sector", Scientific American, pp. 54-62, January 1996
32. Martinelli, L., "Global Warming: A White Paper on the Science, Policies and Control Technologies that Impact the U.S. Semiconductor Industry", SEMATECH Technology Transfer paper #9311207, 1994
33. Roberts, L. (ed.), *World Resources 1998-99*, Oxford University Press (New York), 1999
34. Ayres, R.U. et. Al, "Materials-Cycle Optimisation in the Production of Major Finished Materials – Chapter 10: Electronic Grade Silicon for Semiconductors", INSEAD Working Paper 95/10/EPS, 1995
35. Wilkinson, S., "Industry searches for balance between ecology and economy", Computer Reseller News, May 4, 1998
36. "Carcinogens found in ground water at 4 Osaka factories", Mainichi Daily News, June 25, 1998
37. "Japan: Toshiba reports toxic leakage near 3 Kawasaki plants", Bernama, June 5, 1998
38. Data from "Industry Injury and Illness Data – 1996", US Occupational Health and Safety Administration, 1996
39. Williams, M. (editor), , *Encyclopedia of Occupational Safety and Health*, Chapter 83: Microelectronics and Semiconductors, ??
40. Mazurek, J., Making Microchips: Policy, Globalization, and Economic Restructuring in the Semiconductor Industry, MIT Press (Cambridge, Massachusetts), 1999
41. Richards, B., "Industry Challenge: Computer chip plants aren't as safe and clean as billed, some say", Wall Street Journal, p. A1, Oct. 5, 1998
42. Harber, T., "Coming Clean", Electronic Business magazine, March, 1999
43. "Recycled silicon wafers lower tool design costs", Design News, v. 53(13), Jul 6, pp.60, 1998
44. Adams, J., "Ultra-pure and Environmentally Friendly Wet Chemistry made Possible through On-site Recycling and Reprocessing", in Proceedings of the 1995 IEEE International Symposium on Semiconductor Manufacturing, pp. 187-190
45. Dahlgren, P., "Solvent Recycling for Reuse in Semiconductor Manufacturing", in Proceedings of the 1995 IEEE International Symposium on Semiconductor Manufacturing, pp. 205-209
46. Kanegsberg, B. and Van Arnum, P., "Solvents for wafer surface preparation", Chemical Marketing Reporter, v. 256 (1), Jul. 5, 1999
47. Peters, L., "Ultrapure Water, Rewards of Recycling", Semiconductor International, v. 21 (2), pp. 71-76, 1998
48. Shah, A. and Ploeser, J., "Reusing rinse wastewater at a semiconductor plant", Journal AWWA, v. 91 (8), pp. 58-65, 1999

II.9: Solar cells

1. Johansson, T. et. Al, *Renewable Energy: Sources for Fuels and Electricity*, Earthscan Publications, London, pp. 328-324, 1993
2. Neville, R., *Solar Energy Conversion: The Solar Cell*, Elsevier Science, Amsterdam, 1995
3. International Energy Agency Statistics, 1996 (available over the Internet at http://www.iea.org/stats/files/keystats/stats_98.htm)
4. Sweet, W., "Technology 1999 Analysis & Forecast: Power & Energy", IEEE Spectrum, pp. 62-66, January 1999
5. Benner, J. and Kazmerski, L., "Photovoltaics gaining greater visibility", IEEE Spectrum, pp. 34-42, September 1999
6. Moon, S. (ed.), NREL PV: Working with Industry, National Renewable Energy Laboratory publication BR-210-24692, Second Quarter, p.4, 1998 (available over the Internet at http://www.nrel.gov/pvmat/pvmat_frame.shtml?publications.html)
7. Phylipsen G.J.M. and Alsema, E.A., "Environmental life-cycle assessment of multicrystalline silicon solar cell modules", Report #95057 of Department of Science, Technology, and Society, Utrecht University, 1995 (available over the Internet at http://www.chem.ruu.nl/nws/www/publica/95057.htm)
8. World Bank Website: http://www.worldbank.org/html/fpd/energy/subenergy/solar/solar_pv.htm
9. Maycock. P., PV News, February 1999 and earlier issues
10. Konish, N., "Photovoltaic Market Charges up to Make Money", Electronic Design, pp. 64, November 2, 1998
11. Hasek, G., "Solar Shines Brighter", Industry Week, pp. 24-29, April 20, 1998
12. Farrell, M., "Consolidation in the Solar Industry", In Business, pp. 22-23, July/August 1999
13. Renewable Energy Annual 1998, Energy Information Administration, United States Department of Energy
14. Yoshioka, K. et. Al, "uchu taiyouhatsuden eisei no CO_2 fuka" (The CO_2 Burden of a Space Solar Power Station), Keio University Discussion Paper Gakushinmirai WG2-1 No. 2, 1998 (in Japanese)
15. Alsema, E.A., "Environmental Aspects of Solar Cell Modules: Summary Report", NOVEM Report #96074, ISBN 90-73958-17-2, 1996 (available over the Internet at http://www.chem.ruu.nl/nws/www/publica/96074.htm)
16. Tsuo, Y.S. et Al, "Environmentally Benign Solar Cell Manufacturing", in 2nd World Conference on Photovoltaic Solar Energy Conversion: Proceedings of the International Conference, Vol. II, (European Commission, Italy), pp. 1199-1204, 1998

II.10: Optical fibers

1. Hecht, J., *Understanding Fiber Optics*, Prentice-Hall International (Upper Saddle River, New Jersey), 1999
2. "Bell Labs Innovative Germanium Recovery Process is Economically, Environmentally Friendly", Press Release of Lucent Technologies, Oct. 23, 1997 (available over WWW at http://www.sciencedaily.com/releases/1997/10/971023172421.htm)

3. Fay, P., "Worldwide fiber and cable: demand, production, and price", Lightwave, v. 16 (1), 1999 (available over the Internet at http://lw.pennwellnet.com/home/home.cfm)
4. "Fiber Component Market to Double by 2003", Fiber Optics News, v. 17 (33), 1997
5. Data from the US Department of Commerce
6. "Lucent Claims Global Leadership in Cable: Corning has Substantial Fiber Lead", Fiber Optics News, v. 17 (19), 1997
7. Myers, R. (ed.), *Encyclopedia of Physical Science and Technology*, volume 11, Academic Press, Inc. (San Diego), pp. 611-647, 1992
8. Izawa, T., and Sudo, S., *Optical Fibers: Materials and Fabrication*, KTK Scientific Publishers (Tokyo), 1987
9. Sarkar, A., "Trends in Optical-Fiber Technologies", Lightwave, v. 16(9), 1999 (available over the Internet at http://lw.pennwellnet.com/home/home.cfm)
10. "Demand for Silicon Tetrachloride Soaring for Optical Fiber Use", Comline Daily News Electronics, July 27, 1998
11. Peiter, C., "Contributions of Quartz and New Materials to Reaching the Target of Zero Emissions", in *Proceedings of the First Workshop on QITS*, UNU/IAS publication, 1998 (available over the Internet at www.ias.unu.edu/research_proj/qits/reports.html)
12. Data from the website of the Copper Development Association (available over the WWW at http://marketdata.copper.org/)

Section III: Results of Systems Analysis and Knowledge Survey

1. Tsuo, Y.S. et Al, "Environmentally Benign Solar Cell Manufacturing", in 2nd World Conference on Photovoltaic Solar Energy Conversion: Proceedings of the International Conference, Vol. II, (European Commission, Italy), pp. 1199-1204, 1998
2. Key World Energy Statistics, International Energy Agency, 1998 (available over the Internet at http://www.iea.org/stats/files/keystats/stats_98.htm)
3. Ausubel, J., "The Environment for Future Business: Efficiency will win", Pollution Prevention Review 8(1), pp. 39-52, 1998
4. Delano, D., "Perils in Predicting the Semiconductor Industry", Electronic Business Magazine 25(1), pp. 13-14, July 1999
5. Grant, E. and Gregory, M., "Tacit Knowledge, the Life Cycle, and International Manufacturing Transfer", Technology Analysis & Strategic Management 9(2), pp. 149-161, 1997
6. Knutsen, H., "Environmental practice in the commodity chain: the dyestuff and tanning industries compared", Review of International Political Economy 7(2), pp. 254-288, 2000
7. Adam Payne, personal communication
8. "Major Findings from the CEIS Review of EPA's Toxics Release Inventory Database", Center for Environmental Information and Statistics (available over the Internet at http://www.epa.gov/ceisweb1/ceishome/ceisdocs/tri/tri-exec.htm)
9. "National Air Quality and Emissions Trends Report, 1998", USEPA document #454/R-00-003, 2000 (available over the Internet at http://www.epa.gov/oar/aqtrnd98/toc.html)

10. Ayres, R. and Ayres, L., *Accounting for Resources, 1*, Edward Elgar (Cheltenham, UK), 1998
11. Compilation of Air Pollutant Emission Factors (AP-42), Fifth Edition, USEPA, 1995 (available over the Internet at www.epa.gov/ttn/chief/ap42.html#chapter)
12. Handoutaisangyou ni okeru haikibutsushori houkokusho (Report on Waste Treatment in the Semiconductor Industry), publication of the Electronics Industry Association of Japan, 1997 (in Japanese)
13. *Environmental Management in the Electronics Industry: Semiconductor Manufacture and Assembly*, UNEP/UNIDO Technical Report 23, UN Sales #E94-III-D2, 1993