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Forecasting material and economic flows in the global production chain for silicon

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Abstract

Material and economic flows in a global production chain are analyzed in order to identify shifts in economic structure relevant to environmental issues. Results suggest that the economic and environmental weight of high-tech manufacturing and specialized material sectors will increase significantly relative to extractive and primary commodity sectors, perhaps reaching a similar environmental scale within a few decades. Though further study is needed, the forecasts suggest that a reprioritization of analysis and policy to address these new industries is in order. These results are based on a case study of the global production chain for high-purity silicon and its use in semiconductors, solar cells and optical fiber from primary materials. Forecasts for future material/economic flows are carried out based on the identification of time scales that reveal stable long-term trends. Assuming constant growth over 7–10 year averages reproduces thirty years of historical growth of three global sectors to around 1–2% accuracy. This suggests the constant growth model can be used to forecast with a relatively high degree of confidence.

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1. Background

Globalization calls for global analysis. While a national level picture often sufficed in the past, an international scope is increasingly necessary. This is no less true in the field of the environment. For instance, much of the apparent improvement in environmental performance of developed economies could be due to service-zation and the shift of

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manufacturing to the developing world. One area that stands to benefit from a more international perspective is the study of production chains. Production chains are networks of processes that follow industrial transformations from the extraction of raw materials to the manufacture of “finished” goods and are often analyzed in order to clarify issues relating to the productivity of resources and life cycle environmental impacts. Study of a *global* production chain could shed light on such issues and, in addition, provides a perspective on major economic shifts that affect the environment.

Political economists and economic geographers have studied global production chains, usually using the term “global commodity chain.” Hopkins and Wallerstein define a commodity chain as “a network of labor and production processes whose end result is a finished commodity” [1]. In very general terms, the commodity chain approach endeavors to identify typologies of commodity chains and factors that lead a chain to evolve to a given typology. One example of such is the distinction made between producer driven and buyer driven chains. A producer-driven chain is defined as an industry in which transnational corporations play a central role in controlling the production system, while in a buyer-driven chain the pivotal role is played by large retailers, brand-named merchandisers and trading companies [2]. Much of the commodity chain analysis is oriented towards economics and development issues, though some work also addresses the environment. For example, in an analysis of the dyestuff and tanning industries, Knutsen concludes that “the degree of price competition is a key factor in explaining environmental practice in the two industries” [3].

This work starts from the tradition of Industrial Ecology and, in particular, the focus is on quantitative characterization and forecast of production chains based on materials flows analysis (MFA). Industrial Ecology is “an integrated systems approach to managing the environmental effects of energy, materials and capital in industrial ecosystems” [4]. Industrial Metabolism, a related concept, focuses on an analogy between the metabolism of organisms and the industrial systems [5]. A core analytic tool in these approaches is MFA, which can be characterized as an approach to estimating flows of substances and capital within and between some functional units. The functional unit takes different forms depending on the purpose of the analysis, common examples include nations, national industrial sectors, regions or industrial processes.

This article explores the feasibility of quantitative system analysis of global production chains. The data issue is key, as is the case for nearly all international work. By and large existing MFA, work on production chains has focused on the national level [6], mainly because the data infrastructure is strongest there. A wide variety of information is available for global industrial sectors, usually from consulting firms, sector level industry organizations, and to a lesser extent national government and international organizations. However, this information is both scattered and the coverage incomplete. The former issue can be addressed in recent years due to the proliferation of Information and Communication Technologies (ICTs). It has become possible to undertake data collection unthinkable but a decade ago. The incomplete coverage issue is more serious; published information on semimanufactured goods such as chemicals often simply does not exist. As will be seen, this problem can be addressed via estimation using process input/output data.

Another target is to explore methodologies for forecasting future materials and economic flows. Forecasting is in general an uncertain affair and I approach it with caution. The enormous body of existing work has what can be fairly described as a checkered history. Expert forecasts of short-term sector growth often fail [7] and econometric models of macroeconomic growth generally cannot account for system shocks such as the Asian financial crisis [8]. On the environmental side, none of the global scenarios generated by famous Limits to Growth model were qualitatively correct over the time period indicated [9].

This article pursues the idea that the appropriate choice of time scales is crucial in forecasting. Many systems display stable long-term patterns despite large short-term fluctuations. Stock markets, for instance, usually show stable growth over decade time scales despite severe fluctuations over days, months and even years. This phenomenon overlaps with the study of business cycles, well explored in the economics and business literature [10]. Presuming that some time scale with minimal fluctuations can be identified, forecasting can be based on the assumption that past growth or decline is a reasonable indicator for the future. Empirical analysis of the historical growth of global sectors is carried out to determine what choice of time scales maximizes the confidence level of forecasting via extrapolation.

The organization of the article is as follows: Section 2 contains a definition and discussion of the production chain taken up in the case study. The methodology for estimation of material and capital flows is taken up in Section 3, while Section 4 presents results. The methodology for forecasting future behavior is treated in Section 5, which includes quantitative evaluation of choice of time scales. Section 6 shows results for trends and future flows of the chain for the year 2020. The main interpretation of results is taken up in Section 7; a pattern for global economic shift and its implications for the environmental agenda are proposed.

2. Case study: the silicon production chain

The above issues are explored in the context of a case study of a particular global production chain: the network of sectors associated with producing high-purity silicon from raw materials to its use in semiconductor devices, optical fiber and solar cells. Semiconductor devices and optical fibers are key components of ICTs, the increased application of which is a cornerstone of what many are calling a “digital” or “knowledge” economy [11]. Sectors producing ICT equipment and services, due to continued rapid and sustained growth, are in their own right increasingly relevant for the economy and environment. The silicon chain provides an interesting case in that it contains elements of the old (raw material sectors) and new (ICT infrastructure) economies. Given that solar energy produced via photovoltaic cells is potentially important source of renewable energy, the solar cell sector is evidently relevant from an environmental perspective. The use of purified silicon as a key ingredient is a tie binding the production chains for semiconductors, optical fiber and solar cells together.

To specify the boundaries of the study, the following set of ten interconnected global sectors were taken to represent the production chain: quartz,¹ charcoal, coal, “crude” silicon, chlorosilanes, polysilicon, silicon wafers, semiconductors, solar cells and optical fiber. The functional links between these sectors is displayed in Fig. 2 (which also contains results from Section 4 as well) and briefly reviewed below. Quartz/silica and carbon sources are used to produce elemental silicon in electric furnaces according to the reaction $\text{SiO}_2 + 2\text{C} \rightarrow \text{Si} + 2\text{CO}$. In order to realize the high purity required in high-tech applications, elemental silicon is reacted to from chlorosilane compounds such as silicon tetrachloride (SiCl_4) and trichlorosilane (HSiCl_3), and then purified via distillation. Chlorosilanes are converted back to silicon in the production of polysilicon, a specialized commodity for the semiconductor industry. Polysilicon is made into silicon wafers, thin discs of exceedingly pure silicon, which are used as a base for fabrication of semiconductor devices. Waste silicon from wafer production supplies nearly all demand of the solar cell industry. The pure glass cores of optical fibers are usually fabricated starting with silicon tetrachloride.

The existing body of research concerning the silicon production chain is briefly reviewed. Dicken [12] surveys work done on the semiconductor and electronics sectors from the commodity chain perspective, this focuses on analysis of the changing geographical pattern of global production. These works are by and large oriented towards the semiconductor sector rather than the production chain. Analyses of individual sectors are too numerous to mention here, though data sources for the MFA will be discussed in the appendix of this article. From a production chain perspective, Phylipsen and Alsema [13] performed a detailed life cycle assessment (LCA) of polycrystalline solar cells, which includes descriptions of technologies and input/output data for processes in the early production stages of silicon. The work overlapping most significantly with this one is the article by Ayres et al. [14], which undertakes a technological and MFA of the silicon chain. The current work significantly extends the international and sector coverage of the MFA, includes economic coverage and forecasts future configuration of the chain.

3. Materials and economic flows—methodology

The initial goal of the work is quantify the physical and economic scale of sectors and flows between sectors shown in Fig. 1. There are of course far more flows of materials than those shown in the diagram; the semiconductor industry for example purchases hundreds if not thousands of different input commodities. It is not within the scope of this study to provide a full input/output inventory, though the results have bearing on the future undertaking of such.

¹ To be precise, the quartz sector is identical to the “industrial silica” sector, as defined by the United States Geological Service.

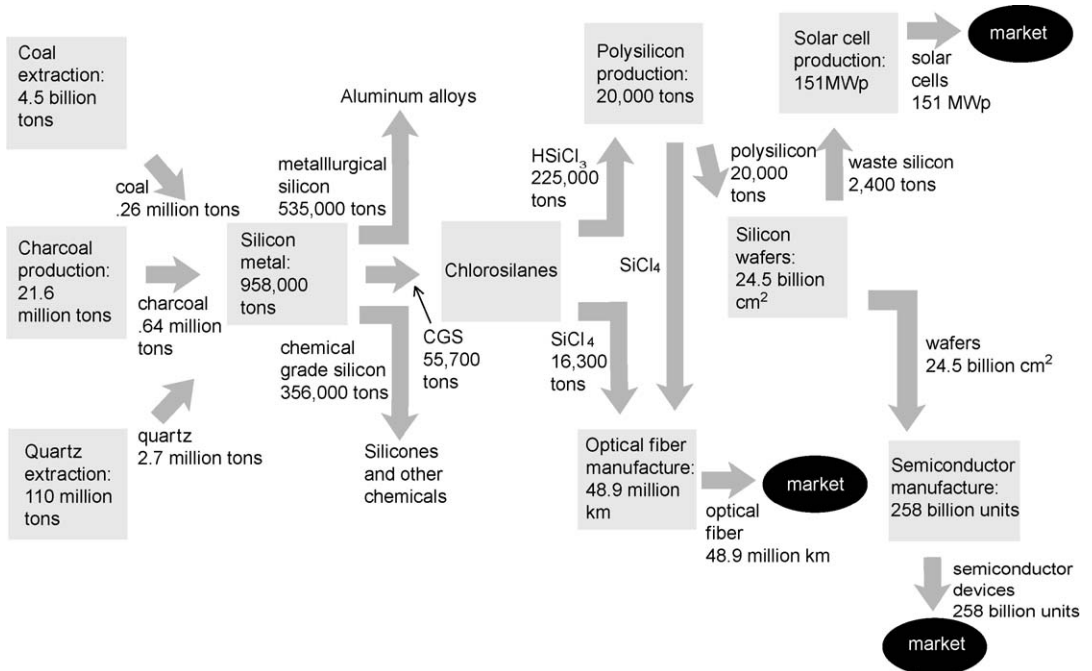


Fig. 1. 1998 materials scale and flows in the global production chain for silicon.

Even this limited task faces substantial data and methodological hurdles. Given that *global* data is a requirement, the availability issue naturally comes to the fore. Data needed to provide the desired description are:

1. global sector economic output,
2. global sector production output (in some physical unit such as weight, units, area),
3. product prices (in the case that either one or two is missing),
4. economic and/or physical measures of branching of sector output.

The main sources of data are consulting firms and sector industry organizations such as Dataquest (who specialize in coverage of electronics industries) and the World Coal Institute. National government agencies and international organizations also play a major role in supplying data for some sectors. For instance, the United States Geological Service is the leading source of data on global minerals production while the UN Food and Agriculture Organization supplies global data on agriculture and forestry commodities. In practice, data coverage is partial: global production statistics are not available for all industrial sectors and data on flows between sectors is extremely scarce. A sector must reach a certain scale before the information market is large enough to make such data collection economically worthwhile for a business intelligence firm. National and international organizations subsidize the data collection task for certain sectors, but some industries fall through the cracks. In particular, information on intermediate materials

such as chemicals is very scarce. This highlights a need to supplement the usual data some form of estimation technique.

The approach to filling in data gaps is to combine macroproduction data with input/output characteristics at the process level. Production technology fixes the ratios of all inputs and outputs; thus, knowledge of one in principle determines all. Technological information should provide “double coverage,” acting as a check on the macroproduction statistics generally gathered through different means. However, technological data is usually at the facility, or at best, the national level. Global aggregates of process data apparently do not yet exist. The key question is thus to what extent local or national level process data can reasonably be used as an international average. The answer clearly depends on the sector. For the semiconductor business, highly globalized under the management of a relatively small number of multinationals, process practice probably does not substantially vary according to region. For the charcoal industry, however, implementation differs radically, especially across the divide of developed and developing countries [15,16].

Keeping these cautions in mind, process input/output data is used to fill in missing data points as well as provide a check on macrostatistics. Common sources of input/output data are LCA process databases, academic works on LCA and industrial ecology, and reports from sector level industry organizations.

4. Material and economic flows—results

4.1. Materials flows

An extensive search for economic and technological data was undertaken for the ten global sectors in Fig. 1, and the above methodology applied to the estimation of materials and capital flows. The sources identified and method used to calculate flows are summarized in Table 1, additional details can be found in another report by the author [17]. The classification “primary” vs. “I/O” distinguishes whether the flow is reported directly from a data source or calculated according to process input/output data. In the latter case, the source indicated is for process data. The results for global material flows in the silicon production chain for 1998 are shown in Fig. 1. In this and all subsequent figures, numbers appearing inside the square boxes denote the value for the global sector; numbers appearing near arrows represent the estimated flow of quantities between sectors. The units chosen to represent physical flow are chosen according to appropriateness for describing functionality of the output. Wafer output, for example, is expressed in square centimeters because area determines capacity for fabrication of integrated circuits. MWp refers to the generating capacity of solar cells in “standard” sunlight, measured in megawatts, and “units” of semiconductor devices refers to the number of devices produced. The amounts of elemental silicon consumed by the world aluminum and silicone² industries appear as they will play an important role in the forecasting of future silicon demand.

² The term silicone refers to a broad class silicon containing polymers, which have a broad variety of applications including use in gums and resins.

Table 1
Data sources and calculation methods for material flows

Sector or intersector flow	Method	Name of data source(s)
Silica	Primary	USGS [18]
Silica → silicon	I/O	Phylipsen and Alsema [13] Harben [19]
Charcoal	Primary	FAO database [20]
Charcoal → silicon	I/O	Phylipsen and Alsema [13] Harben [19]
Coal	Primary	IEA [21]
Coal → silicon	I/O	Phylipsen and Alsema [13]
Silicon	Primary	USGS [22], Roskill [23]
Silicon → chlorosilanes	I/O	O'Mara et al. [24]
Silicon → silicones	Primary	Roskill [23]
Silicon → aluminum alloys	Primary	Roskill [23]
Chlorosilanes	I/O	O'Mara et al. [24]
Chlorosilanes → polysilicon	I/O	O'Mara et al. [24]
Chlorosilanes → optical fiber	Primary/I/O	Comline [25], also anonymous industry source
Polysilicon	Primary	Yamauchi [26] (reporting Dataquest data)
Wafers	Primary	Yamauchi [26]
Wafer waste silicon → solar cells	Primary	Tsuo et al. [27]
Semiconductor devices	Primary	WSTS [28]
Solar cells	Primary	Maycock [29]
Optical fiber	Primary	Fay (reporting KMI data) [30]

Coal extraction clearly stands out by far as the largest mass of production and, although some commodities such as solar cells are not represented in terms of mass units, conversion does not change the situation. This illustrates the general point that mass flows associated with fossil fuels are very significant. The level of production of elemental silicon is modest compared to major metals, for the sake of comparison note that the world production of aluminum is around 20 million tons per annum. The high-tech industries, 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.

4.2. Economic flows

Data on the economic value of production of a global sector, particularly for primary commodities, is often unavailable. In such cases, monetary values of production and flows will be estimated through use of average prices, though care must be taken to account for the variation in price according to the grade of commodity.

Fig. 2 shows estimated 1998 economic scale and intersector flows in the production chain. The number appearing below flow values in parentheses represents a typical price of the commodity. 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, at an

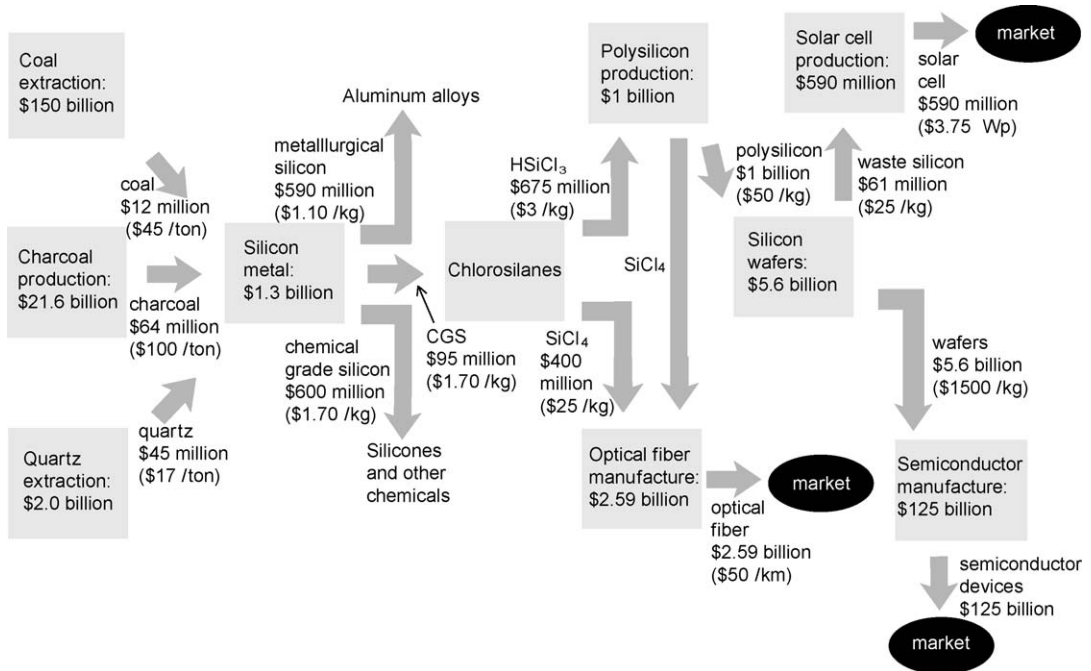


Fig. 2. 1998 economic scale and flows in the global production chain for silicon.

economic scale of \$5.6 billion is quite tremendous considering that it is geared to produce a single specialized ingredient for a single “sector.”

It is interesting to track the value-added along the processing chain by comparing the prices of different commercial forms of silicon. Elemental silicon, 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.

5. Trends and forecasting—methodology

The basic idea of the forecast method is to identify appropriate time scales for which historical growth can be reproduced reliably, and then to extrapolate future behavior assuming “business as usual.” The robustness of such forecasts depends on the extent to stable long-term growth patterns underlie short-term fluctuations. I take a phenomenological approach, meaning that empirical data is matched to a mathematical model, without consideration of the underlying theory for the model.

The centerpiece of forecasting a global production chain is modeling historical growth for the component global industrial sectors. The relevance of time scales will first be illustrated via a

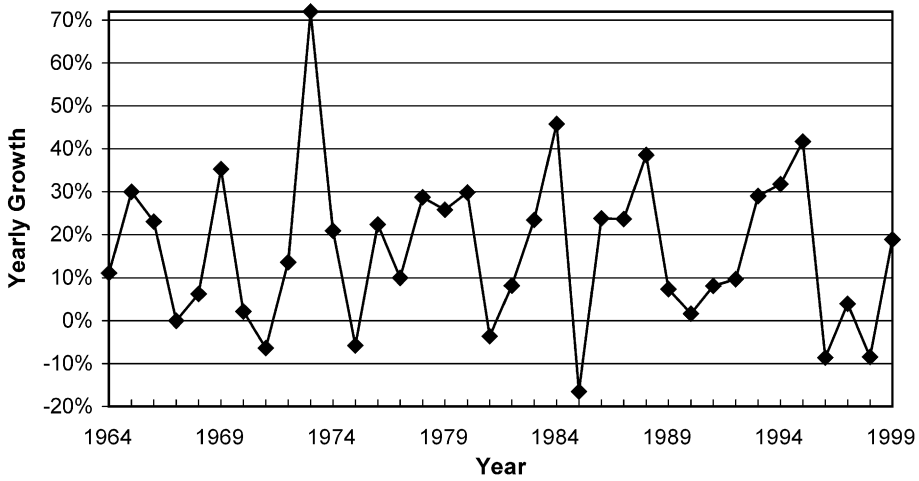


Fig. 3. Growth of the global semiconductor sector over 1-year intervals.

concrete example. Fig. 3 shows historical *yearly* growth of the global semiconductor sector from 1964 to 1999, where yearly growth is calculated in the usual way,

$$\text{Yearly Growth} = \frac{P_{\text{year}} - P_{\text{year}-1}}{P_{\text{year}}}$$

P_{year} is the monetary value of global production in a given year. The extremely large fluctuations clearly indicate that historical yearly growth does *not* provide a good indicator for future behavior.

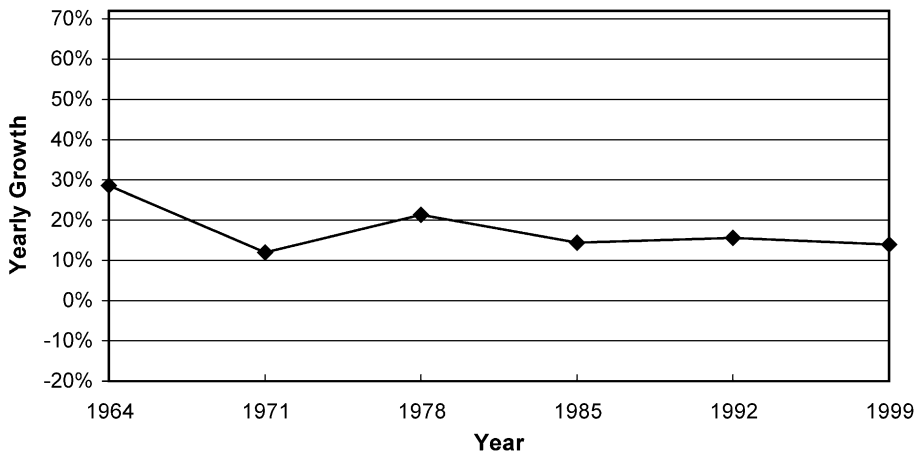


Fig. 4. Growth of the global semiconductor sector over 7-year intervals.

Consider now Fig. 4, which displays yearly growth over 7-year intervals where production in intervening years is ignored. Growth over a 7-year interval is adjusted to yearly growth according to:

$$\text{Yearly Growth} = \left(1 + \frac{P_{\text{year}} - P_{\text{year}-7}}{P_{\text{year}-7}} \right)^{\frac{1}{7}} - 1.$$

Note that growth over intervals displays quite small fluctuations and, in fact, has apparently been nearly *constant* over the last few decades. This is a surprising result given the remarkable expansion of niches of semiconductor applications over this time period. Also, major economic events such as the oil shocks in the 1970s and 1980s as well as the Asian financial crisis in the 1990s apparently “wash” out over longer time scales.

The result for the semiconductor industry suggests a possible model for all global sectors: assume constant growth over time scales chosen to minimize fluctuations. This corresponds to the usual model for exponential growth,

$$\text{Production}(t) = \text{Production}(0)(1 + g)^t,$$

where t is time difference in years or n -year intervals and g is growth assumed to be independent of t . Evaluation of this model involves studying patterns of historical behavior to ascertain if certain choices of yearly intervals do indeed yield nearly constant growth. Also, averages over n -years may yield better results than intervals that ignore intervening years. Numerical tests were performed to evaluate the performance of n -year interval and averages for global sectors for which long-term production data was available. The indicators used to evaluate different choices of n are the standard deviation (S.D.), as well as a modified version defined according to:

$$\text{Modified Standard Deviation} = \sqrt{\sum_1^{N-1} \frac{(g_j - g_N)^2}{N-1}}.$$

N is the number of time intervals, g_j is the growth over time interval j and g_N is the most recent growth figure. This measure differs from the usual standard deviation by the replacement of the average over all intervals by only the most recent value. This modification is used in order to because long-term data is unavailable for many global sectors, thus it is desirable to check how forecasts differ using only recent data.

The results of these tests for the semiconductor sector are graphed in Fig. 5. Not surprisingly, averages over n -years yielded both a smoother curve and somewhat smaller deviations than skipping intervening years. Deviations were smallest for n in the range of 7–10 years, suggesting the presence of an investment (or Juglar) business cycle [10]. How this and subsequent results fit into the context of the literature on business cycles will not be further discussed, as the objective of this section is the development of a self-contained methodology for forecasting production chains.

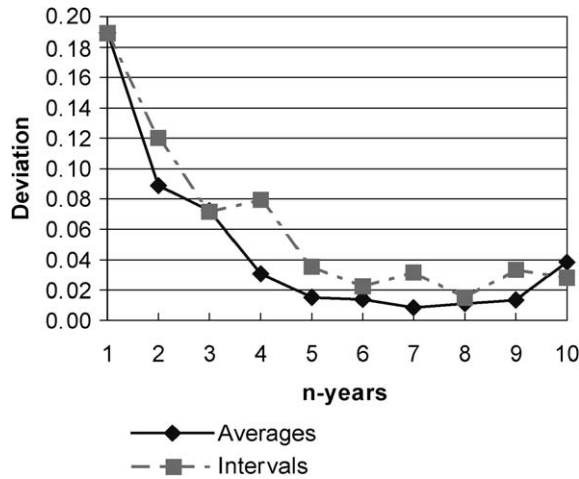


Fig. 5. Standard deviation of growth of the semiconductor sector for *n*-year averages and intervals.

Selected results from three sectors, including modified standard deviations, appear in Table 2. The “optimal” *n* is defined as the choice that yielded the smallest standard deviation. Average and final growth refers to results the entire and final set of intervals, adjusted to a yearly figure. Neighbor standard deviation shows values for choices of *n*, *n* – 1 and *n* + 1, respectively. Their values indicate the steepness of the well in which the optimum lies. In all cases, the graph of deviation vs. *n* follows a U-shape as in Fig. 6. Unfortunately, the behavior for large *n* is unknown due to data limitations; very little global data is available beyond 30–40 years ago. It would be most illuminating to observe the extent to which deviations rise beyond the “optimum,” and whether a secondary minimum occurs at twice the period. At any rate, using the existing data sets and choices of optimal

Table 2
Evaluation of measures of past growth (WSTS [28], PV News [29], IEA [21])

Sector	Data range	Optimal <i>n</i> (years)	Ave. growth (%)	Final growth (%)	S.D. (%)	Neighbor S.D. (%)	Modified S.D. (%)
Semiconductor	1964–1999						
Intervals		8	16.1	13.4	2.1	3.2, 3.3	3.8
Averages		7	16.2	15.2	0.9	1.4, 1.1	1.4
Solar cell	1971–2000						
Intervals		9	22.2	19.6	3.4	8.8, 16	6.1
Averages		8	18.4	16.3	1.9	9.6, 6.6	3.8
Charcoal	1961–1999						
Intervals		9	2.0	1.1	0.72	0.89, 0.93	1.4
Averages		10	2.4	1.5	0.66	0.73, 0.67	1.3

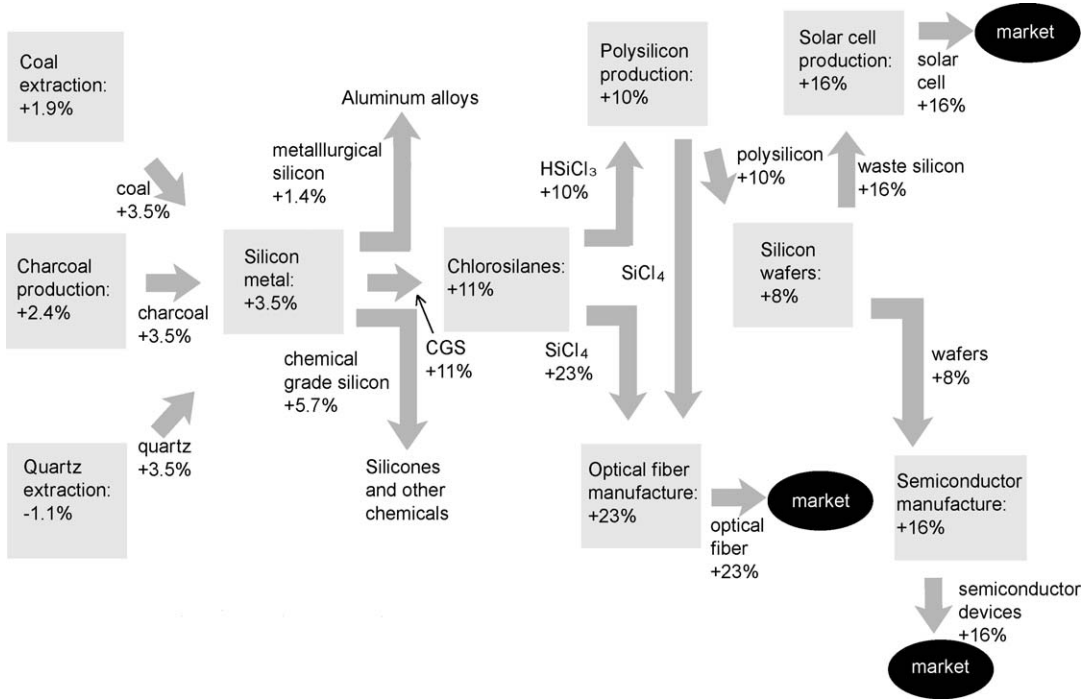


Fig. 6. Trends for 7–10-year aggregate growth (adjusted to yearly figure).

n, deviations from constant growth for time-averaged intervals are in the range of 0.6–2%. Such low deviations significantly validate the model.

6. Trends and forecasting—results

6.1. Trends

The first step in forecasting is calculation of sector growth trends. While time series data is available for many cases, data does not exist for some global sectors (e.g., trichlorosilanes) and most intersector flows (e.g., quartz → silicon). In these cases, process input/output data is used to estimate trends. The key assumption is that the material input/output table remains *constant* over time, setting growth rates of inputs and outputs equal. This is obviously a dangerous assumption to make in the case of a sector with rapidly evolving technology. Cases where input/output data are used in the estimation of trends are: scale of the chlorosilane sector, all flows into the crude silicon sector and the flow of waste silicon from the wafer sector to solar cell production. The rate of technological change in the silicon and chlorosilane sectors is apparently low, thus the assumption of time-independent processes is probably reasonable. This is distinctly not the case for the solar cell sector; thus, the level of confidence in the growth rate of demand for waste silicon is low.

Results for trends in sector scale and intersector flows appear in Fig. 6. For the most part, growth is represented in physical terms such tons of material, Watts of solar cell (Wp), or meters of fiber. The semiconductor sector is the only case where an economic measure is used; this is 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 extent.

The extreme contrast in growth rates between primary commodity and high-tech sectors is notable. Coal, quartz and charcoal sectors are expanding more slowly than world product growth of 2.5% over the same interval, while semiconductors, optical fiber and solar have enjoyed quite spectacular growth for decades. That the global semiconductor sector has recently reached the economic scale of the world coal industry, and is poised to grow to 20 times its size within 20 years, is surely significant. This issue is discussed further in Section 7.

6.2. Projections

Future material flows are forecast for the year 2020, 22 years from the starting point of 1998. The two-decade time scale for projection was chosen as historical evidence supporting the constant growth hypothesis only went back several decades. Longer-term

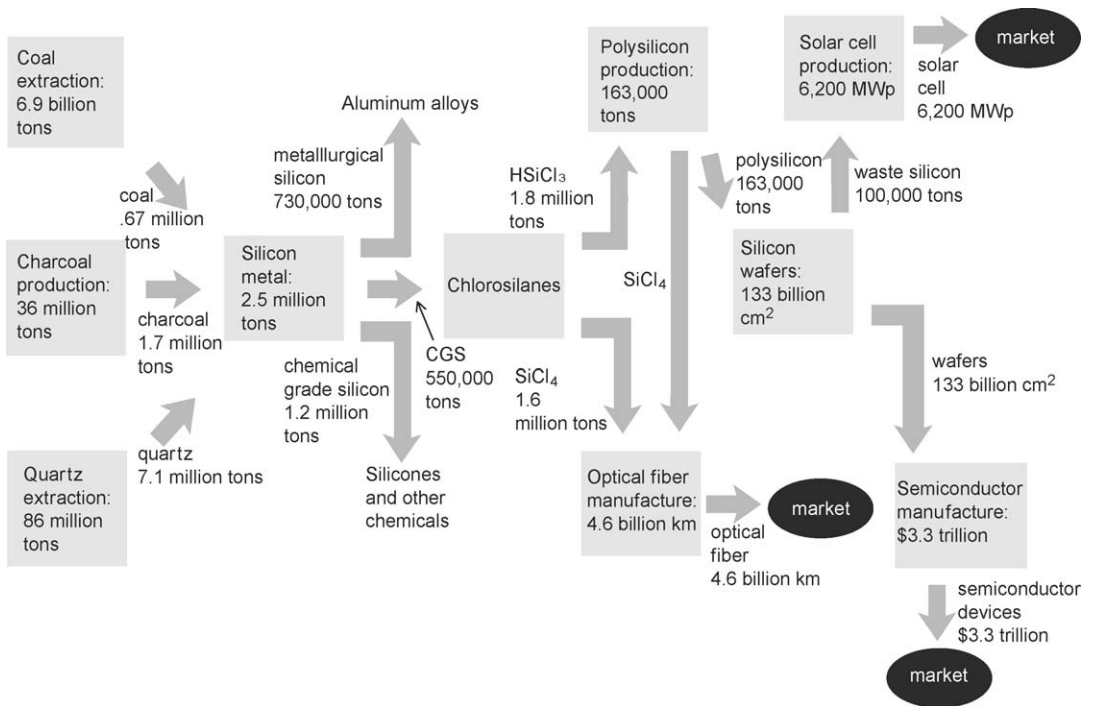


Fig. 7. Forecast materials/economic flows for 2020.

data on global sectors could indicate conditions and an upper bound for using the constant growth scenario.

Results for the forecast of materials flow appear in Fig. 7. The forecast should be interpreted as holding for the average of several years around 2020, as there could easily be short-term fluctuations around the year 2020 itself. “Error” can be estimated by taking the fluctuations in historical growth of 1–2% as applying to the forecast. The product of the error in the aggregate trend in yearly growth times the number of years yields flow forecasts for 2020 accurate to $\pm 20\%$ for a yearly growth error of $\pm 1\%$.

It should be mentioned that the projection for the silicon sector deviates from the single-term exponential growth model. The reason for this is because the different silicon markets have very different growth rates, which suggests that a sum of exponential terms is more appropriate. To illustrate, note that the three drivers of demand, aluminum alloy, chlorosilane and silicone applications have growth rates of 1.4%, 11% and 5.7%, respectively. The growth in demand over 22 years is thus:

$$535,000(1.014)^{22} + 356,000(1.057)^{22} + 53,000(1.11)^{22} = 2.5 \text{ million tons}$$

However, using 3.5% growth in the overall production of silicon as shown in Fig. 7, the result is:

$$958,000(1.035)^{22} = 2.0 \text{ million tons}$$

The difference in these two numbers illustrates the single term growth model can break down in certain cases. This was remedied for the case of the silicon sector by adding terms for each differentiated end-use market, rather than the aggregate growth of the sector itself.

7. Global economic shifts and the environment

The extractive commodity sectors considered (coal, charcoal and quartz) show low growth relative to typical growth in world economic product of 2.5% per annum. Silicon, a primary commodity, has higher growth, driven by high-tech applications such as semiconductors and silicones as opposed to more traditional use in aluminum alloys. Specialized materials (chlorosilanes, polysilicon, wafers) are growing rapidly to meet the increasing demand of high-tech industries such as semiconductors, optical fiber, and solar cells.

These results suggest a possible structural change in the global economy: a distinct decline in relative material scales and economic importance of a broad class of extractive industries, with extremely rapid growth of high-tech sectors and materials supplying them. The material demands of high-tech sectors will increasingly account for a substantial share of the demand for primary materials. For instance, while semiconductor, solar cell and optical fiber applications currently only represent about 5.8% of 1998 of silicon demand, this share is forecast at 22% for 2020. While it is fairly evident that such a shift is occurring in the developed world, this analysis suggests that it applies globally.

Table 3

Estimated energy consumption of global coal and semiconductor sectors (Census [31,32], IEA [21], WSTS [28])

Unit: TJ	1998	2020 forecast
Coal mining	1500	2300
Semiconductor (zero efficiency progress)	210	5900
Semiconductor (historical US progress: 1993–1999)	210	1100

What implications would such a structural shift have on environmental issues? The economic rise of high-tech is tied to increase environmental impacts associated with those industries. High-tech generally has a clean image, but in fact little is known regarding its environmental impacts as compared to traditional industries.

A thorough survey of the state of knowledge of environmental impacts associated with high-tech material and manufacturing is beyond the scope of this work. Such a task is complicated by the difficulty of comparing industries that have quite different profiles of associated environmental issues. However, the issue will be scoped through analysis of energy use in the coal and semiconductor sectors. Both global sectors are currently of similar scale economically, though the semiconductor sector will likely exceed coal by 10–20 times by 2020. To what extent is this economic growth accompanied by energy use? At first glance, one might think that the impacts of producing chips is negligibly small, as the physical output is millions of times smaller than coal for the same economic value. In terms of energy, however, the chip and other high-tech industries are surprisingly energy intensive. Using US Census data to represent energy intensities of global industries, energy consumption of the world semiconductor and coal sectors is estimated at 210 and 1500 TJ, respectively [31,32].³ Semiconductor consumption is indeed lower, but only by one order of magnitude. If one naively assumes that energy use of the semiconductor industry will increase in tandem with the 16% economic growth, the total consumption of the sector is forecast at 5900 TJ in 2020, must be higher than the estimated 2300 TJ for the coal industry. This is probably incorrect, however, as progress of the semiconductor industry towards energy efficiency slows growth in energy consumption. 1993–1999 data from the US semiconductor industry suggests that energy use increases only 7.4% per year [32]. Using this figure to project future use yields an energy consumption of world semiconductor sector of 1100 TJ in 2020. Though still lower than the coal industry, the narrowing of the gap is notable. These calculations are summarized in Table 3. The conclusion of this analysis is that the energy scales of the two industries are quite similar. The semiconductor industry also reputedly uses substantial quantities of chemicals, water and elemental gases, suggesting that the overall environmental intensity of the industry bears serious consideration [17].

Though the jury is still out on the environmental implications of high-tech, indications are that the intensity of these industries is not insignificant. Given their rapid expansion in the near future, some reprioritization of the environmental agenda is in order. It is fair to state that most of attention of analysis and policy has focused on extractive and primary commodity industries, with little attention on high-tech. This needs to change, with appropriate steps

³ This calculation assumes an overall conversion efficiency of fossil fuels to electricity of 30%.

taken to ensure that we first analyze, understand, and then respond to the issues that emerge. There are challenges facing this task. The rapid rate of technological change puts process knowledge at a premium, limiting the availability of information available to analyze environmental effects. Also, most high-tech products are traded in highly competitive international markets and the respective industries are important with respect to strategic national interests. These factors no doubt dim the zeal with which environmental action could be taken. On the other hand, the rapid rate of technological change suggests potential for rapid improvement in environmental performance. The first step in the process in dealing with this industrial shift is knowledge and the will to act, not just at the firm level but from the environmental community as a whole. The scarcity of data inhibits analysis, but it can be argued that data is driven by demand. If society insists on answers strongly enough, the capacity for analysis and response will follow.

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