THE SOLAR PHOTOVOLTAICS INDUSTRY: THE STATUS AND EVOLUTION OF THE TECHNOLOGY AND THE INSTITUTIONS

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PREFACE

This paper is the principal product of the Photovoltaics Technology Supply Industry task of the project entitled "Planning and Analysis for Development of Photovoltaic Energy Conversion System" supported at the MIT Energy Laboratory by the U.S. Energy Research and Development Administration (since incorporated in the U.S. Department of Energy). A second product is "Solar Photovoltaic Technology: Current Processes and Future Options," D. Bottaro and J. Moskowitz, MIT Energy Laboratory Working Paper No. MIT-EL 77-041WP, December, 1977. The task ran over the period from June 1 to August 31, 1977, and the information contained herein is valid as of that period.

The work reported here is not a completed study. A number of the important hypotheses need to be clarified and tested. However, because it is uncertain when the effort on this task will be resumed, the policy implications of the analysis are presented.

Lawrence H. Linden was the Principal Investigator on this task. The data-gathering efforts, reported in Chapters Two and Three were the primary responsibility of Jacob Moskowitz; William C. Ocasio had primary responsibility for the conceptual framework and analysis reported in Chapter Four. Drew Bottaro was responsible for the day-to-day management of the task and the preparation of Chapters Two and Three. The MIT Photovoltaic Program has been under the overall leadership of David O. Wood and Richard D. Tabors.

A number of individuals in the public and private sectors contributed their time to interviews; we hereby express our appreciation. However, the opinions or findings expressed herein are the responsibility of the authors alone. Neither the MIT Energy Laboratory nor the U.S. Department of Energy necessarily concur.

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CHAPTER ONE: INTRODUCTION

The development of new energy technologies is an important public policy measure which can be undertaken now to aid in the resolution of future energy problems. In our system of economic organization, the final development and ultimate entrance of these technologies into the economic structure of the nation will be managed by private industry. The performance of thse industries in this task is thus of paramount public concern. However, our understanding of the process of technological development in industry is very incomplete, leaving efforts to facilitate that process without sound guidance. In the U.S. economy, further confusion arises from the complex role the federal government plays in affecting private industrial behavior.

This report is the result of a preliminary effort to develop an understanding of the process of technology development in one particular industry: that concerned with solar photovoltaics. In the belief that photovoltaics may be one of the important energy resources of the future, the federal government has established an aggressive program for its development. This report was produced to support the government in that effort; it provides an analysis of the technology development process in photovoltaics, and information concerning that process, for use by federal policy-makers. However, the weakness of present knowledge of the process of technology development implies that this effort is not a standard application of existing principles to a new situation. It is in part an effort to develop new principles. As a consequence, the analysis itself must therefore be somewhat tentative in nature.

TECHNOLOGICAL CHANGE AND INDUSTRY PERFORMANCE

In our mixed economy, private decision-makers (individuals and firms) make most economic decisions. Any government efforts to affect the aggregate behavior of a group of firms (an industry) operate in this context of private decision-making. Therefore, effective and efficient governmental efforts to influence an industry and the manner in which it develops a technology must understand the factors that affect that industry's performance.

While a given technology itself is often the object of analysis, it is actually the industry employing a given technology which must be the central focus of policy goals. In this nation almost all goods are distributed through markets in which voluntary transactions between buyers and sellers determine the level of economic activity pertaining to a given product. It is the change in this level of economic activity which is crucial to the extent to which a new technology will influence energy problems. Production, distribution, and marketing activity pertaining to a given product are what is meant by industrial activity, and those firms engaging in that activity form the industry. Hence it is the industry which ultimately becomes the object of concern: what affects its decisions to invest in new production equipment or technology development, what makes it grow, how it responds to consumer demands, etc. In short, concern becomes focused upon the industry's performance.

One aspect of the industry's performance relevant to resolving energy problems is its ability to produce its product in sufficient quantities to meet demands from users of present energy technology wishing to switch to the new technology. Factors affecting this ability include those which affect industrial capacity and the growth of that capacity, and understanding them is important. But another aspect of the industry's performance has a potentially greater impact upon resolution of energy problems, namely the industry's ability to achieve technological change in its product or the process for producing it. Many factors affect technology development; these factors can be divided crudely into those which affect the production capacity of the industry (as a function of price) and those which affect the demand for the industry's products. The interaction of factors of these two types will affect the level of private interest in the industry and hence the growth and opportunities for technology development in the industry.

Several factors affect the industry's capability to produce its goods at a given price in the long run. First, the existence of large (relative to market size) economies of scale or barriers to entry may limit the number of firms in the industry. This in turn may increase price and decrease consumption in the short run and may affect the rate of technological change and the rate of growth in the long run. Also the reasons why a firm would want to enter or invest in the industry might affect the rate of technological change in the industry. For example, the posture of a firm already utilizing a particular production process and filling a backlog of orders might differ from that of a firm seeking to invest in new plant and technology for a new product; the type of technology in which each firm would be disposed to invest might differ with respect to the amount of research needed to make the process commercially feasible and with the likelihood for obtaining substantial cost reductions in the long run. How firms interact with one another and how technology is transferred from firm to firm within and from without the industry might affect long-run cost reduction. Finally, the responsiveness of firms to technological change may matter. The ability of firms to finance large investments in capital equipment (and thus incorporate new equipment and hence new technology into their production process) and the adaptability of current production processes to major technological advances will affect the rate and direction of investment in technological progress and responsiveness to technological progress developed externally. Large reductions in costs of alternatives to present production technology may need to occur before producers risk investing in new processes.

The willingness of consumers to purchase the industry's products at a given price is also affected by several factors. Probably the most important single factor is the price of substitutes for the industry's products and the rate at which consumers respond to relative price changes of substitutes, given the lifetime of the capital equipment in which the substitute technologies are embodied. It could be that only a drastic relative price change could induce technology-switching by consumers. Also, consumer receptiveness to a new product may depend upon uncertainty regarding the performance of the product. Products which are unproven (or which require long periods of time to prove) might make consumers question the wisdom of purchasing such products; these uncertainties could produce uncertainties in overall demand which reduce private investment in capacity to meet that demand.

Design and management of federal programs to stimulate a particular industry must consider how the features of supply and demand touched upon above interact to affect the industry's present and future performance, if those programs are to be effective. The combination of technological possibilities for supplying the industry's products and the potential demand for those products will determine (in part) the level and type of investment in the industry, and to a large extent the type of technological progress which occurs. Policy planning then further requires an understanding of the responsiveness of industry to efforts designed to remedy perceived inadequacies in the industry's performance. How industry's choice of technology will be affected by federally supported research and development projects and procurements will be important. These efforts may have short-run effects which differ from the long-run effects; hence an understanding of both is important.

THE ANALYTICAL APPROACH OF THIS PROJECT

Given the state of knowledge in this area, our goals have been modest. We do not attempt to explore and explain every facet of the process of technology development. Rather, we attempt to develop a simple framework for understanding the various processes in action. The project whose results are reported here is the first step required in meeting policy-makers' needs for a more thorough exploration of the topic.

The project involved two facets. While the facets are distinct conceptually, they proceeded in parallel, and information or concepts garnered in one facet influenced the progress of the other. One facet covered the gathering of available information about the options, both present and possible future, available for photovoltaics and their production and the participants in the photovoltaic industry. The industry was defined broadly to include current and possible future producers and those firms producing inputs used by producers. Our information came from technical journals, government reports, the energy press, and interviews with three firms. The information concerning photovoltaic technical options is presented fully in a supporting working paper (Bottaro and Moskowitz, "Solar Photovoltaic Technology: Current Processes and Future Options") and is summarized in Chapter Two of this report. The information concerning industrial participants is contained in Chapter Three. Due to limitations on our own project resources, we have confined our research and analysis to flat plate collectors, and specifically have not examined concentrator technology or the potential for a concentrator industry.

The other facet of the research aimed to develop a qualitative model of the technology development process in the photovoltaics industry. It drew upon the evidence portrayed by the first facet to aid in the development of the qualitative model while simultaneously providing insights which suggested new avenues of research for the first facet and frameworks for organizing the data collected. In the second facet energy markets were analyzed in economic terms, and several of the most important concepts in the recent technology development literature were integrated into the economic analysis to illustrate conceptually, and as applied to photovoltaics, the impact of technological change upon industrial investment. These results are presented in Chapter Four.

The structure of the report is as follows. Chapter Two begins the report by presenting a summary of photovoltaic operation, present process technology and future options for the reader unfamiliar with them. It may safely be skipped by the reader aware of the state-of-the-art possibilities; the reader interested in further detail should see Bottaro and Moskowitz. In Chapter Three we set forth a brief history of the photovoltaic industry and its evolution to the present, and discuss in detail the present and possible future participants in the photovoltaic industry. Both technology development and production activities are described. A categorization of firms involved with photovoltaic technology is set forth; the key behavioral or technological features in common with each category are presented, as are the differences between categories. In Chapter Four we then develop a framework for the development of the photovoltaic market including the evolution of the product and process technology and the associated institutional structure. Using several key concepts derived from the literature, we describe how different types of opportunities for technological change might affect long-run cost reduction and incentives for investment in the photovoltaic industry and in the development of new technology. Finally, in Chapter Five we present some tentative policy implications drawn from the research to date. They relate to the nature of the changes now occurring in photovoltaics technology and the government's influence on those changes, and to the government's relationship with particular classes of firms and how this may affect the evolution of the industry.

CHAPTER TWO: PHOTOVOLTAIC PROCESS TECHNOLOGY

To facilitate later discussion of photovoltaic industrial participants and their activities, and to lay a foundation for discussion of technology development in photovoltaics, this chapter presents briefly the very basics of photovoltaic technology and the production processes for photovoltaics. The material contained herein is presented in greater detail in a supporting Energy Laboratory working paper (Bottaro and Moskowitz), and several basic references (Chalmers, Meinel, Adler) present good summaries of the technology and some of its history. For ease of reading no references are presented in this simplified discussion of photovoltaic product and process technology; for the related references one should consult Bottaro and Moskowitz.

The chapter begins with a presentation of the elements of photovoltaic operation and design considerations. Following that, process technologies for silicon photovoltaic cells and for cadmium sulfide photovoltaic cells are described. These two technologies are the only two commercial photovoltaic technologies, with silicon in production and plants for cadmium sulfide nearing completion. Other technologies currently under development are then briefly described, and at the chapter's end the key technological choices are summarized.

I. RUDIMENTS OF OPERATION AND BASIC DESIGN CONSIDERATIONS

Photovoltaics convert sunlight to electricity. They are generally made by placing two oppositely doped[1] crystalline structures (semiconductors) next to one another, forming a cell; one semiconductor is doped with an excess of electrons while the other has a shortage. The two semiconductors are joined at what is called the p-n junction. In simple terms, a photovoltaic cell operates when sunlight hits the cell and transfers energy to the electrons, enabling them to migrate across the p-n junction into the other semiconductor. If the two semiconductors are connected by an external circuit, current will flow so long as the cell is illuminated. The power produced by a cell under standard noon sun with standard atmospheric conditions is the peak wattage of the cell (or series of cells); the cell's output is generally referred to in these peak watts.

In a typical photovoltaic unit, the cell converts the sunlight to electricity. It, along with the other cells in its circuit, is placed onto a substrate. A pottant is then placed on the substrate on top of the cells, and the entire structure is then covered by the encapsulant (if the encapsulant and the pottant are different). This encapsulated structure is called a module. In use, photovoltaic modules are often used in clusters called arrays; to hold the modules in place requires some arraying structure for structural support.

Certain design factors affect the output of a photovoltaic unit and the cost of a unit. The optimal design of unit would be the one which

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[1] Doped crystals contain very small amounts of impurities.

minimizes the cost per unit of output over the lifetime of the cell, taking into account the effect upon output and cost of the various design factors. An increase in output from a particular design modification does not necessarily imply lower cost per unit output, since costs could increase more than proportionately with output due to the design modification. There are three basic types of design modifications possible: those affecting cell efficiency, those affecting module efficiency, and those affecting lifetime.

Several factors affect cell efficiency, which is defined as the fraction of light energy reaching the cell which is converted into electrical energy. The material forming the semiconductors affects the cell's efficiency; different materials have different efficiencies in theory and in practice. The purity and uniformity of crystalline structure of the material from which the semiconductors are made affects the extent to which cell efficiency approaches the theoretical limit for the material; while cells improve in efficiency with increased purity and increased crystallinity, either of these comes at a cost, and many promising new techniques involve production of lower-efficiency cells at greatly reduced cost. Some researchers are even attempting to produce cells with no crystalline structure (amorphous semiconductors). Other factors affecting the cell's efficiency include the cell's thickness, its operating temperature, and the amount of light it reflects (and hence fails to convert to electricity). All else being equal, cost per unit output is inversely proportional to efficiency, making efficiency a major cost-determiner. Also, for applications where weight matters, higher efficiency implies a higher power-to-weight ratio.

Module efficiency is defined as the fraction of light energy reaching the module which is converted into electrical energy. Module efficiency is affected by the packing ratio of the module, i.e., the ratio of the surface area of the cells in the module to the module's surface area. For example, square cells can be packed more tightly than round cells and modules containing square cells have a higher packing ratio than those packed with round cells. For a given output, a module with a higher packing ratio is smaller, permitting savings in module materials and arraying costs which may offset any increase in costs necessary to produce the higher packing ratio. Also, the degree to which the electrical characteristics of the individual cells in the module match each other affects the module efficiency.

The lifetime of the cells and module also affect output and cost. The basic determinant of lifetime is the encapsulant's ability to withstand the environment in which the module is placed.

II. SILICON PROCESS TECHNOLOGIES

Current production processes for silicon photovoltaic cells may be broken into five functional stages: mining, materials preparation, cell blank manufacturing, cell manufacturing, and module manufacturing. The remainder of this section will explain generally what occurs during each functional stage and what technological alternatives to current processes are under research. Figure 2.1 (at the end of section to allow the reader to fold it out and to refer from text to figure and back) presents silicon production processes in more detail, showing the options available at each step. It and the processes it refers to are explained in much greater detail in Bottaro and Moskowitz. The central line of the figure, connected by solid arrows, shows present process technology; dotted lines indicate alternatives under development.

A. MINING

Silicon is mined as silicon dioxide, either in relatively pure form as quartzite or in less pure form as sand. Most sand and quartzite are used for construction; some is purified to 96-98% purity silicon of which most is used by the steel industry. Since the steel industry is largely unaffected by mineral impurities of several percent, purifiers of silicon use both sand and quartzite. However, if sufficient quantities of high-purity silicon were demanded, mining of quartzite specifically for semiconductor (high-purity) applications might produce cost savings in subsequent steps.

B. MATERIALS PREPARATION

To remove the oxygen from the silicon dioxide, the sand or quartzite is heated in an electric arc furnace, producing metallurgical-grade silicon of 96-98% purity. This purity is insufficient for making semiconductors though acceptable for steel production (see above), and further purification is required (see below). Dow Corning believes its submerged arc reduction process can be modified to achieve the additional purification necessary in the initial reduction step.

However, presently available processes must purify the metallurgical-grade silicon further to produce semiconductor-grade silicon, which is extremely pure and costly. Three options are available for achieving the further purification: use of an intermediate compound, zone refining, and reactive gas blow-through melt purification. Methods using intermediate compounds, the only ones currently in use, work by reacting the impure silicon with a reagent (such as chlorine or hydrogen) which reacts selectively with the silicon but not its impurities. The reacted silicon (the intermediate compound) is later decomposed into silicon and the reagent. Zone refining methods work by melting a small zone in rods of silicon of initially high purity. As the zone is moved, the silicon recrystallizes, sweeping away impurities and forming a single crystal. Reactive gas blow-through melt purification is actually the converse of the intermediate compound method; it operates by bubbling through the silicon a gas which reacts with the impurities to form compounds which boil out from the molten silicon.

C. CELL BLANK MANUFACTURING

After the silicon is purified it is formed into crystals and then cut into cell blanks. Two basic types of options for crystallization are available. A crystalline ingot of silicon can be produced using various techniques. Ingots are monocrystalline in structure; that is, each ingot is a single crystal. Methods for producing crystalline silicon may also produce silicon in a form containing many smaller crystals; a crystalline structure of this form is termed polycrystalline or semicrystalline, semicrystalline silicon containing larger crystals than polycrystalline. Photovoltaic cells made from monocrystalline silicon have higher cell efficiencies than cells made from polycrystalline or semicrystalline silicon; the monocrystalline silicon, however, costs more. The other type of option involves producing silicon crystals using non-ingot technologies. Non-ingot technologies produce silicon of various degrees of crystallinity, usually in ribbon or sheet form.

Ingot technologies include the standard Czochralski technique, the only process currently in production. In this technique a round seed crystal is placed into a crucible of highly pure molten silicon and slowly withdrawn; the molten silicon crystallizes on the crystal being withdrawn. Another ingot technique, zone refining, is discussed in Section B above. A third technique, the heat exchanger method, involves cooling the molten silicon in the crucible from the center outward. This has the potential advantages of producing larger crystals in the shape of the crucible (thus permitting square crystals and high packing factors) and of using lower-purity silicon initially, since zone refining apparently occurs at the solid/liquid interface.

Non-ingot technologies include several largely unrelated process possibilities. Ribbon technologies, such as Mobil-Tyco's edge-defined film growth (EFG) method and the dendritic web method, produce monocrystalline silicon (or nearly so) from molten silicon in thin ribbons, thus facilitating cell manufacturing (see below). Sheet technologies, such as Solarex's cast silicon process, peeled film technology, or chemical vapor deposition, produce a sheet of silicon which is not monocrystalline but polycrystalline or semicrystalline (and therefore lower efficiency). Sheet technologies have the potential for great cost-savings because they facilitate cell manufacturing and because they may be able to use 'solar grade' silicon, i.e., silicon purer than metallurgical-grade silicon but not as pure as (and not nearly so costly as) semiconductor-grade silicon. Finally, recent breakthroughs in the understanding of the operation of amorphous semiconductors make them a possibility. These semiconductors use inexpensive glasses rather than silicon of some level of purity and offer potential for radical cost reductions.

Once the silicon has been crystallized it must be cut into cell blanks for further processing. For ingot technologies cell blanks are created by slicing the ingot; during the slicing much silicon dust is produced which goes to waste. Research efforts here have been aimed at minimizing this waste and at producing thinner cells, thereby getting more wafers (cell blanks) from each ingot. Non-ingot technologies have the possibility of using simpler and inherently less wasteful techniques such as scribing the ribbon or sheet.

D. CELL MANUFACTURING

In this functional stage the cell blank is made into a photovoltaic cell, capable of producing electricity from sunlight. Current processes perform four basic operations upon the cell blank. The blank is first etched (roughened) to reduce reflectivity and thus improve efficiency. Next a p-n junction is formed from the topmost layer of this blank by diffusing into the silicon small quantities of impurities. (Different methods of junction formation are under research.) After the blank has become a semiconductor, a metal grid is attached to the top of the semiconductor to conduct electrons to the external circuit. Photolithography has been used, but screen printing appears to be precise enough for photovoltaic cells. Finally, an antireflective coating is put onto the metallized semiconductor's surface, completing the cell.

Non-ingot technologies permit drastic automation of the above steps. Currently these steps are done one at a time, and much labor is used to move the cell blanks through the steps. However, non-ingot technologies may permit the use of continuous processes rather than the current batch processes (see Figure 2.1). In these processes the ribbon or sheet would proceed from cell blank manufacture directly through cell manufacture.

E. MODULE MANUFACTURING

After cell manufacturing is completed, the electrical characteristics of the completed cells are measured. Thoe whose characteristics are similar are placed in a module and soldered together in series to form a string. The string is then covered with a pottant such as RTV which in turn may be covered by glass or lexan to increase durability.

FIGURE 2.1
PRODUCTION PROCESSES FOR MONO- OR SEMI-CRYST

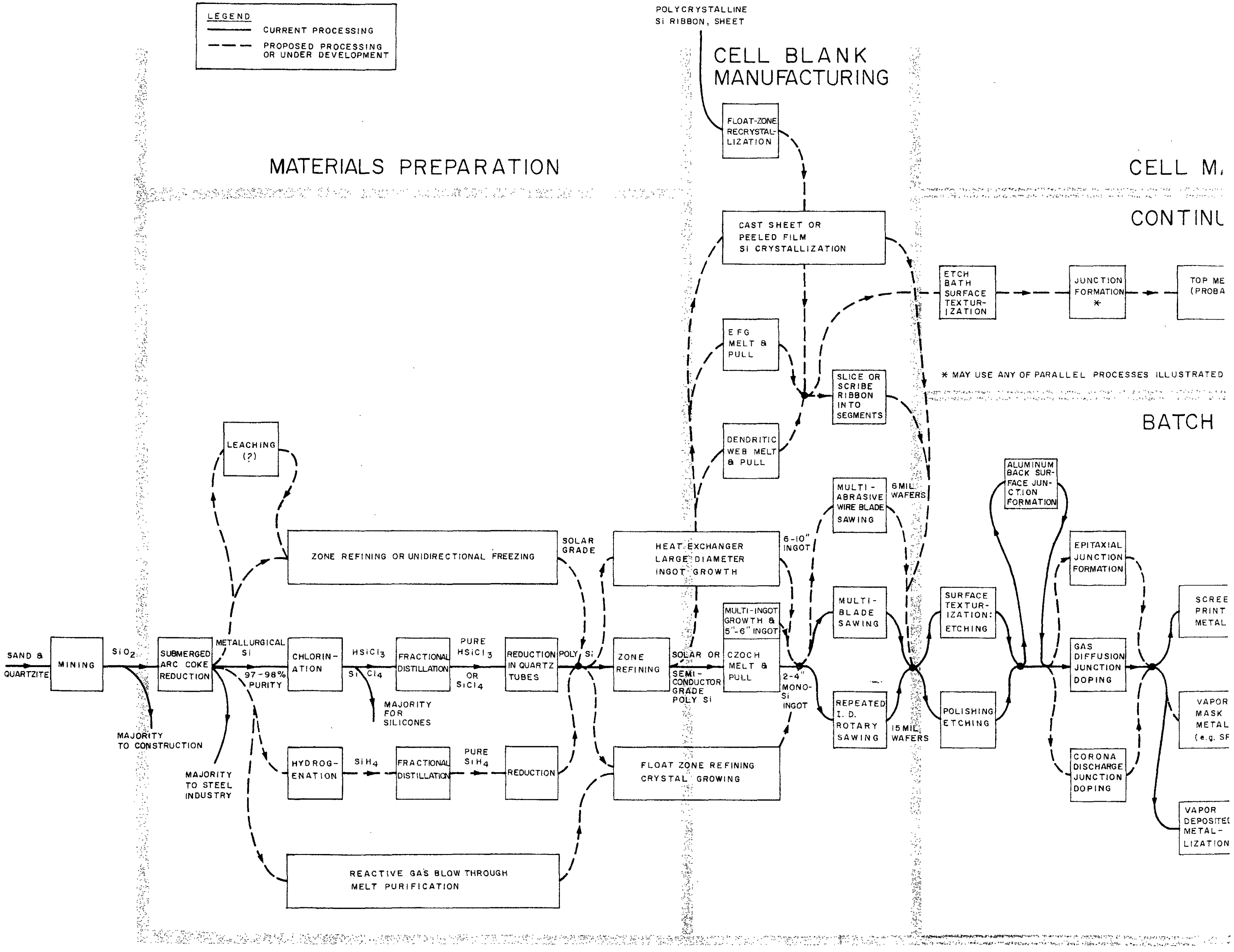
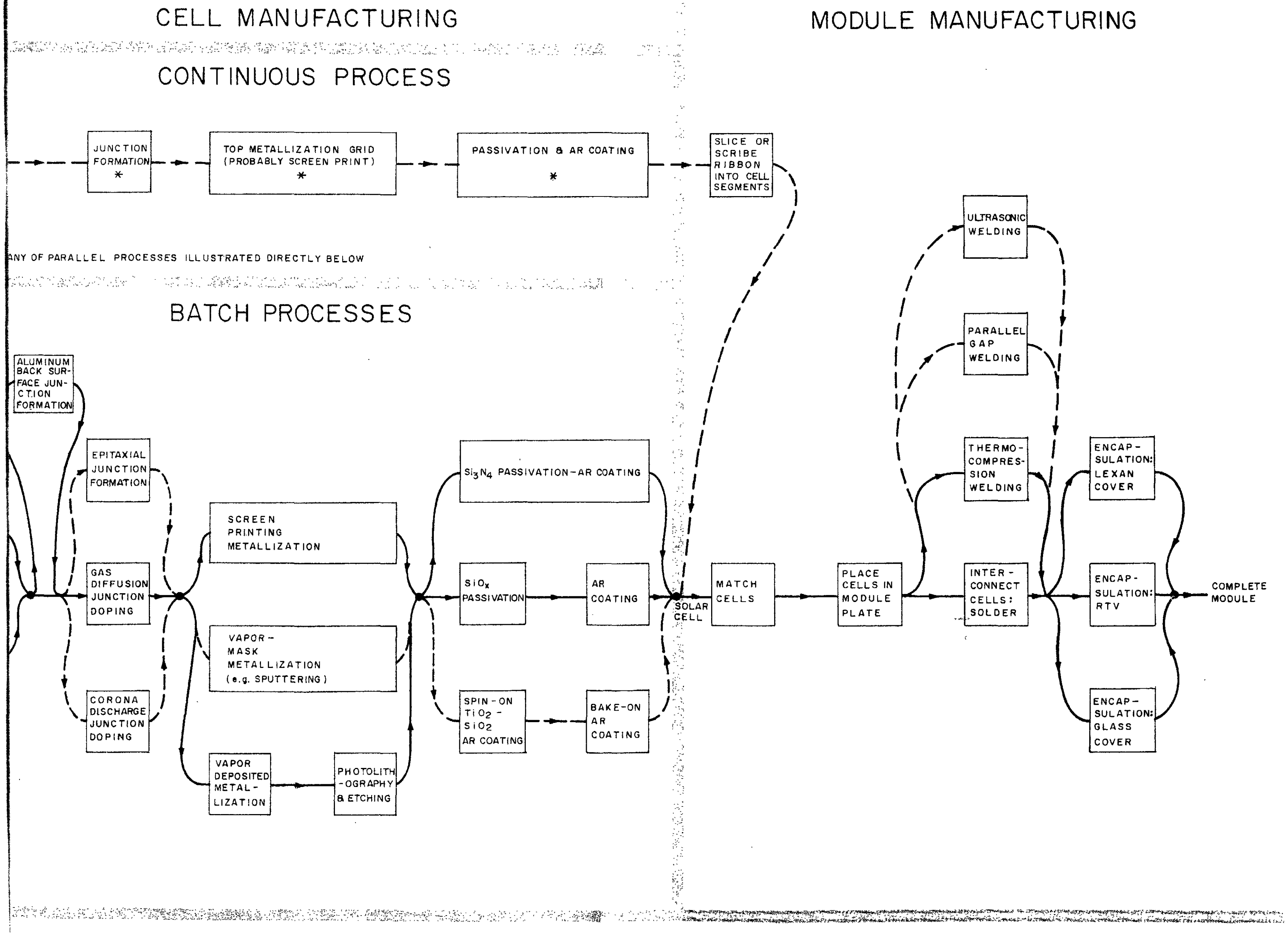


FIGURE 2.1

OR SEMI-CRYSTALLINE SILICON SOLAR CELLS



III. CADMIUM SULFIDE PROCESS TECHNOLOGY

Current cadmium sulfide process technologies are designed to produce photovoltaic cells from polycrystalline cadmium sulfide. Using polycrystalline cadmium sulfide allows the use of thin-film deposition techniques; these techniques permit flexibility in sequencing process steps. Cadmium sulfide photovoltaic production may be broken into five functional steps: raw material production, encapsulation, active layer formation, junction formation, and metallization. Due to the inherent flexibility of the process, the last three steps may occur in reverse order, and encapsulation occurs throughout the process.

Cadmium sulfide is mined as ore (greenockite); it is a by-product of zinc production and is used mainly as a pigment. The production process can be started from the cadmium sulfide directly or from elemental cadmium

Once the starting material is selected and purified sufficiently, production may begin without prior crystallization, unlike silicon processes. Early stages of encapsulation initiate the process. Current plans are for a hermetically sealed encapsulation of the cadmium sulfide cells to exclude all moisture and oxygen from the cells since cadmium sulfide cells degrade irreversibly in the presence of oxygen (either free or in water). The encapsulation would then consist of a metal substrate with a glass cover sealed to the substrate. The encapsulation process may begin with either the metal substrate or the glass; for simplicity we assume in the brief exposition below that it begins with the substrate. If it begins with the glass, the remaining three steps occur in reverse order from what follows, with the initial step being metallization onto hot glass.

Cell manufacturing begins by depositing a thin film of cadmium sulfide onto the substrate, usually by deposition in a vacuum but sometimes by sintering cadmium sulfide powder to the substrate. The cadmium sulfide layer may be deposited selectively upon the substrate, thereby creating several cell areas at once. Next, the p-n junction is formed by producing a thin layer of copper sulfide on the cadmium sulfide, either by dipping the substrate in copper sulfate or by spraying on a thin layer of copper sulfide. Finally, the cells are completed by the spraying of a transparent metallization layer or by the screenprinting of a copper metallization grid. Encapsulation is then completed by soldering the glass cover to the substrate and cell assembly, producing the finished module.

As the above description indicates, cadmium sulfide process technology is oriented toward chemical processes, as contrasted with current silicon technology, which is more physically oriented. Chemical process technology is probably a necessity for any thin film approach and is sufficient for realizing the potential for large cost reductions associated with sheet technologies. Thus, current cadmium sulfide process technology reflects features being sought by research on advanced silicon process technology.

IV. OTHER TECHNOLOGIES

Other technologies for photovoltaics differ from silicon and cadmium sulfide technologies in at least one of two ways: either the material from which the cells are made is different, or the nature of the p-n junction is different. While none of these technologies is available outside the research laboratory, their existence indicates that many opportunities for changing the design of photovoltaics exist which differ from present commercial technologies in many basic respects.

Of the many materials under research, gallium arsenide is particularly interesting because of its high efficiency which stays high at elevated temperatures. These characteristics suit gallium arsenide cells well to use in concentrator systems. Other materials under research include germanium, selenium, indium phosphide, copper sulfide, zinc sulfide, cadmium telluride, and indium selenide.

The p-n junction can differ from the standard model if it is created by the joining of two different materials. Such a junction is called a heterojunction; cadium sulfide cells use such a junction as they are formed by thin layers of cadmium sulfide and copper sulfide. Some research in progress includes joining a semiconductor material directly to metal. Other types of research in progress on the p-n junction include efforts to produce multiple junctions in the cells so that a greater fraction of the light reaching the cell is converted to electricity.

V. SUMMARY

As the above discussion shows, many options for technological advance exist in photovoltaics. These options may be summarized as follows, organized according to the degree by which they differ from the current approach:

1. Options for Monocrystalline Silicon Ingot Technologies

These technologies may be improved in several ways. First, methods for purifying the silicon may be improved, possibly eliminating one or more process steps. Second, better methods of making the silicon ingot are under research; these methods may permit the use of lower purity starting silicon than is now required. Third, the p-n junction may be modified to increase cell efficiency. Fourth, slicing techniques with higher yields may be developed.

2. Options for Non-ingot Silicon Technologies

Several different options exist for producing photovoltaics from silicon without using ingots. The essence of these options is a change in the way in which the silicon is crystallized. Monocrystalline ribbons are one possibility, and polycrystalline or semicrystalline sheet silicon is another. The latter may also be able to use lower purity silicon than is required for monocrystalline silicon. In addition to simplifying the cell blank manufacturing stage, these options can be used in continuous production processes, thereby facilitating cell and module manufacturing.

3. Advanced and Novel Materials Options

These options involve materials other than silicon, such as cadmium sulfide and gallium arsenide, and frequently involve heterojunctions. Many of the process technologies for producing photovoltaics from novel materials are non-ingot, including especially thin-film sheet technology, which is used to produce cadmium sulfide cells.

CHAPTER THREE: PHOTOVOLTAIC INDUSTRY PARTICIPANTS

I. HISTORICAL SUMMARY OF DEVELOPMENT OF PHOTOVOLTAICS AND PHOTOVOLTAIC PRODUCTION

Having previewed photovoltaic process technology in Chapter Two, we now proceed to discuss participants in the current photovoltaic industry and how the industry has reached its present state. This chapter opens with a brief historical summary intended to show the evolution of the technology in modern times and the concomitant industrial developments; the significance of this history will be explored further in Chapter Four. Following the historical summary is a discussion of current photovoltaic industry participants; these participants are grouped into several categories (explained below in Section II of this chapter) to aid analysis of the industry. Some broad comparisons of activities of firms by category conclude the chapter.

A. PHOTOVOLTAICS: DEVELOPMENT AND EARLY INDUSTRY

While the photovoltaic effect has been known to exist since Becquerel discovered it in 1839, it was not well understood until the mid-20th century, and efficiencies remained below 1%. With further understanding of the p-n junction and with the development of the transistor, efficiencies increased, and in 1954 Bell Laboratories invented the modern silicon solar cell. At this time research was continuing on other materials such as cadmium sulfide, cadmium telluride, gallium arsenide, copper oxide (Cu_2O), and selenium, with production runs being made on some (Wolf, 1972, pp. 120, 121).

With the developments at Bell Laboratories came early industrial efforts. A large terrestrial market was perceived, and development of certain applications was attempted. Two companies, Hoffman Semiconductor (later Centralab, still later, OCLI) and International Rectifier, opened production lines for silicon cells in 1956. However, the terrestrial market did not develop, although some photovoltaics were used for remote telemetry repeater stations in Japan as early as 1958 (Rosenblatt, p. 104). Nonterrestrial markets were not foreseen (Wolf, 1972, pp. 121, 123).

B. THE SPACE PROGRAM

As the space program developed through the late 1950s, the need for photovoltaics for space applications grew. For the space program, the ideal photovoltaic would have high efficiency, high power-to-weight ratio, and high reliability. These requirements suggest a monocrystalline wafer cut to allow close packing in the module, thus achieving a high packing factor and high module efficiency. Cell cost was not very important, since the major cost was placing the additional weight into orbit. Of the technologies then available, silicon best fit the desired characteristics. Because of ths fit, starting in the late 1950s a demand for silicon cells designed especially for the space program arose (Wolf, 1972, pp. 119, 120).

Production of silicon cells quickly rose to 10 kW/yr, salvaging the young photovoltaic industry. The two original entrants continued in business while Heliotek (later Spectrolab), RCA, and Texas Instruments entered the silicon photovoltaic field. Through the 1960s demand rose to a peak of about 70 kW/yr and then remained at that level; meanwhile, from 1964 through 1968, three of the five silicon photovoltaic manufacturers left the industry, leaving only Centralab and Heliotek (Wolf, 1972, pp. 120, 121).

While silicon cells were being produced for the space program, research continued upon other promising materials, including cadmium sulfide (see Shirland). Research in cadmium sulfide cells began in 1954 at Air Force Laboratories and Harshaw Chemical Company (now a division of Kewanee Oil) and continued at Clevite (now part of Gould), Eagle-Picher, and RCA (Shirland, pp. 44, 48 in Backus). Since no terrestrial market of any size existed, few sales occurred except those to the space program. Hence, due to the presence of a market for photovoltaics for space applications and the absence of one for terrestrial applications, most photovoltaics sold through 1972 used silicon cells and were designed for space applications.

C. GROWTH OF THE TERRESTRIAL MARKET

While some terrestrial applications for remote telemetry repeaters existed as early as 1958, 1972 marked the first year in which photovoltaics were produced specifically for the terrestrial market, when Solar Power Corp. and Solarex began operations (Inform, pp. 132, 133).

Modules produced for the terrestrial market did not need the close packing, high efficiency, high reliability, or radiation hardening required for space applications. Costs per peak kilowatt were therefore considerably lower than for space modules, but costs per kilowatt-hour were still considerably higher than the cost of power from electric utilities. Terrestrial applications to date have been in remote locations where connection to the grid was costly or impractical and the cost of transporting on-site generating equipment, petroleum products, or batteries is high.

One of the first applications was the mountaintop radio repeater. Prior methods of powering these repeaters used petroleum-fueled (usually diesel) or natural gas-fueled mechanical or thermoelectric generators and rechargeable or primary batteries. All of these methods required several visits yearly to the site by a technician to change batteries or to supply fuel. Solar Power Corporation claims that the initial $2,000 average incremental expenditure for a photovoltaic-powered mountaintop repeater repays itself in two to three years, considering the costs of transporting fuel and personnel to maintain the site otherwise (SPC, p. 2).

Navigational aids on buoys or oil platforms employing lights and horns as signalling devices have also formed a part of the market. The Coast Guard expects to have 20 photovoltaic-powered buoys and 30 fixed navigation markers off the South Florida coast this year (SEIR, December 6, 1976).

Solar Power Corporation considers railroad crossing signals to be a large future market and notes that there are 180,000 such unmarked crossings in the United States (INFORM, p. 112). Warning signs for highways are being explored by ERDA in an Arizona installation that until now has relied on propane-fueled 60-watt generators, cutting annual operating costs in half to $12,000 (Electronics, June 9, 1977). Highway call boxes using solar cells were installed in California as early as 1974 (Rosenblatt).

Some other present markets sharing the need for electric power in a remote location are TV and radio service to primitive African villages; cathodic protection for iron pipes, bridges, and other structures; crop irrigation; and novelty items (toys, watches requiring little power). Battery trickle-chargers for boats have been offered as a consumer item but have not sold well (Addiss).

Recently a nonmarket source of demand has developed. In 1976, Jet Propulsion Laboratory (JPL) began its Large-scale Procurement Task, part of the Low-cost Silicon Solar Array (LSSA) Project which JPL operates under contract from ERDA. The two "buys" which have occurred so far have been for 46 kW and 125 kW, with bids for a 200 kW "add-on" to the second buy submitted. Results of the first two buys are presented in Table 3.1.

Table 3.1

PURCHASES THROUGH LARGE SCALE PROCUREMENT TASK

Successful Bidders	First Buy: First Quarter 1976		Second Buy: Third Quarter 1976	
	Price (Current $)	Quantity	Price Current $)	Quantity
Solar Power Corp.	13.69/W	15kW	23.28/W	15kW
Sensor Technology	20.06/W	8kW	12.80/W	40kW
Spectrolab	25.20/W	10kW	17.55/W	40kW
M-7 International	27.96/W	3kW	-	-
Solarex	28.93/W	10kW	19.76/W	30kW

All watt figures are in peak units.

Source: Jet Propulsion Laboratory

II. CURRENT INDUSTRY

Involvement in the photovoltaic industry today takes one of several forms. Some firms manufacture photovoltaics; others perform research on various aspects of photovoltaic technology or production technolgy; some do both. Involvement by some firms is tentative, while others have committed or plan to commit large amounts of resources to photovoltaic research or manufacture.

In order to describe the industry we have organized the firms exhibiting these various kinds and degrees of activity in the photovoltaic industry into several categories. The categories depend upon the activity of the firm or its parent. That activity's relationship to present and possible future production of photovoltaics suggests possible economic motivations for firms in that category to commit resources to the photovoltaic industry; these motivations, and other comments, are discussed for each category of firms. Table 3.2 previews the categories, each of which is discussed in the text in its own section.

Table 3.2

CATEGORIES OF PHOTOVOLTAIC INDUSTRY PARTICIPANTS

1. Terrestrial photovoltaics manufacturers
2. Space photovoltaics manufacturers
3. Materials manufacturers
4. Semiconductor firms
5. Oil companies
6. Electrical equipment manufacturers
7. Research firms and others

Within each section the firms which the category comprises will be discussed. Some firms arguably fall under more than one category; when appropriate, the firm will be discussed under both categories. Also, our ability to classify particular firms is limited by our not having interviewed very many of them. To the extent that this limitation results in misclassification of a particular firm, the analysis drawn as it applies to that firm may be off the mark. However, we maintain that our analysis as it pertains to the categories of firms remains valid even if the application to a particular firm is in dispute.

Much of the data about the individual firms within each category is summarized in the tables which follow, presenting:

1. Each firm in the category in alphabetical order.
2. The firm's photovoltaic technologies, including both technologies used for production and technologies under research.
3. The development stage of the technologies. We use five development stages: research, initial development, final development, introduction, and production. These stages closely resemble others used elsewhere (see, for example, MIT Energy Laboratory, pp. 41 *et seq*., and ERDA 76-1, vol. I, p. 56). Here they serve to indicate the nearness of the technology to production and the orientation of the firm's activity toward the technology.
4. Federal support for each technology, ranging from "None" to "All". If more specific information, such as percent of funding which is federal, is available, it is given; a question mark following the entry indicates uncertainty about the correctness of the entry, and a "Yes" indicates uncertainty whether internal funds are also used.
5. Comments, if any.

Our categories of development stages are worth amplifying further. In general, as a technology proceeds from research to production the details of how it can best be utilized are worked out and transformed from concepts to physical facilities through the directed efforts of the firm involved. In research, initial development and final development R&D efforts are aimed at gaining technical knowledge; in general, no sales of actual products are made. In the research stage, efforts aim toward understanding the technology's underlying processes, while in the initial development and final development stages, firms direct their attention toward applying the knowledge gained from research to production. Initial development and final development differ in the number of significant research steps or hurdles remaining to completion; note that this distinction does not include a time element, since the last hurdle for one technology may never be crossed while the last ten for another technology may be crossed rapidly. The number of steps remaining, not the time remaining, forms the basis for distinction. Production involves a market transaction for the product. Firms in the intervening stage (introduction) utilize pilot plants, test sales, etc. to introduce the new technology into the market. (A much more detailed description is given in MIT Energy Laboratory.)

The information presented in the tables provides part of the basis for discussing the activities within each category of firms; the rest of the basis follows from Chapter Two or appears directly in the text.

A. TERRESTRIAL PHOTOVOLTAICS MANUFACTURERS

Members of this category include those firms whose production is, to our knowledge, principally directed toward production of photovoltaics for the terrestrial market. Firms not yet producing for immediate profit are excluded. Some firms in this class produce space cells, and space cell manufacturers produce for the terrestrial market, so the cleavage between this category and the following is not clean. Also, one member of this category, Solar Power Corporation, is an oil company subsidiary, and will also be included under oil companies; it is included here to show the similarity of its activities to the other terrestrial cell manufacturers.

Firms in this category address their activities directly to today's terrestrial market which consists of remote applications of photovoltaics. Their interests lie in developing the current and near-term markets for terrestrial photovoltaics, and their technology and marketing operations are addressed to the needs and scale of those markets.

As shown in Table 3.3, all firms in this category use monocrystalline silicon cells in their modules. Some buy ingots and cut wafers from them, while others buy wafers directly. Modules are assembled largely by hand from cells also manufactured largely by hand. Several manufacturers in this category see cost reduction occurring through production and further refinement of the Czochralski process (Lindmayer, 1975, pp. 2373-79; Rubin; Yerkes). We think, however, that the Czochralski process has only a limited potential for cost reduction, and at some rate of production other technologies will dominate. (When or whether this rate will be reached we do not guess.)

Even if breakthroughs do occur with some of the more promising technologies such as EFG, one manufacturer suggests that it would license or purchase whatever it needed to continue production (Yerkes). This possibility may suggest a break in the vertical structure of the industry, with those experienced in assembly, arraying, and marketing purchasing crystalline silicon from others (Yerkes).

Firms in this category, with one exception, are privately held; hence they do not have access to large amounts of a parent corporation's capital.[1] Their internally funded research therefore tends to be shorter-range in nature and usually is closely tied to current production processes or the next foreseen improvements. Table 3.3 shows that all but one have received federal support through the Large Scale Procurement Task, Spectrolab being the only solvent nonterrestrial manufacturer also to receive similar support (see Table 3.1 above). Also, production-related R&D has also received federal R&D support. Interestingly, the research which these firms have undertaken on advanced and polycrystalline materials has not received federal support but has proceeded with internal funds.

Firms without immediate access to large sources of capital sometimes obtain needed capital by affiliating with larger companies. All firms in this category except Solar Power Corporation share this possibility. However, the initial formation of these firms seems to have taken place as spin-offs from larger firms. Three firms were founded by photovoltaic experts who left other companies. Joseph Lindmayer, formerly director of Comsat's Solid State Research Lab where he performed research on space cells, left Comsat in 1973 to form Solarex, now one of the largest solar

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[1] Even the exception, Solar Power Corporation, behaves largely as though it were unaffiliated. Its activities, particularly R&D, are tied to its production activities; Exxon Research and Engineering performs the longer-range research for Exxon (Addiss).

TABLE 3.3

TERRESTRIAL PHOTOVOLTAICS MANUFACTURERS

FIRM	TECHNOLOGY	DEVELOPMENT STAGE	FEDERAL SUPPORT	COMMENTS
Sensor Technology	Monocrystalline silicon	Production	Procurement Program	$10,000,000 sales in 1976, PV's included
	Monocrystalline silicon mass production techniques	Initial Development	Yes	
Solarex	Monocrystalline silicon	Production	Procurement Program	$400,000 to start company; annual sales of $1,000,000
	Semicrystalline cast sheets	Initial Development	None	
	Vertical junction grooved cells	Initial Development	None	
	High efficiency silicon cells	Initial Development	Yes	
Solar Power Corporation (Subsidiary of Exxon)	Monocrystalline silicon	Production	Procurement Program	
Solar Technology	Monocrystalline silicon	Production	Yes	
	Monocrystalline silicon mass production techniques	Initial Development	Yes	
	Cast sheet cells (Wacker semicrystalline material)	Initial Development	None (?)	
Solec	Monocrystalline silicon	Production	None	

cell manufacturers. William Yerkes, founder of Spectrolab, left when Hughes bought it in 1975 and founded Solar Technology. Rubin, co-founder of Sensor Technology, was in charge of space cell manufacture at Hoffman Semiconductor, then at International Rectifier. In 1966 he left to found Sensor Technology. In fact, the possibility of affiliating with larger companies may have motivated the formation of several of these firms. In Section E below we note several instances in which smaller companies have affiliated with larger companies.

B. SPACE PHOTOVOLTAICS MANUFACTURERS

This category comprises manufacturers whose photovoltaic efforts have been directed primarily toward production of modules for use in space. The relatedness of their product to that sold in the terrestrial market motivates their participation in the terrestrial market.

While the technology is quite similar, differences exist. Space cells must be of higher quality than terrestrial cells, and would not contain solar-grade silicon. Photolithography will probably not be replaced by screen-printed metallization. Diffused layers above the junction must be thinner to increase sensitivity to ultraviolet light. Lastly, the cost of putting any weight into orbit requires high packing ratios.

Such cells produce modules higher in price than terrestrial ones, although superior in many ways. However, the superiorities gain the modules no cost-effective advantages in the terrestrial market.

Space cell manufacturers grow their own silicon crystals because they must meet traceability requirements for space and military

TABLE 3.4

SPACE PHOTOVOLTAICS MANUFACTURERS

FIRM	TECHNOLOGY	DEVELOPMENT STAGE	FEDERAL SUPPORT	COMMENTS
Hughes: Research Labs	High-efficiency cells	Research	All (?)	
	Thin film InP/CdS	Research	All (?)	
Spectrolab (Subsidiary of Hughes)	Monocrystalline silicon	Production	Procurement Program	
	Monocrystalline silicon mass production techniques	Initial Development	Yes	
Optical Coating Laboratories, Inc. (OCLI)	Monocrystalline silicon (designed for ruggedness)	Production	None	$750,000 sales in remote PV's in 1975
	Advanced space cells	Initial Development	80%	

customers, making them more highly integrated than terrestrial manufacturers.

Both surviving space cell manufacturers bid in the Large Scale Procurement Task, with one's bid being accepted. Other federal support of these firms for research has addressed mass production techniques, high-efficiency cells, and advanced material research. Little internally funded research appears to be ongoing, even though both manufacturers are owned by, or are part of, larger firms. (See Table 3.4.)

C. MATERIALS MANUFACTURERS

The firms falling within this category manufacture or prepare materials which are or might be used to produce photovoltaics. Their interests follow from the possibility of high growth of the photovoltaic industry, thus producing an increased demand for their products, which range from silicon material to AR coatings to glass substrates for CdS cells.

These firms face uncertainties in the size of the market for their products in the photovoltaic industry for two reasons. First, the rate of the photovoltaic industry's growth is uncertain, thereby making the potential market for materials products as a function of price also uncertain. Second, the cost of photovoltaics is also uncertain, making the market equilibrium uncertain even if the demand curves for the materials products are known. Furthermore, if large cost reductions obtain, the technology which will be used to achieve such cost reductions cannot safely be predicted, and long-range technologies vary considerably in some of their components; therefore, a product currently a component

TABLE 3.5

MATERIALS MANUFACTURERS

FIRM	TECHNOLOGY	DEVELOPMENT STAGE	FEDERAL SUPPORT	COMMENTS
American Cyanamid	AR coating	Research	All	
Crystal Systems	Large ingot growth	Initial Development	Yes	
Dow Corning	Solar grade silicon	Initial Development	Approximately half	A major supplier of semiconductor-grade silicon
Monsanto	Silicon material	Research	Yes	A major supplier of semiconductor-grade silicon
Photon Power (Libbey-Owens subsidiary)	CdS spray onto hot glass	Final Development	None (?)	Libbey-Owens owns 39% of stock
PPG	CdS spray onto glass	Research	None (?)	
Tyco Labs/Mobil-Tyco	EFG	Final Development	None	
Union Carbide	Silicon purification	Initial Development	Yes	

may not be so in the long run. Also, since the total cost reduction depends upon the reduction of component costs, the degree of uncertainty in total cost reduction depends upon the degree of uncertainty in reducing the costs of the materials manufacturer's own product and varies with the product, being in our opinion greatest with silicon purification, crystallization, and cell blank manufacturing.

We venture no hypotheses as to the effects of these simultaneous uncertainties upon the privately funded R&D activities of these manufacturers. However, Table 3.5 shows that the bulk of Czochralski-related R&D has received federal support while ribbon and CdS R&D have been privately supported. Also, one manufacturer, Libbey-Owens, owns a minority interest in Photon Power, a corporation planning production of cadmium sulfide cells.

D. SEMICONDUCTOR FIRMS

This category comprises firms who make semiconductors, generally for inclusion in their own products. Since photovoltaic cells are semiconductors, the interests of these firms in photovoltaics derive from the possibility of a new and growing market for one of their products. Arguably, then, this category falls within the preceding category of materials maufacturers; however, the process for manufacturing semiconductors has several important steps in common with photovoltaic manufacture, and hence we treat semiconductor firms separately.

The steps in photovoltaic manufacture from crystal growth and slicing through metallization correspond to similar steps in semiconductor manufacture. To the extent that the experience gained in the semiconductor industry on these steps can be applied to photovoltaic manufacture, it will benefit semiconductor firms entering the flat-plate photovoltaic industry and provide an incentive for them to do so.

However, several factors suggest that this experience will not prove highly useful, and that the production processes for photovoltaics and for other semiconductors are diverging, not converging.

1. Mass production techniques in the semiconductor industry do not require large throughput of wafers, since each wafer can produce chips for hundreds of devices, whereas the photovoltaic industry clearly requires automatic handling of large areas of silicon.[1] Thus, much of this automation in the present semiconductor field is in processes that are irrelevant to solar cell manufacture, e.g., dice slicing, multiple photolithography and etching steps, tiny epoxy packaging, dice (chip) handling, etc. (Lyman). For example, while the semiconductor device manufacturers are contemplating the switch to electrolithography because the light beam wavelengths (.0004 mm) used in conventional photolithography have become too blunt an instrument for future progress (Electronics, May 12, 1977, pp. 90-98), photovoltaic manufacturers are changing over from photolithography to screen printing, a less precise but cheaper method of metallization.

2. The direction of development in the semiconductor industry has been toward developing highly articulated structures for integrated circuits, a direction which probably will produce nothing of value for photovoltaics and actually results in the handling of smaller silicon chips, therefore separating the process even further from photovoltaic manufacture.

3. Since the cost of the silicon has been a small part of the semiconductor's cost, cost-reduction efforts in the semiconductor industry have not been aimed at the silicon itself; the opposite is necessary in photovoltaics.

4. Since the semiconductor industry requires high-purity monocrystalline silicon, it has no experience with solar-grade silicon, thin film materials, or other novel technologies (many of which are "chemistry-based") which show possibilities for cost reduction of flat plate technology in the long run.

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[1] In fact, one manufacturer of photovoltaics (Solarex) claims that it currently handles as many silicon wafers as the big semiconductor companies (Lindmayer, 1977).

Thus, conveniently similar technology is the tie of the semiconductor firms to photovoltaics, but that technology may be precisely the obstacle to long-run commercialization of flat-plate photovoltaics.

Table 3.6 shows the activities of semiconductor firms. The two firms close to production have reached that state with little or no federal support, while the remaining firms are developing production techniques with federal support. Each of the major semiconductor firms (RCA, Texas Instruments, Motorola) received more than $1,000,000 in ERDA research money in 1976 (ERDA 76-161, pp. 8-16) while in the same year all oil companies combined received less than $700,000. Also, some activity appears concerning advanced and novel techniques, and it has partial federal funding.

Several of the semiconductor firms were involved in the initial space market, as set forth in Section I.B above. It is not known whether the size of the early market led to the withdrawal from the market by several of the firms; however, small market size may be inhibiting entry of some semiconductor firms.[1] These firms may be waiting until the price of photovoltaics drops to a point at which a larger market, different in kind from the current remote terrestrial market, opens. (For further discussion of the possibilities of segmentation of the photovoltaics market, see Chapter Four, Section IV below.) Also, semiconductor firms face a steadily growing market for their product (unlike oil companies -- see Section E below) and do not "need" to diversify in order to protect their industrial position.

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[1] According to Gene Wakefield of Texas Instruments: "Terrestrial solar cells are not a near term business of any magnitude; no major company is going to spend its time for peanuts." (INFORM, p. 137).

TABLE 3.6

SEMICONDUCTOR FIRMS

FIRM	TECHNOLOGY	DEVELOPMENT STAGE	FEDERAL SUPPORT	COMMENTS
International Rectifier	Monocrystalline silicon	Prepared for production but inactive	None	Former space cell manufacturer
Motorola	Monocrystalline silicon	Introduction	None	Received over $1,000,000 in federal research contracts in 1976
	Monocrystalline silicon mass production techniques	Final Development	Most (?)	
	Sheet silicon production	Initial Development	Some	
RCA	Sheet silicon	Initial Development	Yes (50%)	Former space cell manufacturer
	Monocrystalline silicon mass production techniques	Initial Development		
	CdS, polycrystalline silicon, epitaxial growth, amorphous	Research		
Texas Instruments (TI)	Monocrystalline silicon mass production techniques	Initial Development	Almost all	Former space cell manufacturer
	Polycrystalline silicon mass production techniques	Initial Development	Almost all	

E. OIL COMPANIES

Subsidiaries or divisions of oil companies fall within this category. Generally efforts here involve a separate corporation owned at least 50%, and perhaps entirely, by an oil company. In 1970, Exxon founded and continues to fund Solar Power Corp., which makes cells based on current wafer technology. Mobil Oil has provided all of the funding required ($2,000,000) to launch and maintain Mobil-Tyco Solar Energy Corporation and expects to have $30,000,000 invested in Mobil-Tyco by 1982 (Inform, p. 120). Shell Oil started SES, Inc., a prospective cadmium sulfide solar cell manufacturer, with a $3,000,000 stock purchase in 1973 (40%). It recently acquired another 40% with a $3,600,000 investment. Compagnie Francaise des Petroles, France's largest company and one of the world's largest oil companies, acquired 90% of Photon Power in December, 1976, and plans to have over $2,000,000 invested by June, 1978 (Wall Street Journal, December 29, 1976, p. 4). It subsequently resold 39% to Libbey-Owens, retaining majority ownership for itself.

Oil companies operate in an era in which the price of their primary product has risen and reserves of it are depleting, thus providing increasing incentives for consumers to find substitutes for oil. They have been performing research upon and investing in non-oil energy sources; some of these sources have production processes related to oil production, while others do not. Oil companies have expertise in applications of many chemistry-based techniques. This expertise may be of use in developing and producing photovoltaics which use thin-film processes, and may explain why the only two domestic efforts toward production of cadmium sulfide photovoltaics come from oil company subsidiaries.

Some of the energy efforts of oil companies seem aimed at close substitutes for oil (generally other fossil fuels), while others, such as photovoltaics (and also nuclear, geothermal and others) seem aimed at less substitutable energy sources. At some point production of oil will peak and then decline. When this occurs, oil companies will have tremendous financial resources for moving into other energy areas. By expanding into other energy markets these firms will be able to maintain their relative size and importance within the industrial sector.

Because of the situation described above facing the oil companies, oil company efforts in development of new energy technologies may be riskier than efforts of other firms. Efforts by oil companies in new energy technologies might be more important to the oil companies' maintaining relative size and industrial status than such efforts would be to other companies since new energy technologies are substitutes in part or in whole for existing products of oil companies rather than mere additions to product lines of other firms. Failure to invest in potential substitutes for existing products may have graver consequences for a firm than failure to add new products when markets for existing products are stable or growing; hence an oil company may be less bothered by the degree of technological uncertainty associated with a new energy technology and hence more willing to risk an investment.

Oil company efforts with photovoltaics have been largely production-oriented, as shown in Table 3.7; the production-oriented efforts have received little federal support. Some federal support has been received for EFG and organic photovoltaics. While federal support has been by and large refused, one should note the size of the private investments contemplated, as shown under "Comments" in Table 3.7. These can be compared with the projected federal budget for photovoltaics for FY 78 of $57 million.

Some federal concern exists about the horizontal spread of oil companies into non-oil energy markets. The Federal Trade Commission has undertaken a study of possible anticompetitive aspects of the photovoltaic industry, and plans a conference later this year on the industry's structure, concerning (*inter alia*) the ability of oil companies to achieve a technological breakthrough which will allow them to corner the market (Solar Outlook, July 11, 1977). Also, federal horizontal divestiture legislation has been proposed which would inhibit oil company involvement in non-oil energy production.

F. ELECTRICAL EQUIPMENT MANUFACTURERS

Firms here produce central power stations and related distribution, conversion, and utilization equipment. One (General Electric) also makes large power semiconductors used for controlling and switching electric power in heavy power-handling equipment.

To some extent, photovoltaics complement some of the products these manufacturers produce which consume electricity.[1] Any technology which could lower the cost of electricity for some applications would increase the demand for products used in those applications and could create a demand for new products.

TABLE 3.7

OIL COMPANIES

FIRM/SUBSIDIARY	TECHNOLOGY	DEVELOPMENT STAGE	FEDERAL SUPPORT	COMMENTS
CFP/Photon Power	Cadmium Sulfide	Introduction	None	Owns 51% interest; Plans to invest $2,000,000 by 1977-78
Exxon/Exxon Research & Engineering	Undisclosed polycrystalline silicon	Initial Development	None	$3,000,000 so far; 20 researchers
	Photogalvanic-organic photovoltaics	Research	Some	
Exxon/Solar Power Corporation	Monocrystalline silicon	Production	Procurement Program	
Mobil/Mobil-Tyco	EFG	Final Development	Some	Plans to invest $30,000,000 by 1982
Shell/SES	Cadmium Sulfide	Introduction (plant ready to open)	None	$10,000,000 invested through 1977; $10 - 100,000,000 more in next 5-10 years; 80% owned by Shell

Westinghouse and General Electric also make central power generation equipment for which photovoltaics may substitute in part at some time (see Table 3.8). Both have conducted federally supported studies of the use of photovoltaics for central power generation. The existence of competitively priced photovoltaic central power generation equipment could affect the demand for other types of central power generation equipment and may be one reason for the two firms' interest in photovoltaic central power generation. Thus their work on photovoltaics, like their work on other new electric power generation technologies, seems aimed at preserving their role in this market.

Other than central power system studies and McGraw-Edison's small production line, efforts have covered federally supported studies of advanced silicon technologies and privately supported cadmium sulfide studies.

G. RESEARCH FIRMS AND OTHERS

Many of the remaining firms involved in photovoltaics are research firms, as Table 3.9 shows. Some perform studies under federal contract; their product is the research and and their customer the federal government. Others perform research with internally generated funds.

This latter group of research firms performs research with a view to marketing it. Their research is their final product, and their market the private sector. Firms in this group generally have large research

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[1] G.E., the largest manufacturer of electrical equipment, makes no secret that one of its motivations in investing in photovoltaic is to help establish electricity as the universal energy "currency" and hence maximize the role of electricity in U.S. energy consumption.

TABLE 3.8

ELECTRICAL EQUIPMENT MANUFACTURERS

FIRM	TECHNOLOGY	DEVELOPMENT STAGE	FEDERAL SUPPORT	COMMENTS
General Electric	Sheet silicon processes	Initial Development	Yes	10 photovoltaic workers
	Polycrystalline silicon	Initial Development	Yes	
	Central Power Systems studies	Initial Development	Yes	
	Thermomigration	Research	None	Has patent covering photovoltaic uses
McGraw-Edison	Monocrystalline silicon	Production	None	As part of battery charger; expects 16kw production in 1977
Westinghouse	Thin film silicon	Research	Yes	
	Dendritic web	Initial Development	Some	
	Central Power Systems studies	Research	Yes	
	Cadmium Sulfide	Initial Development	None	

TABLE 3.9

RESEARCH FIRMS AND OTHERS

FIRM	TECHNOLOGY	DEVELOPMENT STAGE	FEDERAL SUPPORT	COMMENTS
Arthur D. Little	Satellite solar power station	Research	Some	
	Ribbon gallium arsenide	Research	All	
Bell Labs (subsidiary of AT&T)	Large scale manufacturing process	Initial Development	None	
	Thin film polycrystalline	Initial Development	None	
	Heterojunction work	Initial Development	None	
Boeing	$CuInSe_2$ cells	Research	Yes	
	Satellite solar power station	Research	All	
Cemstat	High efficiency silicon cells	Final Development	None	Licensed to OCLI; 5 photovoltaic researchers
Energy Conversion Devices	Amorphous, chalcogenic glasses	?	?	Insufficient information
Honeywell	Dip-coating polycrystalline silicon	Research	Yes	
IBM	Ribbon, polycrystalline silicon	Initial Development	Some (½ since 1973)	$500,000 invested since 1975
	Gallium arsenide high efficiency cell	Final Development	No	9 GaAs workers

TABLE 3.9 (cont.)

FIRM	TECHNOLOGY	DEVELOPMENT STAGE	FEDERAL SUPPORT	COMMENTS
MITRE	Test system evaluation	Research	Yes	
Rockwell	Chemical vapor deposition, thin films, encapsulation, gallium arsenide	Research or Initial Development	Yes	
Stanford Research Institute	Chemical vapor deposition	Research	Yes	
Varian Associates	Silicon ingot multiblade slicing	Final Development	Yes	
	Thin film gallium arsenide	Initial Development	Yes	
	Concentrating systems	Final Development	Yes	

facilities, and patents sometimes are by-products of other research aimed at development of other products. Generally federal support is refused so that the firm may retain private ownership of the patents. These patents serve as inputs to the photovoltaic industry and revenue-producing products of the research industry.[1].

A few firms in this category do not fall neatly into either group of research firms. Some may have an interest in a specialized market such as Comsat may have for photovoltaics for communications satellites; others may have interests in a long-range, low-probability market developing. One (Energy Conversion Devices) may properly be said to have commercial intentions; however, we know little of its activities except that production is not imminent.

H. SUMMARY

Table 3.10 summarizes the production and R&D activities for the seven categories of firms discussed above. The table is broken down by category of firm and by the type of industrial activity, ranging from production using available techniques through R&D activities aimed at technologies quite different from the present. For each entry on the tables the qualitative fraction of firms pursuing the activity is indicated (all, most, some, none), followed by the degree of federal

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[1] Legal restrictions may limit the profitability of the research products. In particular, a court decision forced Bell Labs to make the original silicon solar cell patent generally available without cost (Inform, p. 106), and AT&T is legally prohibited from manufacturing and marketing equipment not directly concerned with communications.

Table 3.10

PHOTOVOLTAIC PRODUCTION AND R & D ACTIVITY BY CATEGORY OF FIRM

Category of Firm	Silicon Photovoltaic Production		Monocrystalline Silicon Ingot R & D		Non-ingot Silicon R & D		Advanced and Novel Materials R & D		Miscellaneous	
	Activity	Federal Support	Activity	Federal Support	Activity	Federal Support	Activity	Federal Support	Activity	Federal Support
Terrestrial Photovoltaics Manufacturers	All	Most	Most	Most	Some	None				
Space Photovoltaics Manufacturers	All	Some	Some	All(?)			Some	All(?)		
Materials Manufacturers			Some	All(?)	Some	All(?) except EFG	Some	None(?)		
Semiconductor Firms			Most	Most	Some	Most	Some	Some		
Oil Companies	Some	Some			Some (EFG)	None	Some	Some	CdS production and production R & D	None
Electrical Equipment Manufacturers	Some	None			All except producer	All(?)	Some	All(?)	Central power system studies	All(?)
Research Firms and Others			Some	Some	Some	Some	Some	Some		

support for those firms pursuing the activity. Uncertainty in the correctness of an entry is indicated by a question mark following the entry, and qualifications are included in the entry.

In this table we can clearly see the differences in behavior between the categories of firms. First, aside from some work done by "research firms and others," most of the firms involved with silicon photovoltaics (production of photovoltaics, semiconductors or silicon) are doing work on monocyrstalline silicon process technology; oil companies are conspicuously absent. Most of the work in this areaa, across all the categories of firms involved, is federally funded. Second, some firms in every category except the space cell manufacturers are exploring non-ingot silicon technologies; much of this work is federally funded. Third, some firms in every category except the terrestrial photovoltaic manufacturers are working on advanced or novel material developments, and much of this is also federally funded. Fourth, only the oil companies are involved with cadmium sulfide technology. Fifth, and finally, only the oil companies' activities and those activities of the terrestrial photovoltaic manufacturers not directly related to current production are without significant federal support.

In this chapter we have reviewed the pattern of behavior within each category of firms involved with photovoltaic production or development activity, and we have looked at differences between the categories as well. The most important observations concern the three categories of firms which are now producing photovoltaics or which seem close to doing so, namely the present manufacturers, the semiconductor manufacturers, and the oil companies.

The present manufacturers are focusing their efforts on current production. As relatively small firms in a new and uncertain business, their access to capital is limited and the revenues from actual sales are important. Most of the research carried on by these firms is closely related to current production processes. Two of them, however, have extended the entrepreneurial spirit in which they were founded into the domain of technological _innovation_ as well _and_ are working with non-ingot silicon technologies.

The semiconductor firms involved in photovoltaics are not currently engaged in production. They are large firms whose principal technology is in some ways related to current photovoltaic technology, and they are generally working toward ways of entering the photovoltaic market by applying their presumed mass production know-how to modify monocrystalline silicon processes. Presumably they are interested in the expanded market potential following from the lower costs of their processes.

The oil companies have taken a completely different technological tack. One, Exxon, has organized a subsidiary (Solar Power Corp.) which appears to be behaving like the other present manufacturers and is conducting research at its corporate laboratories. Two others, CFP and Shell, have invested in cadmium sulfide technology, and appear to be near production. A fourth, Mobil, has pioneered in a non-ingot silicon process. With the exception of the activities of Solar Power, the oil companies are, like the semiconductor firms, looking beyond the present market. Unlike the semiconductor firms, they are concentrating on technologies which are quite different from those currently in use.

In the following chapters we will explore some of the reasons for, and the policy implications of, these behavior patterns.

CHAPTER FOUR: TECHNOLOGY DEVELOPMENT AND PRODUCTION IN SOLAR PHOTOVOLTAICS: AN ANALYTICAL FRAMEWORK

I. INTRODUCTION

The objective of this chapter is to describe the initial development of a conceptual model or framework of the processes of technology development and of production in the photovoltaic industry. In the present manufacture of photovoltaic arrays or modules a set of techniques, or "blueprints" for production, are being utilized. New production techniques are being developed which may bring about new process or product improvements. The ultimate purpose of the framework is to facilitate the analysis of the factors involved in firms' investment decisions with regard to development of new technologies, as well as with regard to their adoption or commercialization.

A literature review was undertaken to guide in the development of the model (Ocasio). Although the literature surveyed yielded some useful insights into the technological development of invention process and their adoption or commercialization, no general theory exists which can begin to explain a major portion of the factors which appear to be influencing the photovoltaic industry. As Nelson and Winter have noted, "prevailing theory of innovation has neither the breadth nor the strength to provide much guidance regarding the variables that are plausible to change, or to predict with much confidence the effect of significant changes" (p. 38).

Most economic theory treats technological change as "exogenous," that is, as an independent phenomenon unaffected by the events and features of the economic system. This is not due to lack of interest in technological change; a quick glance at any detailed bibliography on the subject will rapidly confirm that a large amount of literature has been concerned with it. But this literature has not been integrated into the traditional analysis of resource allocation. Studies by Nordhaus (1969) and Binswanger (1974) are notable exceptions and while these yield useful insights, their highly restrictive assumptions make their application untenable. Rather, it is our contention that the treatment of technological change as exogenous appears to be due to inconsistencies between technological change and the equilibrium nature of traditional economics. Bliss, in his treatise on capital theory is quite candid about the problems in incorporating technological change into economic theory in general and growth theory in particular:

> ...technical progress is scarcely compatible with (equilibrium growth), unless it be the most simple and unconvincing form. Apart from the problem of imperfect foresight there is even more impossible difficulty. Normally technical progress must fundamentally alter the structure of the economy so that there is impossibility of the pattern of previous events repeating themselves. (p. 11)

This leaves us with little foundation to rely upon. Rather than attempting to apply a particular theory to the case of the photovoltaic, ignoring the inconsistencies that would result between the theories and the facts, we have taken another route: that of building a simple, qualitative model of the economic structure of the industry. The literature review provided some of the "building blocks" for the development of the conceptual framework.

The model is based on the premise that an understanding of the technology development and production processes involves an understanding of the economic structure of the industry. By the phrase, "technology development and production processes," we mean to consider jointly the processes of the development of new technology and the production of products embodying a given level of technology; that is, we view the new technology as evolving "endogenously," as part of the economic system. The structure of that system is defined in terms of prices and markets, as well as of organizational or institutional phenomena. In a world of perfect competition, prices and markets are sufficient to understand economic activity. But the presence of market failures draws responses from organizations (government, firms, social institutions); the allocation of resources for technology development and production is thereby affected. This emphasis on institutional characteristics departs from traditional economics. More fundamental research is needed to achieve a better understanding of how structural and institutional behavior affects the allocation of economic resources.

The conceptual framework was developed to serve two principal purposes within the context of the goals of this study: first, to provide a structure for organizing our present understanding of the investment and production activities of the photovoltaic industry, and second, to yield useful hypotheses about the factors influencing present and future industry behavior, particularly with respect to firms' investment.

As described in the two previous chapters, important phenomena occurring in the photovoltaic industry greatly complicate our analysis.

Government intervention in the technology development process is important. The industry itself is just beginning to take form and there are substantial indications that the market structure is evolving rapidly. Uncertainties about future technological developments as well as of competitive products in other industries is pervasive. These as well as other complicating factors are all playing a crucial role in the formation of the industry and therefore cannot be ignored. These structural characteristics are to be incorporated into our model.

In Section II we develop the simple market framework which serves as a focus for all subsequent analysis. Initially we study the technology development and production processes under the highly idealized market conditions of perfect competition. In Section III we touch upon some of the market failures in these processes and how organizations respond to them. The effects of uncertainty are emphasized. In Section IV we describe how present economic conditions in the production of electricity are at work to segment the market for photovoltaics and how this will affect both invention and production. Section V focuses upon historical considerations of technical choice and technology development for photovoltaics and their effects on present and future investments in productive activity and in additional technology development. The importance of viewing the market for photovoltaics as segmented is incorporated. Finally, Section VI integrates the preceding discussions by focusing on the factors which affect investment in the development of technology to produce photovoltaics and in actual production processes.

Two caveats are in order. First, this is very much an uncompleted study. We have tried to lay the foundations for further, more specific study of factors which will affect the photovoltaic industry. Our work up to this point serves to present a framework which we believe is useful for understanding the industry. But much more research, both of a fundamental nature, and applied to the photovoltaic industry, is needed for a more in-depth understanding of some of the issues just touched upon in this analysis. Second, no attempt has been made to test any of the hypotheses developed. Ideally, econometric models could be built to test them. But data limitations preclude this. As a part of the agenda for future research, data analysis of a more descriptive nature can be used to see if the hypotheses are at least consistent with the facts.

II. A SIMPLE MARKET APPROACH

In this section we will present a simple model to illustrate the interrelated markets which affect the technology development and production processes in the photovoltaics manufacturing industry. Initially, we will utilize the model to analyze how prices and markets affect these processes under highly idealized conditions (perfect competition). In later sections of the study we will expand the model to take account of institutional and organizational factors.

Simple partial equilibrium analysis of demand and supply does not explicitly account for intermarket relationships. For the purpose of this study the simple model shown in Figure 4.1 serves as a compromise: the principal markets which affect technology development and production of photovoltaics are presented. Price and market conditions in other sectors of the economy are treated as exogenous.

In Figure 4.1, production processes are represented by boxes and markets by small diamonds. Each box is a representative firm. The flow of commodities is shown by arrows pointing from producers to consumers. The development of technology and the production or manufacturing of a commodity are considered to be distinct production processes. Markets for technology development are thereby included explicitly. The reason for this separation is that technology development can be considered as a particular form of capital production which is utilized as an intermediate product in the manufacture of photovoltaics, or of any other good. There is no reason why a firm must develop its own technology under perfect market conditions, just as there is no reason for a firm to manufacture the intermediate capital goods it utilizes in its production process. Rather, as will be explained subsequently, any integration of production activity can be viewed as arising out of failures in the market processes (see also Coase and Williamson).

The six production processes incorporated into the simple market framework are

1) the production of electricity;
2) technology development for electricty production;
3) the production of photovoltaics;
4) technology development for photovoltaics;
5) production of input factors; and
6) technology development for input factor production.

"Factor production" is just an aggregate of the intermediate capital goods, such as materials, plant, and equipment, as well as nonproducible goods such as human resources which enter as factors into the production of photovoltaics. Technology development refers in each case to the acquisition of capital in the form of information about new products or processes. This integrates all stages in the development of a technology from early research through final development.

In addition to the six product markets in Figure 4.1, financial markets are also included. But financial markets are ignored in this section since, under the conditions of full information implied by perfect competition, the supply of investment funds can be considered to be perfectly elastic, given an exogenously determined market rate of return.

The simple market framework presented shows the interrelationships between all intermediate physical production and technology development throughout the system. These interrelationships are crucial since in the case of photovoltaics, changes will be occurring not just in photovoltaic production itself but in electricity production and in materials production. With perfect markets, prices will coordinate the system efficiently, but, as subsequent analysis will show, even in the case of imperfect markets prices will be a crucial determinant of economic choice. Prices, demands, and supplies in any one market will affect the activities in all other markets.

A fundamental observation which is crucial for this section as well as for the rest of this chapter is that the demand for photovoltaic arrays or modules is a derived demand from electricity production. photovoltaics modules are just a particular kind of capital equipment which can be utilized to produce energy. The demand for photovoltaics is therefore dependent on the relative costs of production of all alternative techniques of producing electricity.

An exploration of the highly complex issues involved in electricity production and generation are beyond the scope of this paper. But some general comments are in order since photovoltaics are utilized in electricity production. The costs of generating electricity can be divided into capital costs, fuel costs, and operating costs. With photovoltaics there are no fuel costs (solar energy, when available, is free), and operating and maintenance costs are generally assumed to be low (this is not true for concentrator systems). Gas, oil, and coal are the fossil fuels presently utilized in producing electricity.

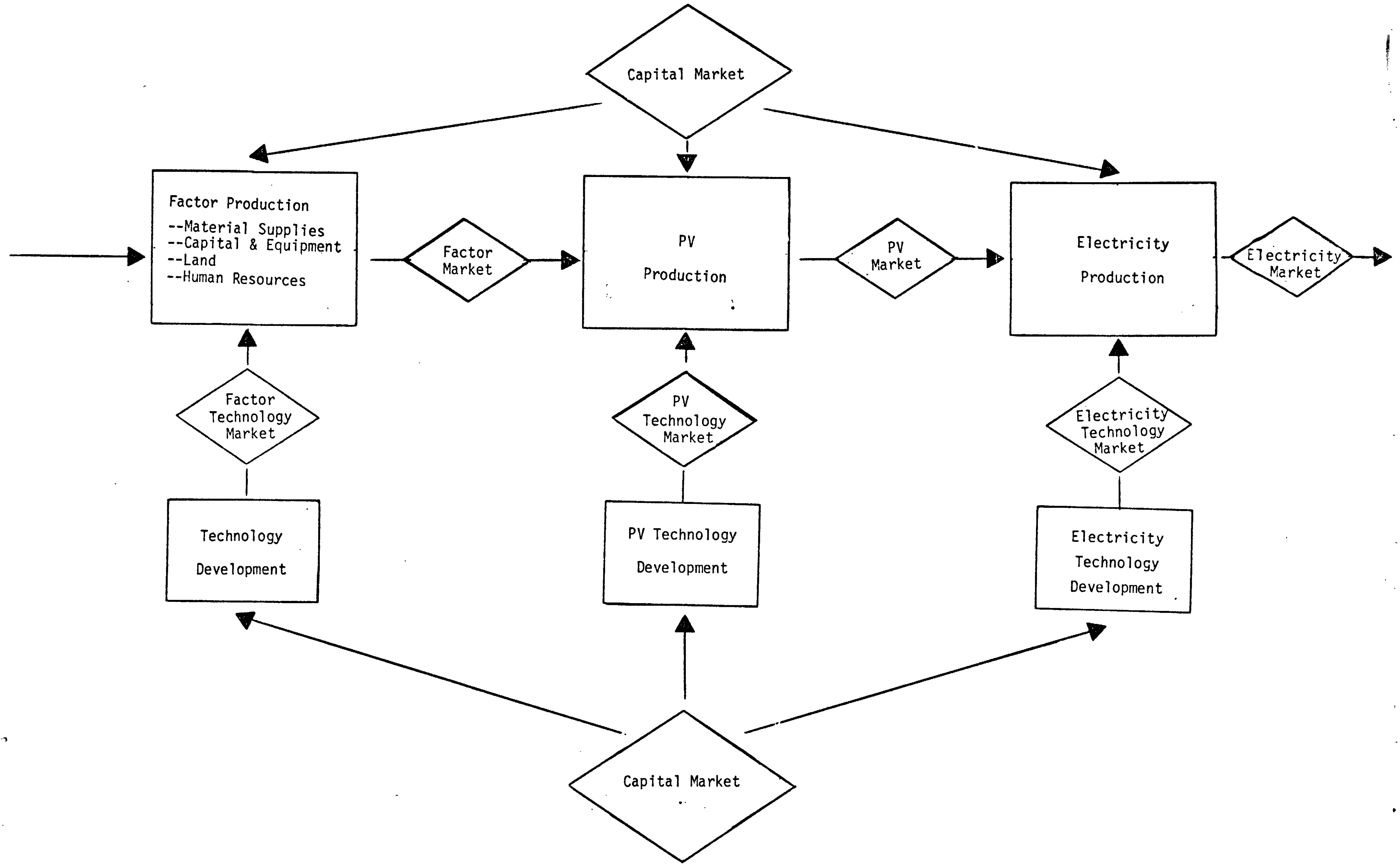

Figure 4.1

Photovoltaic Technology Development and Production Processes and Markets

Hydroelectric power is used where present, and nuclear power is an available alternative. Each production technique for electricity generation has its own set of capital costs, fuel costs, and operation and maintenance costs. Factor substitution in the generation of electricity will occur as the relative prices or cost components of alternative production techniques are altered. Examples of this may be increases in the price of fossil fuels or decreases in capital costs of a particular production technique (i.e., photovoltaics).

With most presently utilized production techniques for generating electricity there are substantial economies of scale. This leads to central power generation by public utilities. Peak-load problems complicate the issues. But transmission and distribution costs for the electricity generated are substantial. For remote applications where transmission and distribution costs make central power generation too costly, on-site generation becomes competitive. This observation is crucial since photovoltaics, where economies of scale are not substantial, are presently used for remote applications where central power is not economically or physically feasible.

Besides capital, fuel, and operating costs, other factors may be important in determining whether photovoltaics are utilized for electricity generation. Land prices may be important since photovoltaics presently require a large amount of space. Other factors such as performance and reliability may also prove important.

Since the demand for photovoltaics is a derived demand, it is dependent on relative prices of alternative technologies for producing electricity as well as on total demand for electricity. At the present set of relative prices photovoltaics are not cost-competitive for most electricity production activity. For the equilibrium production of photovoltaics to increase one or more of the following three things must occur: 1) an increase in the price of producing electricity by alternative methods; 2) development of new technology which decreases the cost of producing photovoltaics; and 3) the attainment of scale economies in the production of photovoltaics. All of these three can be translated to the proposition that an increase in the quantity demanded of photovoltaics will come about from supply considerations, either in alternative energy asources or in photovoltaicss, which will alter the structure of relative prices in favor of photovoltaics.

This leads us to consider the conditions affecting supply in the photovoltaic industry. Ignoring technological developments for the moment, in long-run equilibrium firms will exploit any available scale economies so as to achieve minimum costs of production. Firm investment in plant and capital equipment will depend on the structure of relative prices in factor markets, given available technologies.

To incorporate technology development in our model we will adopt the assumption developed by Nordhaus that invention or technology development is a particular form of capital which by the research, development, and engineering efforts involved, increases technical knowledge, and improves productivity. Technological development is then seen as "any kind of investment that improves the firm's conventional production function" (Nordhaus, p. 18). The additional assumption is that technology is disembodied, or independent of any particular production process chosen.

In the highly idealized perfect market model, the production of technology is just another factor into the production of intermediate capital goods, photovoltaics, or of electricity production. The demand and supply of technology development can be treated as that for any capital good, as responding to the set of prices prevailing throughout the system. Markets, through prices, will work to coordinate the system efficiently. The choice of emphasizing technology development as compared to plant and equipment will depend on the relative costs and benefits of the two.

The perfect market model analyzed above is essentially a static one. The explicit incorporation of time into the model as well as the dropping of the assumption of disembodied technology development will necessarily lead us into the sort of market imperfections analyzed in Section III, for if prices and/or technologies are changing we must have either perfect foresight or market failures resulting from uncertainty.

III. MARKET FAILURES AND ORGANIZATIONAL RESPONSES

In the previous section, we analyzed technology development and production in the photovoltaics industry under highly idealized market conditions. But real markets are never perfect. Markets are sluggish in adjustment and do not respond instantaneously to economic stimuli. Market failures of a more fundamental nature such as uncertainty, externalities, and indivisibilities may also prevail. In this section we will explore how these failures affect the simple market framework presented in Figure 4.1.

Traditional economic literature has dealt with market failures as a rationale for government intervention in the resource process. More recently, the works of Coase, Williamson, and Arrow (1969, 1974) have made us realize that government is neither necessary nor sufficient for correcting market failures and achieving efficient outcomes. This is particularly true with respect to uncertainty as it applies to the behavior of government as well as to firm behavior. The important lesson to be learned from the literature cited above is that firms, as well as government, will respond to failures in the market by strategic organizational behavior.

Two forms of market failure explored are externalities and uncertainty. Externalities refer to interrelated consumption and/or production activities which are not correctly priced. Uncertainty refers to the fact "that we do not have a complete description of the world which we fully believe to be true." (Arrow, 1974, pp. 33-34). It differs from risk in that relevant probabilities cannot be measured.

Uncertainty will affect the economic decision-maker's perception of present and future states of the world. Uncertainties may exist with respect to present market conditions, due to the complexity of economic organization, and to the fact that acquisition of information about the true state of the world is costly. Uncertainties of a more fundamental nature occur when we extend our analysis to a dynamic framework. In the dynamic case, the firm's decisions are not only dependent on present prices and present technology, but on expectations for future prices and for future technology. Perfect foresight would be needed for uncertainties not to occur.

The effect of indivisibility will also be explored. Indivisibility refers to "lumpiness," in production activities, which brings about economies of scale. While indivisibilities are not strictly a form of market failure, if the economies of scale brought about are only fully exploited at levels approximating or exceeding the size of the total market, competitive situations cannot be sustained and noncompetitive market structures with varying degrees of monopoly power may come about.

Different market failures affect decision-makers in different ways. Firms and institutions, through their strategic behavior and internal organization, will take account of market failures. But given the existence of uncertainty, "bounded rationality" is prevalent. Bounded rationality refers to human behavior that is "intendedly rational, but only limitedly so," (Simon, 1961, p. xxiv). As Williamson explains it:

> When transactions are conduction under conditions of uncertainty and complexity, in which event it is very costly, perhaps impossible, to describe the complete decision tree, the bounded rationality constraint is binding. An assessment of alternate organizational modes, in efficiency respects, becomes necessary...Most decision problems...are not deterministic but involve decision-making under uncertainty. For these, the comprehensive decision tree is not apt even to be feasible. (p. 23)

With the existence of asymmetrically distributed information the assumption that economic agents are guided by self-interest makes for the existence and importance of strategic behavior by firms and organizations. Strategic behavior may come about even without asymmetrically distributed information in small-number problems, as in oligopoly situations. And the existence of strategic behavior implies that consideration of factors internal to the organization must be accounted for. Institutional factors are therefore crucial in understanding the allocation of resources.

The incorporation of institutional factors into an analysis of investments in photovoltaic technology development and production is extremely difficult for two main reasons. First, the photovoltaic industry is a very young one and institutional as well as market structures are continuously evolving. No analysis based on a fixed set of institutions, or a fixed set of strategic considerations guiding firm behavior is useful. Second, given considerations of internal organizations, each firm's strategic behavior will differ. The assumption of a representative firm should be abandoned.

Given the great analytical complexities and the lack of fully developed theories on which to base any analysis, a compromise was reached for the purposes of this study. The assumption of representative firms is retained. But indications of where institutional considerations will be important, and where firm behavior may differ, are included. In addition, examples of institutional responses to market failures are given. It should be emphasized that the study of internal organization of firms is currently an area of active basic reseearch. Important questions for public policy have still to be answered. So the analysis presented here will be tentative and subject to further refinement and investigation, as well as testing.

Seven major sources of market failure were identified as affecting the technology development and production processes for photovoltaics. These are as follows: (1) incorrect pricing of energy; (2) production uncertainties; (3) technological uncertainties; (4) interdependence of production and technology development activities; (5) indivisibilities and the inappropriability of technological developments; (6) imperfections in financial markets; and (7) noncompetitive market structures. In most instances the source of these market failures cannot be traced to a single cause but rather they come about from a combination of externalities, uncertainties, and indivisibilities. In our analysis, we will trace the source of these market failures, state their effect upon technology development and production of photovoltaics, and present possible forms of organizational responses to them.

A. INCORRECT ENERGY PRICES

Various factors cause an inefficient pricing of energy sources. The OPEC cartel has affected the price and availability of oil. Certain sources of energy, such as nuclear power, may have substantial deleterious environmental impacts and these external effects may provide a divergence between private and social costs. Oil and natural gas prices are controlled, possibly creating artificial divergences between the quantities demanded and supplied. All these problems will distort prices of alternative energy sources.

The incorrect pricing of energy is a market failure external to the photovoltaics industry. But this will affect the total demand for electricity and the choice of production techniques for electricity. And through the market channels shown in Figure 4.1, it will affect the production and technology development processes for photovoltaics. It should be noted that there is no agreement of what the "optimal pricing" of alternative energy sources should be. Considerations of income distribution are considered by many to be at least as important as economic efficiency. Public policies with regard to energy pricing will be of utmost importance.

The first source of market failure, while external to the photovoltaics industry, will affect it considerably. Given the effect of present prices of energy, and expectations about future prices upon the market for electricity, the technology development and production processes for photovoltaicss will be affected through the regular market channels. But there is another way through which the economic behavior of energy markets will affect the photovoltaic industry. And this comes about not directly because of incorrect energy pricing, but because of the depletable nature of fossil fuels. As discussed in Chapter Three, major oil companies, foreseeing the depletion of low-cost oil deposits, are diversifying their activities to alternative renewable and undepletable sources of energy of which photovoltaic solar power is only one of many. Given the vast financial resources of these firms, this may have a substantial impact upon the future of photovoltaics. This issue is of importance due to imperfections in financial markets will be discussed below.

B. PRODUCTION UNCERTAINTIES

Under perfect market conditions, with full information about prices, firms' production decisions will be such as to achieve minimum total costs of production for any level of output. But in a dynamic framework, firms are uncertain about future prices, and consequently about future demands and future costs. The decision-making behavior of firms will therefore be affected.

Even in the short run, demand and production costs for a commodity are never completely certain. Every business decision entails a certain amount of risk. But in situations where economic events are changing rapidly, uncertainties cannot be objectively measured, and bounded rationality prevails. Such a situation is characteristic of the present state of the photovoltaics industry, in which future demand and production costs are both highly uncertain.

Uncertainties about future prices and supplies of substitutes, as well as about technological development of alternatives, are major factors affecting the long-run demand for photovoltaics. The alternatives have differing performance characteristics; this will bring additional complications. In the short run, uncertainties also come about because consumers do not possess full information about prices and quality differentials of all available alternatives, and therefore their adjustments are gradual and not instantaneous.

When uncertainties are significant, acquisition of information is called for before decision-making takes place. Firms utilize market studies and engineering cost estimates to reduce uncertainty. Rules of thumb which have worked previously, such as "learning curves" and the "product life cycle," will be utilized in some instances. But given bounded rationality, acquisition of full information is not possible. And since costs of making a "wrong" (*ex post*) decision are substantial, firms will tend to utilize an adaptive, sequential decision-making process.

This is of particular importance with respect to firms' investment decisions on plant and equipment designed to attain the long-run minimum costs of production. Given production uncertainties, the optimal scale of plant will not be attempted at once. Since the market is the final arbiter of whether an investment decision is profitable, actual market tests will be utilized. Pilot plants and initial attempts at market penetration are needed. Firms, if risk-averse, will not seek rapid attainment of scale economies, but rather will respond gradually to market signals.

In our analysis of investment decisions in Section VI, we will use the nomenclature developed by the MIT Energy Laboratory Policy Study Group, dividing the sequential stages of production of photovoltaics into two: introduction or commercialization, and mature production or diffusion.

Production uncertainties, while of utmost importance for firm decision-making, are a natural part of *all* production activities and cannot be eliminated. They are especially prevalent in growing industries where market factors are continuously changing. How individual firms respond to these uncertainties in the initial stages of the industry may have a substantial impact upon future market structure. For example, according to Williamson, business acumen and historical accidents which come about from uncertainties may be an important factor in the evolution of dominant firms (1976, pp. 208-233).

C. TECHNOLOGICAL UNCERTAINTIES

At the initiation of any technology development effort, estimates of development cost, development time, and performance are very unreliable. But during the development effort learning takes place and the reliability of the estimates is improved. A process of adaptive sequential decision-making, analogous to that resulting from production uncertainties, will take place. As a result, "parallel development of alternative designs seems called for when technical advances are large, when much additional information can be gained from prototype testing, and when the costs of a few prototypes are small relative to total system cost" (Nelson, p. 361).

Due to uncertainties resulting from the development of alternative technologies, individual projects are highly risky. Given independence of risks between alternative projects, diversification is called for by portfolio-balancing considerations. This has obvious implications for the existence of scale economies in R&D activities.

With the existence of adaptive sequential decision-making for technology development, stages of development can be identified. For our analysis of investment decisions in Section VI, we will utilize the terms initial and final development (see MIT Energy Laboratory Policy Study

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[1] It should be noted that for purposes of the classification of the state of the technologies in Chapter Three "research" was treated as a stage preceding initial development, rather than a part of it.

Group) to classify the stages.[1] While initial development involves parallel development activities to provide technical feasibility, in the final development stages one configuration is usually chosen as best and emphasis is put upon the design of manufacturing processes, or what is sometimes called "engineering development" or "production engineering."

Issues of technological uncertainty are crucial and have important implications both for positive and for normative analysis. More fundamental research is needed in this area before a complete evaluation of their impact upon production and technology development processes in a particular industry becomes possible.

D. INTERDEPENDENCIES OF PRODUCTION AND TECHNOLOGY DEVELOPMENT

In Figure 4.1 the interdependencies of production and of technology development activities in the photovoltaics industry are illustrated through market channels. If markets behave perfectly, all the interdependencies will be handled efficiently through the price mechanism. But in reality a combination of market failures -- externalities, uncertainties and indivisibilities -- are interacting to inhibit the price mechanisms from working properly. Exclusive reliance on prices and markets will not lead to efficient allocation of resources within and between technology development and production activities.

The problem of the convergence of expectations is of particular importance. With the high degree of interdependence between technology development and production activities, and the adaptive sequential decision processes which result from the technological and production uncertainties, prices and the market mechanism may fail to provide coordinated responses:

> Interdependence by itself does not cause difficulty if the pattern of interdependence is stable and fixed. For, in this case, each subprogram can be designed to take account of all the subprograms with which it interacts. Difficulties arise only if program execution rests on contingencies that cannot be predicted perfectly in advance. In this case, coordinating activity is required to secure agreement about the estimates that will be used a the bases for action, or to provide information to each subprogram unit about the activities of the others (March and Simon, p. 159).

Given asymmetrically distributed information and the resulting lack of convergence of expectations between economic decision-makers, organizational and institutional arrangements must be made to coordinate activities. An example might be the coordination of complementary technological developments for factor production, photovoltaics manufacturing, and electricity generation, all of which might be reasons for a certain technology to be viable. A not entirely hypothetical case might be the development of methods to produce, and photovoltaics processes to utilize, a "solar grade" silicon (see Chapter Two). If expectations do not converge, alternative arrangements to the market mechanism are needed. First, a centralized agency, such as government, may coordinate the activities. Second, contractual arrangement between firms is a possible method of coordination. Third, the integration of activities into a particular firm and the coordination by management is another alternative. These are not mutually exclusive arrangements and a combination of them is also possible. In the photovoltaic industry, the institutional arrangements resulting from market failures in the coordination of technology development activities are presently evolving. The first form of organization appears to be the dominant mode today.

The coordination of technology development with production is also an important consideration. Given adaptive sequential decision-making in both processes, investments in each stage "can be thought of as acquiring a new asset, where that asset is expected to yield a favorable return itself, or to open the way to some subsequent investment that will yield a profit," (MIT Energy Laboratory Policy Study Group, p. 42). But when the subsequent investment decision is undertaken by another firm, the lack of convergence of expectations between firms will bring about market failure. Integration of all stages of technology development and production within a firm is possible, as is implicitly assumed for the case of the automotive industry by Linden *et al*. Other organizational forms previously mentioned may also occur.

Even though the particular organizational form adopted depends on a complex set of factors not well understood, some general tendencies can be hypothesized. Utilizing the terminology developed in the Appendix, discrete technology developments and learning-by-doing are two distinct forms of technological improvements. Learning-by-doing is by nature associated with improvements which come about from experience with the particular production process being utilized. The forms of engineering and production development, which are associated with the attainment of mature production capabilities, are more likely to be done by the manufacturing firms since they possess the necessary information. The same is true with respect to the final development of discrete technology improvements, since the activities in this stage will very likely be specific to the manufacturing process utilized by a firm. But with respect to the initial development of discrete technologies, which involves the refinement and testing of prototypes in the laboratories, integration with production activities appears to be less likely. As discussed in Chapter Three, the bulk of the effort going into developing discrete technological improvements -- in products and processes -- is taking place at firms other than those now producing solar cells for the marketplace (see Section V below).

The coordination of technology development and the achievement of scale economies in production is of central importance here. Scale economies which result from indivisibilities in plant and capital equipment are crucial in attaining lowered costs of production. But investments in mechanized operation are embodied in a particular production technology and costly retooling will be necessary if a discrete new production technology is adopted.

Further research is necessary on the problem of interdependencies of technology development and production. Particular emphasis should be put on the forms of vertical integration which may occur. In an emerging industry undergoing simultaneously the rapid expansion of production and the development of technologies, as is occurring in the photovoltaics industry, any analysis of firms' investments is hindered by the fact that organizational forms are still evolving. But it is imperative that the evolution of organizational forms and its simultaneous cause-and-effect relationship with firms' investments be monitored.

E. INDIVISIBILITIES AND THE INAPPROPRIABILITY OF TECHNOLOGY DEVELOPMENTS

Substantial indivisibilities exist in the technology development process.

> "Lumpiness of the costs of invention follows from the fact that knowledge is expensive to produce but cheap to reproduce. Typically, an invention requires substantial investment in order to make a product or process feasible. Once this has been accomplished, however, the costs of transferring knowledge or realizing the services of the stock of knowledge widely available are much less." (Nordhaus, p. 36)

These indivisibilities appear to be of greatest importance at the initial development stage, where engineering and scientific breakthroughs are necessary, as compared to final development and learning-by-doing.

These indivisibilities bring scale economies to technology development activities. For analyzing the investment in technology development by firms it is crucial to consider whether the acquisition of knowledge can be fully or partially internalized or appropriated. Without appropriability, external effects will lead the firm to underinvest in technology developments. On the other hand, full appropriability of an invention may lead to monopoly power.

The issue of externalities in the invention process and the possibility of inappropriability is usually dealt with independently of the existence of indivisibilities. But if the cost of initial production of an invention is equal to the costs of transferring the invention, this issue of appropriability is of much less importance.

Various mechanisms for appropriating inventions are possible. The utilization of patent protection is one. Secrecy is another:

> The extent to which a firm is able to control its inventions after they are sold determines whether a firm will decide to license the invention or keep it secret...If secrecy prevails, the remedy for the situation is definitely not to give subsidies for the performance of research.
>
> The problem of transfer of knowedge is extremely important. Unfortunately, there is little evidence as to the degree of appropriability of inventions once they have been patented and

licensed. It might be suspected that complex inventions "embodied" in machinery would be more susceptible to appropriability than simple "disembodied" inventions. (Nordhaus, pp. 39-40.)

F. IMPERFECTIONS IN FINANCIAL MARKETS

The U.S. economy has a highly developed set of financial institutions to allocate investment funds among activities. But the existence and importance of internal financial capital markets alter the assumptions necessary for perfect competition to take place. As Spence recognizes:

> ...there must be features of the internal capital markets that are qualitatively different from the external markets. Several aspects come to mind. There are well known differences in tax treatments of individual and corporate income. A second is that the investors in internal markets (the managers) may be better informed than external investors, at least about a certain range of investment opportunities. A third is that failure or bankruptcy may be evaluated differently by stockholders and managers, since the loss to management of failure is not confined to their financial involvement in the company as investors. Presumably management reputation is hurt by financial failure. (p. 168)

If internal capital markets are important, the availability of flow of funds from internal sources will be a crucial determinant of investment by firms. Econometric studies of investment in research and development activities by Mueller and Grabowski confirm the importance of past profits and thereby of internal availability of funds in determining investments in technology development. and recent work by Teece confirms this for the petroleum industry.

A firm may acquire access to internal funding by merger with a large corporation with substantial financial resources. As discussed in Chapter Three, this appears to be occurring in the photovoltaic industry where oil companies (Mobil, Shell, and CFP) are acquiring dominant interests in technology development and manufacturing firms.

Further basic and applied research is needed on the importance of internal capital markets for the resource allocation process both between and within firms. Williamson (pp. 132-175) presents an analysis of multidivisional structure and conglomerate organization and their relation to the investment process.

G. NONCOMPETITIVE MARKET STRUCTURE

Market concentration in the forms of oligopoly and monopoly is most commonly attributed to the existence of economies of scale in production. But other forms of market failure such as externalities and uncertainty may also lead to market concentration (Williamson).

A vast amount of literature on the relationship between market structure and technology development and adoption has been developed with few conclusive results to show. This literature is ably reviewed by Kamien and Schwartz. Although practically everyone agrees that market concentration is important, since market concentration may itself come about because of technology developments (Phillips) no conclusive results are available and further research is necessary.

Inappropriability along with technological uncertainty and interdependencies can lead to "myopic" decisions on investment in technology development. That is, the sequential decision-making process favors investments in technology changes which derive closely from technologies in use, in preference to those more distant, even though the latter may be more valuable to society as a whole over the long run.

Localized changes are likely to result in benefits which are more appropriable, and are less likely to require extensive coordination or exploration of new consuming markets than radical changes. Myopic investments may in some cases be the most profitable for the firm.

IV. SEGMENTED MARKETS FOR PHOTOVOLTAICS

When and if the nonremote market for electric power materializes, it will likely be distinct from the remote market just as the remote terrestrial market is now distinct from the space market. That is, key attributes will be valued differently in each of the submarkets. This is especially the case with any attribute related to the cost of being remote -- e.g., reliability, since maintenance is more expensive at remote sites. This is the usual meaning of the phrase, "market segmentation," and the market for photovoltaics is segmented in this sense.

However, it is "segmented" in much more significant ways as well. The demand for photovoltaics will depend on relative costs of production of electricity with available substitute techniques for each particular application. With the present prices of photovoltaic power and of alternatives, photovoltaics are uneconomical for most electricity applications. But photovoltaics are presently produced for space and for remote site applications where centrally generated and distributed electricity is uneconomical. (photovoltaics are also produced for the government's development program.) Given the large degree of difference in the structure of relative prices for remote and nonremote applications, as well as orders of magnitude differentials in size of the market, photovoltaics produced for remote and nonremote electricity power generation may for practical purposes be considered as different products.

It is our contention that viewing the markets for electricity, and consequently the derived market for photovoltaics, to be segmented in this larger sense is a useful way of analyzing the technology development and production processes in the photovoltaic industry. Three principal submarkets are distinguished: 1) the market for space application; 2) the market for remote terrestrial applications; and 3) the market for nonremote terrestrial applications.[1] It should be noted that considering the markets as segmented does not imply that the markets are not interrelated. On the contrary, prices, technologies, and production processes may serve as links between them.

The differences in the cost of closely competitive substitutes between submarkets is a crucial factor accounting for segmentation. In space applications, the long life, minimum power, and low weight characteristics of photovoltaics were factors in their choice by NASA and the Department of Defense for powering satellites. For remote applications, their possibility of generating electricity at small scales, their reliability, and insubstantial costs of operation and maintenance appear to be factors affecting their adoption relative to available alternatives, principally batteries or diesel generators. Nonremote applications, at the present set of relative prices, are not cost-competitive and are thereby not utilized.

Solar cells and modules produced for different submarkets may also prove to be differentiated products. Reliability is crucial for space appliations but less so for remote terrestrial applications in which price considerations take greater importance. Differentiated products will be produced for each submarket. For nonremote applications, if and

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[1] We have lumped together the two nonremote markets which ERDA uses for its planning purposes (the load-center and the utility markets).

when developed, efficiency may be a much more crucial consideration than for the remote power submarket. Differentiated products may well coexist. In general, it can be stated that quality attributes which vary in importance for different applications will bring about differentiated products. The greater the product differences, the greater the degree of market segmentation that may occur. (For a theoretical analysis of how product differences affect demand and supply considerations in competitive markets, see Rosen).

Given quality differentials and their effects upon demand and supply of differentiated photovoltaic products among submarkets, complementary technology developments may also differ among them. For instance, solar concentrators may be important for nonremote markets but unimportant for others. The same may be true for technology developments in factor markets.

Different types of firms are involved in technology development and production for the different segments. In Chapter Three we indicated that the space cell manufacturers tend to focus on production for the space cell market. Similarly, the firms now in production for the remote terrestrial market seem to show less immediate interest in the nonremote market than do the larger oil companies and semiconductor manufacturers.

Finally, but possibly of greatest importance for our analysis, the factors affecting investment decisions for technology development and/or for production of photovoltaics are geared to the different submarkets. Even with product differences, this need not be so under idealized market conditions. But given market and technological uncertainties and the resulting incremental behavior of firms with respect to technology development and production, as described in Section III, firms will take a "myopic," localized view of the submarkets involved. Thus we see (as discussed in Chapter Three) the present producers focusing primarily on incremental improvements for lowering the cost of monocrystalline silicon cells. In contrast, the oil companies and semiconductor manufacturers are looking ahead to the larger, lower-cost markets by developing different product technologies (especially cadmium sulfide) and process technologies (amorphous and sheet monocrystalline). Later in this chapter we will explore more fully the implications of this market segmentation.

V. TECHNICAL CHOICE AND TECHNOLOGY DEVELOPMENTS IN PHOTOVOLTAIC SUBMARKETS

In the previous section we discussed the existence of distinct submarkets for photovoltaics. The three major submarkets identified were the space market, the remote terrestrial market, and the nonremote terrestrial market. This segmentation of the market has implications for the past, present, and future of the technology development process which will be presently analyzed. Emphasis will be put upon the effect of localized technology developments both within and between submarkets. A more complete exposition of some of the concepts and terminology utilized to describe and explain the technology development process is presented in the Appendix.

As described in Section I of Chapter Three, present monocrystalline silicon cell technology was developed in the mid-1950s, but its principal use has been to power satellites in outer space. In 1973 successful production and marketing of photovoltaics for terrestrial use was first undertaken. All indications are that sales of photovoltaic arrays for remote terrestrial sites are now rapidly expanding.

The realization that low-cost sources of energy for producing electricity are becoming scarce has stimulated interest on the part of government, of private individuals, and of corporations in developing alternative sources of energy. This interest has been strongly reinforced by the Arab oil embargo. The overriding interest of many, including the government, appears to be on extending the utilization of photovoltaics into the much larger nonremote terrestrial submarket, and thereby making a substantial contribution to total energy production.

The present technology available for producing solar cells is capable of being applied in nonremote uses, such as central power generation and on-site power for commercial and/or residential structures. The principal barrier to its application is that the costs of producing electricity with silicon solar cells are, at the present, substantially higher than those of competing available techniques. But both the federal government, through ERDA, and private corporations are investing resources in developing alternative technologies for producing photovoltaics, and achieving cost reductions.

It is our contention that there has been some order in the evolution of the processes of technology development and production of photovoltaics. Technical choices have been made and will continue to be made which will affect this evolution. The forces motivating these choices are extremely complex and involve considerations of the economic structure of the industry, including the sort of institutional considerations which were discussed in Section III. These considerations will, for simplicity, be ignored when not crucial for the analysis.

Since the demand for photovoltaic arrays is a derived demand for a capital good, the choice of production technique is best studied from the viewpoint of electricity production. Radical differences exist in the availability of alternatives with the qualitative attributes needed for each submarket. Technical choices between submarkets will then likewise be radically different. Trade-offs between costs and performance and quality attributes are possible within submarkets and account for the utilization (or consideration) of diverse production techniques, but they are of lesser importance. Within each submarket, the production technique utilized is that which minimizes costs over the available process frontier (see the Appendix) with a given set of performance criteria.

As discussed more fully in the Appendix, technological developments may be divided into three categories: short-run learning-by-doing, long-run learning-by-doing, and discrete technical changes. The technological developments occurring within each category differ in two aspects. The range of potential technological choices considered by a firm developing a technology varies with the category, and long-run technological progress within an industry may vary depending upon which category of technological development has been occurring.

Short-run learning-by-doing refers to the process improvements which result during production but are not the result of specially delineated development projects. Thus short-run learning-by-doing is "free" to management and results from the normal pressures for cost reduction. In its narrowest definition, the "learning curve" reflects short-run learning-by-doing. The typical example of short-run learning-by-doing effects is improvements in worker productivity due to increased experience with a particular task. In photovoltaics one might observe this effect in the soldering together of strings of cells and in the handling of the strings.

Long-run learning-by-doing consists of those changes to product or process technology that are modifications of, but closely related to, the dominant technology. It is generally the development focus of firms in production with the dominant technology, because it is the natural outcome of the incremental decision-making process discussed in Section

III. An investment is required to achieve long-run learning-by-doing because, unlike short-run learning-by-doing, long-run learning-by-doing results from deliberate research efforts. In photovoltaics, long-run learning-by-doing includes most of those efforts of industry and government to find cheaper ways of producing monocrystalline silicon solar cells. For example, work to develop larger saws for the Czochralski ingots or to develop new methods for soldering together strings of cells are examples of long-run learning-by-doing.

Discrete technological changes are those which are qualitatively different from the dominant technology. They are generally not developed by firms involved in production with the dominant technology and differ from long-run learning-by-doing effects largely in the nature of the investment undertaken. Investments in discrete technological changes usually reject current process technology almost entirely. In photovoltaics, some clear examples of potential discrete technological change include cadmium sulfide, gallium arsenide, and amorphous photovoltaics and their related production processes. Within silicon technology, examples also exist, such as sheet or cast silicon, EFG, and dendritic web, all alternatives to Czochralski silicon. Certain alternative methods of purifying silicon, such as silane processes, are also discrete technological options.

Successful investment in discrete technological change would thus make many investments in former process technology worthless. For this reason one would expect to see firms currently using the dominant technology to refrain from discrete technological changes.[1]

These concepts of short-run learning-by-doing, long-run learning-by-doing, and discrete technological change add insight to the history of photovoltaics technology. In the photovoltaic market for space applications, the technical choice which resulted in the utilization of monocrystalline silicon solar cells was made by the relevant government agencies. Taking into account the performance attributes needed for generation of electricity, a choice was made among available electricity-production techniques. Manufacturers responded by producing silicon arrays for space use. Localized technological changes (short-run and long-run learning-by-doing) took place, and performance improvements and cost reductions resulted. Given the low efficiency and reliability problems of cadmium sulfide cells, the most fully developed photovoltaic alternative to monocrystalline silicon, and the high degree of technological uncertainty associated with all other alternatives, the space submarket yielded little incentive for discrete technology developments.

The same photovoltaic cells and arrays manufactured for space application were available for terrestrial applications, although their high cost made their use quite limited. Product quality changes and long-run learning-by-doing resulted in process changes which yielded

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[1] A pedagogic example to help illustrate the difference between long-run learning-by-doing and discrete technological change may be useful. Consider the market for methods to eliminate mice. If the mousetrap is the dominant technology, efforts to build a better mousetrap are long-run learning-by-doing while developing mouse repellent would be discrete technological change. While a manufacturer of mousetraps would probably be engaged in building a better mousetrap, it is unlikely that it would develop mouse repellent, or at least no more likely that it would do so rather than another firm which manufactured, say, insect repellents.

cost reductions geared especially for remote terrestrial applications. Thus a new process which evolved from the product of the space submarket became part of the available process frontier for the remote terrestrial submarket. Given the high cost of power for remote applications, photovoltaic arrays compete with other techniques for producing electricity. With a given set of performance criteria, photovoltaics will be adopted if they reduce the cost of producing electricity. Expansion of the remote terrestrial submarket will take place with cost reductions and/or performance improvements. Technology developments are designed to achieve this.

Choices must be made between investments in discrete technology developments and in long-run learning-by-doing. Given the higher degree of uncertainty and inappropriability associated with the former, a "myopic," localized set of technological improvements would, in general, prevail. Discrete developments, while possible, are much more likely to come from outside the manufacturing firm.

Decisions are greatly complicated because of conditions prevailing in the nonremote terrestrial submarket. At the present set of relative prices for producing electricity, photovoltaics are uneconomical for generating either central power or on-site electricity. But given the perceived depletion of low-cost fossil fuels in the near future, a search is underway for alternative energy resources. As discussed in Chapter Three, firms and the government are investing funds in discrete technology developments. Given the small size of the remote submarket and the high technological uncertainty involved, these same improvements were much less likely to be developed with that market in mind, and in fact present manufacturers are not heavily involved in research on discrete changes. Once developed for nonremote applications, these changes will become part of the available process frontier for remote applications.

This implies that the "myopic," localized changes which would take place for the remote submarket may be restrained by expectations about future discrete technology developments which may render inoperative the effects of learning-by-doing and scale economies peculiar to the present technology. This will inhibit investments -- in technology or in plant -- which are tied to the present technology. The degree of importance of this factor depends upon the costs of the particular investment contemplated.

Two principal strategies are available for achieving the cost reduction and quality improvements necessary for penetration of photovoltaics in the nonremote submarket. These are, first, the achievement of localized learning-by-doing with present production technology and second, discrete technology development. Firms' investment in one or the other will depend upon the relative costs of development of each and of the expectations of achieving and appropriating the benefits from the necessary cost reductions.

The choice between these two strategies will have implications for the future availability of production techniques. The greater the cost reductions and quality improvements achieved with learning effects and scale economies with present production techniques, the greater the technical gap between this technology and its alternatives is. Future adoption of alternative technologies will become increasingly difficult.

The greater the difficulty of transferring knowledge and production plant and equipment from one technology to another, the greater is the degree of resulting gaps. Under primary conditions, "myopic" behavior of firms would favor the first strategy. With the opportunities available in the nonremote submarket for electricity, the efforts at developing discrete technogical improvements become much more attractive.

VI. SUMMARY AND CONCLUSIONS: INVESTMENTS IN THE PV INDUSTRY

In the chapter we have initiated the development of a conceptual framework for analyzing the technology development and production processes in the photovoltaic industry. Although considerable further development is obviously necessary, lessons from the analysis to this point will be utilized in this final section to present preliminary hypotheses regarding the direction and magnitude of the factors affecting investments in the process.

Several important concepts have been developed and explored in the analysis presented in this chapter, and they will form the basis for our discussion of the factors influencing investments in technology development and production in photovoltaics. First, and most important, we have treated technology development as an economic activity -- one that is influenced by factors of both supply (costs and likelihood of successful development) and demand (value of the product). However, the market for photovoltaics is exceedingly complex; it is riddled with "market failure." These failures lead to economic activities and organizational structures which are difficult to analyze, but some theoretical hypotheses can be constructed and empirically tested in a simple way against the crude data reported in Chapter Three of this report.

Second, we have adopted the division of technical change into three classes (short-run and long-run learning-by-doing, and discrete changes) and have associated the latter two with developments now taking place in the photovoltaic industry, as discussed in Chapter Two of this report.

Short-run learning-by-doing is an inevitable by-product of production, and is affected by government policy or other external influences only through the quantity procured. Long-run learning-by-doing and discrete technical change result from different sorts of economic decisions, and interact in a way that tends to give past events a strong influence over present decisions. Most significantly in photovoltaics, monocrystalline silicon technology and present production processes tend to be the natural focus of development activities, even though it is not at all clear that they will be superior over the long run.

Finally, we have argued that the photovoltaic market may usefully be viewed as strongly segmented, based on our analysis in three segments -- the markets for electricity in space, at remote terrestrial sites, and at nonremote terrestrial sites. In each segment photovoltaics face different competition and thus must meet different cost goals. Therefore, different technologies are being developed or are in production, and different institutions are involved. Firms presently producing for the remote power market are engaged in long-run learning-by-doing development activities (and most government support is going to related technologies). Institutions interested in the nonremote market are investing in discrete technical changes. Factors influencing the remote power market are likely to have a limited influence on the nonremote market.

With these concepts in mind, we can proceed with an elementary identification and analysis of the factors influencing investments in the different stages of photovoltaic technology development and production.

We will deal exclusively with investments by present and potential manufacturers. Although firms with no manufacturing potential for photovoltaics, nonprofit organizations such as universities, and government will

undoubtedly play an important role, their investment decisions are not analyzed. Given our belief that the segmentation of photovoltaic production into submarkets is a useful tool of analysis, the hypotheses presented will be dependent upon each particular submarket. The space submarket will not be considered.

The six investment decisions considered are:

(1) investments in initial, discrete technology development;

(2) investments in final, discrete technology development;

(3) investments in long-run learning-by-doing;

(4) investments in introduction for the remote terrestrial market;

(5) investments in mature production (plant and capital equipment) for the remote terrestrial market; and

(6) investments in introduction for the nonremote market.

Each individual investment decision of a firm is evaluated with respect to its costs and benefits. The information acquisition potential of each investment must be taken into account if adaptive sequential decision-making is utilized. If the costs and benefits can be quantified, an internal rate of return may be estimated. In any case, subjective factors and internal considerations are part of the evaluation process.

Evaluation of costs and benefits of each investment project must be done on an individual basis with due regard to the interaction among investments. Rather than attempting to list all factors which would be considered, another method was utilized. A preliminary set of hypotheses on the first-order effects of various factors on the six investment decisions considered is presented in two tables. Table 4.1 deals with investments in the development of new photovoltaic technology, while Table 4.2 deals with investments in actual photovoltaic production capacity. The list of factors is selective and not exhaustive, and refers to exogenous influences on the investment process.

The effects considered operate principally through the regular market channels of demand and supply. The hypotheses presented refer to the effects for representative, risk-averse firms. These are derived from elementary economic principles, the concepts developed in this chapter, and the factual evidence on the photovoltaic industry presented in Chapters Two and Three. The tentative nature of the hypotheses is clearly evident; further study and empirical verification is imperative.

Because the results shown in the tables follow so closely from the analysis presented, relatively little direct explanation is necessary. For example, if our hypotheses are correct, then increased demand for photovoltaics in the remote market will have little impact on private sector investments in discrete technological changes because the present remote market can be most readily exploited and even expanded by incremental cost reductions, and long-run learning-by-doing is thus encouraged in this case. Similarly, government investments in long-run learning-by-doing make private investments in discrete change less attractive by tending to delay the time when desired changes will be superior in some market.

The first-order nature of the effects considered should be emphasized. This is not meant to imply that second and higher order effects are not important -- they are. But second and higher order effects are dependent on the relative magnitudes of all interacting effects, which is well beyond the power of the analysis presented here. Empirical evaluation of actual investment data is necessary.

A simple illustration of how second order effects may operate is in order. The government procurement program has been assumed here to last only temporarily, ending before commercialization of photovoltaics for nonremote markets becomes profitable. Given this assumption, its direct effect on investments in introduction in nonremote markets is hypothesized to be "probably unimportant," but second order effects are likely to take place. If the government procurement program increases the profits of photovoltaic manufacturers, greater internal funding of investments will become available. This will have a positive effect. On the other hand, the procurement program also affects investments in the long-run learning-by-doing with the present technology. If this technology cannot become competitive in nonremote markets, the achievement of learning effects may actually retard the introduction of alternative technologies that can. So the second and higher order effects of the government procurement program on private investments in the introduction stage of photovoltaic production for nonremote markets are far from clear. The same applies to second and higher order effects for other factors.

It is clear from this example, as well as the discussion throughout this chapter, that analysis of technological change is an exceedingly

Table 4.1: Factors Affecting Investments in Technology Development of Photovoltaics

	Investments in Discrete Technology Developments		Investments in Long Run	
Factors	Initial Development	Final Development	Learning-by-Doing	Comments
1. Increases in Relative Prices and/or Depletion of Substitutes for Non-Remote Market	Positive Effect Important	Positive Effect Important	Positive Effect Probably Unimportant	Stimulates development of those technologies perceived as being competitive in non-remote market
2. Technological Development of Substitutes for Non-Remote Market	Negative Effect	Negative Effect	Negative Effect Unimportant	Substitute developments make individual projects risky. Diversification possible to decrease risks.
3. Increased Demand for PV's in Remote Terrestrial Market	Positive Effect Unimportant	Positive Effect Limited Importance	Positive Effect Very Important	Due to segmentation in market, effect upon discrete technology developments is limited.
4. Complementary Technological Developments in Electricity and/or Factor Production	Positive Effects Probably Unimportant	Positive Effects Crucial When Relevant	Positive Effects Important	Integration of technology development activities possible.
5. Present Government Procurement Program	Uncertain Probably Unimportant	Uncertain	Positive Effect Important	Same as above.
6. Government Investments in Long Run Learning-by-Doing	Negative Effect	Negative Effect	Negative Effect, substitution of government for private funding likely	Government support of present technology hinders development of alternatives.

Table 4.1 (Cont.)

7. Government Investments in Discrete Technology Development	Uncertain	Uncertain	Negative Effect Probably Unimportant	Further study is needed to determine if government funding just substitutes for private funding.
8. Availability of Internal Funding	Positive Effect Very important due to high technological uncertainty	Positive Effect	Positive Effect Less Important	Corporate mergers to obtain funding possible.

Table 4.2: Factors Affecting Investments in Production of Photovoltaics

Factors	Investments in Remote Terrestrial Market		Investments in Non-Remote Market	Comments
	Introduction	Mature Production	Introduction	
1. Increases in Relative Prices and/or Depletion of Substitutes for Non-Remote Market	Positive Effect	Positive Effect	Positive Effect Very Important	Introduction in remote markets may be perceived as facilitating future introduction in non-remote market.
2. Technological Development of Substitutes for Non-Remote Market	Probably Unimportant	Probably Unimportant	Negative Effect	
3. Increased Demand for PV's in Remote Terrestrial Market	Positive Effect Crucial	Positive Effect Crucial	Unimportant	
4. Complementary Technological Developments in Electricity and/or Factor Production	Positive Effect	Positive Effect	Positive Effect	May be crucial when necessary for commercial success. Integratopm of activities to achieve it is possible.
5. Present Government Procurement Program	Positive Effect Important	Positive Effects Important	Probably Unimportant	Due to market segmentation, affects principally remote terrestrial market.
6. Government Investment in Long Run Learning-by-Doing	Positive Effect	Positive Effect	Positive Effect only if the technology government subsidises is utilized	

Table 4.2 (Cont.)

7. Government Investment in Discrete Technology Development	Uncertain Effect	Uncertain Effect	Uncertain Effect	First order effects unlikely, higher order effects uncertain.
8. Availability of Internal Funding	Positive Effect	Positive Effect	Positive Effect	When uncertainties are decreased, external funding is more readily available.

difficult task. No serious analysis of the effects of policy variables or other exogenous factors can take place without a more formal modeling effort combined with empirical study of actual investment data. In the case of the emerging photovoltaics industry, both theory and data are in short supply. However, the conceptual effort reported in this chapter provides at least a framework for thinking about the behavior of the photovoltaics industry and some of the policy issues associated with its development.

CHAPTER FIVE: POLICY IMPLICATIONS

In this report we have presented the results of a preliminary effort aimed, first, at determining the present status and structure of the industry developing and producing solar photovoltaics and, second, at outlining an initial conceptual framework for understanding that structure and, more importantly, analyzing the evolution of this industry and the associated technology. In this chapter we present a number of considerations, deriving from the work reported here, that should be incorporated in the development of federal policy toward photovoltaic technology.

If the concepts emerging from our study of the photovoltaic industry are valid (and certainly they remain to be formulated rigorously and tested), they have implications for the formulation of federal policy with respect to the development of photovoltaics. Because of the preliminary nature of our work, we utilize these implications only to raise issues or possibilities that should be considered in the policy-making process; we do not offer any hard recommendations for the policies emerging from that process.

Many possible modes and tools of federal intervention might be invoked to correct the features in the market for photovoltaics and photovoltaics technology and to support federal photovoltaics policy. They would include everything from doing nothing, or passively correcting prices for photovoltaics or photovoltaics technology, to total coordination of the evolving market. We here restrict our comments to analysis of those activities the federal government is now undertaking, rather than to the design of alternative policies.

TECHNOLOGY CHOICE

The most important issues arise with respect to the interrelationships between the opportunities for technological change in photovoltaics and the relation of those opportunities to the structure of the photovoltaic market. We have divided the technical options in photovoltaics into three classes: short-run and long-run learning-by-doing and discrete changes. Roughly speaking, short-run learning-by-doing includes those small, incremental changes to present product and process technology which derive naturally from actual production. Such changes are occurring now in the industry and are presumably responsible for some part of the cost reductions which occurred over the last decade as photovoltaics expanded from the space market into remote terrestrial applications, and in the last two or three years, as costs for remote terrestrial applications have fallen. Long-run learning-by-doing consists of those distinct but still incremental modifications to present production processes, i.e., less expensive ways of manufacturing monocrystalline silicon cells based on the Czochralski technique. Discrete changes would include the numerous alternatives to the dominant technology -- monocrystalline silicon sheets, amorphous silicon, other materials, etc.

Most identifiable development efforts in any field are generally focused on long-run learning-by-doing. The reasons for this, as discussed in Chapter Four, are related principally to the decision-making process in the face of high levels of uncertainty and to appropriability problems. This focus can have important effects on the ultimate evolution of the technology. Most significantly, such behavior is often "myopic," in the sense that over the long run, society might be better off if efforts had been focused on discrete changes. The "myopia" is self-reinforcing in that as the dominant technology responds to efforts at long-run learning-by-doing, discrete changes look less attractive and are less likely to draw investment.

Myopic technology choice may be occurring in photovoltaic development programs today. As discussed in Chapter Three, much of the total (public and private) photovoltaic RD&D effort seems to be aimed at long-run learning-by-doing, and for the usual reasons. Especially in the case of the federally-supported efforts, the sense of urgency and the associated tight deadlines result in a focus on modifications to present production techniques. Planning is explicitly based on a notion of continuous reductions in cost, reductions that are apparently based on the concept of a continuously evolving technology. Thus, meeting industry cost goals in 1980 or 1982 is viewed as a necessary precondition to meeting much more ambitious goals later in the 1980's. Our analysis indicates that this concept, and therefore the plans based upon it, should be seriously questioned.

The issue is especially important in the light of the segmentation of the photovoltaic market. As discussed in Chapter Four, the photovoltaic market can be viewed as three related but distinct submarkets -- those involving cells for use in outer space, at remote terrestrial sites, and at nonremote terrestrial sites. The product and process technologies, the costs of competing electric power sources, and the institutions (researchers, buyers, sellers, and others) are reasonably distinct for each submarket. It is clear that photovoltaics will contribute to federal energy goals only if they can penetrate the nonremote market. However, the segmentation implies that institutional and economic success in the remote market may be relatively unrelated to success in the nonremote market. The accessibility of the remote market to long-run learning-by-doing (and success in meeting "interim" goals) thus does not imply that discrete changes will not be needed for success in the nonremote market (and for meeting "long-run" goals). In fact, emphasis on modifications to monocrystalline silicon processes now may have the effect of limiting the availability of superior technologies in the future.

SELECTION OF FIRMS AND INDUSTRIES

A related set of issues is associated with the federal government's actions to promote or inhibit investments by certain categories of firms in photovoltaic technology development and production. Many considerations bear upon these issues, including high-level social decisions relating to equity and the political power accruing to large corporations; we will confine our comments to the implications of our analysis, and these relate principally to efficiency issues. First, as discussed in Chapter Three, the federal government is now subsidizing the acquisition by semiconductor firms of large increments in process technology (long-run learning-by-doing). (Some discrete developments are being subsidized in that industry as well.) No other category of firms receives this sort of assistance to nearly the same extent. The selection of the semiconductor firms was the result of a widely held view that low-cost solar cell manufacturing will be closely related to present semiconductor process technologies because presently dominant semiconductor and photovoltaic technologies both center around monocrystalline silicon structures.

However, for reasons discussed in Chapter Three, we have concluded that this relationship is not nearly as close as it appears to be. Most importantly, semiconductor process technology involves placing many electronic functions on tiny silicon chips, while monocrystalline silicon solar cell processes involve doing very little to large areas of silicon. Further, the processes seem to be diverging -- as new techniques are being developed for implanting microcircuits, and as many of the discrete technical options for flat-plate photovoltaics do not involve expensive silicon monocrystals. Thus, good reason exists to question the evolving partnership between the semiconductor industry and the federal government in this area. These reasons should be equally valid within the semiconductor firms and in public policy forums, and this may explain why many of the semiconductor firms' efforts are supported by the federal government rather than by the firms themselves.

Somewhat to the contrary, there is a commitment to photovoltaics by oil companies which is surprisingly large given the apparent lack of any technical connection. As discussed in Chapter Three, in these firms the internal pressures to maintain the size of the firm in the face of recent and anticipated declines in the natural resource base they control have led them into investments in substitutes for petroleum. The problems new ventures often have in finding capital can make such internal capital markets an important source of funds for the development of new energy technologies such as photovoltaics. Furthermore, the oil companies are investing a very high proportion of the photovoltaic effort in discrete technological advances, in marked contrast to the semiconductor firms. It seems that the lack of commitment to monocrystalline silicon technology, combined with the relatively long time horizon associated with the serious depletion of petroleum resources (several decades), has freed the oil firms from the potentially "myopic" view of the semiconductor firms and the federal government. If development and widespread utilization of photovoltaics is desirable (and this certainly seems to be a central tenet of the federal government's photovoltaic policy), then oil company efforts in this area should not be discouraged. In particular, policies concerning horizontal divestiture should be seriously questioned, at least with respect to photovoltaic development.

However, any discussion of the role of particular industries in the evolving photovoltaic market is somewhat off the mark from the start. One of the important lessons to be learned from historical studies of technological change is that very often innovations occur as firms from initially unrelated industries invade the territory of established firms. It is presumptous on our part, or the federal government's, to estimate at this early stage in the development of photovoltaics which firms or class of firms are most likely to be successful in a big way. Thus, while there is serious doubt about the efficacy of market forces in guiding particular firms into or out of photovoltaics, there is equally serious doubt about the ability of the government to know how to make appropriate corrections to the market's guidance. It is tempting, under the circumstances, to recommend policy neutrality in this respect. That is, that federal development or procurement funding should not be targeted toward or away from particular firms or industries. This would represent a preference for errors in the marketplace over errors in government policy, clearly a value-laden choice. The most that can be said, therefore, is that any such policy should be preceded by a careful analysis of both technical and market relationships. Ultimately, it is to be hoped that fundamental research in this area might aid in such policy decisions.

Some of these issues in photovoltaic policy are the subject of ongoing discussion and are deservedly controversial. Some presently are not issues at all. While our analysis would seem to offer some hints as to appropriate policy directions, we can offer little in the way of empirical support. We assert with little hesitation, however, that each of these issues is deserving of attention in the policy process.

APPENDIX: TECHNICAL CHOICE AND TECHNOLOGY DEVELOPMENT

A crucial concept underlying the analysis in Chapter Four is that technology development involves the utilization of economic resources and responds to economic stimuli. Investment in technology development is motivated by profit considerations and is induced by expectations about future demand and supply and by changes in relative factor prices. The model of technical choice and innovation developed by Paul David, which we will utilize, permits us to understand the crucial links between changes in relative factor prices and technology development. The David model was highly influenced by previous work on technical change done by Salter, and by Atkinson and Stiglitz.

In making economic decisions the firm is constrained by existing technical knowledge. In traditional economic analysis the existing technology can be characterized fully by the concept of a production function. The production function embodies the purely technical relationships which represent at any time the best state-of-the-art methods for converting any combination of inputs into outputs, independently of present (or past) relative factor prices.

In applying this concept to actual production processes Chenery found that only a limited set of techniques or blueprints for production were available at a point in time. A much wider set of potential production processes, more in correspondence with the concept of a production function, were thought to be technically feasible. But they were not yet ready for production. Choices had been made in the past with respect to which particular productive techniques to develop fully to the stage where they were capable of being used in actual production. This resulted from the fact that the development effort involves the utilization of substantial economic resources. As Salter describes the problem:

> ...First, a choice must be made as to which of the countless methods that are technically feasible in principle are sufficiently commercially promising to be worth developing in detail. No engineer goes to the trouble and expense of developing techniques which he is certain will prove uneconomic. The difficulty is that even at this early stage, costs, and through them factor prices, intrude to some extent. A method, rejected for detailed development on the grounds that it is commercially impracticable, may have been regarded as promising if factor prices were differernt. For example, oil-fired locomotives were probably technically feasible fifty years ago but would not have been considered worth developing in view of the relative prices of oil and coal then prevailing. Secondly, in even the simplest designed process there are numerous alternatives which must be decided on the basis of cost: whether control should be automatic or manual, whether bearings should be of bronze or steel, or countless other everyday decisions of engineers, are essentially cost decisions within the framework of technical restraint; they are quasi-economic decisions which precede choice by businessmen. (p. 14.)

To clarify the distinction between the economic concept of a production function and the notion of a limited set of discrete production processes the concepts of "Fundamental Production Function" and "Available Process Frontier" were introduced by Chenery and Salter and adopted by David. The first, which includes the broad set of potential production processes which can be developed with reasonable prospects of technological success, corresponds more closely to what is usually meant by a production function. It is constrained by present engineering knowledge. But the attainment of any particular technique on the Fundamental Production Function may involve substantial development costs. On the other hand, the latter concept corresponds to the limited set of processes which can be presently put to use in the production of a commodity. These processes which are presently available are a result of past economic choice of which processes to develop fully.

An implication of the above concepts is immediately clear. The traditional distinction between factor substitution, or change in technique, and technical change, which involves the development of new technologies, becomes blurred. This is shown in Figure A.1, for the production of a homogeneous good, measured as Y. Two factors of production labor, L, and capital, K, are considered. The available process frontier is denoted by APF and the fundamental production function by FPF. At initial relative prices, p, point A represents the cost-minimizing factor combination. That is, pp is one of a set of parallel lines of constant cost per unit of output (their slope is given by p), and A is the point on the APF which lies on the constant cost line closest to the origin, pp. Ray α is the activity line representing a constant ratio of labor to capital per unit of output. The technology at A is assumed to be in long-run equilibrium, where the available production technique coincides with the maximum technological development attainable, given present engineering knowledge. An increase in the relative price of labor from p to p' will induce the development of technology to point B on the FPF. Whether the technology at point B will actually be developed will depend on whether the costs of development are smaller than the benefits to be attained by the technological change.

David extended the above analysis in two dimensions: first, by recognizing "that the price-guided choices made along the APF will be altering the position of the latter frontier, and also that of the FPF via the effect such decisions must have upon the acquisition of

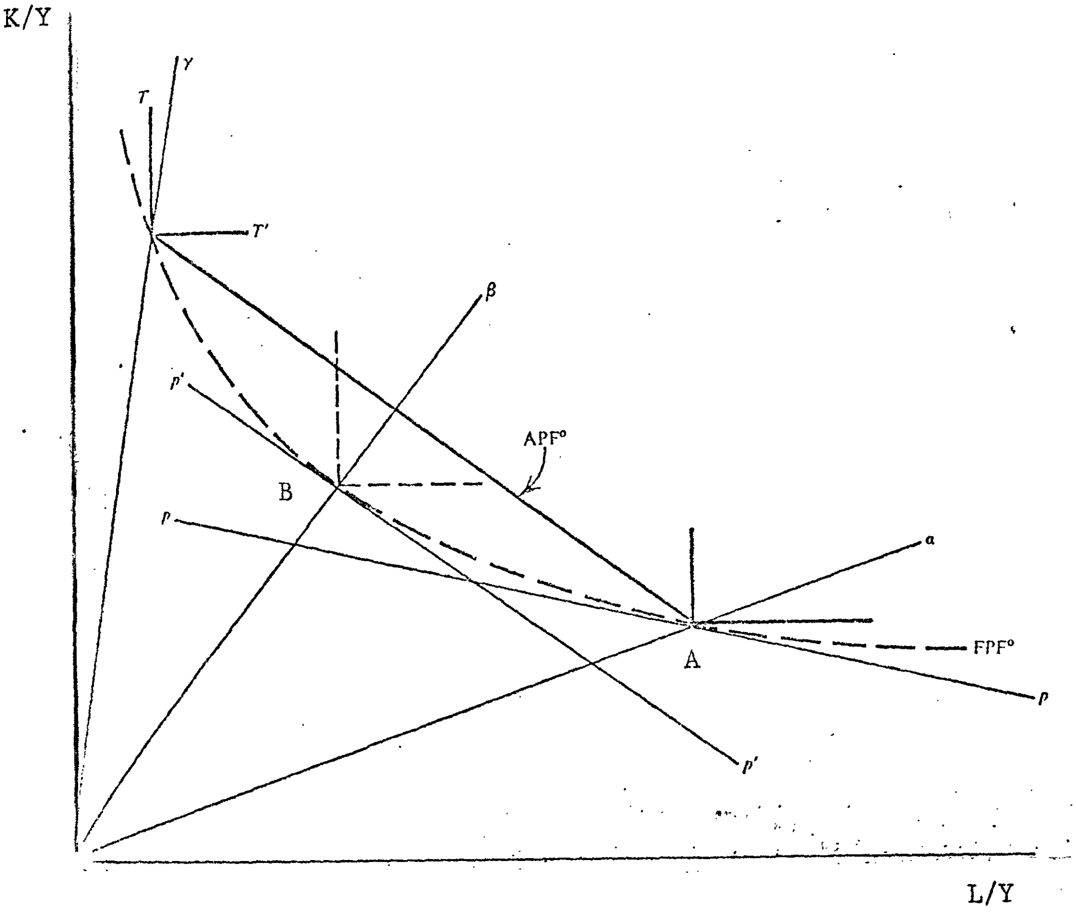

Figure A.1

Technical Innovation Viewed as Substitution

(David, p.63)

engineering knowledge," (p. 65); and second, by extending the analysis to include the conclusion of Atkinson and Stiglitz that learning-by-doing gives rise to localized technical change.

Learning-by-doing refers to the improvements in productivity which grow out of production experience and are thereby correlated with cumulative output. Although a given technical advance occasioned by learning-by-doing may give rise to some spillover or external effects, it will very often be "localized," that is, applicable only (or primarily) to the production process (or ray) being utilized at any given time. In general, such localized technical improvement will bias the APF and possibly the FPF toward the direction of present productive processes. A choice of technique for present production will bias the availability of techniques, since some techniques will be more fully developed and improved upon than others, therefore making drastic changes in technique less likely. This has implications for a normative theory of technology development since a myopic technical choice, which does not consider the potentials of future improvements in different technologies, but only their cost-competitiveness in the present and near future, will not be optimal in any dynamic sense. According to David, due to the difficulties in internalizing the benefits from technology developments, firms will make their technical choices myopically.

As Rosenberg suggests, the local character of learning-by-doing comes about from people's preoccupation with problems found in actual experience with production techniques. Internal technical relations between the elements of a productive activity will generate a succession of "compulsive sequences" of readily apparent "engineering challenges" which will focus inventive activity in a particular direction. Physical bottlenecks in the production process serve as signals to engineers, and technological refinements emerge as responses to them. According to David, "this constitutes a long-run form of learning-by-doing, a process of interplay between men and machines, or between groups and organizations, rather than the passive conformity of the ordinary agents of production to rules and systems laid down by heroic inventor-entrepreneurs" (pp. 59-60).

David draws the distinction between <u>long-run learning-by-doing</u> and <u>short-run learning-by-doing</u>, as forms of increases in productivity. The former involves localized technological improvements and consequently implies that economic resources must be utilized (i.e., investments must be made) for the development of this type of productivity improvement. The latter involves productivity increases which may come about as a result of increased management efficiency and the attainment of experience by the labor force with a fixed physical capital investment.

Learning-by-doing implies an irreversible form of increasing returns to scale. The generation of these localized (activity-specific) innovations may thereby lead to increased market concentration as long as the learning effects are fully internal to (appropriable by) the firm generating them. In the other extreme case, learning-by-doing effects are completely external to the firm (nonappropriable), and all competing producers benefit from these effects. A more likely outcome is a middle ground, where some learning effects can be appropriated, but where there are still substantial externalities among firms. It should be noted that the amount of a firm's investment in achieving long-run learning effects will depend upon the appropriability of that same effect by the firm that undertakes that investment.

Substantial evidence exists that learning-by-doing effects have empirical validity and are not merely a theoretical curiosity. David studied the existence of long-run learning-by-doing in the cotton textile industry in the United States during the nineteenth century. An interesting conclusion of that study is that many of the learning effects obtained by firms were simply repetition of learning effects previously obtained by other firms. Short-run learning effects have been experienced in Swedish steel works at Horndal in 1835-36 where no further investments in physical capital were made, but where labor productivity increased around 2 percent per year. This gave the name of "Horndal effect" to short-run learning effects. Other carefully recorded examples are the reduction of labor costs of airframe production and the experience of integrated cotton textile mills in Lowell, Massachusetts. (See David, pp. 171-191.)

A similar conception of the process of technology development is found in the study by Abernathy and Utterback entitled "Innovation and the Evolution of Technology in the Firm." This analysis permits us to understand the distinction between two specific patterns of technological innovations. One is referred to as "radical product changes," or discrete technology developments. These involve an entrepreneurial act and require drastic reorientation of productive activity. The other specific pattern is incremental in nature, is associated with a particular product line and corresponds to the concept of learning-by-doing (long-run). Abernathy and Utterback emphasize the importance of a "dominant product design" in the transition from what we shall call discrete technology development to innovations motivated by learning-by-doing. Products such as the DC-3 or the Model T Ford are seen as examples of dominant product designs. These designs serve as paradigms for future innovations, and such improvements will consist of minor refinements until the time when a new discrete technology is produced and is able to supersede it as a dominant product design. It should be noted that what may be perceived as a discrete technology development for a particular step in the production process, may well be considered a minor process improvement for the total product.

In the simple model developed by David, discrete technology developments will usually come about only through substantial changes in factor prices. The reason is that historical choices among techniques constrain the direction of future technical choices. This can be seen from Figure A.2. Localized changes induced by learning-by-doing are perceived by David to take the form of "persisting advance toward the origin <u>along a specific process-ray</u> (which) plays a quite crucial role in explaining how factor-prices may govern the long-run bias of technology progress." (p. 65.) In Figure A.2 we see how relative price changes from p to p' will "bring an incidental, myopic exploration of the β ray. But as learning proceeds the power of price variations to halt the emerging labor-saving drift of the APF begins to diminish" (David, p. 66). Only a "dramatic alteration of input prices" would restore the historical bias. That is, even if the relative price changes back to p, the β ray remains the most economic process (as the intersection of the dotted iso-cost line and APF' indicate in the figure). David goes on to characterize the process of technical change induced by learning-by-doing as a stochastic, Markov process. This is clearly unsatisfactory for our purposes. But the David model does yield important lessons for our analysis:

(1) Significant cost advantages are necessary for discrete changes in technology to be implemented. Discrete technology developments are guided by changes in relative factor prices. Not only present factor prices but also expectations about future prices, and thereby future shifts in demands, will initiate a search for discrete technology improvements.

(2) The achievement of learning effects is not consistent with the simultaneous achievement of discrete technology improvements. As David shows, and as emphasized by Abernathy and Utterback, and by Abernathy and Wayne, the achievement of a dominant product design in a production unit, with constant relative prices, can lead to substantial long-run learning effects, reducing the desirability of level of investment in, and ability to make discrete technological changes.

(3) The succession of minor process refinements associated with learning-by-doing will bias the direction of technical advances, and the availability of options in the future. Once a dominant design has been developed extensively through a historical evolutionary process only drastic changes in factor prices or important performance characteristics will permit the dominant product design to be superseded.

The last point is particularly important; some of the implications of the localized nature of technical change for a normative theory of development have been given by Atkinson and Stiglitz. The implication is

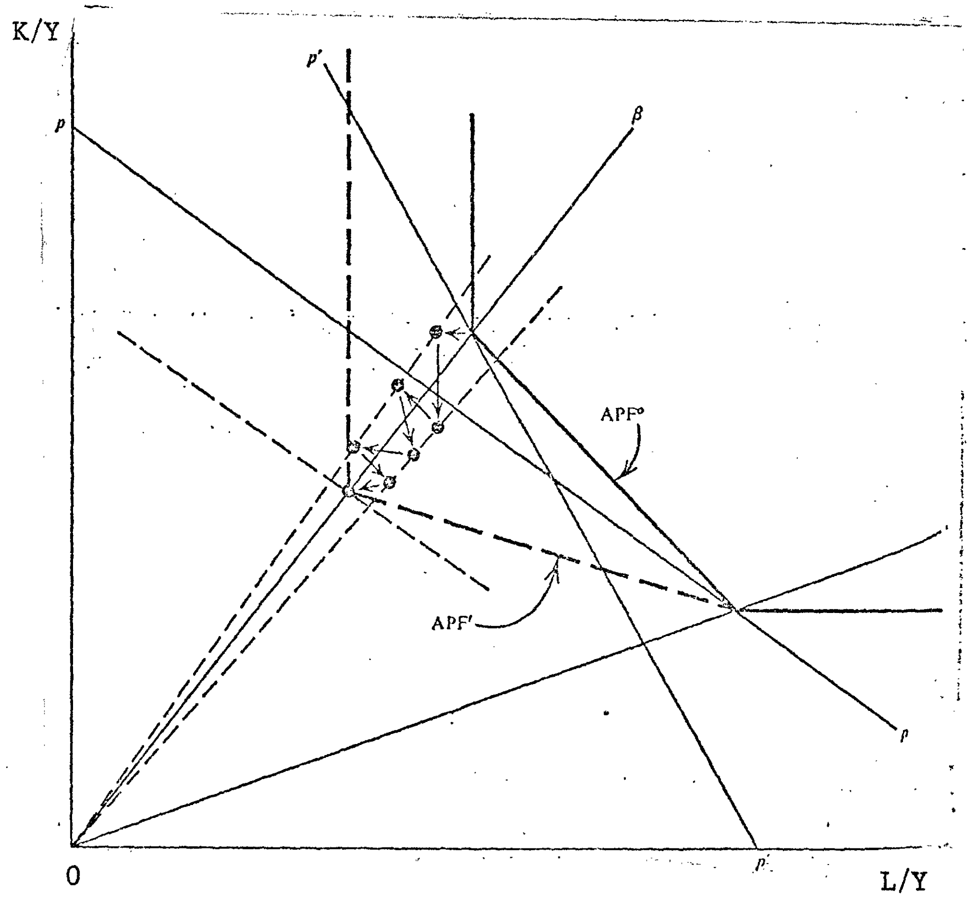

Figure A.2

Localized Learning and the
Global Bias of Technological Progress
(David, p.66)

clear: history is important in the technology development process. Even a casual examination of particular examples will illustrate its operation. Due to changes in relative prices (and supplies) of energy, research and development are taking place on alternative automotive power plants. But the fact is that there are substantial obstacles, both with respect to costs and with respect to performance in supplanting the present internal combustion engine with any of the available alternatives. The initial choice of the internal combustion engine for powering automobiles serves to restrict present choices, since learning effects and a succession of minor process and product improvements in the development of the internal combustion engine have already taken place. These same learning effects have had limited impact on alternative technologies (Linden, _et_ _al_.)

The model described helps us understand how factor price changes and how expectations about future prices and future demand may affect the direction of the technology development process. Experience with production techniques also signals avenues for technology improvements and thereby causes a more localized, evolutionary form of technical change. But a major part of technology improvements is not explained with the above model. This results from the fact that the David model assumes a homogenous commodity. As soon as we are considering a good which can be differentiated, technological developments may come about from a perceived demand for a differentiated product. According to Abernathy and Utterback, this is the principal means by which radical product changes come to be implemented. Generally, these major technical changes may be at a cost disadvantage since they have not been able to get the type of cost reduction which may come about from learning-by-doing. But if the performance characteristics of the product, or any other differentiating factor, is sufficient to counteract any initial cost disadvantages, then the product will be developed and introduced.

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