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A COST INFORMATION SYSTEM AS APPLIED TO A SOLAR CELL DEVELOPMENT PROJECT

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Abstract. As part of national R&D program of new energy resources named Sunshine Project, R&D efforts have been made on solar photovoltaic conversion system since 1974. It is the point for practical use of the conversion system, to establish the production process of low-cost silicon solar cells. In this paper we present a Cost Information System which has been developed to evaluate the production cost of solar cells for several conceptual production lines designed in the New Energy Development Organization, Japan.

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1. INTRODUCTION

An important aspect of R&D and production management programs is how to estimate the production cost of the products when the new technologies were introduced. Rapid technological innovations force project managers to forecast when the technology transfer will occur and the lower bound of production cost of the new technology. Also, policy makers need such analyses in order to develop national programs. These requirements point to the need for a design of a new cost information system.

The following is a trial attempt along this line. Its aims are:

(1) to be analytic
(2) to be parametric with respect to cost factors
(3) to simulate hardware systems by software
(4) to help finding the best policy for new technology development.

2. METHODOLOGY

2.1 Reverse Relation between Flows of Material and Flows of Information

The most fundamental finding exists in the recognition of the reverse relation between flows of material and flows of information. Generally speaking, flows of material start with raw materials and finish as end products via several processes (fig. 1).

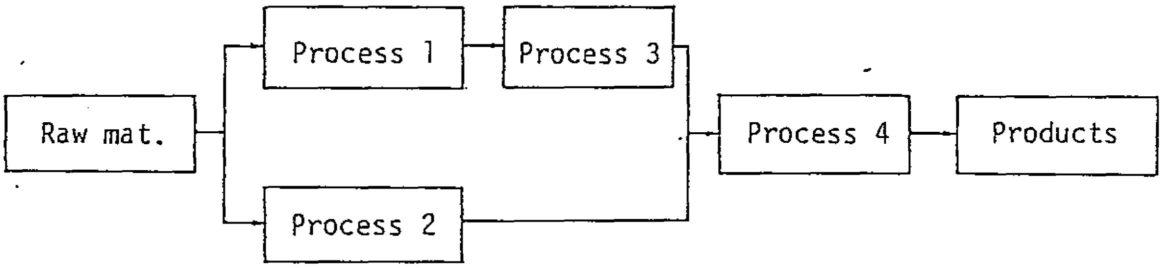


fig. 1 Flows of Material

On the other hand, flows of information start with the requirement of end products and go back to raw materials in the reverse order (fig. 2).

For example, the operation level of Process 4 in fig. 2 will be determined in accordance with the amounts of the end products. In a similar manner, the amounts of raw materials needed will be determined by the operation level of Process 1 and Process 2.

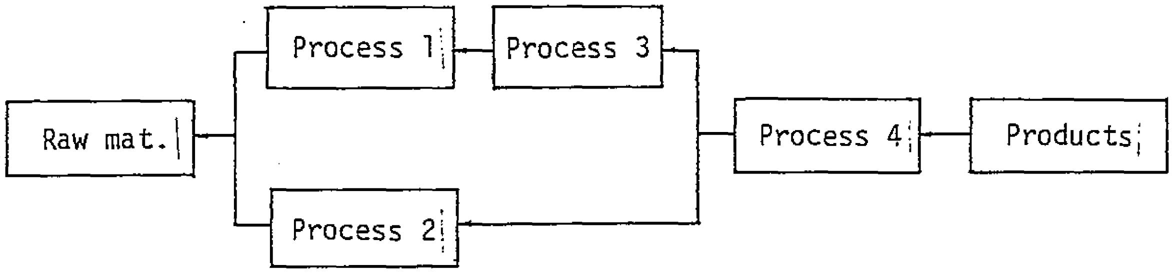


fig. 2 Flows of Information

The reasons why recognition of the reverse relationship is crucial, are as follows:

(1) The total production cost varies as the production level does. Also a choice of alternative technologies may occur if the production level goes beyond some limits. Therefore, cost information should be gathered through the system in the reverse order of flows of material.

(2) The schedules of processes are usually determined backwards from end to start. This relation influences the cost structure of the system.

(3) If some chemical processes are involved in the system, the operation time of each subprocesses is usually determined by solving the corresponding models in which output amounts are given as predetermined and input amounts of materials and operation times are determined optimally by the models. This situation suggests the reverse relationship between flows of material and flows of information.

2.2 Characteristics of the Cost Information System

Based on the recognition described above, the main steps for building the cost information system are as follows:

(1) *Process chart of production*

A flow chart is typically used to represent the system. Then, define the interfaces of materials to be delivered.

(2) *Characteristics of each process*

This can be done by enumerating all characteristics concerning to the cost for each process. For example, the unit prices of raw materials, manpower, electric power and so forth. Also, the process line speed, failure rate and yield rate are important factors to be taken into account. These characteristics are divided into *common* characteristics which are common in all process, and *individual* characteristics for each process. Define the name and the unit of each process.

(3) *Functional relations between the characteristics and the cost*

Information from the succeeding processes and cost characteristics of the process are unified to define the cost functions of the process. Informations to be delivered to the predecessors are also defined. Fig. 3 explains the basic structure of the system.

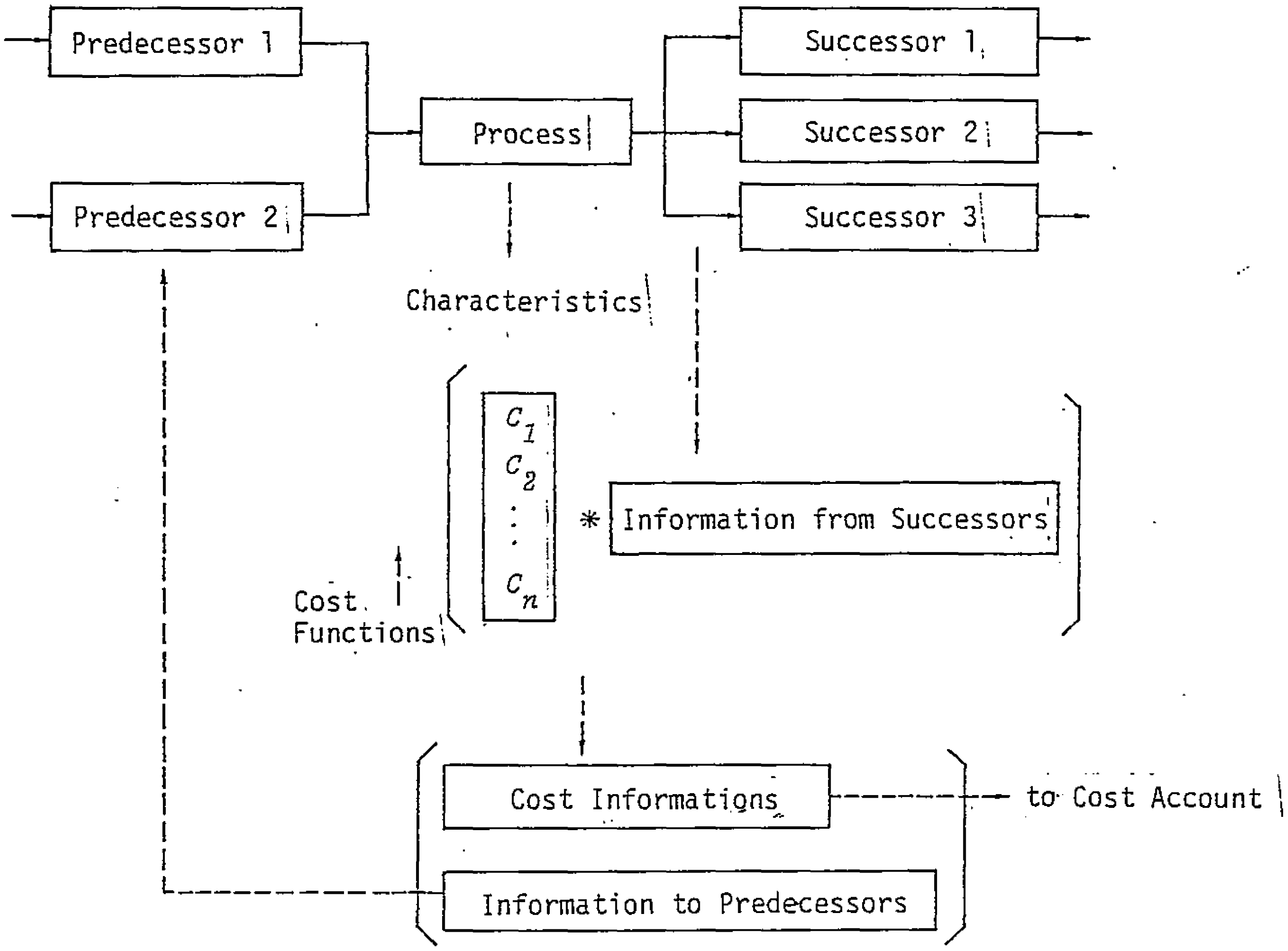
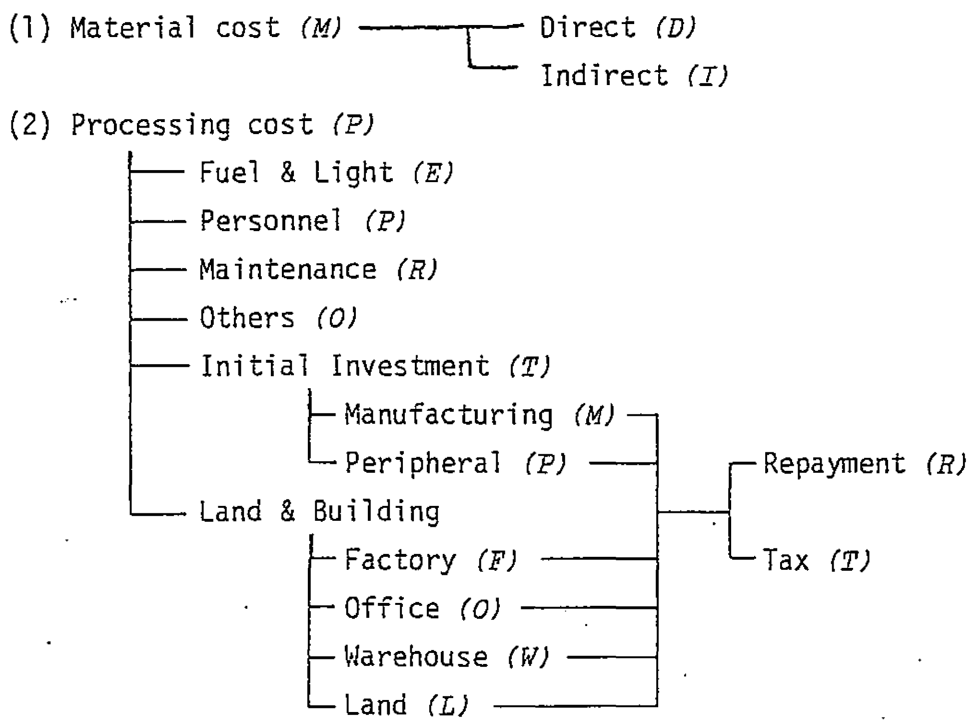


fig. 3 Basic Structure

2.3 Cost Items

This system provides standard cost items as follows:



For example, the labor cost of the Subprocess *3* in the Process *A* is identified by *A3PM*.

2.4 Variables

There are two kinds of variables in the system.

(1) Common Variables

Unit price of electricity, water, labor, engineer, administration, tax rate and so forth.

(2) Process Variables

Yield rate, number of machines or equipments, line speed, failure rate, number of labor, amount of production and so forth.

2.5 General Formulae for Cost Items

The amount of production of the final process is decided from the production level of the end product. Considering the yield rate of each process, the requirements to the predecessors are decided, and finally, the amounts of raw materials are determined.

The processing time T_i of each subprocess i is determined from the result of process simulator, which may be discrete event simulator or an equibilium model in the case of chemical process, or simply as a function of the amount of production, line speed, yield rate and number of machines in the subprocess.

Next, we present several general formulae for the cost items. The meaning of subscripts in the formulae are as follows:

i : subprocess ($i=0$ means the common subprocess)
j : peripheral equipment in each subprocess
k : peripheral equipment in the common subprocess
l : direct material
m : indirect material

and the first character of variables \$ means the Process name.

(1) Direct Material Cost of Process \$ ($\$MD_i$)

$$\$MD_i = (\sum_{l} \mathit{INPUT\ RATE}_{il} * \mathit{UNIT\ PRICE}_{il}) * \mathit{AMOUNT\ OF\ PRODUCTION}_i$$

(2) Indirect Material Cost of Process \$ ($\$MI_i$)

$$\begin{aligned}\$MI_i = {} & (\sum_{m} \mathit{INPUT\ RATE}_{im} * \mathit{UNIT\ PRICE}_{im}) * \mathit{AMOUNT\ OF\ PRODUCTION}_i \\ & + (\sum_{m} \mathit{INPUT\ RATE\ FOR\ TIME}_{im} * \mathit{UNIT\ PRICE}_{im}) * T_i\end{aligned}$$

(3) Fuel & Light

a. Electricity ($\$PEE_i$)

$$\begin{aligned}\$PEE_i &= \text{Cost in operation time} + \text{Cost in idling time} \\ &= (\sum_{j} \mathit{CONSUMPTION\ BY\ PERIPHERAL}_{ij} + \mathit{CONSUMPTION\ BY\ EQUIPMENT}_i * \\ &\quad \mathit{NO.\ OF\ EQUIPMENT}_i) * \mathit{UNIT\ PRICE\ OF\ ELECTRICITY} * (1 + \mathit{LOSS} \\ &\quad \mathit{RATE\ FOR\ STARTING}_i) * T_i + (\mathit{ANNUAL\ OPERATION\ TIME} - T_i) * \\ &\quad (\sum_{j} \mathit{CONSUMPTION\ BY\ PERIPHERAL\ IN\ IDLE\ TIME}_{ij} + \mathit{CONSUMPTION\ BY} \\ &\quad \mathit{EQUIPMENT\ IN\ IDLE\ TIME}_i * \mathit{NO.\ OF\ EQUIPMENTS}_i) * \mathit{UNIT\ PRICE\ OF} \\ &\quad \mathit{ELECTRICITY}\end{aligned}$$

$$\begin{aligned}\$PEE_0 &= (\sum_{k} \mathit{CONSUMPTION\ BY\ COMMON\ PERIPHERAL}_{0k}) * \mathit{MAX\ OF}\ T_i * \mathit{UNIT} \\ &\quad \mathit{PRICE\ OF\ ELECTRICITY}\end{aligned}$$

b. City Water ($\$PEW_i$)

c. Gas ($\$PEG_i$)

d. Others

(4) Personnel Expenses

a. Labor Cost ($\$PPD_i$)

$$\$PPD_i = NO.\ OF\ LABORERS_i * NO.\ OF\ EQUIPMENTS_i * (1 + FAILURE\ RATE\ OF\ EQUIPMENT_i) * T_i * UNIT\ PRICE\ OF\ LABORER$$

b. Engineer Cost ($\$PPI_i$)

c. Clerk Cost ($\$PPA_i$)

(5) Manufacturing Equipment

a. Repayment ($\$PTMR_i$)

$$\$PTMR_i = PRICE\ OF\ EQUIPMENT_i * NO.\ OF\ EQUIPMENT_i\ /\ REPAYMENT\ YEARS_i$$

b. Tax ($\$PTMT_i$)

$$\$PTMT_i = \$PTMR_i * (REPAYMENT\ YEARS_i - 2) * TAX\ RATE_i$$

Similar formulae can be described for Peripheral Equipment, Factories, Offices and Warehouses.

(6) Tax for Land ($\$PGLT$)

$$\$PGLT = AREA\ OF\ LAND * VALUE\ OF\ LAND * TAX\ RATE\ OF\ LAND$$

(7) Maintenance ($\$PR$)

$$\begin{aligned}\$PR = {} & \sum_i (PRICE\ OF\ EQUIPMENT_i * NO.\ OF\ EQUIPMENT_i * MAINTENANCE\ FEE\ RATE_i \\ & + FAILURE\ RATE_i * T_i * REPAIR\ PARTS\ RATE_i) \\ & + \sum\sum_{ij} (PRICE\ OF\ PERIPHERAL\ EQUIPMENT_{ij} * MAINTENANCE\ FEE\ RATE_{ij} \\ & + FAILURE\ RATE_{ij} * T_i * REPAIR\ PARTS\ RATE_{ij}) \\ & + \sum_k (PRICE\ OF\ COMMON\ PERIPHERAL\ EQUIPMENT_{ok} * MAINTENANCE\ FEE \\ & RATE_{ok} + FAILURE\ RATE_{ok} * MAX\ OF\ T_i * REPAIR\ PARTS\ RATE_{ok})\end{aligned}$$

2.6 Use of The System

In order to set the system in operation, we have to determine the following values:

(1) Annual production quantity

(2) Level of each variable

These input data are stored in a data-base of the system and may be accessed whenever necessary. For those variables that are not deterministic, we may use three points estimate, i.e. *optimistic* value, *most likely* value and *pessimistic* value. After the determination of these variables, the calculations will start with the final process, and go back iteratively to the raw materials. We can obtain the results from the system as follows:

(1) Information of production for each process

(2) Cost information for each process

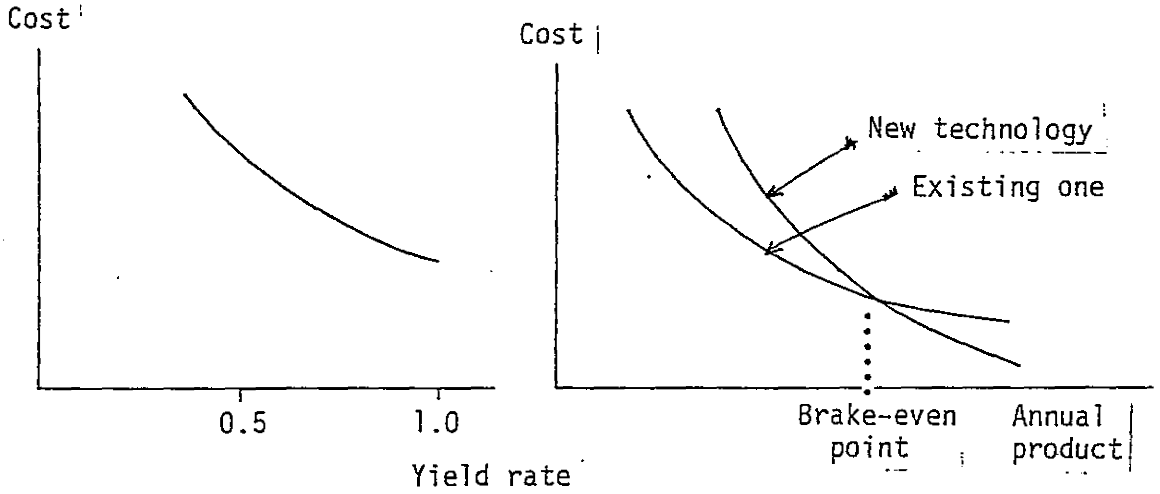
(3) Summary for each cost item and total cost

(4) Result of parametric analysis for certain variables (fig. 4(a))

(5) Influences of replacement of the process

(6) Estimation of the lower bound of cost of the existing technology

(7) Trade off of the proposed technology (fig. 4(b))



(a) Parametric analysis (b) Trade-off analysis

fig. 4 Use of the System

2.7 Remarks

Through this system, we can obtain several kinds of interesting information other than the cost. For example, in the project of solar cell development, the amount of energy needed to get a unit of solar cell power could be calculated by summing the energies thrown into the processes.

3. APPLICATION TO THE SOLAR CELL DEVELOPMENT PROJECT AT NEDO

3.1 Out-line of the NEDO Projects

The New Energy Development Organization (NEDO), as part of the national research and development project for new energy resources, the Sunshine Project, completed an experimental plant for manufacturing photovoltaic modules (flat plate) with an annual capacity of 500 kW in March 1983. The objectives of this plant are, firstly, to demonstrate the mass production method of producing photovoltaic modules, secondly, to confirm the conversion efficiency of the produced modules using solar grade silicon, and thirdly, to improve the manufacturing methods from the point of view of reducing the cost of module production.

This plant includes:

(1) a silicon materials process containing the integrated facilities necessary to produce solar grade silicon (SOG-Si);

(2) a large area silicon sheet process which consists of two methods (a SOG-Si casting and multi-slicing method and a ribbon crystalline growth method);

(3) a cell fabrication process which consists of two methods (a doped-spin-on diffusion and metallization method and an ion-implantation and electroplating method); and,

(4) a module assembly process containing automatic wiring and superstrative glass panelling facilities.

The production process are shown in fig. 5.

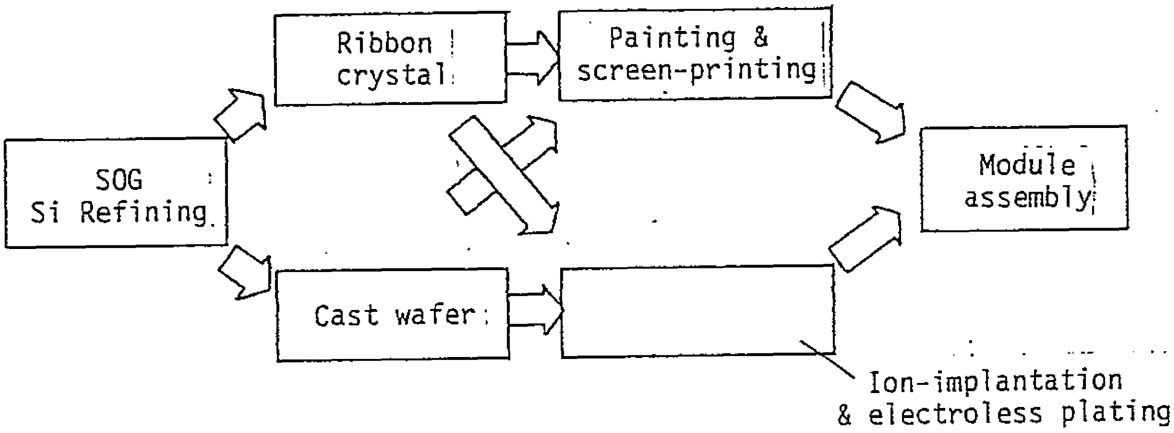


fig. 5 Block Diagram of Process

Silicon material process: In this process, SOG granular polycrystalline silicon is produces by trichlorosilane (TCS) distillation and its reduction, as shown in fig. 6. The by-product, tetrachlorosilane, can be recycled by adding hydrogen which transforms it back into TCS, and replacing the reduction reaction with a fluidized-bed reaction can considerably lower power consumption.

Silicon sheet process using casting process: The basic research on silicon casting technology has been carried out and 120 mm diameter ingots are now available. The solar cell efficiency obtained using SEG silicon is not less than 10%. Several kinds of slicing technology are also being investigated to reduce kerf loss.

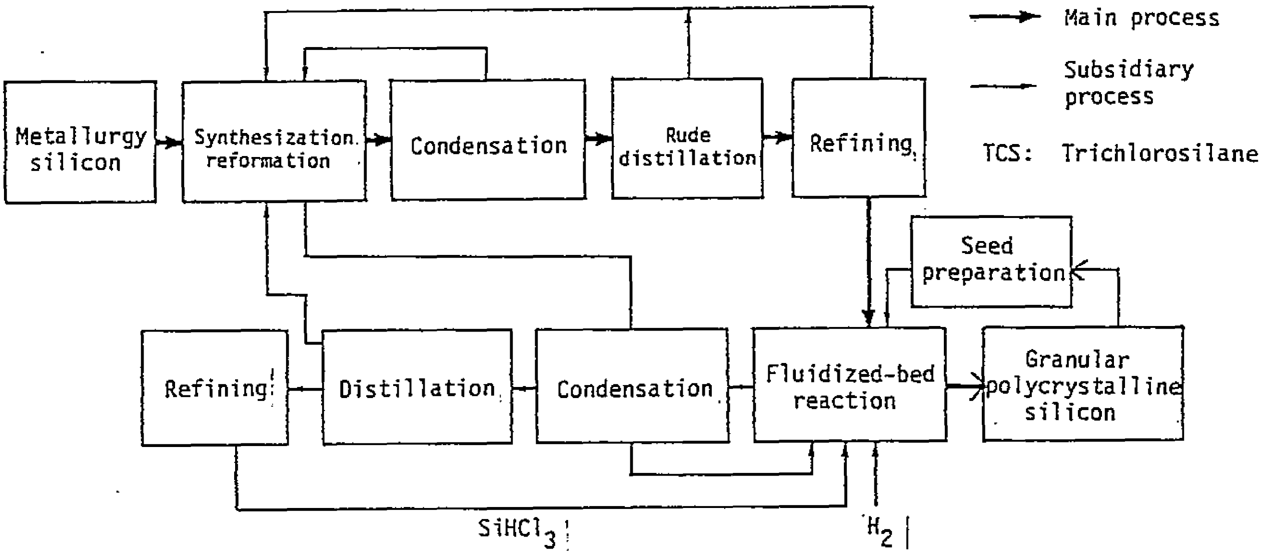


fig. 6 Silicon Material Process

Silicon sheet process using ribbon growth: A 20 mm/min growth rate and a thickness of 0.3 mm have been achieved. Ribbon 100 mm in width was obtained using position-adjustable carbon blocks to achieve horizontal temperature uniformity. Ribbons will be cut using a YAG laser cutter and granular silicon will be continuously charged while ribbons are being pulled in the plant. The tentative goal for cell efficiency is set at 9% for both the casting and ribbon growing methods using SOG silicon.

Cell fabrication process using ion implantation and electroless plating: To lower the production cost on a larger scale, a new high-current ion implanter was developed with a coaxial microwave ion source, an ion-beam scanning magnet, and a specially designed process chamber. Solar cells were fabricated by means of this implanter, and a conversion efficiency of over 13% was obtained using SEG CZ.

Experimental studies are in progress on a combined electrode structure consisting of electroless-plated electrodes and conductive anti-reflection (AR) film.

Cell fabrication process using painting and printing process: A compound painting solution containing diffusion dopant was prepared so that the p-n junction and AR cost are formed at the same time during the heat treatment of the silicon substrate paint. A screen printing technique was applied to replace the conventional electrode forming method. This process enables a fast, straightforward automatic cell fabrication process. A conversion efficiency of 16% was obtained using SEG CZ.

Solar cell module assembly process: This process covers the serial connection of cells, and packaging and framing them in one continuous automatic process. The module structure is superstrative with 4-mm low-iron glass on the front, PVB sealant and polyfluoride vinyl protection on the back. The automatic wiring process used is collective nonflux soldering.

3.2 Needs for Cost Analysis

Fig. 7 shows the historical transition of the production amounts of solar cells and the cost per watt from 1975 to 1982 and their future outlook in Japan. The production amounts have grown rapidly during the last several years. However, in order to accomplish the Sunshine Project, it is necessary to expand the production amount at least 1000 times of the existing scale and to drop the cost per watt at least by a factor of 10 ∿ 20. For this purpose, we need more reliable cost estimates for the elements of production line. The analysis should be done based on the live data added by the future technological innovations and the economy of scale should be taken into account.

According to the basic methodology mentioned in the preceding section, we have tried to apply the cost information system to the production of silicon crystal solar cells including the module assembly.

3.3 Cost Analysis and Results

The analyses and main results are as follows:

(1) We determined the process chart of the production line and defined the characteristics and their functional relationship.

(2) The data were estimated by the contract companies. Three mode estimates are used usually.

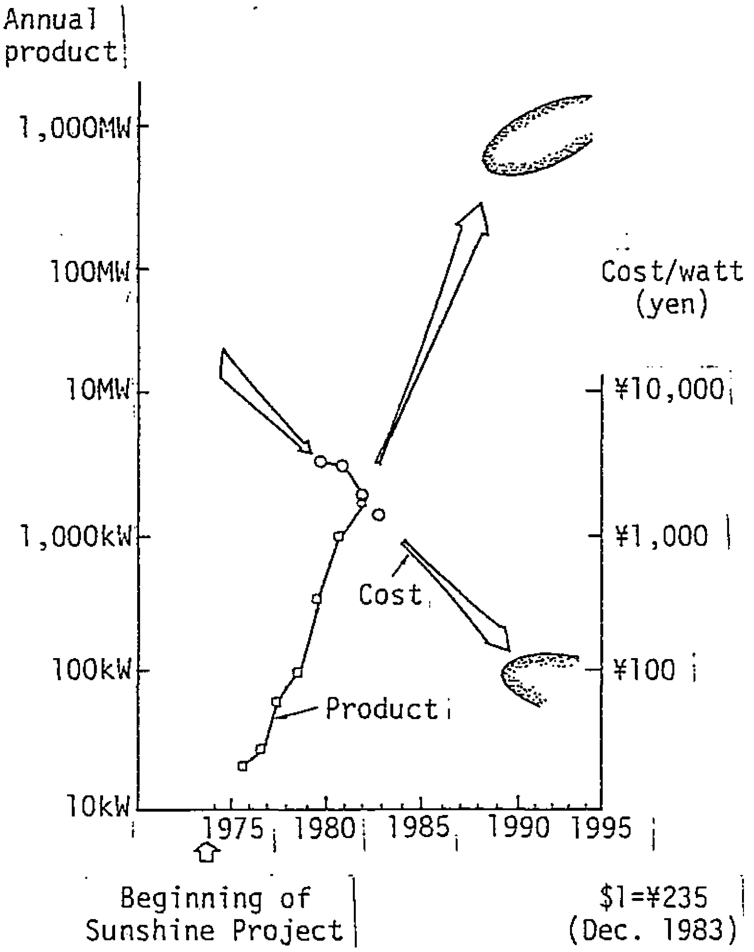


fig. 7 Trends of the Annual Product and Cost of Solar Cells in Japan

(3) We calculated the cost of each process and each cost item and summed them up into the total cost.

(4) From the analysis, we could find the most cost-critical elements in the production line and could make improvements on them. Fig. 8 shows an example of improvement on the ion-implantation and electroless plating process, cooperated with increase in the production scale. The improvements came mainly from the followings: cut in production line, relaxation of degree in the clean room, drop in processing temperature and reduction of the personnel cost.

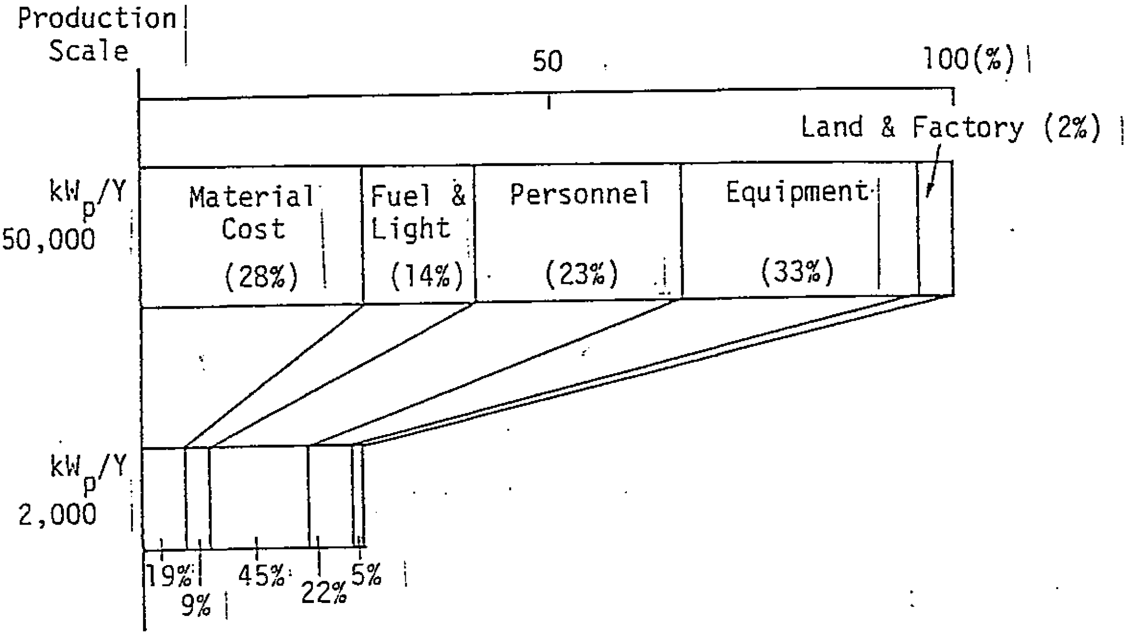


fig. 8 Improvements on Ion-implantation & Electroless Plating

(5) We tried several parametric analyses by taking the most crucial variables as parameters. Figs. 9 & 10 show the relations between the cost per watt and the production scale. Also we can see the cost limit of the existing technologies from the figures.

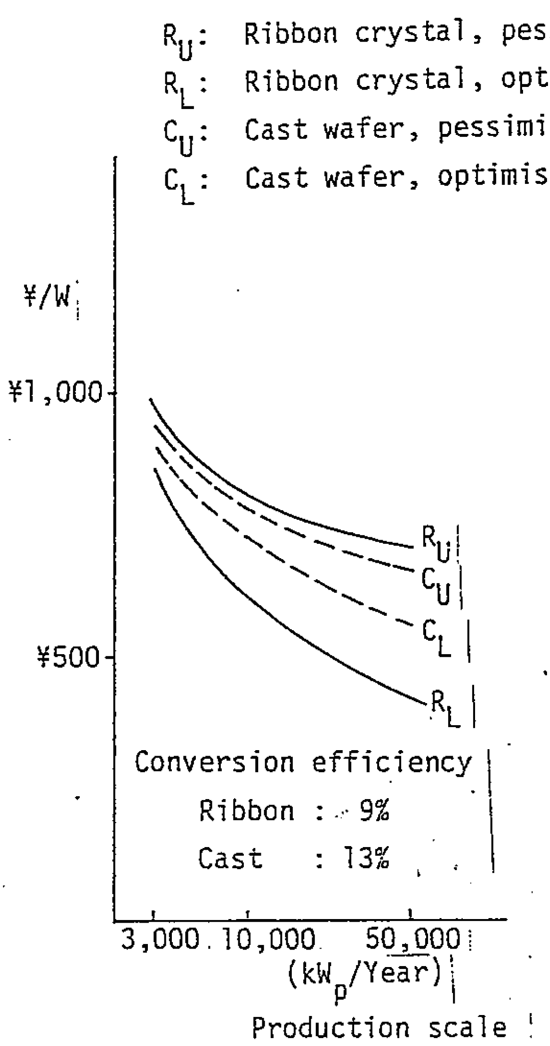


fig. 9 Cost vs. Production Scale - Case 1

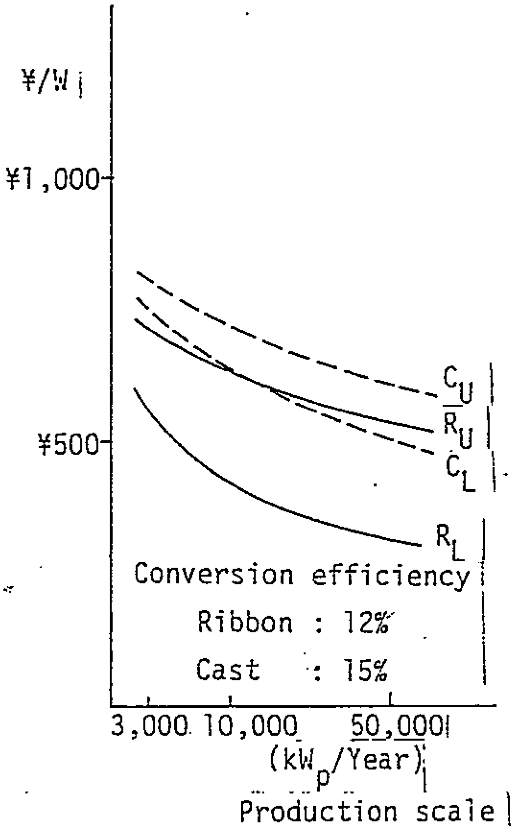


fig. 10 Case 2

3.4 Future Policy

The photovoltaic power system is in the way to the practical use via the development stage. Tremendous number of technological innovations have been proposed in the recent days. Reliable cost estimates and cost forecasts are necessary to determine which technology should be chosen and which should be cut off. The results of the analyses affect the policy makers and contractors in designing the minimum cost production line and in finding the shortest route for the achievement of the NEDO Project.

Finally, fig. 11 shows the general strategies for making the solar photovoltaic power system fit for practical use.

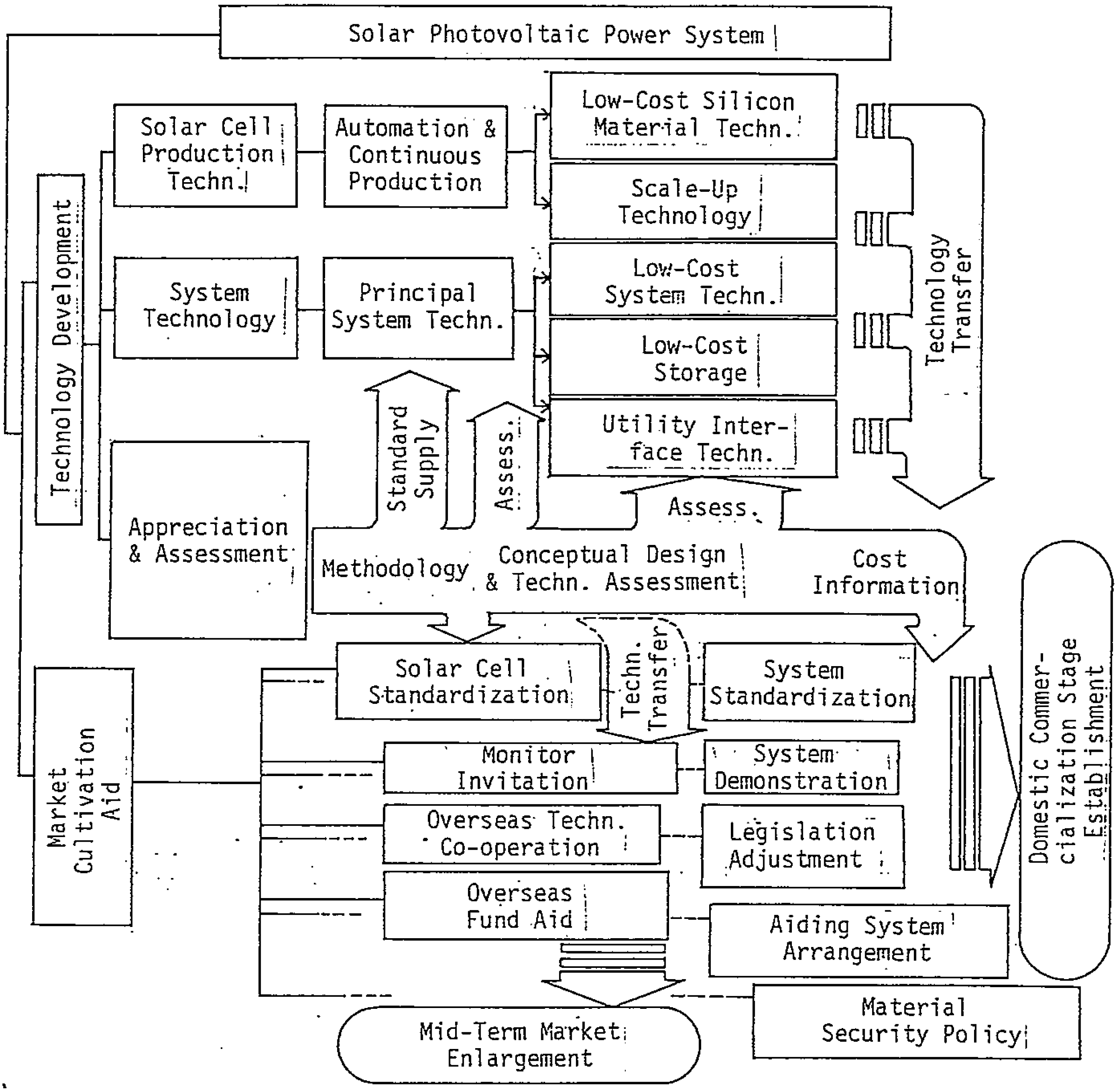


fig. 11 Strategies for making Solar Photovoltaic Power System fit for Practical Use

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