

DETERMINING TRADE-OFFS BETWEEN COSTS OF PRODUCTION AND CELL/MODULE-EFFICIENCY WITH THE CONCEPT OF INDIFFERENCE CURVES

J. Jaus, J. Rentsch, and R. Preu
 Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstr. 2, D-79110 Freiburg, Germany
 email: Joachim.Jaus@ise.fraunhofer.de

ABSTRACT: Currently, there are many new technologies in development which all aim at reducing production costs for photovoltaic (PV) electricity. For answering the question if a new technology in PV supports the cost reduction targets at all, and if yes, to what extent, an economic evaluation of a new technology in an early stage of its development is necessary. If a new cell production technology is evaluated based upon economic criteria, the evaluation process normally includes the cell level, comparing costs/cell or costs/ W_p . The implications of different technologies (resulting in different cell-efficiencies) on the other components of a PV-system are often omitted, either due to the lack of appropriate cost data or the complexity of interactions between cell-efficiency and total system cost. Using the concept of experience curves, these complex interactions can be expressed in a single figure and therefore be easily and intuitively included in the manifold economic analyses that are accomplished in PV research and industry. Furthermore, it allows the comparison of different production technologies on an abstract level.

Keywords: Costs, efficiency, indifference curve

1 INTRODUCTION

One of the most important drivers for the development of the PV-market are the costs of a PV-system and the costs for the electricity it produces. As these costs are still comparably high, the main challenge for research and development is to thrive for new technologies to tackle with the costs of PV-technology by rising cell and module efficiency and/or by reducing production costs.

However, very often an increase in cell efficiency can only be achieved by more complex and more expensive production processes. The main question is whether the higher production costs are offset by the increased efficiency, taking into account all system costs dependent on the cell efficiency, e.g. module and cell area, landuse, or construction costs.

For a strategic decision making process a concept is needed to easily determine the trade-off between a change in efficiency and a change in production cost, taking into account the numerous impacts efficiency-improvements have on the whole PV-system. These trade-off costs can also serve as a measurement for the value of an increase in module efficiency to the customer of a PV system.

2 ECONOMIC ANALYSIS OF MANUFACTURING PROCESSES

For every process of a PV-production line (e.g. damage-etch, diffusion, ...) a process-cost pool is created, comprising all cost categories accountable to this process.

For the detailed economic analysis of manufacturing processes, it is useful to trace as many costs to cost objects so they can be treated as direct costs. In order to allocate some of the costs which are usually treated indirect costs (like utilities such as water, sewage treatment, ...) directly to the different processes, an Activity Based Costing approach [1] has been chosen. The delivery of these services is regarded as separate activities with corresponding cost pools, each with its own cost categories like depreciation, maintenance, direct materials, etc.

For each utility and service for which a transformation to direct costs has to be accomplished, the demand is aggregated through every process-cost pool, e. g. the demand for de-ionized (DI)-water is cumulated over all the processes needed to manufacture a solar cell. This aggregated demand is used to calculate average internal utility & service prices. Internal prices finally allow the tracing of the costs back to the process-cost pools and therefore to transform the costs of utilities and services to direct costs. This concept is illustrated in Figure 1.

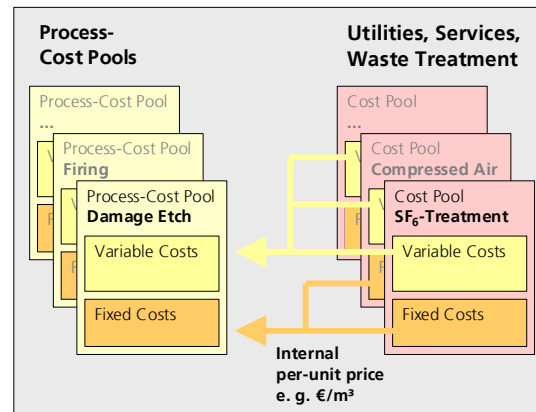


Figure 1: Cost pools for utilities and services are used to calculate per-unit prices that serve to calculate direct costs in the process-cost pool.

The following utility and factory-wide service costs are calculated and traced to process-cost pools by the method described in Figure 1:

- DI-water
- Compressed air
- Chilled water
- Normal and fluoride sewage treatment

3 LEC AND SYSTEM COSTS

As the main measurement for the economic performance of a PV-system the Levelized Electricity Costs (LECs).

are a commonly used benchmark. The LEC calculation method used in this work is depicted in Eq. 1.

$$LEC = \frac{C_{Sys} \cdot \left(\frac{(1+i)^t}{1-(1+i)^{-t}} + OM \right)}{E_{Real}} \quad (1)$$

with

LEC	Levelized Electricity Costs	[€/kW _p]
C_{Sys}	Total system costs	[€/kW _p]
t	Life span of the PV-System	[years]
i	Interest rate	[%]
OM	Operation & Maintenance factor	[1]
E_{Real}	Energy output (see text)	[kWh/kW _p]

The energy output of the PV System depends on the annual irradiation (in kWh/m²) and the Performance Factor with accounts for losses due to partial shadowing, voltage conversion and other.

The total system costs are calculated by adding the costs of the different components of a PV System together. These costs comprise module related costs, inverter costs, and costs for mounting and construction (Eq. 2):

$$C_{Sys} = \frac{C_{Con} + C_{Mod}}{\eta_{cell} \cdot \tau \cdot PF} + \frac{C_{Cell}}{\eta_{cell} \cdot \tau \cdot a_{Cell}} + C_{Ret} + C_{Inv} + P \quad (2)$$

with

C_{Sys}	Total system costs	[€/kW _p]
C_{Con}	Costs for mounting & construction	[€/m ²]
C_{Mod}	Costs for module manufacturing	[€/m ²]
η_{Cell}	Reference efficiency of solar cell	[%]
τ	Transmission factor	[1]
PF	Packaging factor	[1]
C_{Cell}	Costs for cell manufacturing	[€/wafer]
a_{Cell}	Wafer size / cell area	[m ²]
C_{Ret}	Retail/wholesale/logistic	[€/kW _p]
C_{Inv}	Inverter costs	[€/kW _p]
P	Profit in the supply chain (see text)	[€/kW _p]

For the economic calculations in this work, there are two different approaches used to source cost data: One is building cost data from the scrap through analyzing production data, the other source used here is information collected by owners of solar systems. To match these two information sources and to be able to calculate absolute LECs, the variable P has been introduced which represents the profit in the supply chain from the cell manufacturer to the end-customer. If no other data is available, the profits are calculated with 10% of the added value. However, for the scope of the paper, this value is of very little importance because for small changes in absolute cell efficiency, it does not interfere with the efficiency-cost relationship.

Essentially for this model, as with any cost estimation, is the choice of the proper cost drivers for the different cost categories. The best cost drivers are those which generate the best cause-and-effect relationship. For example for the cost for mounting and construction work the cost driver with the best fit is the total module size.

The total system costs calculated with Eq. 2 can be used to evaluate production processes by analyzing the buying decisions of a PV-customer and how this affects manufacturing process selection.

It is assumed that the customer who makes his buying decision on economic reasons only prefers one PV-

system over another, if the corresponding LEC is lower. If two PV-systems have the same LEC (even though based on different technologies), economically speaking he/she allots the same utility to both systems, which makes him/her indifferent between the two systems.

As can be easily seen from Eq. 1, the LECs of two systems are the same ($LEC_1 = LEC_2$) if the total system costs C_{Sys} are the same:

$$C_{Sys1} = C_{Sys2} \quad (3)$$

As the purpose of the calculations in this work is to support economic evaluation of different manufacturing process for solar cells, it is particularly interesting to analyze the effects that different cell costs and cell efficiencies have to the total system costs. Using Eq. 3 and Eq. 2 for different cell costs C_{cell} and efficiencies η_{cell} leads to Eq 4:

$$\frac{C_{Con} + C_{Mod}}{\eta_{cell1} \cdot \tau \cdot PF} + \frac{C_{Cell1}}{\eta_{cell1} \cdot \tau \cdot a_{Cell}} = \frac{C_{Con} + C_{Mod}}{\eta_{cell2} \cdot \tau \cdot PF} + \frac{C_{Cell2}}{\eta_{cell2} \cdot \tau \cdot a_{Cell}} \quad (4)$$

In order to find out between which combinations of cell efficiency and cell costs the customer is indifferent, a correlation between the cell efficiency of a PV-system and the production costs of the cell leading to the same LECs must be found. The different combinations of cell efficiency and cell production cost yielding the same LECs form a cost-efficiency indifference curve.

4 INDIFFERENCE CURVES

To analyze cost-efficiency relationships, Eq. 4 can be resolved into

$$C_{Cell2} = \eta_{cell2} \left(a_{Cell} \frac{C_{Con} + C_{Mod}}{\eta_{cell1} \cdot PF} + \frac{C_{Cell1}}{\eta_{cell1}} \right) - a_{Cell} \frac{C_{Con} + C_{Mod}}{PF} \quad (5)$$

In Eq. 5 a linear correlation between cell efficiency and cell cost can be observed.

To quantitatively analyze the relationship between costs and efficiency with the equations developed above, the variables which were introduced in Eq. 1-5 must be filled with costing data based on the current PV-market.

Therefore, different costing-data has been analyzed [2, 3] in order to determine the costs for module construction, module mounting & construction work, Balance-of-System, and other. The data for this purpose was derived, among other sources, mainly from statistics on the German 100.000 roof program, a financing and loan program launched in 1999 and phased out in 2003. On the basis of this program, 65.702 PV-projects were realized with a total peak power of 346 MW_p [2]. As the participants of this program had to file a standardized report on the application of the loans, the statistical data collected through this program is a valuable resource for the information needed here. For some utilities standard cost-of-ownership data from the semiconductor-industry is available [4] and was adjusted and utilized for this work. For determining the costs of cell production, the models developed in the German project ‘‘Solpro’’ [5] were adopted.

Table 1: Selected parameters used for determining cost-efficiency indifference curves. The items in the upper part of the table have a direct influence on the cost/efficiency graph, the figures in the lower part determine absolute LEC for typical irradiation values in Germany.

Mounting and construction	C_{con}	83 €/m ²
Costs of Module Making	C_{Mod}	97 €/m ²
Cell Area	a_{cell}	0,0156 m ²
Reference Efficiency of a cell	η_{cell}	14,50%
Manufacturing costs / cell	C_{Cell}	3,76 €/Cell
Transmission Factor	τ	0,9
Packaging Factor	PF	0,96
Resulting Module Efficiency		12,53%
Inverter	C_{Inv}	510 €/kWp
Energy Output of PV-System	E_{Real}	870 kWh/kWp
Costs for Sales & Logistics	C_{Ret}	850 €/kWp
Depretiation Period	t	20 Years
Operation and Maintenance Factor	OM	1,50%
Interest Rate	i	6,00%

With these parameters a graph representing the correlation between cell efficiency and cell costs over a range of possible cell efficiencies can be calculated, as is illustrated in figure 2.

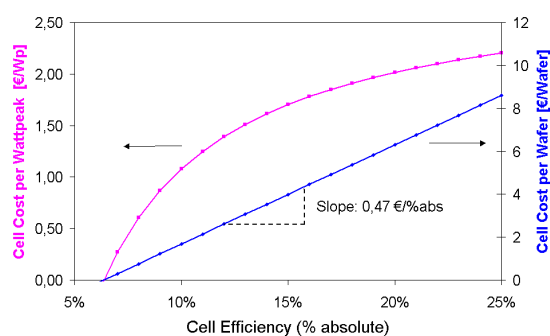


Figure 2: Cost-efficiency indifference curve based on a set of parameters as described in Table 1. Cell costs are measured in €/W_p (left axis) or €/wafer (right axis).

The slope of the indifference curve represents the total value of an efficiency increase to the customer. This value can be interpreted in several ways, depending on the application and whether the viewpoint of the customer or the manufacturer is taken:

- The customer's willingness to pay for an efficiency increase.
- The cost increase a more complex production process may cause if it raises cell efficiency
- The efficiency loss a simpler process may cause if the simpler process yields lower production costs

With the given set of conditions and based on the analyzed cost data, the slope of Figure 2 is 0,47 €/wafer per percent absolute efficiency increase. This means for example that the increase in cell production costs due to a new process may not exceed 0,47 €/wafer without loosing or gaining in profit if this new process raises cell efficiency by 1% absolute. If it does not raise production cost at all, the customer's willingness to pay of for the increased efficiency is 0,47 €/wafer. It then depends on the market (buyer's market or seller's market) to what extend this increased willingness to pay can be converted

by a cell-manufacturer to yield higher sales prices per wafer.

With the parameters shown in the lower part of table 1, the indifference curve in figure 2 represents LECs of 0,55 €/kWh. For other annual irradiation values, the indifference curve has the same shape but reflects other absolute LECs (see also Eq. 1 & 3).

For analyzing many production processes in PV cell & module manufacturing, it is useful for many applications to analyze relative changes rather than absolute, which is depicted in figure 3.

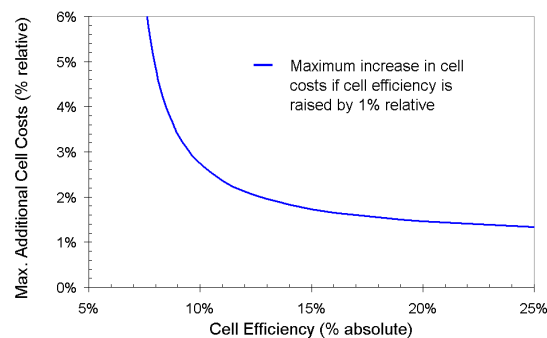


Figure 3: Experience curve demonstrating effects of relative efficiency and cost changes based on a set of parameters as described in Tab 1.

The reading for Figure 3 is for example: a 1% relative increase in cell efficiency from 15% to 15,15% may not cause production cost increases (in €/cell) of more than 1,7% in order to yield lower total system costs and therefore lower LECs.

With increasing absolute efficiency this graph also illustrates the diminishing maximal allowable additional cell costs. At higher absolute efficiencies, a relative efficiency improvement of 1% only allows for lower cost changes than it is the case with lower absolute efficiencies.

Figures 2 and 3 show that also systems with much lower or higher efficiency can yield the same total system costs (and therefore LECs), if the production costs for the photovoltaic cell is not higher than value stated on the y-axis. Yet it has to be noticed that the explanatory power only applies to a range of some percent around the reference value of 14,5% and decreases rapidly when leaving this range. This applies particularly when entering the efficiency ranges of other technologies like thin film materials or concentrating systems, because the module manufacturing technologies and the mounting and construction costs for these PV-Technologies are quite different.

5 TECHNOLOGY EXAMPLE

The costing model and the collected cost data is in use to analyze new production processes developed at the Fraunhofer ISE.

For example, with a dynamic inline plasma etch reactor (Figure 4), a plasma texturing process for multicrystalline silicon solar cells has been developed [6].

For this process an economic evaluation was made in a manufacturing environment with a throughput of

1000 wafers/h (cell area 125x125 mm²), resulting in a production capacity of 7,2 million/wafers per year (including loss of production and breakage). The total costs per wafer of the plasma-etch process-cost pool were found to be 0,22 €/wafer [6], which is more than a state-of-the-art wet chemistry etch (~0,12 €/wafer).



Figure 4: Dynamic inline plasma etch system installed at the Fraunhofer ISE as developed by Roth&Rau.

In contrast to the state-of-the art damage etch process with KOH/NaOH-solution, the texturization of the cell achieved by the plasma etch process leads to higher cell efficiencies. This efficiency gain can offset the higher process costs, as demonstrated in Figure 5.

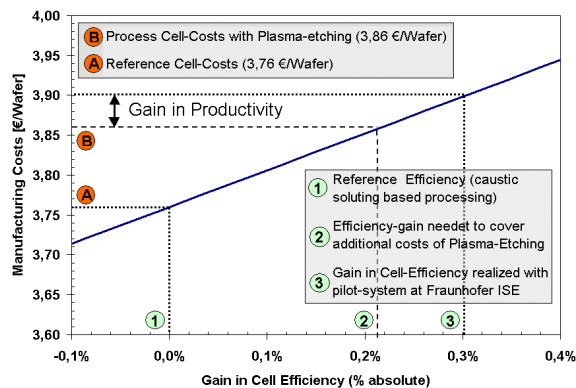


Figure 5: Comparison of cost data for plasma-etching and standard caustic solution based damage etch process.

In Figure 5 the efficiency increase needed to offset higher production costs per cell can be determined with the indifference curve and accounts to ~0,2 % absolute cell efficiency. As the first experimental evaluation of the plasma damage-etch and texturing process showed gains of 0,3 % absolute cell efficiency, a positive contribution to manufacturing costs can be expected.

6 RESULTS AND CONCLUSION

For the economic evaluation of different production processes for silicon solar cells, current cost data for cells, modules and balance-of-system costs has been

analyzed and supplemented by a process-cost calculation for all relevant production processes. For the comparison of production processes, cost-efficiency indifference curves have been used which indicate the combinations of cost and efficiency a customer allots the same utility to. Based on the set of data mainly derived from the German 100.000 roof program, the customers willingness to pay is 0,47 € per percent increase in absolute cell efficiency.

For a certain improvement of a given cell efficiency the experience curve also expresses the maximum relative production cost increase tolerable in order to reach LECs that are equal or lower than those of a system with the given cell efficiency. Here the calculations revealed for example, that a 1% increase in cell efficiency from 15% to 15,15% may not entail production cost increases (in €/cell) of more than 1,7% relative in order to yield lower LECs.

For plasma etching it has been demonstrated that the higher cell-efficiency offsets the increased cell production costs and leads to a gain in productivity of ~0,04 €/wafer

7 ACKNOWLEDGEMENTS

The author would like to thank Stefan Peters (Deutsche Cell GmbH), and Kristin Roth (Roth&Rau AG) for the provision of costing data.

Financial support by the German Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU) under contract No. 329933E is gratefully acknowledged.

8 REFERENCES

- [1] Horngren, C. , Datar, S., Foster, G., 2003, *Cost Accounting*, Prentice Hall, Pearson Education, Upper Saddle River, NJ
- [2] KfW-Research, “Das 100.000 Dächer-Solarstrom-Programm: Eine Schlussbilanz”, in *Mittelstands- und Strukturpolitik*, Issue 31, Kreditanstalt für Wiederaufbau (KfW), (2004)
- [3] Frantzi, L., “Opportunities for cost reduction in photovoltaic modules”, Proc. 16th European Photovoltaic Solar Energy Conference (2000)
- [4] O'Halloran, M., “Fab Utility cost Values for Cost of Ownership (CoO) Calculations”, International SEMATECH Technology Transfer, (2002)
- [5] Preu, R. et al. „Innovative Production Technologies for Solar Cells – SOLPRO“, Proc. 16th European Photovoltaic Solar Energy Conference (2000) S. 1551-1454)
- [5] Rentsch, J., Bamberg, F., Roth, K., Peters, S., Lüdemann, R., and Preu, R. “Isotropic plasma texturing of MC-Si for industrial solar cell fabrication”, Proc. 31st IEEE Photovoltaic Specialists Conference, Orlando, USA (2005) in print.
- [6] Rentsch, J., Jaus, J., and Preu, R., “Economical and ecological aspects of plasma processing for industrial solar cell fabrication”, Proc. 31st IEEE Photovoltaic Specialists Conference, Orlando, USA (2005) in print.