Total Cost of Ownership in PV Manufacturing Guide

SEMI and VDMA are committed to support the PV industry in calculation cost of ownership to better understand the needs in purchasing discussions.

NOTICE:

This guide is intended only to provide an overview of the benefits of strategy-oriented cost management in the PV industry through the use of cost of ownership (COO) and/or lifecycle cost (LCC) calculations and analyses for better decision making. To help the reader to better understand these cost calculations and their associated standards, it also contains a high-level overview and comparison of some key corresponding SEMI and VDMA Standards related to measuring equipment performance for reliability, availability, maintainability (RAM), and productivity that are key inputs into these cost analyses. **This guide is not intended and should not replace the use of the actual standards** that contain the necessary details for correct implementation and compliance.

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I. Executive Summary

Purchasing decisions for capital goods (i.e. machinery, equipment, components and plants) are influenced more and more by indirect costs. Many companies and industry associations have begun to deal with life-cycle models, such as total cost of ownership (COO) and life cycle costs as part of their strategy-oriented cost management. The individual models are often developed for very specific applications and are thus difficult to compare for suppliers and buyers of industrial products. To counter this deficiency, the usage of standards has to be more widely accepted.

In sales negotiations throughout the photovoltaic value chain, equipment suppliers and plant manufacturing companies are invariably faced with the fact that customers apply simple acquisition cost comparisons and do not thoroughly analyze the determinants for the profitability of the individual offers. Such a comprehensive analysis would have to include the investment project with all its direct and indirect financial implications across the entire lifecycle. In most cases, mechanical engineering manufacturers are not in the position to provide a corresponding analysis, since they do not possess the required information about the customer's planned production programs.

However, considering that acquisition costs alone only contribute to a fraction of the total costs that accrue across the entire lifetime of investment goods, these operating costs and their proportion to the acquisition costs have to be taken into account.

In the past, the PV industry did not use existing standards in their sales negotiations and/or discussions among suppliers and manufacturers. After numerous discussions with stakeholders along the supply chain it became clear that the calculation of cost of ownership is perceived as important, however, frequently the tools are not known. As a result of a survey among key contributors to standardization activities it was determined that the different terminology and methodology is a key burden for the calculation.

SEMI, the global trade association for equipment and material suppliers, and VDMA, the German engineering association for machinery, compared the existing standards and illustrate in this guide how different timing views/terminology must be understood to reach comparable results – regardless of which standard has been used.

II. SEMI Standards

In photovoltaic related industries or in silicon–based technology, such as the semiconductor industry, the SEMI E10, SEMI E35 and SEMI E79 standards⋆ are applied to calculate the cost of ownership for equipment.

The following chapter provides an extract from SEMI E10 and E35 to better explain the content of the SEMI standards documents.

The SEMI standard E10 establishes a common basis for communication between users and suppliers of semiconductor manufacturing equipment by providing a standardized methodology for measuring reliability, availability, and maintainability (RAM) and utilization performance of equipment in a manufacturing environment.
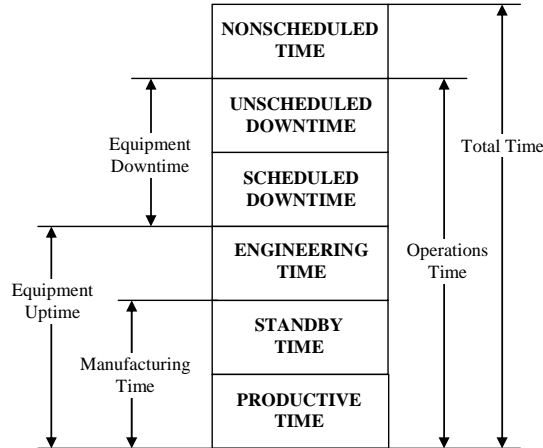

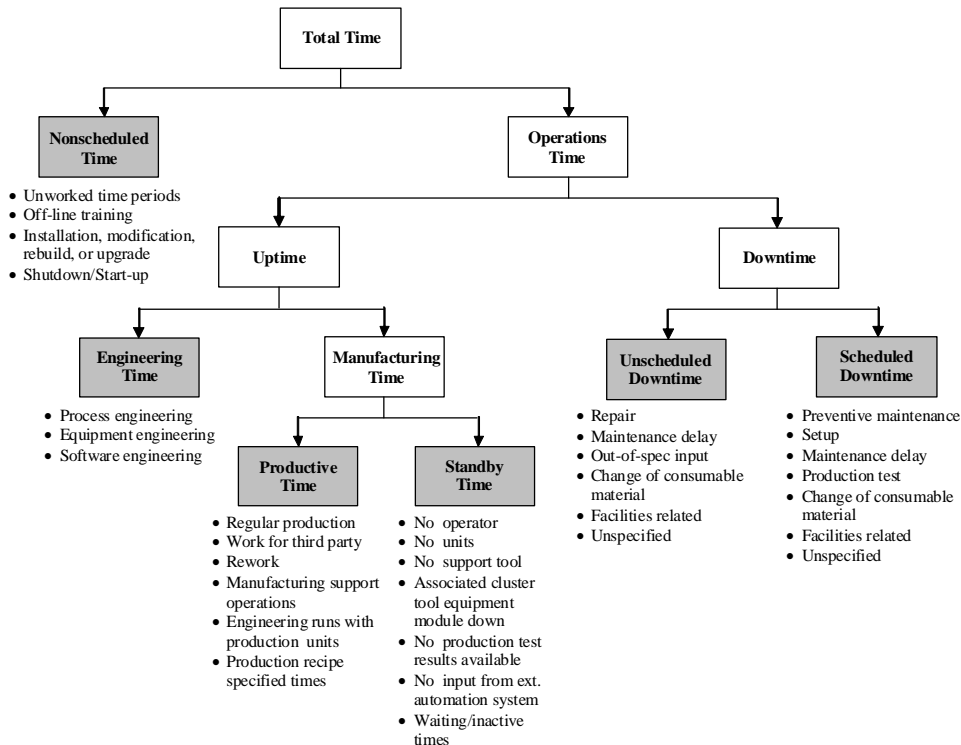*Figure 1: Extract from SEMI E10 Equipment State Stack Chart*

Figure 2: Extract from SEMI E10 Equipment State Hierarchy

To measure equipment performance (e.g., RAM metrics), SEMI E10 defines six basic equipment states into which all equipment conditions and periods of time must fall. Each equipment system must be in one and only one SEMI E10 state at any point in time. Each equipment system must be subject to at most one failure at any point in time regardless of the number of underlying constituent problems contributing to or arising from that failure.

The equipment states are determined by function, not by organization. Any given maintenance procedure, for example, is classified the same way no matter who performs it (e.g., an operator, a production technician, a maintenance technician, a process engineer).

Figure 1 is a stack chart of the six basic equipment states. These basic equipment states can be divided into as many substates as are required to achieve the equipment tracking resolution that a manufacturing operation desires. SEMI E10 makes no attempt to list all possible substates, but does give some that are required to support certain metrics and other examples for guidance.

Key blocks of time associated with the basic states and substates are given in Figure 2. These blocks of time are used in the RAM equations given later in the standard SEMI E10. The blocks of time associated with the basic states and substates are described in the following sections.

The main purpose of Fig. 1 is to illustrate the six (and that there are only six) basic (i.e., top level, major), mutually exclusive equipment states that cover total time during an observation period for each equipment system. Combinations of the times in these six basic equipment states are then defined into categories of times that somewhat describe how the equipment system is being used. For example, there are two types of downtime, scheduled (i.e., planned) and unscheduled (i.e., unplanned), that summed together define all of the downtime for the equipment system. Most of times in these six basic equipment states are directly used in some of the calculated metrics. It is important to note that the equipment system being measured can only be in one and only one equipment state or substate within an equipment state at any point of time during the observation period. Also, E10 has the flexibility to allow a user to define additional E10-compliant metrics based on these states and substates that they may find useful for them. For example, the user may choose to further subdivide an individual substate into more detailed lower-level substates to better understand the factors driving the time in that substate and as a basis to define additional metrics.

Fig. 2 shows the same information as Fig. 1, but in a hierarchical manner where the six basic equipment states are in

gray boxes. Under each of these six basic equipment states, there are examples of the types of substates that exist for each one. Some of these individual substates are also used in some of the calculated metrics in section 8. For example, the times in three of the scheduled downtime (SDT) substates (i.e., SDT preventive maintenance time, SDT setup time, SDT change of consumable material time) are summed to calculate the equipment-dependent scheduled downtime metric, which is then used in another calculation to determine the percentage of time that an equipment system is in the equipment-dependent scheduled downtime state relative to the equipment-dependent portion of operations time.

The metrics in E10 are basically time-based metrics determined from the times that the equipment system is in one or more of the six basic equipment states or their individual substates. However, there are other values used in the calculations that are based on what happens while the equipment is in one of the six basic equipment states or their individual substates. For example, the number of equipment failures that occur during the productive state is used in multiple calculations/metrics. Most of E10 is used to carefully define how the user determines which equipment state and substate the equipment system being measured is in at any point in time during the observation period as well as defining the most commonly used and useful metrics for determining the equipment system's reliability, availability, maintainability, and utilization performance. These states/times are also used in other SEMI Standards, such as in E79 as the basis to determine other equipment system's performance metrics related to its productivity.

This latest version of E10 also deals with the more complicated equipment systems called multi-path cluster tools where different portions (e.g., modules) of the equipment system may be in different states and substates during the same point in time. E10 now provides an official, systematic way to determine the overall equipment system's one state or substate at any point in time based on the combination of the often different states or substates that its individual portions are in at that same point in time. Note that the E10 metrics can be separately determined for each of these individual portions of the equipment system with very different values. For example, one particular module could be 100% down for an entire observation period while the multi-path cluster tool it is a part of could be 100% up and available for running production during that same observation period.
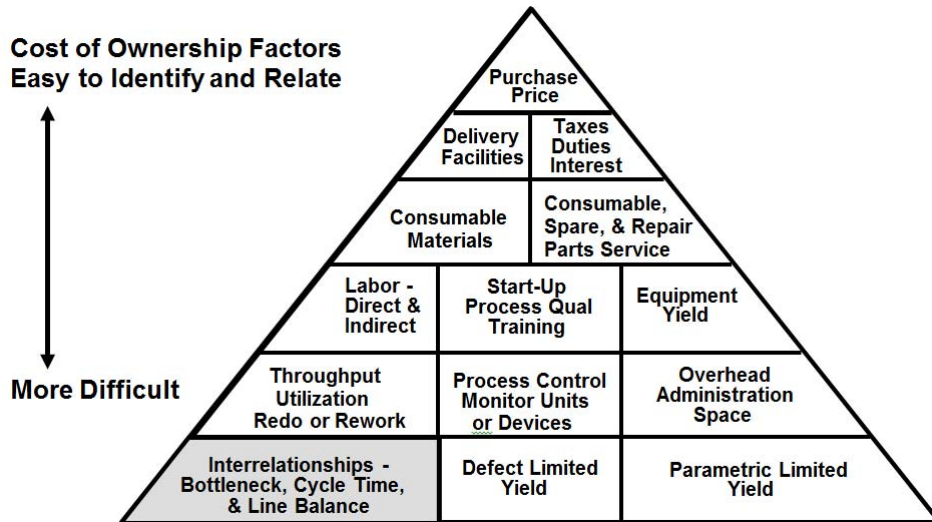
Figure 3: Extract from SEMI E35
Relationship of Factors to Difficulty of Collection and Validation

Certain cost factors are more difficult than others to accurately determine. Figure 3 depicts the relationship of some of the COO model input factors in order to have the ability to collect and validate them. The accuracy of a COO calculation may be prone to a variety of errors or omissions.

The 'cost factor pyramid' is intended to break out many of the individual cost factors and show a relative relationship between them based on the typical level of difficulty in identifying and accurately determining the values for them to include in the overall COO calculation. These individual cost factors basically relate the individual cost elements of each cost category to each other based on this level of difficulty in accurately determining their values. For example, the purchase price of the equipment is generally the easiest direct cost factor to obtain and include in the calculation while accurate defect limited yield and parametric limited yield values are typically the hardest ones. This is because it is very difficult to accurately determine the specific impact of individual equipment and specific process(es) to these 'end of the process flow' electrical measurements that are impacted by all of the individual equipment and their processes in the production process. These yield cost factors can and often will 'overwhelm' the impact of all of the other cost factors and inaccuracies in them can cause the overall accuracy of the COO value to be greatly reduced. For this reason, the COO is often calculated as separate values with and without these factors included to better understand them and their impact on the overall COO analysis.

Bottlenecks, cycle times, and line balance interrelationships are not included in the COO calculation. They are not included because it is difficult, in an individual COO model, to show the impact of equipment being modeled on the complete manufacturing factory. A factory-level cost and/or simulation model should be used for these purposes.

The interrelationship cost factors are shaded to show that they are different from the others in the pyramid. As explained, there is no attempt to include these real cost factors in the COO calculation as defined later in E35 as they are much beyond the scope and require a much more comprehensive cost model with orders of magnitude more data needed to be able to include them. Typically, these more comprehensive cost models do not provide the granularity in understanding of the individual cost factors, nor the impact of a good COO model. While the COO value calculated is considered to be 'incomplete' by omitting them, it can still be extremely useful for the specific purpose of the analysis for which it is being used. The COO modeler needs to understand this limitation of what can and cannot be included when making decisions based on a COO analysis and whether it is appropriate to use a COO model to accurately address the question(s) to be answered for the purpose of the analysis.

A COO calculation may have more detail than presented explicitly in this SEMI E35 Guide. The structure of the Guide, however, allows for these situations.

It is virtually impossible to include every possible cost factor of each individual cost element in their descriptions. Several of the cost factors can be further subdivided into additional inputs and modeled. For example, burdened labor costs for each labor type is usually an overall estimate that includes the direct hourly wage plus burdened cost factors such as benefits, taxes, etc. While these actually vary by individual employee, most companies have a value for the average hourly wage paid to each type of employee and a generic percentage of their overall burdened costs (i.e., what is the real total additional cost of each employee to the company) based on the average wage. Breaking down these individual inputs to this level of potential detail and including them individually into a COO calculation would very rarely be worth the additional effort involved to answer most questions and make good decisions based on the purpose of the COO analysis. In practice, some individual cost factors included in the pyramid may not be included in an individual COO analysis or a very rough estimate may be included if the COO modeler has a very good reason to believe that these cost factors will have no significant impact on

the COO analysis. Also, the COO modeler can test their assumption by performing the COO calculation using a range of potential values to see if there is any significant impact (i.e., a sensitivity analysis). For example, almost all COO analyses involve performing multiple COO calculations with different cost factor inputs to compare their results. One common usage is to compare the COO analyses/values for one supplier's equipment to another supplier's equipment to better understand the relative long-term costs of choosing to purchase one instead of the other. If a particular cost factor/input (e.g., burdened labor cost) is not expected to be significantly different between the choices being modeled, then the absolute accuracy of these inputs will not have much impact on the final analysis and decision. Of course, there are several other important factors in this equipment selection decision besides COO, but it should be included to make the best overall decision. Other typical usages are to compare the COOs before and after a proposed equipment upgrade/modification or process change to determine the cost impact and return on investment (ROI).

(★SEMI Standards licenses (company license or single viewer license) for the standards mentioned above can be purchased at www.semi.org/standards.)

III. VDMA

Forecasting Model VDMA Standard 34160

This standard sheet describes a forecasting model for calculating lifecycle costs. The model does not include financing, capital costs or other price effects. The period under consideration is the machine lifecycle starting with the acquisition and ending after a respective specified utilization period. Anything related to the machine prior to its acquisition or after the period of consideration is only included in the analysis if it affects costs during the period under consideration. Modifications that are not performed in the course of maintenance are treated as further utilization and terminate the respective period under consideration. If lifecycle costs across several modifications are to be analyzed, the model has to be applied repeatedly for the respective sub–periods.
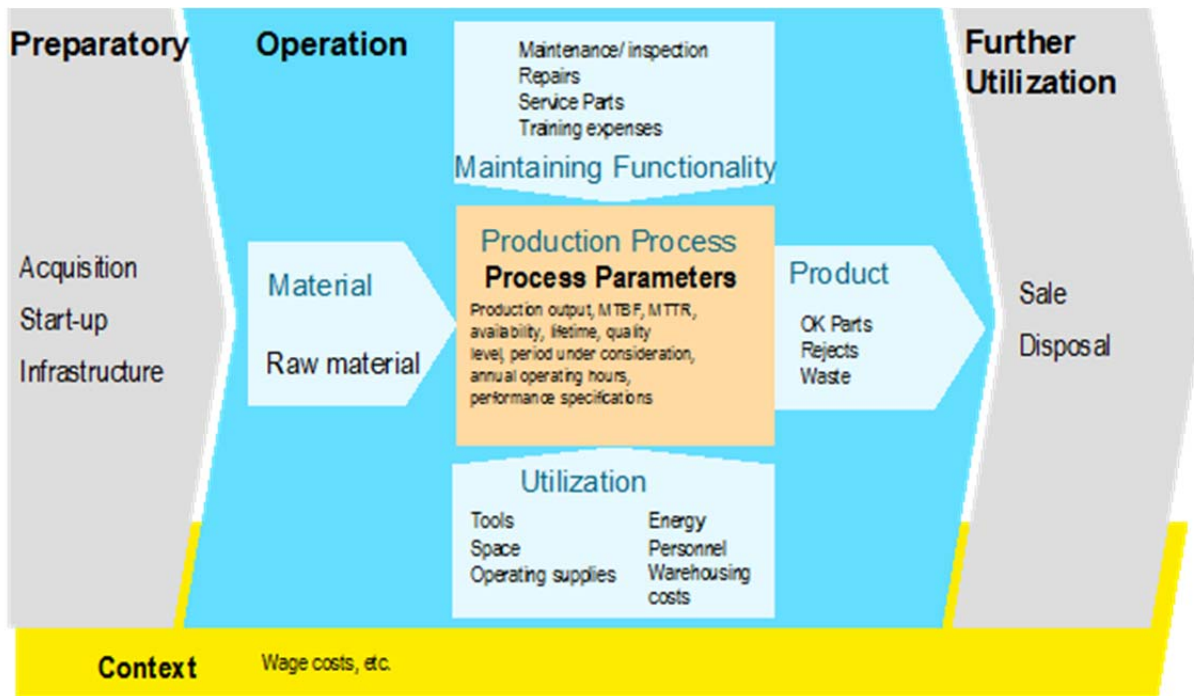
Figure 4 — Structure of forecasting model for calculating lifecycle costs during period of consideration

In the case of modifications, the residual value from the period prior to the modification represents the acquisition costs for the new period under consideration. The model differentiates between three phases: preparatory, operation and further utilization. For each phase, the individual, relevant cost pools are identified. The lifecycle costs arise from the sum of the costs in the three phases.

For each phase, the model determines the cost pools along with the pertinent calculation rules. During the preparatory phase, the focus is on acquisition, start-up and provision of the required infrastructure.

In the operating phase, the model differentiates according to four aspects, "material", "product", "utilization" and "maintaining functionality", taking into account the production process conditions specified by the customer.

In the further utilization phase, the model includes both costs arising from disposal or refurbishment of the machine as well as proceeds resulting from a residual value analysis or sale of the machine.
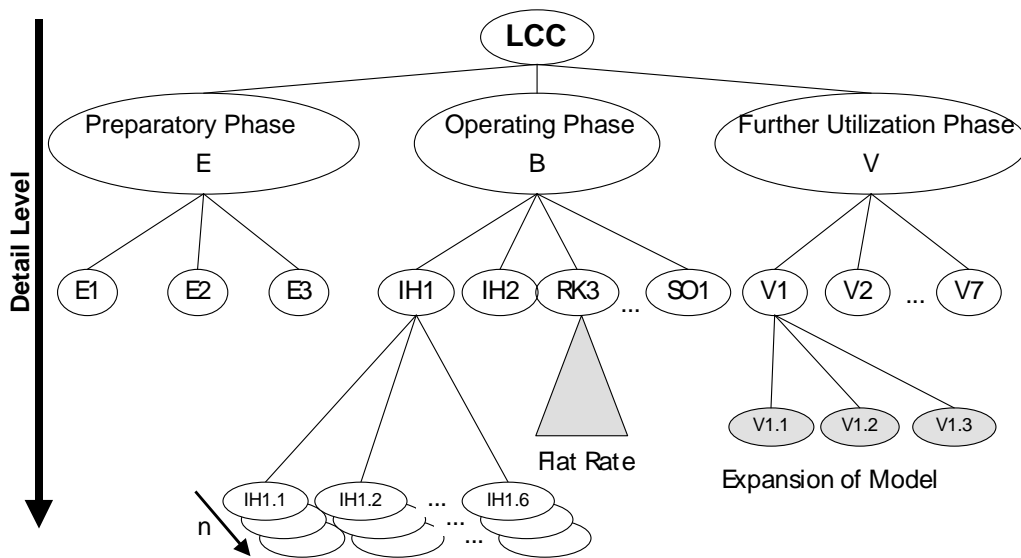

Figure 5 — Cost pool structure of forecasting model

This standard sheet specifies items, names and detail levels for ordinary costs as the cost pools are structured. Individual cost items are added on a step-by-step basis, thus resulting in the total cost of a cost pool.

P			Preparation
	E1		Acquisition
	E2		Infrastructure costs
	E3		Other preparatory costs
B			Operating costs
		IH1	Maintenance and inspection
		IH2	Repairs
		IH3	Unscheduled repairs
		RK1	Occupancy costs
		MK1	Material costs
		EK1	Energy costs
		HB1	Production and process materials
		EN1	Disposal costs
		PK1	Personnel costs
		WK1	Tool costs
		RU1	Set-up costs
		LK1	Warehouse costs
		SO1	Other operating costs
V			Further utilization costs
	V1		Dismantling
	V2		Residual value
	V3		Other further utilization costs

Figure 6: Cost elements von VDMA 34160

The structure of the model facilitates a systematic expansion of its components.

- For example, on each aggregate level of a phase, the "Other" item, e.g. *SO1*, allows the inclusion of additional costs.

- Each amount can be specified as defined or entered as a lump sum, e.g. flat rate for *Set-up Costs RK3*.

- Each input value can be described in greater detail on an additional sub-level; e.g. *Disassembly V1* could be further differentiated into personnel expenses and material costs, if required.

- In order to describe various aspects of a cost pool, the respective level can be indexed, which is the case with, e.g. *Maintenance and Inspection IH1*.

The forecast is based on the framework conditions for machine operation as specified by the customer or operator. A comparison of the forecasts for different machines requires the identical framework conditions for the technical specifications and the specified basic data for the forecasts.

Technical availability of machines and production lines - VDI 3423

This guideline is intended to specify the necessary definitions, for single machines and system components, and for the entire system, as well as to list the criteria for a continuous and traceable record of the operational procedure. This is required to:

a) document occupied times,
b) identify downtimes due to organizational or technical problems, or to preventive maintenance
c) determine availability, utilization ratio and failure rates

The data thus determined can be used to:
- locate weak points
- furnish proof in case of warranty claims
- compare different production facilities and their components
- compare different divisions of a company
- calculate economic efficiency
- support investment decisions
- support life cycle cost estimations

Figure 7: Time definition (based on VDI 3423)

Further information about VDMA Standard 34160 and its application for the photovoltaic industry can be found at http://www.vdma.org/en_GB/article/-/articleview/1180530.

IV. Comparison VDMA – SEMI

Looking deeper at SEMI and VDMA standards it can be ascertained that armed with a dedicated definition of the various parameters the different standards can be compared to each other.

To better understand the inherent differences in the standards one needs to look at the viewpoint of the standards. SEMI E10 reflects the timing observation from a user perspective, whereas, the VDI 3426 observes the timing from an equipment maker's perspective. This basically can be considered as the main difference between the two standards (as shown in Figure 8.)
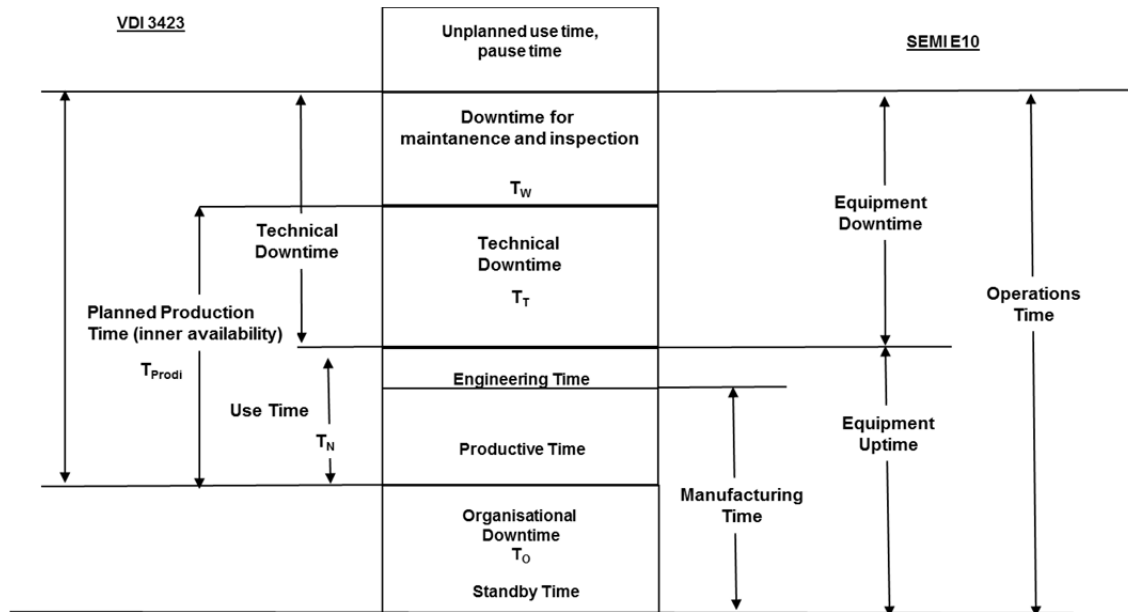
Figure 8: Time definitions VDI 3423 – SEMI E10 as given by the standards

From the point of view of the equipment supplier, organizational Down Time, Standby Time, Engineering Time and unplanned use time are all in the domain of the end-user (as shown in figure 9.)

Figure 9: Responsibilities for Time aspects based on SEMI E79

It is necessary to be clear which of these Time aspects have to be converted during the purchasing process.

To make the SEMI E10 and VDI 3426 more compatible to each other, the following conclusion between SEMI and VDMA was reached (see also Figure 9 and 10):

- The organizational Downtime T_0 will be set to "zero" for the LCC calculation and Standby Time will be set to "zero" for the COO calculation. By doing so, the "manufacturing time" equals the "utilization time".
- The "engineering time" will be added to and considered part of the "productive time." As a result, the expanded "productive time" of SEMI E10 equals the "use time" T_n of VDI 3426
- The baseline for all calculations is 7 days/week, 24 hours/day, called Total Time in SEMI E10. As a result, all time calculations of VDI 3426 are referring to "planned production time" $T_{PROD\ddot{A}}$, while SEMI E10 uses different denominators depending on the specific metric. If Nonscheduled Time is set to or assumed to be zero, then VDI 3426 Production Time and SEMI E10 Operations Time will be equal.
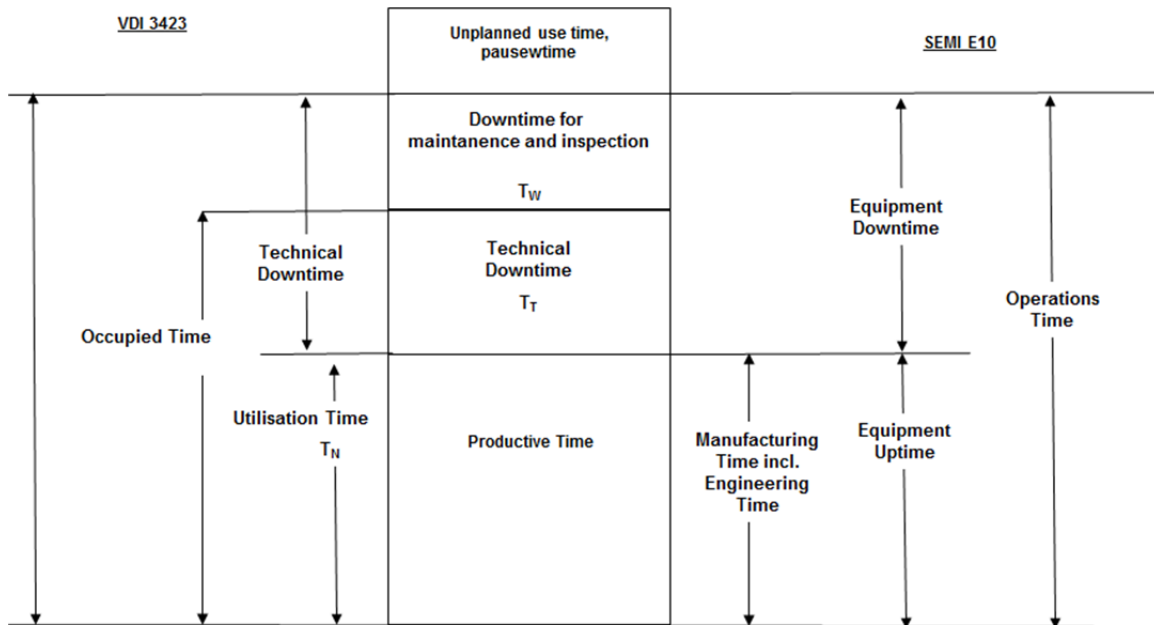

Figure 10: Time definitions VDI 3423 – SEMI E10 by using this agreement

The related OEE-figures will be the same by using this agreement.

OEE-figures	Based on VDI 3423	Based on SEMI E 10/ E 79
Availability Efficiency	$\dfrac{\text{Utilisation Time}}{\text{Production Time}} \times 100\%$	$\dfrac{\text{Equipment Uptime}}{\text{Operations Time}} \times 100\%$
Performance Efficiency	$\dfrac{\text{Production Time}}{\text{Production Time + org. Down Time}} \times 100\%$	$\dfrac{\text{Theoretical Production Time for Actual Units}}{\text{Equipment Uptime}} \times 100\%$
Quality Efficiency	Input	$\dfrac{\text{Theoretical Production Time for Effective Units}}{\text{Theoretical Production Time for Actual Units}} \times 100\%$

Figure 11: Comparison of OEE Figures

V. Conclusion

Strategy-oriented cost management includes detailed life-cycle models, such as total cost of ownership and life-cycle costs. Standards and standardization belong to the core strategic management toolsets utilized in every industry. Standardization facilitates the technical and economic cooperation at national, local and international levels. Certainly, this also applies for total cost of ownership calculations in the PV industry. This Guide illustrates in a simple way how every stakeholder in the PV industry can either use SEMI standards or VDMA standards to reach the same results. It therefore acts as an instruction to translate the perspective of a PV manufacturer (SEMI E10) into the perspective of a machine supplier (VDI 3423) and vice versa. In this context it is decisive for the tool user to carefully adjust the parameters to the same base level. The PV industry is in a maturing stage. Therefore, it is crucial to consider cost of ownership calculations. This significantly reduces miscommunication between suppliers and manufacturers.

SEMI and VDMA are committed to support the PV industry in calculation of cost of ownership to better understand the needs in purchasing discussions.

VI. References

Relevant Standards

- **VDI 3423:2011:** Availability of machinery and equipment, definitions, meanings, time recording and calculation

- **VDMA 34160:2006:** Forecast model for the lifecycle costs of machinery and equipment

- **SEMI E10:** Specification for Definition and Measurement of Equipment Reliability, Availability, and Maintainability (RAM) and Utilization

- **SEMI E35:** Guide to Calculate Cost of Ownership (COO) Metrics for Semiconductor Manufacturing Equipment

- **SEMI E79:** Specification for Definition and Measurement of Equipment Productivity

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About SEMI
SEMI is the global industry association serving the nano- and microelectronic manufacturing supply chains. SEMI supports its members through a global network of offices and services including advocacy, standards development, industry research, and events. SEMICON expositions are held in every major semiconductor manufacturing region of the world — the premier platform for business, networking, collaboration, and education. SEMI maintains offices in Bangalore, Beijing, Berlin, Brussels, Grenoble, Hsinchu, Moscow, San Jose, Seoul, Shanghai, Singapore, Tokyo, and Washington, D.C. www.semi.org.

About VDMA
VDMA represents over 3,100 mainly small/medium size member companies in the engineering industry, making it one of the largest and most important industrial associations in Europe. VDMA's headquarter is in Frankfurt, Germany. VDMA maintains representative offices in Beijing, Shanghai, Kolkata, Tokyo, Moscow, Sao Paulo, Brussels and Berlin. www.vdma.org.