SEMI S23-1021[E]
GUIDE FOR ENERGY, UTILITIES, AND MATERIALS USE EFFICIENCY OF SEMICONDUCTOR MANUFACTURING EQUIPMENT

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[E] This Standard was editorially modified in February 2022 to correct several sections. Changes were made to § 6, Table A1-3, and Table A1-4.

NOTICE: Paragraphs entitled 'NOTE:' are not an official part of this Standard or Safety Guideline and are not intended to modify or supersede the official Standard or Safety Guideline. These have been supplied by the global technical committee to enhance the usage of the Standard or Safety Guideline.

NOTICE: The section symbol (§) is used to reference a numbered section, paragraph, or header and all subordinate paragraphs, headers, and embedded material (i.e., EXCEPTIONs, lists) therein. The paragraph symbol (¶) is used to reference a particular numbered paragraph and embedded material therein. When duplicated (i.e., §§ and ¶¶) the symbols are used to reference more than one section or paragraph, respectively.

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1 Purpose

1.1 This Guide addresses concepts related to energy, utilities, and materials use efficiency of semiconductor manufacturing equipment (SME).

1.2 This Guide is intended to be a tool that can be used to analyze energy, utilities, and materials use by SME.

1.3 This Guide also addresses measurements related to energy, utilities, and materials use in SME.

1.4 This Guide also addresses continuous improvement planning for energy, utilities, and materials use in SME in order to promote efficiency.

1.5 This Guide is a series of options and instructions intended to increase awareness of the reader to available techniques in the area of energy, utilities, and materials use efficiency. A particular course of action is suggested for energy, utilities, and materials use measurement and conversion of use measurements into equivalent energy.

NOTE 1: Because this SEMI Standard is a Guide, all criteria are considered optional.

2 Scope

2.1 This Guide describes methods for reporting energy, utilities, and material use rate and efficiency improvement in SME.

2.2 This Guide also suggests use of energy equivalent values in order to facilitate quantification of overall energy consumption related to SME as well as planning of energy efficiency improvement.

2.3 Additionally, this Guide describes setting targets for, verifying, and improving the use or efficiency of utilities, materials, or energy.

2.4 This Guide addresses the process, idle, rest, and sleep modes of the use stage of the SME life cycle.

NOTE 2: Life cycle of the SME includes;

- raw materials procurement,
- manufacturing,
- packaging,
- transportation (shipment),
- use (process, idle, sleep, rest, maintenance, and service modes)
- decommissioning, and
- disposal.

NOTICE: SEMI Standards and Safety Guidelines do not purport to address all safety issues associated with their use. It is the responsibility of the users of the Documents to establish appropriate safety and health practices, and determine the applicability of regulatory or other limitations prior to use.

3 Limitations

3.1 This Guide is not intended to supersede the applicable codes and regulations of the region where the SME is used.

3.2 This Guide focuses only on the use stage of the SME life cycle and addresses a limited set of utilities and materials to be considered.

3.3 This Guide is not intended to provide definite targets for improvement on use or efficiency of utilities, materials, or energy.

3.4 The information suggested in this Guide need not be provided by the SME supplier to the user unless that is the agreement between those parties.

4 Referenced Standards and Documents

4.1 *SEMI Standards and Safety Guidelines*

SEMI E6 — Guide for Semiconductor Equipment Installation Documentation

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

SEMI S2 — Environment, Health, and Safety Guideline for Semiconductor Manufacturing Equipment

NOTICE: Unless otherwise indicated, all documents cited shall be the latest published versions.

5 Terminology

5.1 *Abbreviations and Acronyms*

5.1.1 *COP* — coefficient of performance

5.1.2 *DIW* — de-ionized water

5.1.3 *ECF* — energy conversion factor

5.1.4 *LCA* — life cycle assessment

5.1.5 *PCW* — process cooling water

5.1.6 *PCW-C* — chiller-cooled process cooling water

5.1.7 *PCW-D* — dual-cooled process cooling water

5.1.8 *PCW-T* — tower-cooled process cooling water

5.1.9 *SME* — semiconductor manufacturing equipment

5.1.10 *UPW* — ultra pure water

5.2 *Definitions*

5.2.1 Definitions in SEMI S2 and SEMI E6 are incorporated herein by reference unless a term is otherwise specified below.

5.2.2 *annualized*— calculated or estimated on a per-year basis.

NOTE 3: The use of 'annualized' refers to the basis of a rate calculation. The usage is not intended to suggest that the data were collected over the course of a year, or that the collection, analysis, and reporting are to be done each year.

5.2.3 *annualized reporting* — reporting the annualized usage of one or more utilities or materials for a piece of SME, as described in § 13.

NOTE 4: Separate workbooks for generic annualized reporting and location-specific annualized reporting are provided among the Supplementary Materials on the SEMI Website: http://dom.semi.org/web/wstandards.nsf/supvm.

5.2.3.1 *generic annualized reporting* — annualized reporting, without consideration of a specific location, using the ECFs and time allotments provided in this Guide.

5.2.3.2 *location-specific annualized reporting* — annualized reporting, with consideration of a specific location, using ECFs for that location and time allotments based on those provided in this Guide, on the equipment supplier's expectations regarding equipment usage, or on the location's observed or estimated equipment usage.

NOTE 5: As stated in ¶ 13.2.3.2 the ECFs for a location may be the ECFs provided in this Guide, or may be ECFs developed for that location.

5.2.4 *baseline* — for the purposes of this Document, 'baseline' refers to operating conditions, including process chemistry, for which the equipment was designed and manufactured. [SEMI S2]

5.2.5 *documents provided to the equipment user* — documents provided by the equipment supplier, such as operation manual, maintenance manual, installation manual, safety manual, or OEM manual, not only printed paper, or cleanroom paper but also multimedia information such as CD/DVD or material provided by Internet, which are intended for use with equipment. [SEMI S13]

NOTE 6: In the context of this Guide, 'equipment' in the definitions of 'baseline' and 'documents provided to the equipment user' may be considered to refer the SME or an SME's subsystem(s).

5.2.6 *energy conversion factor* — the equivalent electrical energy per unit of a utility or a material.

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5.2.7 *energy efficiency* — the quantity of goods or services produced per unit of energy consumed.

NOTE 7: Energy efficiency is a ratio. The dimension of the numerator depends on what is being produced, the dimension of the denominator is energy. For example, if Machine A produces 4 boxes for each 100 joules it consumes, its energy efficiency is 0.04 boxes/joule. If Machine B produces 4 boxes for each 50 joules it consumes, its energy efficiency is 0.08 boxes/joule. If Machine C produces 2 boxes for each 50 joules it consumes, its energy efficiency is 0.04 boxes/joule. In this example, Machines A and C have the same energy efficiency; that is, neither is more energy efficient than the other. Machine B, however, is more energy efficient than Machine A or Machine C. If Machine Z produces 9 bottles for each 50 joules of energy it consumes, its energy efficiency is 0.18 bottles/joule. The energy efficiency of Machine Z cannot be compared to the energy efficiencies of Machines A, B, and C, because 'boxes' are different from 'bottles' and so the things produced (and, therefore, the units of energy efficiency) are different.

5.2.8 *energy impact* — positive or negative effects on the amount of energy required to produce or provide an item or material, or to execute a process or step.

5.2.9 *environmental impact* — positive and negative effects to the Earth's environment from a variety of sources, including people and their activities, and from the operation of SME and facilities.

5.2.10 *exhaust* — airflow by means of facility fans moving air from SME to a location outside of a fab or laboratory area.

5.2.11 *heat load* — the sum of all heat energy transferred by conduction, convection, and radiation outside the envelope of the equipment.

5.2.12 *idle mode* — the mode in which the SME is ready for processing within 15 seconds but is not in process mode.

5.2.13 *life cycle assessment (LCA)* — a methodology used to evaluate the environmental impact of SME throughout its life cycle, including raw material procurement, manufacturing, transportation, use, and disposal.

5.2.14 *performance factor* — a quantification of SME functional performance metrics that is not directly measured as quantity outputs (e.g., minimum detectable particle size, smallest pattern pitch that can be processed) for a given SME model relative to some other model of a similar type. The choice of which functional performance to be compared as well as the method to quantify the selected functional performance is a subjective judgement of the SME supplier.

5.2.15 *process cooling water (PCW)* — water provided by a facility closed loop to remove heat from semiconductor manufacturing equipment.

NOTE 8: More information and a schematic diagram are included in Related Information 2.

NOTE 9: The PCW terminology described below is not meant to be interpreted as a facility pipe labeling convention imposed by SEMI S23. However, it can be used as a labeling convention at a facility.

5.2.15.1 *chiller-cooled process cooling water (PCW-C)* — process cooling water from which heat is removed through a heat exchanger to a chilled water system.

NOTE 10: This Guide uses the term 'chiller-cooled', rather than 'refrigeration-cooled', for water cooled by mechanical refrigeration because the abbreviation 'PCW-R' has been used, traditionally, to designate 'process cooling water return'.

5.2.15.2 *dual-cooled process cooling water (PCW-D)* — process cooling water from which heat is removed through a heat exchanger to a cooling tower system, a heat exchanger to a chilled water system, or both. The cooling tower system is used when the wet-bulb temperature is low enough to cool the PCW-D to below its return temperature and the chiller system is used (supplementally or exclusively) when the wet-bulb temperature is too high to cool the PCW-D to its supply temperature without mechanical refrigeration.

NOTE 11: Some parties use the terms 'high temperature process cooling water' and 'HTPCW' to refer to dual-cooled process cooling water (PCW-D).

5.2.15.3 *tower-cooled process cooling water (PCW-T)* — process cooling water from which heat is removed through a heat exchanger to a cooling tower system.

5.2.16 *process mode* — the mode in which the SME is performing its intended function on target materials (such as implanting wafers, or inspecting photo-masks).

5.2.17 *rest mode* — the mode, entered automatically by the SME, in which there will be a delay to return to idle but it is otherwise ready for processing. Average equivalent energy use rate in this mode is less than in idle mode.

5.2.18 *return temperature (of cooling water)* — the temperature at which cooling water exits the cooled equipment.

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NOTE 12: Within SEMI S23, the temperature is not considered to change in the facility piping, so 'return temperature' refers to both the temperature at which the cooling water leaves the cooled equipment and the temperature at which it reaches the facility apparatus that cools it.

5.2.19 *roadmap* — a sequence for the incremental introduction or improvement of technology over time with milestones and supporting information.

5.2.20 *semiconductor manufacturing equipment (SME)* — equipment used to manufacture, measure, assemble, or test semiconductor products. It includes the equipment that processes substrates (e.g., silicon wafers, reticles), its component parts, and its auxiliary, support, or peripheral equipment (e.g., chemical controllers, chemical delivery systems, vacuum pumps). SME also includes other items (e.g., structures, piping, ductwork, effluent treatment systems, valve manifold boxes, filtration, and heaters) specific to and provided with the aforementioned equipment, but does not include such an item if the item is part of a facility and can support more than one piece of SME. [SEMI S3, SEMI S6, SEMI S28]

5.2.21 *sleep level* — one or more of functional configurations of SME in sleep mode. Different sleep levels will provide different equivalent energy consumption rates.

5.2.22 *sleep mode* — the mode, entered by the SME in response to an external command, in which there will be a delay to return to idle but it is otherwise ready for processing. Average equivalent energy use rate in this mode is less than in idle mode.

NOTE 13: The external command is a signal provided to the SME, such as through an actuator, through an electronic interface, or as a message received through factory control software. Entry into the sleep mode does not require manual actions, other than, possibly, initiation of the sleep mode by an actuator.

5.2.23 *subsystem* — a functionally related aggregate of components that is a part of a piece of SME, that operates as a unit and is capable of performing one or more specific functions. A subsystem may be a constituent of another subsystem.

NOTE 14: The mode concepts of SME can be applied to subsystems. Some subsystems might not have an idle, rest, or sleep mode.

NOTE 15: The mode of a piece of SME's subsystem(s) might not necessarily be the same as SME's overall mode at a given time. For example, when a piece of SME is in process mode, one of its subsystems could be in idle, rest, or sleep mode.

5.2.24 *supply temperature (of cooling water)* — the temperature at which cooling water enters the cooled equipment.

NOTE 16: Within SEMI S23, the temperature is not considered to change in the facility piping, so 'supply temperature' refers to both the temperature at which the cooling water leaves the facility apparatus that cools it and the temperature at which it reaches the cooled equipment.

5.2.25 *use rate* — the amount of a certain resource such as energy, utility, or material consumed by SME per unit of time.

5.2.26 *utilization* — the percentage of time the equipment systems is performing its intended function during a specified time period. [SEMI E10]

6 General Concepts

6.1 Energy is used to produce the various utilities and materials that go into the manufacturing, packaging, shipping, installing, use, decommissioning and disposing of a piece of SME. Reducing the energy used in any of these life cycle steps will improve the environmental impact of the SME.

NOTE 17: This Guide focuses on only the 'use' life cycle stage.

6.2 Given the state of the industry with regard to energy efficiency information and measurements, the use stage of the SME life cycle appears to be the most effective stage to analyze for energy efficiency improvement opportunities. The energy used in the use stage is the best derived from the use rate measurement of utilities and materials during that stage.

6.3 Various methods have been proposed for converting specific utilities and materials into equivalent energy values. The energy used to produce any particular utility or material varies from location to location and from time to time. While any single set of energy conversion factors cannot be valid worldwide, some parties find value in the conversion exercise, particularly in identifying a utility or material that has a greater energy impact than others.

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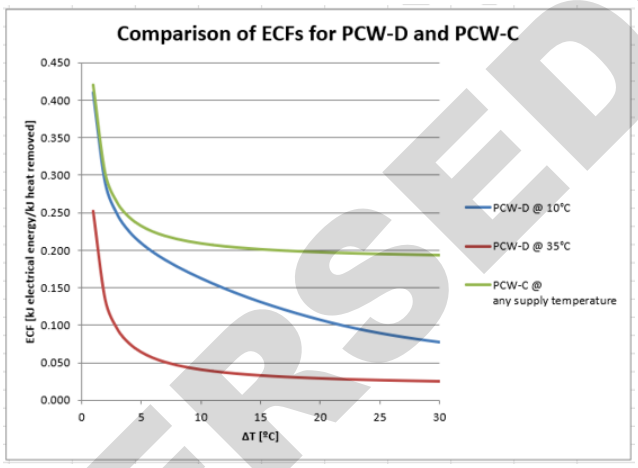
6.4 Cooling towers are more energy efficient equipment for removing heat from process cooling water (PCW) than are refrigeration systems. However, the regions in which most high-volume manufacturing occurs are often too hot to provide, by cooling tower alone, the PCW temperatures required by most semiconductor manufacturing equipment. A hybrid (or 'dual-cooled') PCW system that uses tower cooling as much as possible, combined with refrigeration for hotter days, can be economically justified both for new factories and as a change to existing factories. Additionally, the more equipment suppliers design their products to work from higher PCW temperatures (even to the point of designing equipment with a higher temperature PCW circuit, separate from a lower temperature one, for the components and subsystems in their equipment that can be more easily designed or selected to use the higher temperature), the more energy efficiency improvements can be realized across the industry, and the more dual-cooled PCW systems can be justified.

NOTE 18: The October 2021 revision of SEMI S23 introduced ECFs for, and provided significant amounts of related information to support the consideration and adoption of, dual-cooled PCW.

NOTE 19: As a comparison aid, the following graph shows the relative ECF values (based on the values presented in Table 3 in § 9) for PCW-C as compared to PCW-D at both a 10°C supply temperature and a 35°C supply temperature, over a range of ΔT values (due to heat added to the water by the equipment). A lower ECF indicates a more efficient use of energy.



6.5 The SME suppliers should investigate use rate of each utility and material in their SME and identify and implement design or process changes that lessen the energy impact of the SME.

6.5.1 The investigation should include careful evaluation of alternate utility specifications (e.g., high pressure clean dry air or medium to low pressure clean dry air; cooling water supply temperature; heat exchanger's mean temperature difference) to determine if a utility with a lower energy impact can be used.

6.5.2 The expense of implementing these changes should be balanced against the potential improvement of energy impact, including a change in SME functional performance, when developing an energy efficiency improvement plan.

NOTE 20: Changes in use rate can also affect the users cost of ownership for the SME. This can also be considered in the cost-benefit analysis.

6.6 An SME user can consider supplier-reported utilities and materials use rates, equivalent power values, and planned improvements when making its purchasing decisions. Users can also evaluate their own utilities and decide to use more energy efficient utilities when tool specifications allow (e.g., use of tower-cooled cooling water instead of refrigerated cooling water).

6.7 The use rate of utilities and materials for a piece of SME depends on the particular control parameters used to achieve the desired effect on a wafer (i.e., it depends on the process recipe) as well as the particular hardware used in the SME and the conditions under which the measurements are taken. It is important to record this and other particular information when use rate measurements are conducted.

NOTE 21: Suppliers and users of SME are encouraged to use SEMI E6 as the framework for documenting SME use rates.

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6.8 Semiconductor wafers go through many processing steps. The amount of energy invested in a single semiconductor die can be quite large, on the order of 5.4 MJ (1.5 kWh) or more per square centimeter for a completed device. The more complex the device being manufactured, and the later the step in the manufacturing process, the more energy will have been invested in each die. Therefore, any SME modifications that improve yield and otherwise limit potential damage to the die being processed will significantly improve the effective energy efficiency of the SME.

NOTE 22: For a discussion of the per die energy investment see, for example, "The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices", which itself cites several industry studies and related per-square-centimeter energy investment metrics."[1]

6.9 The SME supplier should set targets for energy, utilities, and materials use efficiency improvement and should consider continuous improvement programs.

6.10 The characterization and quantification of energy, utilities, and materials consumption should be based on a supplier baseline process.

7 Baseline Process(es)

7.1 The measurement of utilities and material use rates, assessment of energy efficiency improvement, and reporting should be based on one or several supplier baseline process(es). The SME supplier is encouraged to consider baseline process(es) which also meet the needs of the users.

7.2 Considering the range of use a supplier intends for the SME, several baseline processes may be used when utilities and materials use rate measurements are conducted.

NOTE 23: For users to make effective cost of ownership or energy efficiency comparisons among pieces of SME, it is useful to have data that can be compared among suppliers. As each piece of SME may well have different ways of achieving the same desired effect on a substrate (or other material), it is recommended that suppliers discuss with their users what desired effect and use rate data will most facilitate effective comparisons.

7.3 The impact of any particular baseline process recipe on the use rate of a material or a utility such as electricity can vary depending on the SME optional hardware that is installed and how the optional hardware is participating in the SME modes (e.g., it may consume utilities and materials even if it is idle). Therefore, when baseline processes are designed, the particular hardware configuration can be a significant parameter and should be considered.

NOTE 24: In the course of analysis, the supplier may discover that for two or more recipes which have the same desired effect, one recipe is more energy efficient than another.

8 Utilities and Materials Use Rate Measurement

8.1 A first step in determining the energy impact of a particular piece of SME during any life cycle stage is to measure the use rate of utilities and materials in that stage.

8.2 Table 1 contains the recommended minimum set of utility and material parameters for which to measure use rates while the SME is in its various modes (e.g., process, idle).

NOTE 25: Related Information 1 contains additional use rate information that may be useful.

NOTE 26: Process chemicals might be used in the process mode of some SME. Process chemicals are not included in Table 1 because equivalent energy conversion factors are generally not available for them. The SME supplier may, however, wish to measure and record their use rate anyway.

8.3 The units used in Table 1 are those used in SEMI E6, which contains criteria for documenting all utility requirements for every connection point on a piece of SME. If the instruments used to gather data do not report values in the indicated units, the values should be converted to the correct units.

8.4 *Measurement Method*

8.4.1 For the process mode measurements, the average value of each parameter over the course of several processing cycles should be recorded as well as the length of the cycle. If the SME processes substrates, a 10 run average (either 10 substrates or 10 batches, whichever is applicable) should be recorded. If a SME subsystem is being analyzed and

[1] Eric D. Williams, Robert U. Ayres, and Miriam Heller; published in Environmental Science & Technology, 2002, 36 (24), pp. 5504–5510.

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it processes a material other than a substrate (e.g., in case of a vacuum pump), the average over a 30 minute processing period should be recorded.

8.4.2 For the idle mode measurements, the average value of each parameter over a period of 30 minutes should be recorded.

NOTE 27: It is assumed that energy use during the transition between the idle and process modes is not significant because the transition time is short (by definition, less than 15 seconds).

8.4.3 For rest and sleep modes, at least three separate measurements should be taken of each parameter in each of the following periods; 1) during transition period from the idle mode to reach the stable lower equivalent energy use rate condition, 2) during the stable lower equivalent energy use rate condition period, and 3) during transition period from the stable lower equivalent energy use rate condition to the idle mode. Those values should be averaged for each parameter for each period.

8.4.4 The energy used in transition down to a lower power mode and up to a higher power mode should be included in the overall lower power mode average.

Table 1 Recommended Minimum Set of Utility and Material Parameters

Utility or Material	*Basic Use Rate Metrics and Units*	*Related SEMI E6 Sections (0303 Version)*
Exhaust	Static Pressure (Pa) Flow (m^3/hr) Inlet Temp (°C) Outlet Temp (°C)	§ 18
Vacuum	Pressure (Pa) Flow (m^3/hr)	§ 17
Clean Dry Air High Pressure Clean Dry Air, and Nitrogen (N2)	Inlet Pressure (Pa) Flow (m^3/hr) Inlet Temp (°C)	§ 16
Chiller-Cooled Process Cooling Water (PCW-C), Dual-Cooled Process Cooling Water (PCW-D), and Tower-Cooled Process Cooling Water (PCW-T)	Inlet Pressure (kPa) Outlet Pressure (kPa) Flow (m^3/hr) Inlet Temp (°C) Outlet Temp (°C)	§ 13
Ultra Pure Water (UPW) or De-Ionized Water	Purity Requirements Inlet Temp (°C) Flow (m^3/hr)	§ 13
Electricity (Electrical Energy = Electrical Power × Measurement Period)	Real Power[#1] (watts) For single phase circuits, Real Power[#1] = $V_{RMS} \times I_{RMS} \times PF$ For three phase circuits, Real Power[#1] = $V_{RMS} \times I_{RMS} \times PF \times 1.73$ Alternately, the average Real Power as indicated by a power meter may be used.	§ 12

#1 'Real Power' is sometimes known as 'True Power' or 'Effective Power.'

8.5 The data described in Table 2 should be recorded in addition to the use rate data of Table 1. The goal is to record enough information to document the measurement event so that it can be reproduced, such as to analyze the effect of SME changes.

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Table 2 Recommended Additional Data to Record for the Measurement Events

Data Title	*Description*
Date	When the measurements were taken.
Equipment Under Test (EUT)	The equipment (SME or a subsystem of the SME) from which the measurements were taken. Provide information such as general description, model number, and serial number.
EUT Configuration	The configuration of the equipment (SME or a subsystem of the SME) during the measurements, such as subsystems that were or were not used and optional hardware that was installed.
Test Location	Where the measurement testing was done such as the particular test laboratory or manufacturing location.
Principal Test Personnel	The principal personnel involved in developing the test plan and conducting the testing.
Test Recipe	The baseline recipe used when conducting the test.
Test Throughput (per hour)	How many substrates or other material quantity was processed per hour during the test.
Throughput Calculation Method	How throughput is determined.
Wafer Size (or size of relevant substrate)	What size wafer/substrate is processed by the SME.
Test Duration	How long the SME was operating for gathering the test data.
Test Setup	How the various pieces of test equipment were connected to the EUT.
Test Equipment and relevant Calibration Information for measuring Exhaust Vacuum Clean Dry Air (CDA) High Pressure Clean Dry Air (HPCDA) Nitrogen Process Gas (at or above atmospheric pressure) Process Gas (below atmospheric pressure) Process Solids Process Liquids Chiller-Cooled Process Cooling Water (PCW-C) Tower-Cooled Process Cooling Water (PCW-T) Dual-Cooled Process Cooling Water (PCW-D) Ultra Pure Water (UPW) Hot UPW Electricity Heat Load/Cooling Load to air conditioner	The test equipment that was used to measure the use rate of each utility or material and its relevant calibration information such as when the test equipment was last calibrated and when it should be calibrated again. Refer to Table 1 Recommended Minimum Set of Utility and Material Parameters as applicable. Heat load/Cooling Load to air conditioner may be derived as measurement is normally not possible

NOTE 28: See Related Information 1 for additional recommendations.

8.6 *Annual Estimated Energy Consumption*

8.6.1 See ¶¶ 8.4.1, 8.4.2, and 8.4.3 for energy use rate measurement methods to be used for process, idle, and rest and sleep modes, respectively.

8.6.2 *Generic Annualized Reporting*

8.6.2.1 For reporting annual estimated energy consumption, account for 24 hours a day, 365 days a year (for a total of 8,760 hours of opportunity) with 5% (438 hours) as down time, 70% (6,132 hours) spent in process mode, and 25% (6 hours/day = 2190 hours/year) of free time which should be distributed (and the selected distribution detailed in the report) among idle, rest, and sleep modes, according to the capabilities of the SME, in 2 hour periods, as follows:

- 365 two hour periods in idle mode.

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- 730 two hour periods in idle, rest, or sleep mode.

8.6.2.2 The procedure for assigning free time is shown in Figure 1.

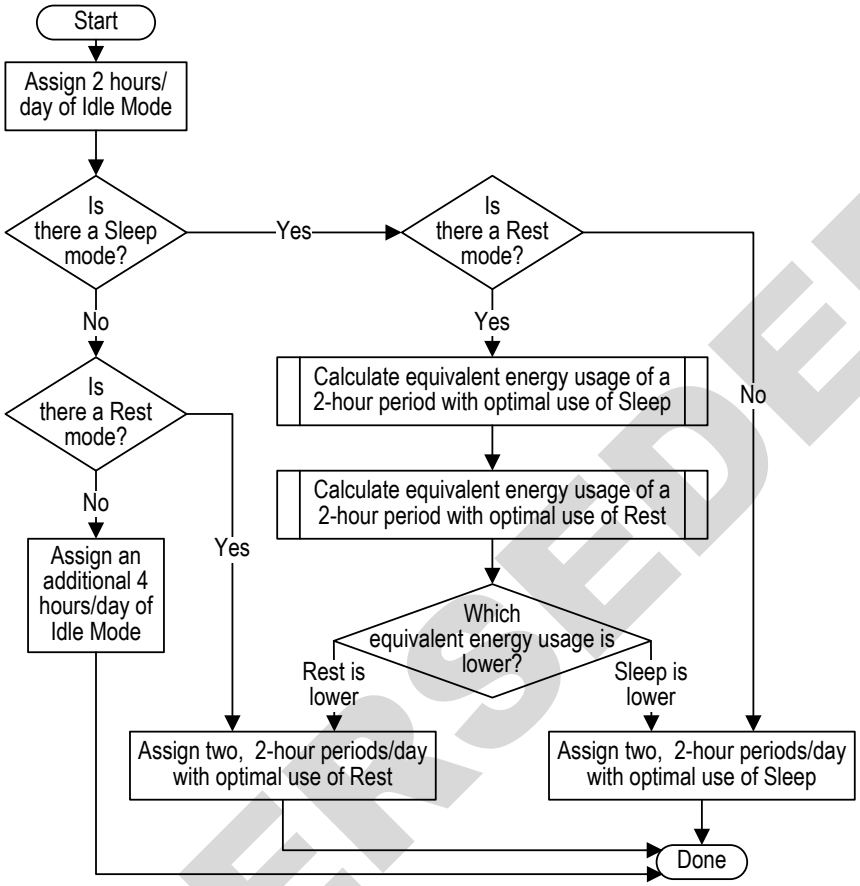

Figure 1
Procedure for Assigning the Six Hours/Day of Free Time

8.6.3 *Location-Specific Annualized Reporting* — The allotment of time for location-specific annualized reporting is at the discretion of the party preparing the report. It should, however, reflect the observed or foreseen use of the equipment.

9 Conversion Factors for Equivalent Energy and Power

9.1 Conversion factors can be used to convert the utility and material use rate data gathered for a particular baseline process recipe into equivalent power consumption data.

9.2 The actual electrical energy required to provide a particular utility or material will, of course, vary among the locations where the SME will be installed. Therefore, the output of the conversion calculation will not be correct for any particular location. However, if a reasonable set of conversion factors is used, the output of the conversion can be used to identify those utilities and materials which, generally speaking, have a higher environmental impact.

NOTE 29: The use of a standard set of conversion factors also allows comparison of results from tests of various models of SME.

9.3 Table 3 contains a recommended set of conversion factors. Comparison of different models of SME based on the use of the conversion factors may be useful, even though the total calculated energy is correct only for the hypothetical facility for which the conversion factors are correct.

NOTE 30: Related Information 1 contains additional conversion factor information that may be useful.

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9.4 The output units of all conversions are kilojoules (kJ). This can be understood as the energy impact of the particular utility or material used.

NOTE 31: 1 kiloWatt hour (kWh) = 3600 kJ.

NOTE 32: See Related Information 1 for example calculations.

9.5 *Cooling Water*

9.5.1 ECFs are provided for three different types of cooling water. For generic annualized reporting, use Figure 2 to determine which ECF(s) are to be used in each case.

9.5.2 Chiller-cooled process cooling water (PCW-C) is the traditional facility-supplied cooling water available in semiconductor manufacturing facilities. The distinguishing feature of PCW-C is that heat is removed from PCW-C through a heat exchanger to a chilled water system. Because a chilled water system uses refrigeration to remove heat, the energy required by the use of PCW-C is higher than that of PCW-D or PCW-T. Contrarily, the use of refrigeration makes PCW-C the least sensitive to weather.

9.5.3 Heat is removed from tower-cooled cooling water (PCW-T) through a heat exchanger to a cooling tower system. Because refrigeration is not used, PCW-T requires the least amount of energy, but it is the most sensitive to weather. In most locations, the cooling water temperatures traditionally used in semiconductor manufacturing equipment cannot be achieved year-round with PCW-T.

9.5.4 Heat is removed from dual-cooled process cooling water (PCW-D) through a heat exchanger to a cooling tower system (to the extent permitted by weather) and a heat exchanger to a chilled water system (to the extent, if any, needed to achieve the supply temperature). Proper bypass control in such a system maximizes the use of low-energy tower cooling while providing the less weather-dependent temperature control of refrigeration. Because the heat removal is apportioned to the methods based on the PCW-D supply temperature and the weather (specifically, the ambient wet-bulb temperature), the energy cost of PCW-D depends strongly on those factors.

NOTE 33: Related Information 2 contains additional information and recommendations related to PCW-D systems.

9.6 If SEMI S23 does not provide an ECF for a material or utility required by equipment, the party providing the report may determine an appropriate ECF for that material or utility. The report should include such ECFs, accompanied by rationales for their values and for their use.

9.7 Generic annualized reporting may also use an alternate set of conversion factors.

NOTE 34: The phrase "may also use" permits generic annualized reports to contain alternate ECFs in addition to the ECFs provided in this Guide. It does not permit the use of alternate ECFs instead of the ECFs provided in this Guide. If alternate ECFs for the same utilities and materials are used, then two results will be reported.

9.7.1 If alternate conversion factors are used, these factors should be accompanied, in the report, by rationales for their values and for their use.

9.8 A conversion factor is better if it accurately represents the actual electrical energy required to create and distribute a particular utility or material at the SME's end use location.

9.9 Determining reasonable energy conversion factors for most process chemicals has not yet entered the state of the art. Therefore, conversion factors are not recommended for them.

NOTE 35: See Related Information 1 for additional information.

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Table 3 Recommended Energy Conversion Factors

Utility or Material	*Energy Conversion Factor*	*Supplementary Information*
Exhaust	13.3 kJ/m^3 (0.0037 kWh/m^3)	This factor does not account for energy required to operate an exhaust treatment device (e.g., scrubber) other than its resistance to air flow. The ECF for exhaust which exits directly into the cleanroom is 0.0. See Related Information 1, Table R1-1 for more information.
Vacuum	216 kJ/m^3 (0.060 kWh/m^3)	
Clean Dry Air (CDA) (Not HPCDA)	529 kJ/m^3 (0.147 kWh/m^3)	This conversion factor should be applied to the equivalent air volume at 101 kPa (1 atmosphere) and 20°C.
High Pressure Clean Dry Air (HPCDA) 827–1,034 kPa gauge (120–150 psig)	630 kJ/m^3 (0.175 kWh/m^3)	This conversion factor should be applied to the equivalent air volume at 101 kPa (1 atmosphere) and 20°C. It is recommended that pressures higher than 1,034 kPa gauge (150 psig) not be used because the related pressure systems may fall within scope of local high pressure gas laws.
Chiller-Cooled Process Cooling Water (PCW-C)[#1#2#3#4]	ECF values in kJ/kJ of heat removed = 0.186 + 0.235K/ΔT (K) ECF values in kJ/m^3 of PCW-C[#5] = 778 (kJ/m^{3}K) × ΔT + 980 (kJ/m^3) (= 0.216 (kWh/m^3·K) × ΔT + 0.272 kWh/m^3)	The ECF equations are based on an assumed efficiency of a factory level process cooling water refrigeration system. Related Information 1, § R1-4 contains an example calculation of equipment heat removal by cooling water.
Tower-Cooled Process Cooling-Water (PCW-T)[#1#2#3#4]	ECF values in kJ/kJ of heat removed = 0.0177+ 0.235K/ΔT ECF values in kJ/m^3 of PCW-T[#5] = 74 (kJ/m^3·K) × ΔT + 980 (kJ/m^3) (= 0.0206 (kWh/m^3·K) × ΔT + 0.272 kWh/m^3)	PCW-T is also known as 'Free Cooling' Exclusive use of tower-cooled cooling water is rare and possible only in cold/dry climate conditions. This ECF is provided to illustrate this limiting case.
Dual-Cooled Process Cooling Water (PCW-D)[#1#2#3#4]	Generic Annualized Reporting: See Appendix 1. Location-Specific Annualized Reporting: Use the ECF(s) for the location: If ECFs have not been assigned for the location, use the ECFs in Appendix 1.	Related Information 2, § R2-3.7 provides instructions on determining ECFs for a site.
UPW or DIW Temp ≤25°C	3.24 × 10^4 kJ/m^3 (9.0 kWh/m^3)	Because of the large amount of energy required for purification, no qualification is provided regarding water temperature.
Hot UPW or DIW pressurized Temp >85°C	3.32 × 10^5 kJ/m^3 (92.2 kWh/m^3)	There is no conversion factor stipulated for UPW or DIW supplied at a temperature between 25°C and 85°C.
Air Conditioning (Heat Load) (Cooling Load)	0.287 kJ/kJ (kWh/kWh)	This ECF pertains to heat removed from a cleanroom by an air conditioning system. It is sometimes called the 'heat load' or the 'cooling load' of the SME. To estimate the heat that is otherwise removed by air and water in related calculations (see, for example, Table R1-3 in Related Information 1) the specific heat of air and water are 1.17 kJ/m^3°C (3.24 × 10^{-4} kWh/m^3°C) and 4.18 × 103 kJ/m^3°C (1.16 kWh/m^3°C), respectively.

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Utility or Material	*Energy Conversion Factor*	*Supplementary Information*
$N2^{\#6}$	900 kJ/m^3 (0.250 kWh/m^3)	This conversion factor should be applied to the equivalent nitrogen volume at 101 kPa (1 atmosphere) and 20°C.
Electricity	1.00 kJ/kJ (kWh/kWh)	Electricity is the basis of all of the other ECFs.

#1 No heat is removed when ΔT is zero, but it is foreseeable that PCW flow could continue in such a condition. The ECF expressed in kJ/kJ becomes infinite in such cases, but the ECF expressed in kJ/m^3 is both finite and meaningful in such a condition, as energy is still used to pump the PCW.

#2 PCW-C and PCW-D systems typically provide PCW at a temperature within 0.5°C (1°F) of their nominal supply temperatures. Similar temperature stability can be achieved with PCW-T by selecting a PCW-T supply temperature that is high enough to be achieved throughout the range of weather conditions at the location and by using variable speed drives of the fan motors in cooling towers and of the pump motors. A PCW-T system that is operated to supply to coldest water achievable at each time, however, will have a supply temperature that varies with the weather. PCW systems typically have a differential pressure (supply pressure – return pressure) of at least 400 kPa (60 psi).

#3 ΔT is the difference between the equipment water inlet and outlet temperatures in Kelvin. When ΔT is not known, assume a value of 5K.

#4 See § 13.2.3 to determine which ECF(s) are to be used for generic equipment equivalent energy reporting.

#5 The ECF in kJ/m^3 of PCW can be calculated from the ECF in kJ(electric)/kJ(thermal) by multiplying by a constant representing the amount of heat in water per unit volume and unit temperature change and by the temperature change of the water.

$$\mathrm{ECF}\left(\mathrm{in}\,\frac{\mathrm{kJ}}{\mathrm{m^3\,of\,PCW}}\right) = \left(\mathrm{ECF}\left(\mathrm{in}\,\frac{\mathrm{kJ(electric)}}{\mathrm{kJ(thermal)}}\right)\right) \times \left[\frac{\mathrm{kJ(thermal)}}{(\mathrm{volume\ of\ water}) \times (\mathrm{temperature\ change})}\right] \times \Delta T = \left(\mathrm{ECF}\left(\mathrm{in}\,\frac{\mathrm{kJ(electric)}}{\mathrm{kJ(thermal)}}\right)\right) \times \left[\frac{4168\ \mathrm{kJ}}{(1\ \mathrm{m^3}) \times (1\mathrm{K})}\right] \times \Delta T$$

#6 Source for N_2: International SEMATECH Manufacturing Initiative (ISMI)/SEMATECH "TEE Tool Correction Factor Calculator."

10 Rest Mode

10.1 SME suppliers can provide a rest mode for their SME. The goal of a rest mode is to allow SME to enter a reduced materials, utilities, and power state without external command.

NOTE 36: Providing a rest mode that becomes active after the SME has been in idle mode for a certain period of time can realize a balance between reducing resource consumption and process readiness of the SME. The effect of rest mode on process readiness of the SME is generally assumed to be smaller than that of sleep mode.

10.2 It is recommended that if the SME has a load port, it should be available to load and unload carriers from/to automated material handling systems (AMHS) during rest mode and during transition states between idle and rest mode when it is in on-line remote operation under the factory host.

10.3 If a rest mode is provided, the SME supplier should characterize the rest mode with at least the metrics given in § 10.4. The information should be included in the documents provided to the equipment user.

10.4 *Rest Mode Metrics*

10.4.1 *Functional Effect* — The SME supplier should provide a narrative description of the effect on the SME of entering and leaving rest mode. For example, the information should discuss what valves, relays, actuators, or other devices change state; which utility systems are affected; which indicators change state; what impact there is to equipment SME safety systems (if any); what equipment SME effluent streams might be altered; what particular pumps or motors are stopped; and any other information describing the functional reaction of the SME. If the SME reaction includes coordination with subsystems such as utilizing subsystem sleep modes, this detail should be provided.

10.4.2 *Rest Initiation* — It is recommended that the SME supplier describe the conditions under which the SME will initiate and the conditions under which the SME will conclude the rest mode.

10.4.2.1 It is recommended that the SME provide an indication of when it is going into a rest mode, when it has achieved the rest mode, when it is recovering from the rest mode, and when it is no longer in that mode. The indications could be by means of an indicator or an on-screen display.

10.4.2.2 *Time to Transition into Rest* — The SME supplier should provide an estimate of the time (e.g., measured in seconds or minutes) in idle mode after which SME will initiate rest mode from its idle mode, and the time it will take to transition to the rest mode. If different levels of rest are provided and there are foreseen differences in these times for the different rest levels that is greater than 10% and that are also greater than 2 seconds, it could be useful to provide providing this detail in a table or other effective means in the documents provided to the equipment user.

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10.4.2.3 *Time to Transition into Idle* — The SME supplier should provide an estimate of the time (e.g., measured in seconds or minutes) it will take for SME to transition from the rest mode into the idle mode.

10.4.3 *Energy Use Rate Reduction in Rest Mode* — The SME supplier should characterize the materials, utilities, and energy consumption rate of its SME when it is in a rest mode by providing data on the use rate of the various utilities, as well as the equivalent power of those utilities when the energy conversion factors recommended in Table 3 are applied to them, including consideration of utility use rates when entering and exiting the rest mode.

11 Sleep Mode

11.1 SME suppliers can provide a sleep mode for their SME. The goal of a sleep mode is to provide a means to coordinate a reduced materials, utilities, and energy consumption rate state of the SME with demand gaps in the SME utilization as understood by the facility control system(s) or personnel.

NOTE 37: When utilization demand is significantly lower than the available time (i.e., time in which SME in process or idle mode), letting the SME be in sleep mode can realize a balance between reducing resource consumption and readiness of the SME. The effect of sleep mode on production readiness of the SME is smaller than that of shutting down the SME.

11.2 It is recommended that if the SME has a load port, it should be available to load and unload carriers from/to automated material handling systems (AMHS) during sleep mode and during transition states between idle and sleep modes when it is in on-line remote operation under the factory host. If the availability of the SME load port is restricted by sleep mode, such restriction should be included in the functional effect information as per § 11.5.1.

NOTE 38: A factory's operation may require carriers to be queued at the SME even if that SME might not be ordered to process wafer for a while.

11.3 If a sleep mode is provided, the SME supplier should characterize the sleep mode of its SME with at least the metrics given in § 11.5. The information should be included in the documents provided to the equipment user.

11.4 *Mode Differentiation* — If the SME provides more than one level of sleep mode (e.g., each having different materials, utilities, and energy consumption rates, or different sleep or wake times), each level should be clearly titled, and the metrics given in § 11.5 should be provided for each one. It is recommended that each sleep level be differentiated in title by a very simple designation such as S1, S2, and so on.

11.5 *Sleep Mode Metrics*

11.5.1 *Functional Effect* — The SME supplier should provide a description of the effect on the SME of entering and leaving a sleep mode and a particular sleep level. For example, the information should discuss what valves, relays, actuators, or other devices change state; which utility systems are affected; which indicators change state; what impact there is to SME safety systems (if any); what SME effluent streams might be altered; what particular pumps or motors are stopped; and any other information describing the functional reaction of the equipment. If the SME reaction includes sleep mode coordination with subsystems which have their own sleep modes (e.g., a dry pump or chiller), this detail should particularly be provided.

11.5.2 *Sleep Control* — The SME supplier should describe what signals or commands are used to initiate and conclude the sleep mode. It is recommended that SME which provides a sleep mode, have a command or control that causes it to transition into the sleep condition (e.g., a 'sleep' command), and one that initiates the transition of the SME from the sleep condition to the idle condition (e.g., a 'wake' command). The sleep mode could be initiated, for example, by the press of a button, a keyboard command sequence, or a software command received by the SME control system. The sleep command could be communicated by an electronic signal received at an interface connector.

11.5.2.1 It is recommended that the SME provide an indication of when it is going into a sleep mode, when it has achieved the sleep mode, when it is recovering from a sleep mode, and when it is no longer in that mode. The indications could be by means of an SME indicator, a handshake signal through an interface connector, an on-screen display, or some manner of status or acknowledgement commands via a software control interface.

11.5.2.2 It could also be useful to provide signals, communications or displays that indicate the estimated time remaining to achieve the various sleep mode points described in¶ 11.5.2.1.

11.5.2.3 It is possible that the SME might not be available to go into a sleep mode when commanded (e.g., when it is executing a process step that cannot be interrupted). In this case, an indication of this in response to the sleep command could be helpful.

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11.5.3 *Time to Transition into Sleep* — The SME supplier should provide an estimate of the time (e.g., measured in seconds or minutes) it will take for the SME to transition from its idle mode or process mode to a particular sleep level in the sleep mode. If there are foreseen variations in this time greater than 10% that are also greater than 5 seconds (e.g., depending on what the SME is doing when the sleep request is received), providing this detail in a table or other effective means in the documents provided to the SME user is recommended.

11.5.4 *Time to Transition into Idle* — The SME supplier should provide an estimate of the time (measured in seconds or minutes) it will take for the SME to transition from the sleep mode into the idle mode.

11.5.5 *Sleep Abort Limitations* — When a 'sleep' command is received; the SME will begin taking related actions. It is possible that the SME will be unavailable for further mode changes for some amount of time (e.g., the wake-up process cannot be started until the sleep process is complete). The SME supplier should detail the SME behavior of in this regard.

11.5.6 *Use Rate Reduction in Sleep Mode* — The SME supplier should characterize the materials, utilities, and energy consumption rates of its SME when it is in a sleep mode by providing data on the use rates, as well as the equivalent power of those rates when the energy conversion factors recommended in Table 3 are applied to them. Entering and exiting sleep mode should be considered separately if the use rates are different when entering and exiting the sleep mode.

11.5.7 It is possible that an SME supplier will integrate subsystems (e.g., pumps and chillers) which have their own sleep modes. In which case, it is recommended that SME suppliers develop an SME-level sleep mode that at least uses these subsystem sleep capabilities in a manner appropriately coordinating subsystem sleep commands within the overall SME function.

12 Target Setting and Improvement

12.1 Energy efficiency improvement can be understood as either a change in the design of SME such that it accomplishes the same task using less energy or a design change that brings an expansion of SME functionality using proportionally less energy. In the latter case, an objective annual energy savings might be demonstrable because the new SME has a performance metric (e.g., throughput) that is better than the previous model, or a subjective energy saving might be inferred because the new SME achieves a functional performance (e.g., capability of forming finer patterns, detecting smaller defects) that is better than the previous model, or some mixture of these points.

Example 1: An implanter Model A could be redesigned as Model B such that it has exactly the same operating specifications but uses more efficient vacuum pumps so that its overall annual energy use is lower.

Example 2: An etch system Model U could be redesigned as Model V with faster wafer handling and gate valve mechanisms so that its overall annual energy use is higher, but its throughput is improved, and so its energy per square centimeter of processed wafer is lower, which can be extrapolated to an overall inferred annual energy savings.

Example 3: A physical vapor deposition system Model C could be upgraded as Model D, in which energy used per wafer as well as the overall annual energy use is higher, but because of uniformity of film thickness and resistivity is significantly improved the percentage of the wafer surface area that meets a specific process criterion (i.e., the yield) provides an inferred annual energy savings that is more than the increase in energy use by Model D.

Example 4: A pattern defect detection system, Model X, could be redesigned as Model Y such that it can detect defects that could not be detected by the previous model, and such functionality is necessary to enable processing at new, advanced process nodes. Model Y's annual energy use is higher than that of Model X, however, Model X would be unable to perform the required task for the new process node and it is not feasible, therefore, to extrapolate the improvements in Y to an inferred annual energy savings. Nonetheless, the increased energy use in Model Y is subjectively justified.

NOTE 39: Energy efficiency improvement shown in Example 1 might be also referred as energy (also utility or material use) reduction or conservation on SME.

NOTE 40: While Example 4 may not achieve less energy consumption on the SME, it might contribute to higher process performance that is needed to produce product of more advanced technologies. The task force suggests that energy efficiency improvement in a manner similar to Example 3 should be evaluated properly according to this Guide.

NOTE 41: It is important to understand that the energy and material use rates for SME such as Model Y, highlighted in Example 4 may not be directly comparable to prior generations of similar SME because disproportionate changes in energy or material use

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rates are needed in order to achieve a specific goal required by new advanced process nodes. In these cases, it may be necessary to establish new baseline use rates to be used in measuring future power efficiency improvements.

12.2 The SME supplier should set and report targets for SME energy efficiency, and utilities and materials use rate levels for the SME and develop timelines for achieving them. The SME supplier should also report an explanation of how each target will be achieved.

12.3 *Objective Energy Efficiency Improvement Evaluation Method*

12.3.1 *Objective Annual Energy Savings Resulting from Energy Efficiency Improvement* — Energy efficiency improvements can be made to SME that can be extrapolated into an objective annual energy savings. Examples of such changes are those which impact:

- The SME throughput.
- The process yield (e.g., improved particle contamination or electro-static discharge control).
- The amount of SME needed to achieve a given process goal (e.g., integration of pre-aligners or metrology functions to eliminate the need for certain upstream or downstream process SME).

12.3.1.1 If energy efficiency comparison is performed using an objective annual energy savings, the report (see § 13.2) should clearly specify the following:

- The SME performance metric being compared.
- The value of the performance metric for each SME.
- The way in which the performance metric was measured.
- How the newer SME differs from the previous model of SME to achieve the improved metric.
- An extrapolation of the improved metric to an estimated of annual energy savings.

NOTE 42: Related Information 3 provides examples of energy efficiency comparisons using an objective annual energy savings.

12.4 *Subjective Energy Efficiency Improvement Evaluation Method* — Energy efficiency improvements might be made to SME that can only be expressed in a subjective manner such as by using a performance factor (PF).

12.4.1 Prior energy use rates might no longer be comparable upon the introduction of new enabling capabilities, even for SME in the same category of prior models. In order to compare the energy efficiency of new models of SME with previous models of SME in the same or similar category, various functional metrics can be taken into account to characterize the change in energy efficiency from one model to the other. Such improvements might include:

- smaller feature size of devices that can be processed,
- faster provision of analysis results, or
- improved defect detection by the advanced model.

NOTE 43: It is important to recognize that new enabling technology may require a new use rate budget, unrelated to previous SME which is no longer sufficient to meet processing requirements. Simple comparison of energy efficiency would result in disproportional increase of use rate and use rate per processed area without consideration of functionality expansion.

12.4.1.1 If a subjective energy efficiency comparison is performed per § 12.4.1, it is recommended that PF be selected to quantify the improvement of a performance metric related to the intended function(s) of the SME, and the following should be provided:

- Explanation of the functional metric that is the subject of performance improvement quantification, and
- The score of each model in the performance comparison, and
- An explanation of how each particular performance metric is measured, and
- An explanation of design changes that resulted in the metric being improved in the newer SME model.

12.4.1.2 Performance metrics may be different for different types of SME, and there may be more than one. The supplier should explain how each of such metrics is taken into consideration in the PF.

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