SEMI S23-1216
GUIDE FOR ENERGY, UTILITIES, AND MATERIALS USE EFFICIENCY OF SEMICONDUCTOR MANUFACTURING EQUIPMENT

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NOTICE: This Document was completely rewritten in 2016.

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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 *ISMT* — International SEMATECH

5.1.4 *SME* — semiconductor manufacturing equipment

5.1.5 *LCA* — life cycle assessment

5.1.6 *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 *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]

5.2.3 *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 3: In the context of this Guide, 'equipment' in the definition of 'baseline' and 'documents provided to the equipment user' may be considered to refer the SME or an SME's subsystem(s).

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

NOTE 4: 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.

5.2.5 *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.

5.2.6 *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

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

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

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

5.2.10 *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.

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5.2.11 *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.

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

5.2.13 *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.

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

5.2.15 *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. [S3, S6, S28]

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

5.2.17 *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 5: 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.

5.2.18 *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 6: The mode concepts of SME can be applied to subsystems. Some subsystems might not have an idle, rest, or sleep mode.

NOTE 7: 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.

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

5.2.20 *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 8: 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 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.

6.4.1 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.

6.4.2 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 9: 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.

6.5 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).

6.6 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 10: Suppliers and users of SME are encouraged to use SEMI E6 as the framework for documenting SME use rates.

6.7 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 11: 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", Eric D. Williams, Robert U. Ayres, and Miriam Heller; published in Environmental Science & Technology, 2002, 36 (24), pp 5504–5510, Publication Date (Web): October 25, 2002, which itself cites several industry studies and related per-square-centimeter energy investment metrics."

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

6.9 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 12: 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 13: 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.

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

NOTE 15: 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 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 16: 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.

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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
Refrigerated Cooling Water or Tower-cooled Cooling Water	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.

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.

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Data Title	*Description*
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 Refrigerated Cooling Water Tower Cooled Cooling Water 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 17: See Related Information 1 for additional recommendations.

8.6 *Annual Estimated Energy Consumption*

8.6.1 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.
- 730 two hour periods in idle, rest, or sleep mode.

8.6.2 See ¶¶ 8.4.1, 8.4.2, and 8.4.3 for energy use rate measurement method in process, idle, and rest or sleep, modes respectively.

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

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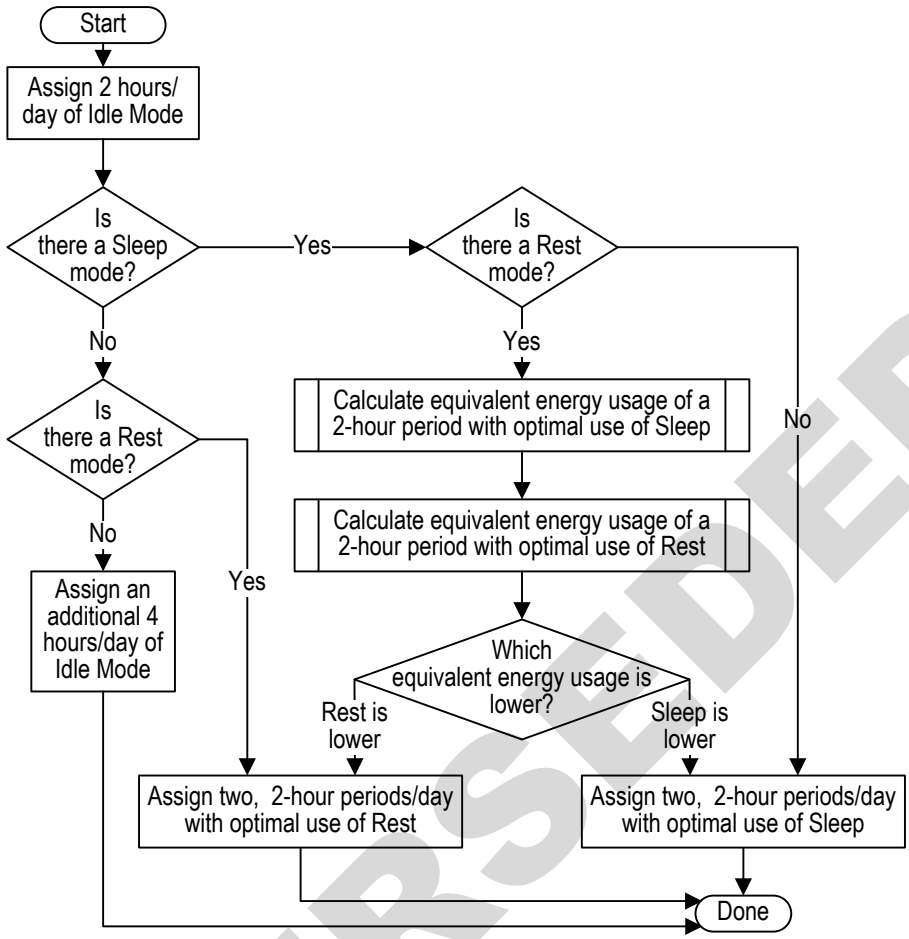

Figure 1
Procedure for Assigning the Six Hours/Day of Free Time

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 are used, the output of the conversion can be used to identify those utilities and materials which, generally speaking, have a higher environmental impact.

NOTE 18: 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 19: Related Information 1 contains additional conversion factor information that may be useful.

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 20: 1 kiloWatt hour (kWh) = 3600 kJ.

NOTE 21: See Related Information 1 for example calculations.

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9.5 The SME supplier may also use an alternate set of conversion factors.

9.5.1 If alternate conversion factors are used, the factors should be documented in the report of the results.

9.6 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.

9.7 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 22: See Related Information 1 for additional information.

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 clean room 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.
Water Cooled by Refrigeration	Energy/Volume = 929 (kJ/m^{3}K) × ΔT + 983 (kJ/m^3) (= 0.258 (kWh/m^{3}K) × ΔT + 0.273 kWh/m^3)	ΔT is the difference between the water inlet and outlet temperatures in Kelvin. When ΔT is not known, assume a value of 5 K.
	Equivalent Energy/Heat Energy Removed = Equivalent Power/Heat Power Removed = 0.222 + 0.235 K/ΔT (K)	
Water Cooled by Cooling-tower	936 kJ/m^3 (0.260 kWh/m^3)	Assume refrigerated cooling for water supplied to the tool at <25°C and cooling-tower for ≥25°C unless more specific information about the SME user's facility is available.
UPW or DIW Temp ≤25°C	3.24 × 104 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 × 105 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.

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