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A comparative study on energy performance assessment for HVAC systems in high-tech fabs

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ABSTRACT

High-technology fabrication plants (fabs) such as semiconductors generally consume enormous energy, where HVAC system accounts for the second largest part at roughly 40–50%. Therefore, the energy performance for HVAC system in semiconductor industry is undoubtedly essential. In this study, several EPMs (Energy Performance Metrics), namely SCL, ω_{scl}, EI_{AFR}, was proposed to estimate and assess the energy using for HVAC system in a fab through the analysis of theoretical model and influential factors. The energy performance comparison cases were conducted in both sub-system level and system level through comparative analysis on the operation data, simultaneously the presented EPMs were verified and applied in two air systems and two fabs studied. Most importantly, the results show the advantages of SCL in estimating overall cooling load in high-tech fabs, which can be used in the future for designing HVAC system in fabs that with higher energy efficiency and ω_{scl} that can be applied to evaluating the stability and validation in maintaining indoor environmental metrics including indoor temperature, humidity, particles and pressure difference. Moreover, it is generally proved that the annual EPMs like EI_{AFR} (kWh/Air Flow Rate) turn to provide more consistent comparison than the traditional metrics like EI kWh/Floor Area) and SEUP (kWh/Unit of Production) in assessing overall energy performance of HVAC system in high-tech fabs.

1. Introduction

High-technology fabrication plants (fabs) such as semiconductors generally consume enormous energy and the energy performance for semiconductor industry is undoubtedly essential. Previous studies have shown that Heating, Ventilation, and Air conditioning (HVAC) system accounts for the second largest energy consumption in high-fabs, at about 40%–50% and energy density of HVAC system for cleanroom in high-tech fabs is generally 10 times that for thermal comfort [1]. Therefore, many studies regarding energy conservation for HVAC system in cleanroom of semiconductor fabs have been conducted. For example, Brown [2] discussed an energy-saving opportunity for the make-up air unit (MAU) of a semiconductor fab. Hu and Tsao [3] compared energy efficiency performance of five different HVAC systems for cleanrooms and pointed out that the MAU + FFU systems exhibited the highest energy efficiency. Tsao and Hu [4,5] et al. investigated the difference in energy efficiency performance of MAU with different pre-cooling and preheating/humidification schemes. K. Kircher et al. [6] made an assessment of three energy-saving opportunities by modeling and simulation and calculate both the energy reduction and payback time to recommend the best strategy for energy efficiency.

Meanwhile, there is a series of energy benchmark works having been done in the past 20 years. Xu [7,8] reported energy consumption and particle control of facility systems and characterized fab energy use in terms of energy use or power demand. In 1997, ISMI sponsored and participated in the international benchmarking study of fourteen 150 mm and 200 mm fabs around the world collecting and sharing energy consumption data for fab process areas and facility operations equipment [10]. Hu et al., in 1999 [9] studied energy benchmark for nine fabs producing 150 mm and 200 mm wafers in Taiwan, China. In 2008, Hu [11] and his team established the energy benchmark of a typical 8-in. DRAM semiconductor fab through field measurement data for chilled water system, PCW system, nitrogen system, vacuum system and UPW system, respectively, which can assess the efficiency of different energy-saving schemes and as a good reference for factory authorities. Then, they [12] characterized the electric energy consumption and

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Table 1
Characteristic of the fabs studied.

Fab	Clean room floor area/ m^2	Wafer diameter/ in	Annual production	Service years	Clean room class	Design cooling load/kW
Fab1	5091	6	247266	11	ISO5-7	3971
Fab2	3533	8	182380	3	ISO5-7	3653

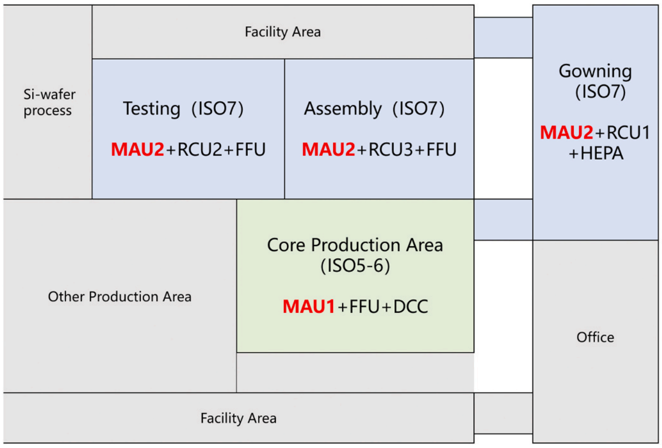

Fig. 1. The lay-out and system specification of fab1.

production of 300 mm DRAM fabs by using various performance metrics, including PEI, EUI and UOP in 2010. Chang and Hu et al. [13] identified the specific energy consumption of all major energy consuming segments of the Dynamic Random Access Memory module supply chain, including 12" Si-wafer (ingot), wafer fabrication, assembly, testing, and printed circuit board in 2012. By 2017, Hu [14] lead the team developed a new calculator to provide energy conversion factors for each sub-system in the fab, which can be used as a straightforward tool for energy-saving and future design. Published studies for fabs refer to energy consumption normalized by either per unit wafer area or per unit fab area [7–14]. Energy consumption levels in 200 mm and 300 mm semiconductor fabs in Asia, North America, and Europe were studied to gather baseline data on different facility systems to develop energy efficiency metrics, as the effectiveness of the present EPMs described as energy consumption either per unit wafer area or per unit fab area varies a lot in fabs with different energy consumption levels [15].

However, the published data on energy demand for semiconductor fabs is quite limited, largely due to the facts that energy consumption data are considered as confidential information for manufacturers. As a result, few studies focus on the energy benchmark and energy performance for the facility system, especially for HVAC system. The objective of this study, based on measured data or appropriate assumptions when operating data is not available, is to develop better EPMs (Energy Performance Metrics) to estimate and assess the energy uses for HAVC systems. This paper briefly introduces the specification of the fabs and air systems studied in the first place. Through several theoretical models and influential factor analysis of cooling load in high-fabs, the new EPMs is presented. The new EPMs is verified and applied in the following comparative cases, on sub-system level (air systems) and system level (two fabs) separately. Finally, conclusions are drawn.

2. Methodology

2.1. Characteristic of the fabs studied

The fabs studied are located in Zhuzhou, Hunan Province, China. The names of participating entities are kept anonymous. One 6 in fab and one 8 in fab was selected in this study, which provide most of the production of Insulated Gate Bipolar Transistor (IGBT) module in China. The characterization of energy use of the fabs can largely represent the wafer fabs in China. Table .1 shows the specific information of the two fabs.

Fig. 1 illustrate the lay-out of fab1. System MAU1 is the core production area of the fab, which is also the area with the highest clean class (ISO5) and the greatest energy consumption. The total clean room floor

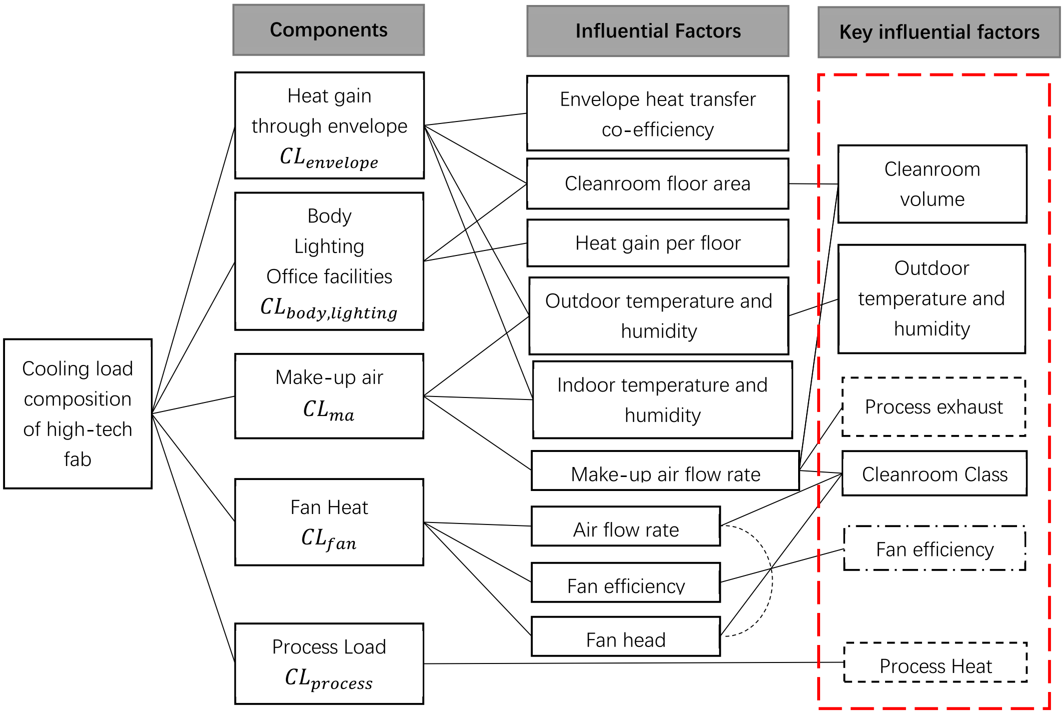

Fig. 2. Components and influential factors of cooling load in high-tech fab.

area is about 813 m^2. The air system form of MAU1 is MAU + FFU + DCC, where the fan frequency mainly is controlled by monitoring the positive pressure value in the pre-evaporation area, and adjusts the air valve that extends to the photolithography area by monitoring the positive pressure value in the photolithography area. The pressure difference is measured to be relatively stable and fan runs at max load throughout the year with frequency basically maintained at 48–50 Hz. System MAU2 is the testing, assembly and support area with the class of ISO7, the total clean room floor area is about 1750 m^2. The air system form of MAU2 is MAU + FFU + RCU, the Make-up Air Unit (MAU) is connected with three parallel Recirculation Air Unit (RCU) where the make-up air and return air is mixed before supplying to clean room instead of using the air interlayer. Both of pressure difference and the fan frequency is relatively stable. Each RCU can change the make-up air rate by adjusting the make-up air valve according to the indoor pressure difference demand.

The refrigeration plant of fab1 adopted double-temperature chilled water systems and heat exchangers for cooling. The chilled water (12/17 °C) mainly supplies dry coils to remove the sensible load in clean room and pre-cools air in air handling unit. When the outdoor wet-bulb temperature reaches the limitation for free cooling, heat exchangers are used to produce chilled water (12/17 °C). In addition, the chilled water (12/17 °C) partly supplies to the pure water station for process use. The chilled water (5/10 °C) is mainly used for cooling and dehumidification in air handling units. The hot water system adopted a gas boiler which is used for air-conditioning and process warm water.

2.2. Data collection

Field data was collected and compiled from measurements performed by on-site engineers, which span over a one-year period (from January of 2019 to January of 2020) using central monitoring systems. The fab facility engineers and managers provided the energy data gathered from the energy management systems. Second, the project team performed measurements at various selected points in fab using a standard data collection survey form. The measured data were then aggregated to facility systems and subsystems. Our project team performed data validations and calibrations when necessary and coordinated with the on-site engineers and facility managers to correct measurement errors of recording from their energy management systems.

2.3. Theoretical analysis of load in high-tech fab

Fig. 2 describes the cooling load composition of typical high-tech fab. As a kind of industrial building, the main objective of high-tech fab is the stability of the production environment, therefore the cooling load composition and its main influential factors are different from those of general buildings.

a) The cooling load introduced through the envelope, $CL_{envelope}$

High-tech fab generally adopt a nested structure, the clean area is composed of heat-insulating color steel plates surrounded by the outer envelope. The heat transfer coefficient is extremely small. There is no external window; the clean room remains positive pressure and the doors and windows are well sealed, which is considered no air penetration and air intrusion. Therefore, engineering experience estimates cooling load of this part is 10–15 W/㎡, accounting for a very small proportion.

b) The cooling load from body, lighting and office facilities, $CL_{body,lighting}$

Due to high-tech fab are generally operated 24 h a year (only short-term suspensions) and workers are required to wear tight isolation suits under production, this part of cooling load is stable and unobvious, which can be considered as a steady load only related to floor area.

c) Make-up air cooling load, CL_{ma}

With the continuous development of industrial production automation, the number of personnel required for high-tech fab is getting less and less, thus the amount of make-up air required to ensure positive pressure is much greater than the amount of that required to human comfort in cleanrooms. The make-up air cooling load generally account for more than 40% of the total load, even higher.

d) Process load, $CL_{process}$

According to our actual investigation, the density of equipment in the process production area of high-tech fab is quite large. The background temperature of tested environment is about 22 °C, the average temperature of the general process facilities is between 30 and 50 °C and the temperature of the heat exhaust equipment is above 80–100 °C, while the temperature of the diffusion furnace reaches above 260 °C. Therefore, this part has a considerable impact on the thermal environment and has become one of the main load components. In system design, however, this part of the heat dissipation is not properly accounted for, which is commonly estimated by the process equipment manufacturer or referring the organization Semiconductor Equipment and Materials International (SEMI) issued guideline SEMI S23-0813.

e) Cooling load caused by circulation fans, CL_{fan}

The clean air system in high-tech fab operate 24 h a year and the waste heat generated by the circulation fans become the main component of the cooling load. The total pressure of the circulation fans is mainly related to the internal resistance and the external residual pressure and the resistance of the filter is large. According to the research [16], the temperature rise of AHU at 1400Pa can reach 1.5–1.6 °C and that of FFU at 300Pa can reach 0.5 °C. In addition, the heat generated by circulation fans in ISO 6 cleanroom of 100㎡ account for 50% of the total sensible load.

In summary, the total cooling load of the high-tech fab is determined by:

$$CL = CL_{envelope} + CL_{body,lighting} + CL_{ma} + CL_{process} + CL_{fan} \tag{1}$$

From the above analysis, $CL_{envelope}$ and $CL_{body,lighting}$ can be considered as the steady-state cooling load related to the cleanroom floor area; $CL_{process}$ is directly measured according to the data provided by the process equipment manufacturer; CL_{ma} is mainly related to the make-up air flow rate and the outdoor environment, which be obtained by referring guidelines to obtain the estimated flow rate of make-up air under different clean class and the pressure difference; CL_{fan} is mainly related to the air flow rate and the total pressure of fan, the air flow rate is mainly related to the clean class, the total pressure of fan is related to the filter resistance and the air flow rate, which is further related to the cleanroom floor area and clean class.

Based on Fig. 4, except for process factors, the cooling load of high-tech fab is affected by the cleanroom floor area and clean class. Facilities exhaust and process heat can be separately included by the process side and the fan efficiency can be based on specific project estimates. The cleanroom floor area and the clean class jointly determine the total air supply, consequently we define Specific Cooling Load (SCL) as the total cooling load excluding the process heat divided by flow rate for contamination removal.

The make-up air cooling load, $CL_{ma}$and indoor cooling load, CL_{indoor} can be expressed as Eqs. (2) and (3),

$$CL_{ma} = G_{ma} \cdot (h_{oa} - h_s) \tag{2}$$

$$CL_{indoor} = G_{cr} \cdot (h_s - h_{ia}) \tag{3}$$

where the G, G_{ma} is the air flow rate of clean air and make-up air, separately, and h_{oa}, h_s, h_{ia} are the enthalpies for outdoor air, supply air and indoor air, separately.

According to the definition of SCL, SCL can be written as Eq. (4). G_{ma} is determined by process exhaust, G_{cr} is determined by clean class, h_{oa} and h_{ia} keep constant for most circumstances, h_s is determined by process heat. Therefore, in a certain clean room, SCL is only determined by the process heat and exhaust, while as we define SCL is load excluding the process heat, the process exhaust should the only influential factor. Thus, SCL for fabs with similar process may keep in a narrow range.

$$\mathrm{SCL} = \frac{CL_{ma} + CL_{indoor}}{G_{cr}} = \frac{G_{ma}}{G_{cr}} \cdot (h_{oa} - h_s) + h_s - h_{ia} \tag{4}$$

From Eq. (4), it can be noticed that G_{ma} is related to the pressure difference, G_{cr} is related to contamination removal and h_s is related to indoor temperature and humidity. Therefore, it is believed that the distant between real-time SCL and design SCL could reveal the stability and validity of indoor environment controlling. Therefore, we define the percentage difference between real-time SCL and design SCL as ω_{scl}.

2.4. Energy performance metrics

According to the above theoretical analysis, the cooling load and power consumption of the air-conditioning system in high-tech fabs are linearly related to the amount of clean air flow rate. Therefore, the metrics per unit flow rate turn to be more accurate on reflecting the energy consumption level and providing more consistent comparisons than that per unit floor area, which will be proved in the following operating data analysis. The annual energy consumption metrics can characterize the annual power consumption intensity as a whole under conditions of certain operation mode and time. The energy performance metrics in this study are as follows:

1) SCL, the specific cooling load (per unit flow rate) with unit of kW/(m^3. h)

$$\mathrm{SCL} = \frac{CL}{G_{cr}} \tag{5}$$

2) ω_{scl}, the percentage of SCL difference with design with the unit of %

$$\omega_{scl} = \frac{|SCL - \mathrm{SCL}_d|}{\mathrm{SCL}_d} \times 100\% \tag{6}$$

3) SFC, the specific fan electric consumption (per unit flow rate) with unit of kWh/(m^3. h)

$$\mathrm{SFC} = \frac{E_{cf}}{G_{cr}} = \int SFP \cdot t_f \tag{7}$$

4) EI_{AFR}, the annual specific energy consumption (per unit flow rate) with unit of kWh/(m^3. h)

$$EI_{AFR} = \frac{E_{cf} + E_{rp}}{G_{cr}} = \int \frac{\mathrm{SCL} \cdot t_r}{EER} + \int SFP \cdot t_f \tag{8}$$

where CL is Cooling load (J/m^3); G_{cr} is total air flow rate for contamination removal (m^3/s);E_{cf} is annual energy consumption of circulation fans; E_{rp} is annual energy consumption of refrigeration plant. SCL_d is the SCL of design.

Table 2
The operating conditions of air system facilities in fab1.

Facilities	Floor Area /m^2	Air Flow Rate/ m^3/h	Cooling Demand/ kW	Air Change Rate /h
MAU1	190	28000	300	11.5
MAU2	1750	42000	368	5.9
RCU1	543	39000	103.3	23.9
RCU2	765	30000	73.3	13.1
RCU3	442	60000	122	45.2

3. Application and discussion

3.1. Comparative analysis of energy performance on air systems

3.1.1. Operation analysis

Table .2 demonstrates the specification of measured AHUs in both air systems. The air system MAU1 mainly serves area containing the photolithography room, with floor area of 190 m^2, where the energy consumption represents the highest level in the entire fab. Air flow rate of MAU1 was measured to be 28,000 m^3/h, and the total supply air flow rate was 35,000 m^3/h, accounting for 82% of the total make-up air flow rate. It is calculated that the cooling capacity of MAU1 is 300 kW, the heating capacity is 45 kW, and the cooling capacity of DCC is 84 kW. Air system MAU2 serves the largest adjacent area of the same clean class, with floor area of 1750 m^2. The air flow rate of MAU2 is 129,000 m^3/h and its cooling capacity is 368 kW.

It’s obvious that the fan in MAU1 has experienced some performance degradation and its operating power has deviated from the rated value. The ACR of the clean rooms in system MAU1 was measured to be 11.5 h^{-1}. The design make-up air flow rate in photolithography area accounted for about 62% in MAU1, which is considered too large to energy-saving. The fan of MAU2 run at full load, with 102% air flow rate compared to design value. Due to the low clean class, the ACR in MAU2 is only 50% of that in MAU1, while the pressure difference is basically maintained at 15Pa, which indicating that both operation and design are better than MAU1. In addition, although the clean rooms served by RCUs are all ISO7, the measured ACR distinguish by a max of three times when the cleanliness still meets the standard. Therefore, both MAU1 and all RCUs can reduce air flow rate during design and operation for energy-saving in circulation fans.

The specific energy consumption of all clean rooms in both air system is obtained in Table .3. The cooling load per unit floor in the photolithography room is 5.3 times greater than the total actual cooling load per unit area 334 W/m^2, the cooling load per unit of AFR (Air Flow Rate), by contrast, is much close to the total actual cooling load per unit of AFR 15.1 kJ/m^3, at only 1.36 times. Furthermore, for clean rooms with the same clean class, the cooling load per unit floor ranges from 208 W/m^2 to 663.3 W/m^2. However, the cooling load per unit AFR in cleanrooms is concentrated between 17.6 kJ/$\mathrm{m}^3$and 20.5 kJ/m^3. The design cooling load per unit of AFR of the fab is calculated to be 17.4 kJ/m^3, which is only 1% different from lower limit of the above range. In addition, the actual cooling load per unit of AFR is measured to be 19.2 kJ/m^3, which stay within the above range. By linearly fitting the test points, the relationship between the cooling load CL and the clean air flow rate G is: G = 18.7367CL+52.2171, with the coefficient R^2 reaching 0.9871, which verifies that the cooling load is linearly related to clean air flow rate and the main factor for the intercept is the heat produced by the process, strongly supporting the previous theoretical analysis.

In contrast, under the same clean class, there is 2–3 times difference in the cooling load per unit floor and, even 10 times at maximum difference in all cases, which is apparently not appropriate to estimate the overall cooling load interval of fab. Consequently, it is verified that SCL metric in assessing energy efficiency levels of fab can provide more consistent comparisons than using metric normalized by floor area. The overall energy consumption of the fab is highly related to the system

Table 3
Energy consumption level of main process area in fab 1.

Process area	Total cooling load per floor W/m^2	Make up air load per floor W/m^2	Process load per floor W/m^2	Total cooling load per AFR kJ/m^3	Make up air load per AFR kJ/m^3	Process load per AFR kJ/m^3
Photolithography	1784	1374	410	20.5	18.8	1.7
AT1	208	112	96	19.1	10.3	8.8
AT2	663.3	387.3	276	17.6	10.3	7.3
Gowning	395.2	205	190.2	19.8	10.3	9.5

Table 4
MAU2 system fan energy consumption level in fab 1.

Sub-system	Clean air flow rate m^3/h	Circulation fan power kW	FFU power kW	SFP kJ/m^3	SCL kJ/m^3	SCL$_d$ kJ/m^3	ω_{scl} %
MAU1	144500	17.7	25.5	1.08	20.5	14.9	38%
MAU2	90645	47.15	11.7	2.33	18.6	19.1	3%

load level and energy efficiency of refrigeration. By estimating load level, the energy consumption level of different fabs can be determined and the evaluation, guidance and constraints can be conducted for the whole industrial in the future.

3.1.2. Comparison of energy efficiency merics

Table .4 gives AFR, circulation fan power and calculated energy efficiency metrics in clean air system MAU1 and MAU2. SFP indicates the efficiency of air supply in air systems [17]. It can be seen that the SFP of the system MAU2 (MAU + FFU + RCU) is approximately twice that of MAU1 (MAU + FFU + DCC), so the energy efficiency for air supply is much lower than MAU1. Although systems with MAU + FFU + RCU consumes more energy, it saves the construction cost of the lower interlayer, so the economics of the two kinds of systems need to be further considered. On the other hand, the ω_{scl} of MAU2, at 3%, is much smaller than that of MAU1, at 38%, indicating that control of indoor

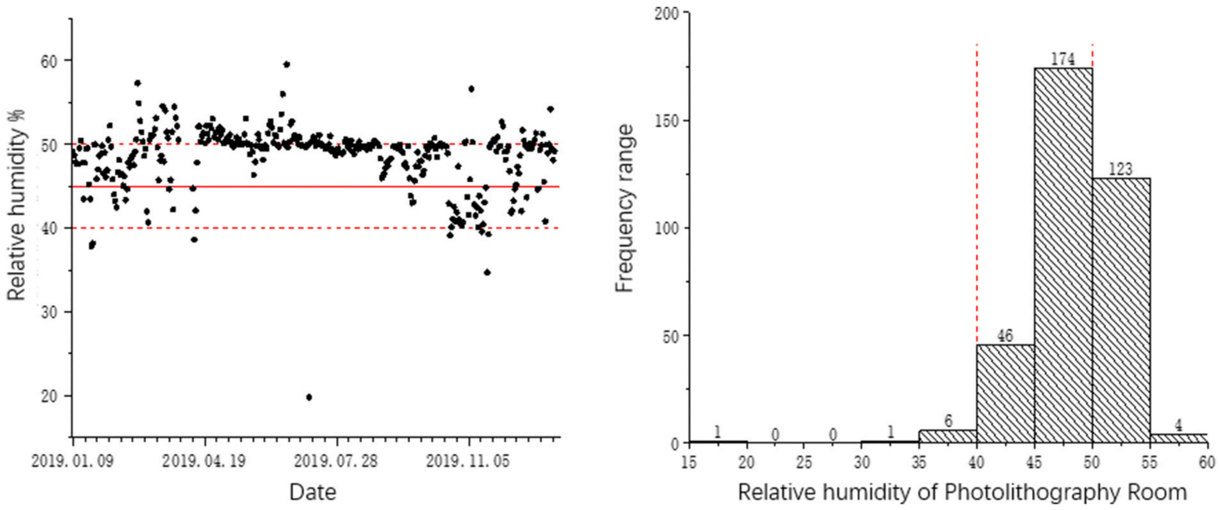

Fig. 3. Daily average relative humidity statistics during three-line lithography.

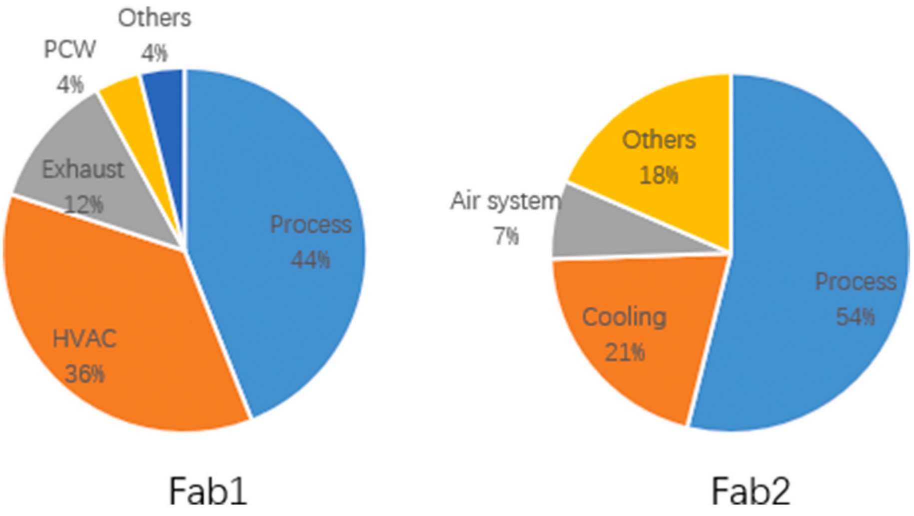

Fig. 4. The percentage breakdown of annual energy consumption of the two fabs.

Table 5

Comparison of energy efficiency of refrigeration plants in two fabs.

Facility/System	Energy efficiency metrics	Fab1	Fab2	Lower limitation
Chiller (5/10 °C)	PCR	0.62	0.70	
	COP	4.2	4.5	5.1
	WTFchw	50.2	79.3	35
	WTFcw	38.7	78.7	30
Chiller (12/17 °C)	PCR	0.61	0.92	
	COP	4.64	5.45	5.1
	WTFchw	33.8	72.1	35
	WTFcw	31.0	80	30
Refrigeration Plant	EER_{Plant}	3.49	4.14	

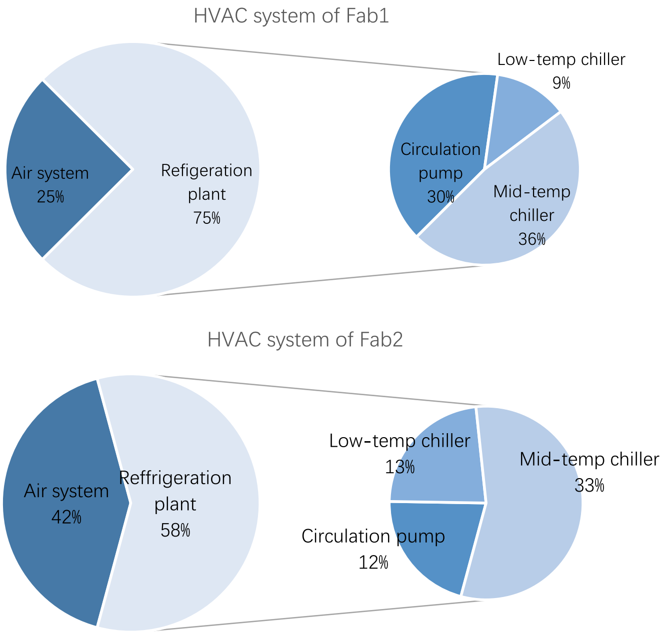

Fig. 5. The percentage breakdown of annual energy consumption of the two fabs.

environmental parameters in system MAU2 is more stable and effective than that in MAU1. Through practical investigation, it is found that about 30% of the FFU in the MAU1 deviates from the rated state, the actual full coverage rate is 41%, and the average indoor air supply speed is 0.14 m/s, which is less than the lower limit recommended by authority standards, at 0.2 m/s, although the cleanliness still meets the requirements. Fig. 3 shows the daily average relative humidity in photolithography room. The relative humidity in photolithography room is required to be 45 ± 5%, the annual average and median are about 50%, about 50% of the measured points are concentrated between 45 and 50%, revealing that nearly half of the year may experience high humidity risk in production. Therefore, it is suggested that ω_{scl} can reflect the stability and efficiency in maintaining indoor environmental parameters in clean air systems.

3.2. Comparative analysis of energy performance on two fabs

3.2.1. Energy performance on refrigeration plants

Table .5 compared the energy efficiency of the refrigeration plants in the two fabs. It is quite noticeable that all energy efficiency metrics for both systems in the fab 2 are better than that in the fab1. Each Metric in Fab1 is seen to reach the lower limitation in standards, where furthermore the overall EERr is 18.6% less than that in the fab2. By referring ASHARE energy efficiency scale, fab1 is considered to be in the urgent need of improvement section, while fab2 is in the average section. Through the actual investigation, the efficiency of the cooling water pump in the fab2 is less than 40%, which is the same in the fab1, indicating that there are problems in selecting the cooling water pump in both two fabs.

Table 6

Comparison of cooling demand of air-conditioning system in two fabs.

Energy efficiency metrics	Fab1	Fab2
Total cooling load per floor W/m^2	504	820
Make up air per floor W/m^2	388	560
Process load per floor W/m^2	116	260
Total cooling load per AFR (SCL) kJ/m^3	20.5	11.3
Make up air per AFR kJ/m^3	18.8	7.7
Process load per AFR kJ/m^3	1.7	3.6

3.2.2. Energy consumption

Fig. 4 shows the percentage breakdown of annual energy consumption in the two fabs during 2018–2019. The energy consumption of HVAC in fab1 and fab2 accounts for 30% and 36% of the annual power consumption, respectively, which is only inferior to that of the process facilities, at 44% and 54%, respectively. Fig. 5 shows the percentage breakdown of HVAC energy consumption in the two fabs. The energy consumption of refrigeration plant and circulation water system in the two fabs accounts for the greatest proportion, up to 75% and 58%, respectively. The energy consumption of chillers (12/17 °C) and circulating pumps in fab1 is the main part of its HVAC energy consumption, accounting for 36% and 30%, respectively. As a result, there may be a large surplus in the selection of chillers in fab1. On the contrary, the proportion of energy consumption of air system increased significantly in the fab2, due to its advanced process requiring higher clean class. Moreover, the energy consumption proportion of the two kinds of chiller in fab2 is 33% for 12/17 °C and 13% for 5/10 °C. Compared to Fab1, in short, the energy consumption proportion of the fab2 is more reasonable and closer to their expected condition.

Table .6 gives load per unit floor and load per unit AFR in the two fabs. It is also noted that the cooling load per unit floor is quite different, while the cooling load per unit AFR still falls in the interval obtained above, which once again verifies the advantages of metrics per unit AFR. Simultaneously, it was found that actual SCL of fab2 is far less than design (16.4 kJ/m^3), resulting from relative higher ACR, at overall 64 $times/h^{-1}$. On the other hand, given the attenuation of the fan and the excessive design load, SCL under the actual operating conditions are similar to design conditions. Since the design AFR of high-tech fab is commonly too large currently, the optimized design AFR should be used for energy-saving. The smaller SCL is, the lower cooling energy level for the fab will be. The optimized design AFR requires future researches to improve the energy efficiency of high-tech fab.

Table .7 compared the annual energy consumption of the two fabs by EI, ASCL (Annual SCL), SEUP [17], ASFC (Annual SFC) and EI_{AFR}. The gap in EI between the two fabs is noted excessively large, fab2 is nearly two times that of fab1, derived from the huge difference of production demand, which is consistent with nearly two times difference in SEUP. Nevertheless, $EI_{AFR}$is found almost the same, energy performance of fab2 is slightly better than fab1 due to the lower SCL and higher EER_{plant} compared to fab1. Moreover, ASFC of fab2 is 40% higher than the fab1, indicating that the air supply efficiency of the fab2 is much lower than that of fab1, which balance EI_{AFR} between two fabs in overall energy performance to the same level. To summarize, the overall energy consumption performance of fab2 is slightly better than that of fab1. Therefore, it is recommended that metrics SFC and EI_{AFR} in accessing energy consumption performance provide more comprehensive and consistent comparison among different fabs than using metric EI and SEUP alone.

Table 7
Comparison of annual energy performance of two fabs.

EPMs	EI kW·h /m^2	ASCL kW·h/(m^3/s)	EER$_{plant}$	SEUP kW·h /UOP	ASFC kW·h/(m^3/s)	EI$_{AFR}$ kW·h/(m^3/s)
Fab1	655.5	53478.7	3.49	13.5	6006.1	21329.5
Fab2	1304.2	43755.2	4.14	25.3	10092	20660.9

4. Conclusion

In this study, energy consumption on two sub-systems and two fabs was compared separately adopting new energy performance metrics in high-tech fabs, which developed by theoretical analysis and verification based on measurements. First, basic information of two fabs and air systems is briefly introduced, followed by detailed analysis of components and influential factors in cooling load. The results show that the cooling load of high-tech fab is mostly affected by the cleanroom floor area and clean class excluding process factors, consequently new energy performance metrics like SCL and ω_{scl} is presented. Through comparative analyzing the operation data of two air systems and two fabs separately, the results illustrate that the energy efficiency of air system (MAU + FFU + DCC) is approximately twice that of air system (MAU + FFU + RCU) and the HAVC consumes the second largest power in fabs where the refrigeration plant accounts for the greatest part further. Most importantly, the results verify the feasibility of SCL in estimating overall cooling load in high-tech fabs, which can be used in the future for designing fabs that with higher energy efficiency and ω_{scl} that can be applied to accessing the stability and validation in maintaining indoor environment metrics. Moreover, it is proved that the annual energy consumption metrics by kWh/Unit Air Flow Rate (EI$_{AFR}$) are believed to be more appropriate than the traditional metrics in kWh/floor area (EI) and kWh/Unit of production (SEUP) when evaluating overall energy performance of high-tech fabs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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