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Estimated Energy Consumption in Utility Equipments for Manufacturer

Sittichoke Pookpunt, Choopong Chuaypen, and Pittawat Jenjob

Abstract— *This paper presents an investigated electrical power model for utility equipment in a general manufacturing industry, including air compressors, air conditioners, chillers, air handling units, and cooling towers. The productivity of each machine is influenced by its energy consumption. Technical data were gathered by evaluating power capacity, workload, and machine output. Here, workload represents the percentage of output relative to full load, which correlates with the ratio of load time to total operation cycle time. Average power consumption was derived based on workload as a percentage of full capacity, while total energy consumption was calculated from average power and operation time. The Specific Energy Consumption (SEC) metric was defined as the ratio of machine output to average power at a specified workload percentage. The comparison between machine productivity and power usage at varying load levels reveals that, as workload increases, SEC declines across all machine capacities due to a reduction in standby or idle loss. This model aids in operational planning by identifying optimal workload ranges for efficient energy use.*

Keywords— **Estimated Energy Consumption, Utility Equipment, Specific Energy Consumption.**

1. INTRODUCTION

Most energy consumption in the manufacturing process depends on the main equipment electric load and the period of production from startup to shut down. However, there is a large portion of energy consumption in the utility equipment used to support the main production. Utility equipment represents any equipment, or machine supplied the facilities surrounding services supported the main manufacturing process. For example, air compressor supplies compressed air, boiler supplies steam, air conditioning or chiller supplies cooling or heating environment etc. No manufacturer could produce without this supported equipment. These utility machines have different energy consumption behaviors depending on the sizing, capacity, workload characteristics and operation time responding to the requirements of manufacturing process, quality of raw material and its environmental surrounding which is unpredictable electric load. Therefore, categorizing and developing mathematical models for these machines is necessary to understand their structure and simulate their electricity consumption behavior. Moreover, the energy consumption models must also align with the actual energy data of the respective manufacturing sectors [1, 2]. This paper develops electrical power models to observe the energy consumption behavior of utility equipment, including variables related to the energy usage of each machine type. Energy consumption data from the factory aligned with production was compared, and variables such as the Load Factor of Power (LFP) and Load Factor of Time (LFT) for all machines were validated to estimated energy usage that corresponds with production behavior in the manufacturer.

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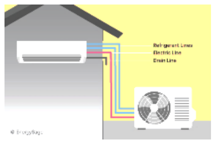
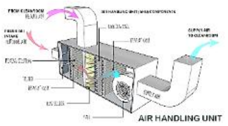
2. UTILITY EQUIPMENT

Utility equipment generally supplies the facilities surrounding supported the main manufacturing process such as compressed air, cooling air, cooling water and hot steam etc. This study focused on the equipment consuming electricity form because of higher quality and higher price than other energy form. The equipment consuming electricity included an air compressor, air conditioner, chiller, air handling unit and cooling tower as shown in Table 1.

Table 1. electricity consuming utility equipment in manufacturer (source : http://energyauditorthai.com)

Equipment	Description
Reciprocating air compressor 	A reciprocating air compressor is a positive-displacement machine using a piston driven by a crankshaft to compress and deliver air at high pressure.
Screw type air compressor 	A screw or rotary air compressor is a positive-displacement machine using two rotating screws or rotors to produce compressed air.
Split type air conditioner 	A split system air conditioner has two units, one inside is called indoor absorbing heat, and one outside called outdoor discharging heat to surroundings. Both units are connected by a copper tube and electric cable.

Equipment	Description
Chiller 	A chiller uses to cool the water for industrial processes such as machine cooling or for air conditioning in a central air conditioning system. It disperses heat by using water-cooling tower or air-cooled exchanger.
Air Handling Unit (AHU) 	AHU is used to supply cooling air by exchanging heat load from air space to cooled water from chiller. Air quality controlled by the mixing between fresh air from outdoor infiltration and room return air.
Cooling Tower 	A cooling tower is used to cool water by dissipating heat from evaporating spray water through surrounding air. It is a component of a water-cooled refrigeration system used in industrial processes and air conditioning systems.

3. ENERGY CONSUMPTION MODEL

Utility equipment refers to machines which provide any environmental facilities support to the primary machines in a main production process including air compressors, air conditioners and chillers etc. In general, these machines operate in three modes. First, load cycling and unloading: The electrical load fluctuates between loaded and unloaded states such as screw-type air compressors. Loaded state consumes higher electrical power depending on pressure level but unloaded state set for oil cooling with lower power consume. Second, load cycling and off-loading: The electrical load cycles between loaded and off states. Piston-type air compressors are a typical example. Lastly, on-loading: The machine operates continuously loaded state while simultaneously operates with the primary machine cycles between loaded, unloaded, or off states. It could be a constant load following particular revolution or variable load following frequency controlled by inverter. Example machines on this mode include fan coil of air conditioners, cooling fan in chillers, and cooling towers.

Power and Energy in Utility Equipment

The electric power supplied to a machine is determined by the amount of electric current flowing through it. Thus, for a machine connected to a circuit with a fixed voltage, the electric power can vary depending on the current flowing through the machine. It could be constant or variable depending on load demand. Accordingly, electrical energy is the electrical power consumed over a period measuring in watt-hours (Wh) or kilowatt-hours (kWh). Once the power consumption of an electrical appliance is known, the electrical energy consumed by the appliance can be calculated as following equation.

$$E = \int_{t_0}^{t} P(t)dt \qquad (1)$$

where P is electric power (kW) and time is a period of operating in hours(h) then electrical energy (E) derived as kWh called a unit of electricity.

In manufacturing, there are several equipment with different characteristics operation. Total energy consumption is difficult to calculate in the mathematics model. It is generally collected by metering devices such as power meter or kilo-watt hour meter. To determine the energy consumption, the area under the fluctuation in power collected data can be determined, which is equivalent to the product of the average power (Pa) and the average operating time of the equipment (ta) as in Figure 1.

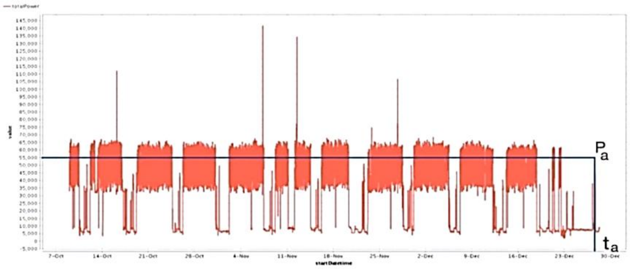


Fig.1. Equivalent energy from collected data and mathematics model

This paper aims to simplify the energy consumption model in utility equipment which usually operates all the time of manufacture from starting up to shutting down. Equipment operation characteristics were classified into three types including 2a) continuous on-loading, 2b) interchange between on-loading to off-loading state and, 2c) interchange between on-loading to unloading-state and 2d) variable load follows demand using inverter-controlled equipment as shown in figure 2.

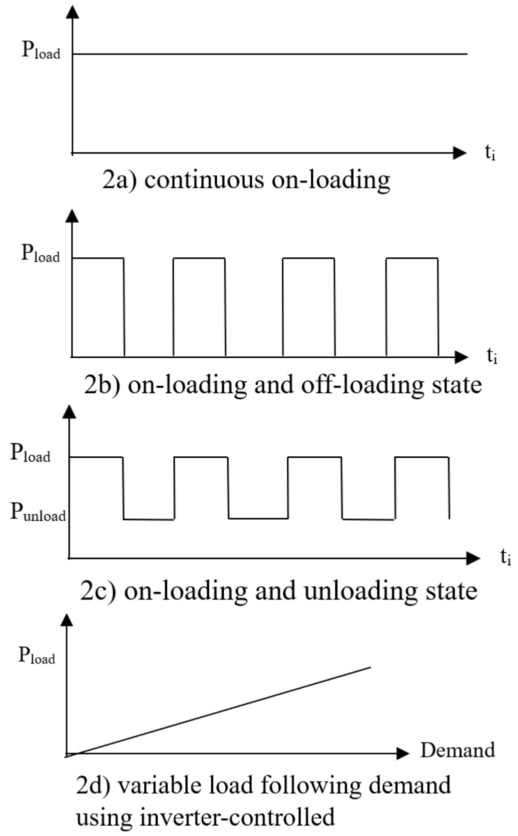


Fig.2. Characteristics operation of utility equipment

Load Factor of Power (LF_P) and Load Factor of Time (LF_T) are defined. LF_P presents an average ratio of load demand to full load, while LF_T presents an average ratio of time operation or percentage of operation time. The energy consumption model of utility equipment (E_t) could be developed as following;

$$E_t = \sum_{i=1}^{n} \left(P_i \times LF_{P,i} \right) \times \left(t_i \times LF_{T,i} \right) \qquad (2)$$

where, E_t is total energy consumption, P_i is power rating of equipment i (i is a number of utility machine used in manufacturing), t_i is total operation time,

$LF_{P,i}$ = average load demand / full load and,
$LF_{T,i}$ = period on load state / total time.

The model shows average power of each equipment ($P_{a,i}$) as the power rating (P_i) and $LF_{P,i}$, while average operating time ($t_{a,i}$) as the total operating time (t_i) and $LF_{T,i}$.

Specific Energy Consumption

Specific Energy Consumption (SEC) is an index that measures the amount of energy consumed per unit of production. It is used to monitor and improve industrial energy efficiency. Therefore, controlling a plant's SEC is one of the most effective ways to manage energy conservation [3-5]. SEC can be determined by dividing the plant's energy consumption during a specific period, usually a month, by the production output for that period as shown in equation 3.

$$SEC = \frac{E_t}{Q} \qquad (3)$$

where, Q is an amount of production. The unit of SEC could be present as electricity per unit as kWh/weight or heating energy per unit as MJ/weight depending on characteristics of a finishing product. This index is extremely useful for monitoring and controlling energy consumption. It also reflects the historical energy efficiency trends, indicating whether there has been improvement or decline. Furthermore, this index can be benchmarked against industry standards (SEC Benchmarking) to assess a plant's relative energy performance. If the production quantity increases, the energy consumption per unit of production will decrease, resulting in a lower SEC. In other words, the lower SEC means better energy efficiency. In this situation, the machines will operate continuously, reducing losses from idle time. SEC are plotted against the monthly production quantity showing a linear relationship as in Figure 3. However, for utility equipment, the energy consumption behavior may differ from that of the main product.

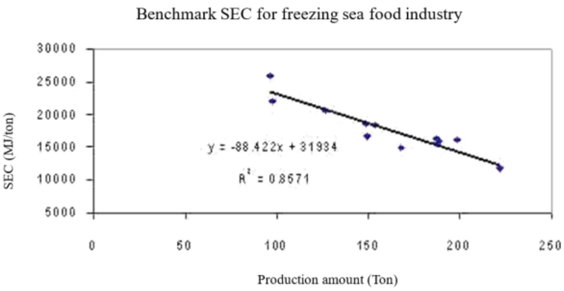


Fig.3. Linearity trend between variable amounts of main production and SEC [2]

SEC Model for Utility Equipment

Previously section, the SEC model could develop using linear regression. However, SEC of utility equipment shows exponential trends following the demand load. By rearranging the equation using logarithms or linear regression, load demand (Qi) is an independent variable, SECi as a dependent variable and a, b for regression constants. Load demand could be formulated using $LF_{P,i}$ as a percentage of production at full load (Q_{FL}) as following;

$$Q_i = LF_{P,i} \times Q_{FL} \qquad (4)$$

Linear regression presents by $SEC_i = a + b \times Q_i + \varepsilon$, while transformed logarithms could be shown as $SEC_i = b \times Q_i^a + \varepsilon$,using for utility equipment i.

4. RESULT AND DISCUSSION

Air Compressor

In general, there are two types of air compressors with different modes of operation in manufacturing. A reciprocating type operates between on-loading and off-loading state ,while a screw type operates on-loading and unloading state which depending on cut-in and cut-off pressure switch. From commercial specification with multiple sizing as shown in Table 2, power and air delivery with variable load demand ranging 10% to 100% of full loading could be determined as in equation (2) and (4). The result of flow rate as demand and SEC is shown in figure 4a) for screw type and 4b) for reciprocating type.

Table 2 general commercial air compressor specifications

Air compressor	Reciprocating type			Screw type				
	10HP	15HP	30HP	10HP	15HP	30HP	50HP	75HP
Power rating (kW)	7	11	22	7.5	11	22	37	55
Max pressure (bar)	8	10	10	12.5	12.5	12.5	12.5	12.5
Air delivery (m^3/min)	0.81	1.23	3.81	0.81	1.23	2.8	4.6	7.3

Figure 4a) illustrate the relationship between air delivery rate and SEC of a 30HP screw air compressor. The air delivery rate increases, the SEC decreases. Machine efficiency improves when it operates at full load. However, when machines operate at lower delivery air than at rated capacity, the SEC is significantly higher. This is because the machine reaches its rated air delivery at full load, but switches to unloaded condition while lower air delivery. SEC is higher with the longer the unloaded period, the more energy losses as there is no air being produced, known as idle loss or standby loss.

Figure 4b) shows the constant SEC with different air delivery rate and SEC of a 30HP reciprocating air compressor. There is no electrical energy consumption when there is no compressed air production meaning no idle loss. The operation of this type is at full efficiency when it produces compressed air at its rated capacity, then it stops operating without consuming any electrical energy.

When comparing the SEC for air compressors ranging from 10HP to 75HP, it was found that all screw-type compressors showed a decreasing trend in the index as the delivery air increased, as shown in Figure 5. From this model, it is not advisable to use an oversized air compressor for lower air demand. This leads to excessive energy consumption. With the similar air delivery demand such as 5 m^3/min, the larger rating of 75HP compressor will consume more energy than a 50HP compressor.

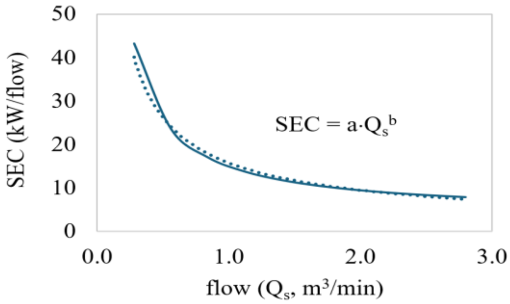


Fig.4a. SEC characteristics of Screw-type Air Compressor

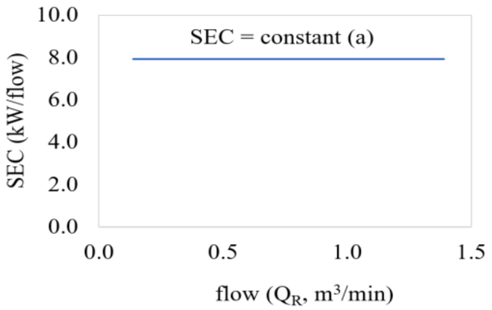


Fig.4b. SEC characteristics of Reciprocating-type Air Compressor

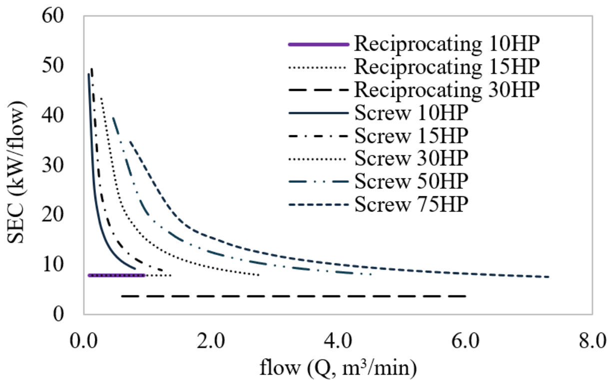


Fig.5. SEC of air compressors ranging from 10HP to 75HP

Air Conditioners

Split type air conditioners consume energy in two main components: the condenser or outdoor unit and the evaporator or indoor unit. Table 3 shows specific data for air conditioners at various capacities used for calculating power and energy with different cooling loads. Outdoor unit operates between on-loading and off-loading state depending on set-up temperature, while indoor unit always operates on-loading state.

Table 3 general commercial split-type air conditioner specifications

type	Split-type		Air cooled - Central Unit	
Cooling Capacity Max	12,100	36,000	100,000	120,000
Power Consumption (W)	1500	4870	9,562	11,934
Indoor Power consumption (W)	260	670	752	470 x 2
Outdoor Power consumption (W)	1240	4200	8810	10940
Efficiency COP	2.86	2.52	3.06	3.28
Efficiency EER	9.76	8.57	10.46	10.52
Power Supply	220V/1p/50Hz		380V/3p/50Hz	
Refrigerant	R-32		R410a	

Figure 6a) illustrates the relationship between cooling load and SEC of air conditioners. When the cooling load increases, SEC decreases. Machine efficiency improves when it operates at full load. However, when the cooling production is lower than rated capacity, the SEC is higher. This is because there is a higher proportion of energy consumed during the unloaded period, which is a time when there is no cooling, resulting in wasted energy without producing any cool air. This is referred to as idle loss or standby loss. It is not advisable to use a larger capacity for a smaller cooling demand. This leads to excessive energy consumption. For instance, an implementation of a larger sizing air conditioner in a small room will frequently cycle on and off, resulting in a higher SEC due to increased losses. On the other hand, it is not recommended to use multiple smaller air conditioners in a huge cooling load. Apart from a higher SEC, it also increases the maintenance costs.

Chiller

Chiller consumes energy in three main components: the compressor, AHU and cooling tower. Table 4 shows specific data for chillers at various capacities used for calculating power and energy with different cooling loads. Compressor operates on-loading and unloading state which depends on the water temperature setting point. AHU and cooling tower always operate continuously on-loading state.

Table 4 general commercial water-cooled chiller specifications

Cooling Capacity (RT / kW)	100 / 351.7	200 / 703.4	350 / 1231	1000 / 3517	1500 / 5275
COP	6.337	5.953	6.178	0.168	0.168
Air flow rate in evaporator (m^3/min)	15.12	30.23	52.91	168.1	252.1
Water flow rate in condenser (m3/h)	18.81	37.86	66.01	197.5	296
Input power (kW)	55.49	118.2	199.2	589.5	884.9
Refrigerant Charge (psi)	215	260	470	949	949
Compressor type	centrifugal				
Refrigerants type	HFC-134a				

The chiller operates with the supporting equipment including compressor, cooling tower and AHU. Figure 6b) shows the relationship between cooling load and SEC of chiller. The SEC decreases as the cooling load increases. The spike at 100 RT is the activation of a second AHU to support the increased cooling load of the chiller which is higher than one AHU load.

Figure 7 shows SEC comparison of chillers ranging from 100 to 1,500 RT. It shows the decreasing SEC when increasing the cooling load. When the chiller closely operates to rated capacity, resulting in a lower SEC or higher efficiency. Therefore, it is not advisable to use multiple smaller chillers for a huge cooling load. This is because a smaller size chiller not only results in a lower SEC but also higher maintenance costs. The spike in SEC line is the activation of the other AHUs to support the increased cooling load.

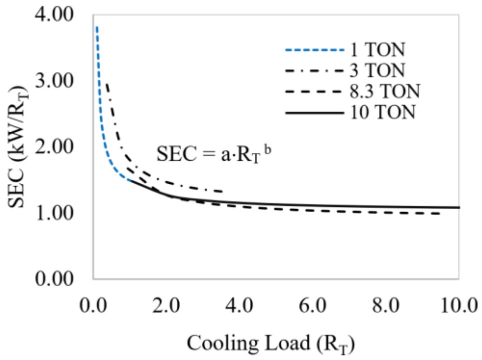


Fig.6a. SEC of air Conditioners ranging from 1 to 10 Ton-

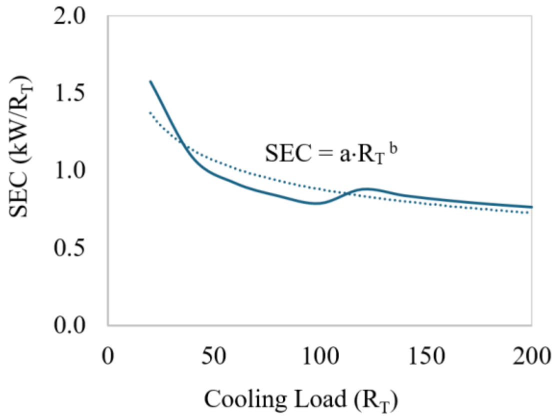


Fig.6b. SEC of Chiller 200 Ton-RT cooling capacity

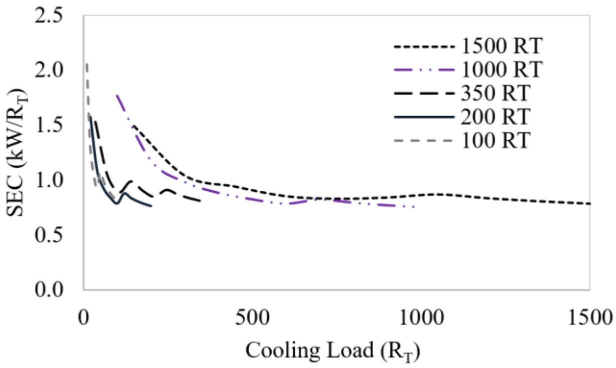


Fig.7. SEC characteristics of Chiller ranging from 100 to 1500 Ton-RT cooling capacity

5. CONCLUSION

This paper developed mathematical models to estimate electrical energy consumption in the utility equipment based on productivity index called a specific energy consumption (SEC) including air compressors, air conditioner and chiller. Technical data of the machines were collected, including electrical power, load capacity, or output, such as compressed air volume and heat load. By calculating the average electrical power at different load levels and comparing it to the machine's output, SEC was derived. Then, SEC referred to the ratio of energy consumption per unit of supply service. The estimated model developed by using regression analysis to predict energy consumption for the other operational states of requirement. The study found that for all types of utility equipment, SEC decreased as the load increased. This is because of the reduced energy losses and decreased unload state at higher load demand.

These models can be used as a simple tool for selecting the most suitable machine for a specific application. By comparing the SEC of machines with various capacity ratings, the trend of decreasing electrical power consumption per unit of demand can be observed. This allows for a clear comparison between small and large-sized machines. It is found that larger machines tend to have a better reduction in the SEC compared to smaller ones when operating at their rated capacity. However, using a large machine for a low load application would be inefficient in terms of energy consumption. Conversely, using a large machine that is well-suited to the load is more efficient than using multiple smaller machines. The model provides a low level of accuracy because the calculations are based on the maximum load specifications. In practical operation, machines do not always operate at full capacity, and their electrical power consumption is not constant. To improve accuracy, it is necessary to measure the actual electrical energy consumption of the machine during operation, covering the entire process from start-up, partial to full load operation till shut down.

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