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ARTICLE

Energy Consumption Analysis and Characterization of Aerospace Manufacturing Facilities in the United States–A Step towards Sustainable Development

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ABSTRACT

In this study, information on energy usage in the United States (U.S.) aerospace manufacturing sector has been analyzed and then represented as energy intensities (kWh/m^2) to establish benchmark data and to compare facilities of varying sizes. First, public sources were identified and the data from these previously published sources were aggregated to determine the energy usage of aerospace manufacturing facilities within the U.S. From this dataset, a sample of 28 buildings were selected and the energy intensity for each building was estimated from the data. Next, as a part of this study the energy data for three additional aerospace manufacturing facilities in the U.S. were collected firsthand. That data was analyzed and the energy intensity (kWh/m^2) for each facility was calculated and then compared with the energy intensities of the 28 buildings from the sample. Three different indicators of energy consumption in aerospace manufacturing facilities were used as comparators to assist facility managers with determining potential energy savings and help in the decision-making process. On average, aerospace manufacturing facilities in the United States spent 4 cents for each dollar of sale on energy. The energy intensity (kWh/m^2) and the power intensity (W/m^2) for each facility were calculated based on the actual facility energy bills. The power intensity for these facilities ranges from 34 to 134 W/m^2. The energy intensity ranged from 232 to 949 kWh/m^2. We found that the power intensity could be used to estimate energy consumption when the annual operating hours of the facility are considered. and to estimate the energy-related carbon dioxide emissions.

KEYWORDS

Aerospace facilities energy consumption; life cycle information in aerospace manufacturing buildings; sustainable manufacturing buildings

1 Introduction

As shown in Fig. 1, the U.S. industrial sector uses more energy than either the commercial or residential sectors. The industrial sector consumed more than 32,709 trillion Btu (9.59 trillion kWh) in 2018 and 32,556 trillion Btu (9.54 trillion kWh) in 2019. This is equivalent to more than 32% of the total U.S. energy consumption (EIA, 2019). As with the other sectors, there has been significant and relatively consistent growth in the energy consumed in the U.S. industrial sector last 70 years as shown in Fig. 1.

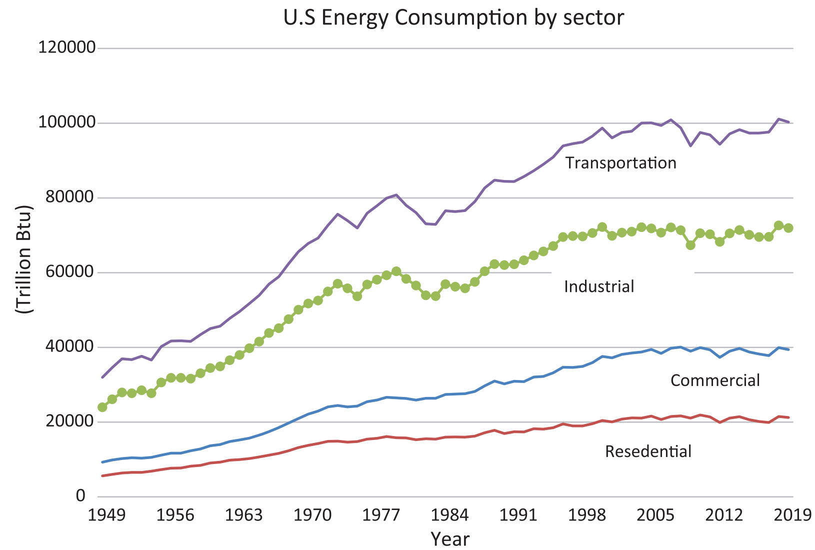

Figure 1: U.S. energy consumption by end sector [1]

Buildings are one of the major contributors to climate change and account for more than one third of global energy consumption and responsible for one fourth of CO_2 emissions [2]. Because of the enormity of this usage, energy is one of the most significant considerations when analyzing and looking for potential savings in the industrial sector. According to the annual energy outlook report for the year 2020, the manufacturing sector is responsible for more than 77% of the U.S. industrial energy sector consumption, as shown in Fig. 2 [3].

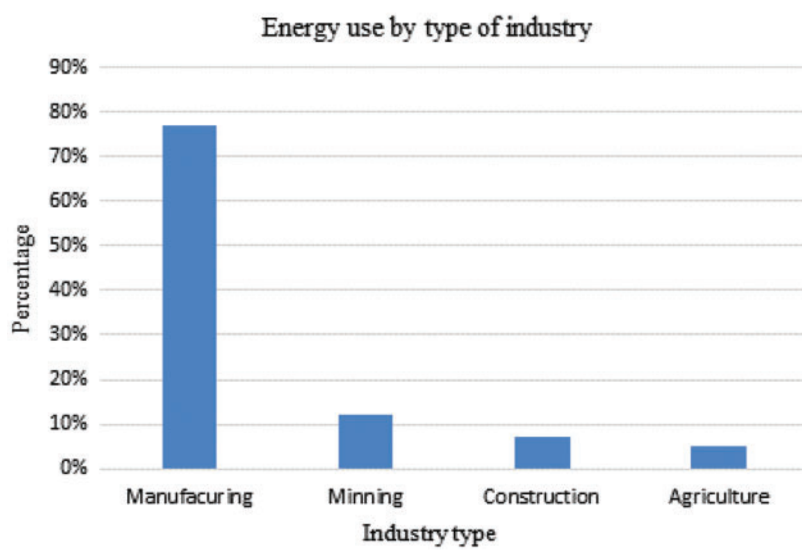

Figure 2: U.S. energy use by industry [3]

In this research, a focus was placed on the energy consumption within aerospace manufacturing. This is an important area and while there are examples of energy intensity quantification for commercial and government sectors Bawaneh et al. [4] and Esmaeili et al. [5–7] little literature has been found on it relating to energy consumption of the entire manufacturing facility. article about the energy intensity of computer manufacturing [8], study of the impact of automation on manufacturing energy intensity [9]. Publication about the energy intensity changes in Indian manufacturing sector [10], and the suggested approach for energy and carbon intensity quantifications by Gutowski [11] are all examples in the literature that highlight the need for and importance of the energy intensity analysis for each specific type of manufacturing facilities. However, based on the conducted literature review by authors, most of the studies have focused on comparing energy consumption for different materials and the amount of energy per unit of production volume. For example, Sihag et al. [12] provided a methodology to estimate that the energy demand of the HVAC for machining 1 kg of aluminum was 11.86 kWh/kg. Sihag et al. [12] and Huang et al. [13] quantified energy intensity of additive manufacturing processes to be used in aerospace facilities, Cooper et al. [14] focused on energy requirement of five metal forming processes. Furthermore, an analysis of the energy required for manufacturing processes for sheet metal used in the aerospace industry conducted by Rossie shows that forming titanium requires 337 kWh/part and for aluminum 156 kWh/part [15]. This research attempts to specifically look at aerospace manufacturing while broadly viewing the data for the facilities as whole. An analysis was made to estimate the industrial facility non process energy using the utility bills and/or production rate. The results of this analysis indicated that non process energy ranges from 7 to 26 kWh/ft^2 [16].

According to the National Association of Manufacturers, around 93% of the U.S. manufacturing companies believe that high energy prices have negative financial effects on their businesses. Therefore, it is important to reduce and control energy consumption to be able to minimize its negative impacts on these businesses [17]. The United States Aerospace Industries Association reported that aerospace and defense are responsible for $909 billion in sales in 2019 and contributed more than 1.8% of the U.S. GDP in 2018 [18]. The annual revenue and market capitalization for the top U.S. aerospace/aviation companies and manufacturers are shown in Table 1 [18].

Table 1: Top U.S. aerospace manufacturers

Company	Annual revenue ($Millions)	Market capitalization ($Billions)
Boeing	93392	193.96
United Technologies	59837	99.94
Lockheed Martin	51048	85.5
Honeywell International, Inc.	40534	108.26
General Dynamics Corporation	30973	56.34
Northrop Grumman	25803	53.86
Raytheon	25348	56.02
BAE Systems	21248	26.66
Safran	19159	64.69
Bombardier	16199	2.29

The United States Census Bureau reported that in 2018, aerospace products, aerospace parts, and defense manufacturers spent more than 1.4 billion dollars on electricity and fuels. The aerospace industries spend a disproportion amount on electricity and fuel when comparisons are made to other industries [19]. According to the Energy Information Administration, the total energy consumed by the aerospace parts industries in the United States in 2018 was estimated to be 20 billion kWh. This is more than double the energy consumed by the automobile industry. This data and the energy consumption for other similar sectors are shown in Table 2 with their NAICS codes.

Table 2: Annual energy consumption for different industrial sectors [20]

NAICS code	Subsector and industry	Total (Billion kWh)
336111	Automobiles	99.7
336112	Light trucks	1111.4
3364	Aerospace parts	2020.2
336411	Aircraft	66.7

According to the EPA report, which was released in the year 2018, energy-related carbon dioxide emissions account for 84 percent of the total emissions in the United States. The industrial sector consumes nearly 33% of the annual energy usage in the United States [20]. Because of the high cost of energy, facility managers need to look for more efficient ways to use energy and take care of environmental requirements [21]. Studying the characterization of the energy usage within aerospace manufacturing facilities will allow us to determine the potential for reductions in energy usage and allow us to look for effective ways to manage energy and reduce the environmental impacts of aerospace manufacturing. The main objective of this study is to collect and analyze the publicly available data in the literature related to aerospace manufacturing facilities and estimate their energy intensity per building. Additionally, energy data for three aerospace manufacturing facilities in the United States were collected firsthand as a part of this research and analyzed. The energy intensities for these buildings were calculated and compared with those from the publicly available data to determine possible improvements and to evaluate the environmental impacts for aerospace manufacturing facilities energy.

2 Methodology

The main objective of this study is to analyze energy use in aerospace manufacturing facilities using published data from the literature and government reports. In addition to the published data, the energy data for three aerospace manufacturing facilities in the U.S. were collected firsthand and analyzed. The energy intensity is defined in this research, as the power consumed in kWh per square meter (kWh/m^2) of the building's footprint. To understand and analyze the energy consumption in aerospace manufacturing facilities, the following approach was followed:

1. Published information on energy usage for aerospace parts manufacturing facilities has been analyzed and compiled.

2. The energy intensity for each manufacturing building was estimated based on the annual energy consumption, the square footage for each facility, and the operating hours.

$$\text{The Energy intensity} = \frac{\text{Annual Energy Consumption}}{\text{Total Facility Area}} \tag{1}$$

3. The energy data on utility bills, operating hours, and building area for three aerospace facilities in the U.S. were collected and analyzed.

4. The energy intensity for each of these three facilities was calculated using the actual annual energy consumption and summarized to allow for comparison of trends.

3 Results

Presented in this section are individual results for three different aerospace facilities in the United States followed by data from a sample of other facilities.

3.1 Facility 1

The facility produces metal formed aerospace parts in the Midwest. The energy data for this facility was collected. The total area of the facility was estimated to be around 4293.047 m^2. While this data was collected, the facility was operating at only one 8-h shift per day. As shown in Table 3, the monthly energy consumption for the case 1 facility ranges from 63,400 kWh in November to 144,365 kWh in January. The monthly energy consumption is affected by the weather and the production rate of the facility.

Table 3: Monthly energy consumption for case 1

Month	Total energy(kWh)	Total energy(MJ)
January	144,365	519,714
February	136,290	490,644
March	102,710	369,756
April	105,404	379,454
May	144,260	519,335
June	141,260	508,535
July	131,620	473,831
August	130,860	471,095
September	106,300	382,679
October	121,540	437,543
November	63,400	228,239
December	122,685	441,666
Total	1,450,692	5,222,491

To analyze and understand the energy characteristics for this aerospace facility, the utility bills, operating hours, and building information were collected from the facility. Then the energy intensity was calculated. The annual energy consumption for this facility, based on the utility bills, was provided in kWh and it is equal to 1,450,692 kWh (5,222,484 MJ). The energy intensity is the total energy (in kWh or MJ) divided by the facility area (in square foot or square meter). We have used a unit of kWh/m^2 for energy intensity and found the value for this facility to be 337 kWh/m^2.

3.2 Facility 2

The facility produces metal formed aerospace parts and it is located in the Midwest area of the United States. The total area of the facility was estimated to be 10,172 m^2. The data were collected while the facility was running three 8-h shifts per day. To analyze and understand the energy usage for this facility, the utility bills, and building information were collected from the facility. Then the energy intensity was calculated. The energy consumption for 12 months for this facility, based on the utility bills, was equal to 5356311.38 kWh. The energy intensity was found to be equal to 526 kWh/m^2.

3.3 Facility 3

The facility which located in the Midwest and produces metal formed aerospace parts. The total area of the facility was 5520 m^2. The annual energy consumption for this facility, based on the utility bills, was equal to 3,424,488.88 kWh. The monthly energy consumption for the facility ranges from 878,086 MJ in April to 1,260,979 MJ in December. The energy intensity was estimated to be equal to 620 kWh/m^2.

3.4 Data from Other Sources

In the 2006, the U.S. Department of Energy initiated the Industrial Assessment Center (IAC). The IAC has centers in different areas of the United States to implement industrial energy assessments. Each center implements energy assessments and investigate potential energy savings and find most effective ways to improve energy efficiency such as energy waste minimization and other improvements. The energy assessments include the SIC number, all energy consumption information, annual production rate, facility information and recommendations for savings after changes. To analyze and understand the energy consumption for these facilities, the building and energy information were collected from these IAC reports. Then the energy intensity was calculated. The annual energy consumption for 28 aerospace facilities was collected and analyzed based on the information published on the IAC website. As an example, the Oklahoma State University Industrial Assessment Center conducted an assessment for an aerospace facility in Kansas in 2021 and a sample of the facility information is shown in Table 4 [22].

Table 4: Aerospace energy assessment sample

IAC Center	Oklahoma State University
Assessment year	2021
SIC	3728
Principal product	Aircraft parts
Sales	\$1,000,000–\$5,000,000
Plant area (m^2)	9847.718 106,000
Production hrs. annual	2,860
Annual energy (kWh)	1,926,024 (6,933,686 MJ)

The energy intensity was calculated as follows:

For this example:

$$Energy\ intensity = \frac{1{,}926{,}024}{9{,}848} = 196\, kWh/m^2$$

The energy intensity was calculated using the same method for the 27 other aerospace facilities shown in Table 5.

Table 5: Aerospace facilities sales and annual energy consumption [22]

SIC.	Annual sales	Area, mm^2	Products	Operating hours	Annual energy total, kWh	Energy intensity, kWh/m^2	Power intensity, W/m^2
3728		9,848	Other aircraft parts and auxiliary equipment manufacturing	2,860	1,926,024	196	68.384
3728	$23,000,000	6,880	Aircraft galleys	8,760	2,554,220	371	42.378
3724	–	37,161	Aircraft engines-service & parts	8,760	14,873,090	400	45.688
3728	–	18,581	Other aircraft parts and auxiliary equipment manufacturing	8,760	1,751,120	949	10.758
3728	$10,000,000	13,378	Aircraft servicing	8,736	6,345,580	474	54.295
3728		33,097	Aircraft manufacturing	8,760	10,078,080	305	34.760
3724		67,355	Aircraft engines & parts (rebuild & repair)	8,760	32,202,335	478	54.577
3359	$15,000,000	6,957	Aircraft and airport lighting systems	4,680	1,783,260	256	54.773
3463	$7,000,000	13,935	Aircraft and missile components	4,160	3,226,529	232	55.657
3728	$15,000,000	5,481	Aerospace and land-based turbines	5,200	1,719,937	314	60.343
3728	$50,000,000	22,297	Aerospace products	6,000	8,622,000	387	64.448
3599	$24,000,000	7,990	Aircraft parts	6,552	3,695,740	463	70.599
3452	$25,000,000	7,1541	Aerospace fasteners	5,087	2,691,274	376	73.956
3724	$12,000,000	5,201	Aircraft components	4,400	1,947,949	375	85.126
3728	–	9,290	Aircraft parts	2,535	2,057,280	221	87.354
3647	$15,000,000	13,935	Aircraft lighting systems	2,210	2,730,047	196	88.645
3724	$10,000,000	4,225	Aircraft engine parts remanufacturing	4,250	1,648,320	390	91.791
3728	$12,000,000	13,935	Aerospace structural components	4,732	6,054,589	434	91.816
3728	$38,000,000	10,034	Aircraft landing gear repair and re-manufacture	5,824	5,905,558	589	101.061
3728	$30,000,000	9,290	Aircraft parts	7,296	7,902,015	851	116.579
3645	$15,000,000	41,806	Lighting fixtures	3,000	16,235,731	388	129.451
2531	$33,000,000	9,941	Aircraft seat manufacturing	3,536	4,724,596	475	134.412
SIC	**Annual sales**	**Area, ft^2**	**Products**	**Operating hours**	**Annual energy total, kWh**	**Energy intensity, kWh/m^2**	**Power intensity, W/m^2**
3728	$17,000,000	14585	Aircraft Propellers and Drive Systems	4,312	8,536,116	585.2358	135.722
		17744					
3585	$30,000,000	6317	Aircraft Components	5,148	5,252,912	831.4985	161.518
3728	$78,000,000	35303	Aircraft Flooring, Aircraft Ducting	4,000	23,999,834	679.8215	169.955
3728	–	3716	Aircraft Components	2,340	1,433,762	385.8223	164.881
3728	–	32516	Aerospace Metal Processing and Plating	6,240	3,773,600	116.0535	18.598

4 Discussion of Results

To get a better understanding of the energy consumption and to compare the case studies energy consumptions with the literature on aerospace facilities energy consumptions, a Boxplot of the energy and power intensities was created. As shown in Fig. 3, the energy intensity ranges from 399 to 851 kWh/m^2 with a median equal to 381 kWh/m^2. The energy intensity for the case 1 facility was estimated to be equal to 337 kWh/m^2, which is below average. Therefore, we would be using this message does not expect significant energy savings from this facility. Meanwhile, the case 3 facility had an energy intensity of 620 kWh/m^2, which is above the average for other similar facilities. Based on this result, a major energy assessment should be conducted to investigate the energy consumption for potential savings.

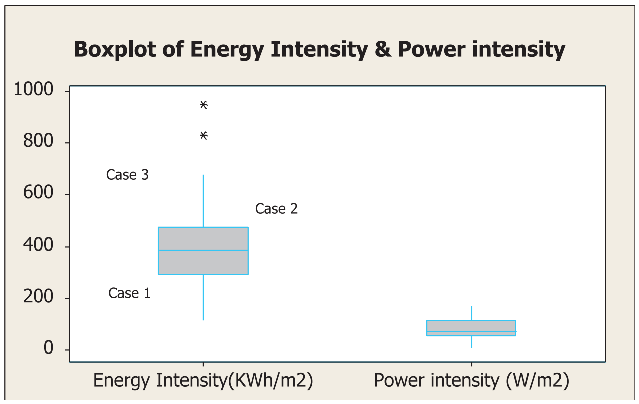

Figure 3: Boxplot of aerospace facilities energy & power intensities

The energy intensity (kWh/m^2) indicator reflects the actual annual energy consumption for a manufacturing facility which can be used to compare the energy consumption for different facilities with the same operating hours. Comparing the energy consumption for facilities with different operating hours requires another indicator that consider the operating hours. To get a better understanding of the energy usage, another comparison indicator can be used such as the power intensity (W/m^2) that has the operating hours considered in the calculations. The power intensity can be calculated as follows:

$$Power\ intensity = \frac{Annual\ energy\ consumption}{plant\ area} \div Operating\ hours \tag{2}$$

$$Power\ intensity\ \ (case\ 1) = \frac{1{,}450{,}692\, kWh}{4293\, m^2} \div 2340\ h = 144\ Watts/m^2$$

$$Power\ intensity\ \ (case\ 2) = \frac{5356311\, kWh}{1017\, m^2} \div 6480\ h = 81\ Watts/m^2$$

$$Power\ intensity\ \ (case\ 3) = \frac{3424488\, kWh}{5520\, m^2} \div 4270\ h = 145\ Watts/m^2$$

As shown in Fig. 4, the power intensity ranges from 11 to 134 W/m^2 with the median equal to 129 W/m^2. The power intensity for case 3 was estimated to be equal to 13.5 Watts/ft^2 which is above the average of the power intensity for the sample.

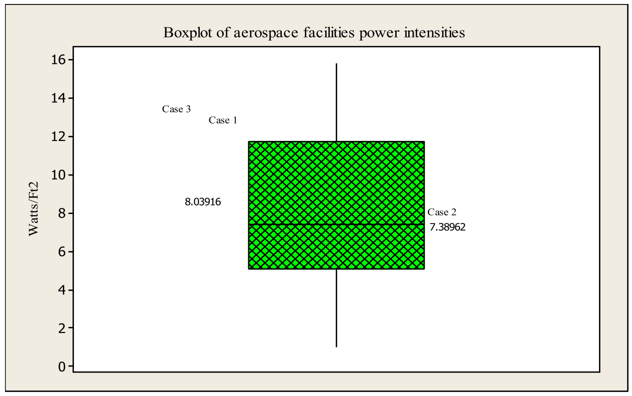

Figure 4: Boxplot of power intensities for 3 case studies

Another indicator that relates the annual sales to the kWh consumed can be used to compare the cost of energy for each facility with the annual sales. For example, a facility with $23,000,000 annual sales and 9,195,192 kWh annual energy consumption, the $/kWh can be calculated as follows:

$$Doolars\ per\ kWh = \frac{\$23{,}000{,}000}{9{,}195{,}192\, kWh} = 2.5\ \$/kWh$$

This means that for every kWh or energy used, this facility has $2.5 dollars in sales. If the price of 1 kWh is 20 cents, then for each one dollar of sale, this business spent 8 cents for energy. The amount of money spent on energy per dollar of sale were calculated for each facility. As shown in Fig. 5, the average $/kWh is equal to 4.9 while the median is 5.6 $/kWh. On average, the U.S. aerospace manufacturing business spends 4 cents for each dollar of sale on energy.

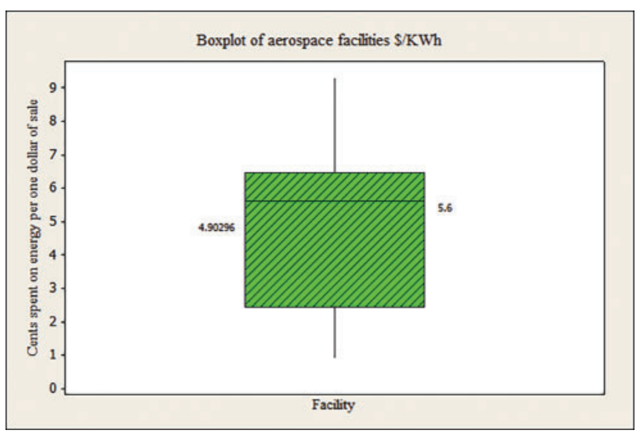

Figure 5: Boxplot of aerospace facilities $/kWh

Table 6: Summary of energy intensity and power intensity aerospace facilities

	Energy intensity, kWh/m^2	Power intensity, W/m^2
Average	465465	9595
Standard deviation	284284	4747
Median	389389	8888
Range	11891189	151151

5 Conclusions

Three aerospace manufacturing facilities were studied and the energy data for these facilities were collected. The energy intensity (kWh/m^2) and the power intensity (W/m^2) for each facility were calculated based on the actual facility energy bills. The power intensity for these facilities ranges from 80 kW/mm^2 for the case 2 facility to 145 W/mm^2 for the case 3 facility. It is concluded that the power intensity is a better estimate for energy consumption than the energy intensity since the annual operating hours are considered.

Two different estimated values were used to compare the energy consumption for aerospace manufacturing facilities, energy intensity and power intensity. The average, range, and standard deviation for the power and energy intensity are shown in Table 6. This result further contributes to the life cycle of products by using the power intensity.

This paper has provided a more complete review of the energy information for the aerospace manufacturing facilities in the United States. This result further contributes to the life cycle of aerospace manufacturing buildings and products by using the result for energy consumption for facilities per square foot or meter. These results can be used in life cycle studies of aerospace manufacturing facilities and products. In this study, three different indicators of energy consumption in aerospace manufacturing facilities were used as comparators. These comparators have been shown to be valuable in assisting facility managers to determine potential energy savings and to help in the decision-making process.

Data Availability Statement: The authors confirm that all data, models, and code generated or used during the study appear in the submitted article.

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