Projecting Power Converter Specific Power Through 2050 for Aerospace Applications

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***Abstract*- In order to analyze the potential fuel burn benefit from the electrification of aircraft powertrains, it is important to quantify the amount of weight that will be added to the aircraft for each additional component of the electric powertrain. This paper provides a projection of the specific power and efficiency of power converters, (AC-DC, DC-AC, or DC-DC), through the year 2050. Data was first collected on state of the art power converters in multiple application areas, creating a power converter database. Relevant specific powers were added to a set of historical data from 1976-2020, and then three different logistic curves were fit through the historical data to represent S-curve shaped growth through the year 2050. The three curves were differentiated by conservative, nominal, and aggressive assumptions for the year in which the logistic curve begins to bend down towards slower growth. With a 30% knockdown factor accounting for the additional weight required for a high altitude converter, projections range from the aggressive specific power projection of 52.9 kW/kg in 2050 to a much more conservative specific power of 12 kW/kg in which growth is limited due to certifiability concerns. Little historical data was found on converter efficiencies to project efficiency based on historical trends. Projections are based on expert opinion on yearly decreases in converter losses. 2050 projections range from 0.987 to 0.997.**

I. Introduction

Each push to reduce aviation carbon emissions has led to a research focus on the electrification of aircraft propulsion through hybrid, turboelectric, and fuel cell driven concepts. These concepts rely on power electronics such as DC-AC inverters and AC-DC rectifiers to convert between DC power at the battery or fuel cell and the 3-phase AC power required by the motor and DC-DC converters to step DC voltage up or down coming out of the battery or connecting subsystems to the high voltage bus. Electrical energy in the battery is converted to 3-phase AC current for the combined motor-generator. The motor adds power to the LPC shaft of the turbine engine to increase peak power capability and allow the core to be downsized to a more efficient size. The powertrain can also operate in the reverse direction where the generator draws power off the LPC shaft, and the power is converted from AC to DC power by the rectifier and used to recharge the battery.

To estimate the fuel burn benefits of the electrification of a baseline vehicle, it is vital to accurately estimate the amount of weight that would be added by including the electric powertrain. This can be done parametrically according to the power level of the electric powertrain by assuming an achievable specific power for each component. Efficiency is important in modeling thermal management because the losses would manifest as heat produced, and efficiency is also important because any losses in the powertrain need to be made up with extra battery capacity. The specific power and efficiency assumptions need to correspond to the specific power achievable at the time the aircraft is built, so specific power and efficiency need to be projected into the future to determine what is achievable at any year an electrified aircraft is put into service.

This paper will examine the specific power and efficiency of power converters. First, the paper will cover the performance of power converters that have been created in recent years. Next, the paper will examine possible avenues of improvement to raise specific power and efficiency in the future. Finally, historical data will be used to project progress in power converter specific power and efficiency through 2050.

II. Current State of Power Converters

A. Specific Power

The first step in the projection of the future specific power for power converters is to determine the current state of power converters. To do this, a database of power converters was built by searching for commercially available converters and university research converters. The AC-DC and DC-AC converters included in the data set can be split into 5 rough categories. 10 of the converters can be used for aerospace applications, mostly low power converters used as UAV motor controllers. Half are converters with automotive applications, either traction inverters or charging modules on electric vehicles. Most of the rest have industrial uses controlling motors that drive fans, pumps or other industrial machinery. Several of the industrial converters were advertised to be available for maritime applications as well. The remaining converters were either developed as part of university research projects or are reference inverters created by semiconductor companies for the purpose of demonstrating their switch technology.

The distribution of the specific powers of the converters in the database can be seen in Fig. 1. The mean specific powers by application can be seen in TABLE I. There is considerable variety both in between and within the different applications. Unsurprisingly, the industrial converters have the lowest specific power because weight is not nearly as much of an issue for a converter that does not move. On the other end of the spectrum, the switch evaluation inverters have a very high average specific power because first, they are demonstrating the use of the newest top end switches which previously were not available to other inverter manufacturers, but also because the inverters do not need any ruggedness to their design because they would not actually be used to run any motors. The aerospace, automotive, and research converters all have a similar average specific power. The design goals run in similar directions for all three. Weight is paramount for a converter installed on an aircraft. Volume is a secondary consideration because the converter will have to be installed in limited space on the aircraft. The priorities are reversed for automotive converters. Weight does not add to energy requirements as directly, so power density is generally tracked in automotive converters rather than specific power. However, as will be seen later, weight and volume are correlated with each other, so efforts to increase automotive converter power density also tend to increase specific power. The research inverters included in the database were aiming for improvements to aerospace and automotive applications and therefore shared the same goals of increased specific power and power density.

It is instructive to also examine the power levels of the inverters in the database. An electrified powertrain will have to combine a high specific power with enough total power to drive the motors, a number that can exceed 1 MW. A plot of specific power vs total power can be seen in Fig. 2. The vast majority of the power converters in the database are well below the megawatt range, and all but one of those that exceed 1 MW are industrial inverters that are on the bottom end of specific power. As such, projections using the non-industrial power converters in the database will be an extrapolation not just in time but in power as well because only one converter was found of the desired total power. However, the data in Fig. 2 is encouraging in that, excluding the industrial converters, there seems to be a positive correlation between power and specific power. This implies that a high target for specific power may be easier to achieve for a large power converter, although the trend could also simply be an artifact of the power converters included in the database.

In examining the numbers, it is important to note several things. First, most of the power converters are water cooled, but the weights cited are all dry weights. If cooling fluid is included in the weight calculation, the specific powers would decrease. Second, the converters included can be assumed to be designed for low altitude use. High specific powers are more difficult to achieve for power converters at an aircraft cruise altitude because the low air density at high altitudes reduces the dielectric strength of the air as an insulator between the electrical components and increases the clearance required to prevent arcing between components for the design voltage of the power converter. Air with reduced density is also not as effective at removing heat from the converter, so for an air-cooled converter, either more airflow

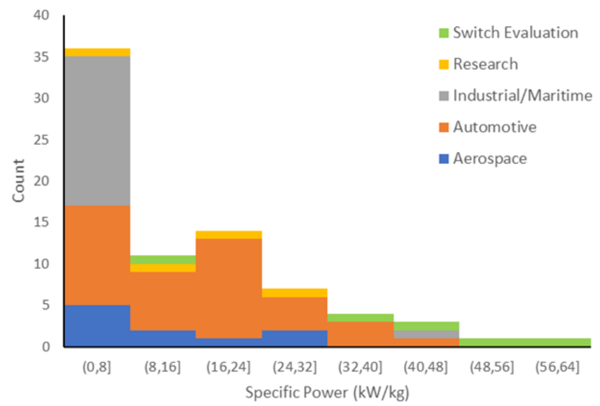

Fig. 1. Distribution of specific powers of the converters included in the database.

TABLE I
MEAN SPECIFIC POWERS FOR THE DIFFERENT APPLICATIONS

Application	Mean Specific Power (kW/kg)
Switch Evaluation	39.7
Research	15.9
Industrial/Maritime	4.3
Automotive	16.3
Aerospace	12.9

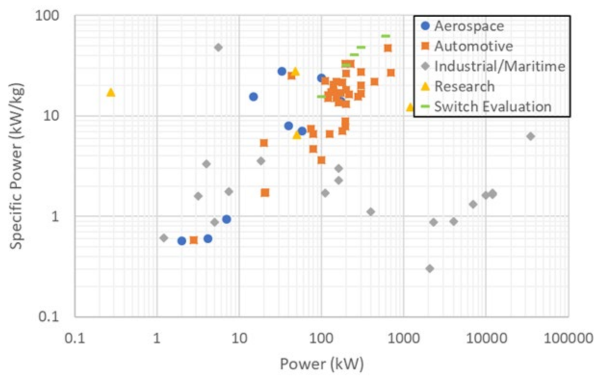

Fig. 2. Specific power vs maximum power of the power converters in the database.

or a larger heatsink is required. Finally, commercial aircraft regulations are more stringent than those that govern the other applications. Additional redundancy must be built into the system, adding weight. All of this combines to make it so that the data on the specific powers of the converters in the database cannot be directly used to project the specific power for a converter to be used on an electric aircraft. To account for the penalties incurred in the design of a high altitude, certifiable converter where cooling weight must also be considered, it will be necessary to include a knockdown factor on the projection acquired using the raw data.

The above data is all from AC-DC and DC-AC converters. Less data existed for DC-DC converters, but in general, the highest specific power DC-DC converters were in line with the typical AC-DC and DC-AC converters. Because the components and principles behind the different converter types are similar, DC-DC converters were folded into the AC-DC and DC-AC projections.

B. Efficiency

The efficiencies of the power converters were not reported as often as the specific powers. A few DC-AC and AC-DC power converters reported efficiencies around 99%, but the majority were 98% and below. The DC-DC converters topped out at 98%. 98% was chosen to be a high performing but achievable representation of the current state of power converter efficiency.

III. Potential Improvements

Improvements to power converter specific power will mostly come from three areas: switch material, thermal management, converter topology. The switches used in power converters have historically been made out of silicon, but it has long been known that changing to wide band gap semiconductors, silicon carbide (SiC) or gallium nitride (GaN), would be instrumental in increasing specific power and power density. There are two competing trends in power converter size with regard to switching frequency. In general, increasing switching frequency allows the passive components in the converter (capacitors, inductors, and resistors) to be smaller in size which has large impact on the total weight and volume of the converter. However, increasing switching frequency also tends to increase switching losses which hurts efficiency and requires more weight for thermal management. The wide band gap materials provide benefit because they have significantly lower losses at the same switching frequency as silicon or equivalently the same losses at a significantly higher frequency.[1][2]

Although the potential benefits from wide band gap materials have long been known and converters using SiC and GaN are already on the market, some converters continue to be made with the cheaper and more well understood silicon. Further improvements can be expected in the average specific power of power converters through a more widespread embrace of wide band gap materials. There still exists plenty of room for improvement for power converters with wide band gap materials, but long term it is possible that even more improvement will be achieved by using ultrawide band gap materials such as AlGaN or Ga2O3 to operate at even higher frequencies.[3][4][5][6]

Reaping the benefits of the new materials relies, at least in part, on improving the thermal management of the power converters. Reducing the size of the power converter makes the removal of heat more difficult with less area available to interact with the cooling medium. The ability to remove heat and keep the switches at an allowable temperature acts as constraint that limits the frequency at which the converter can operate. If thermal management is improved, more losses can be handled so frequency can be increased, decreasing the size of the power converter and increasing specific power. Suggestions for how to improve thermal management include improved power converter packaging possibly involving 3-D printing to improve heat sink geometry and cryogenic cooling for aircraft equipped with the capacity to do so.[1][2]

Finally, improvements to specific power could come from improvements to converter topology. For instance, a topology change that has led to improvements in converter design is the change from 1-level to multilevel converters. The signals from multiple switches are added together, better approximating a sine wave to provide a cleaner signal. The switches also see a smaller voltage step which reduces electromagnetic interference. The main weight impact occurs because the power is split between multiple switches, and lower power switches are cheaper, lighter, and give better performance than their equivalent power in a higher power switch. Further topology innovations could provide additional benefit in the future.[7][8][9]

IV. Performance Projections

A. Specific Power

Projections for future power converter specific power were made using historical data in addition to the data collected on recent power converters. The historical data is taken from a plot from a paper in 2008 that has data from 1976 all the way to projections up until 2020. The plot can be seen in Fig. 3. This paper is not considering AC-AC conversion, so the only data points from the plot that were used were the three 1-phase AC-DC points in the bottom left, the four 3-phase AC-DC points in the middle right, and the two DC-DC points between the others. The other troublesome part of the plot is that power density is tracked rather than specific power, reflecting the fact that aerospace applications are only recently beginning to become drivers in the development of power converters. Volume constraints have historically been more important for automotive and industrial applications and therefore historical data uses power density rather than specific power.

The sources from which the power density data was pulled did not also provide any weight information, so it was decided to use the converter database to find a relationship between specific power and power density so the plot could be approximately converted to specific power rather than power density. A plot in Fig. 4 of specific power vs power density for the converters in the database shows that they are reasonably well correlated with each other. The relationship is given by (1):

$$log(Specific\ Power) \approx 1.08 * \log(PowerDensity) - 0.091 \quad (1)$$

In addition to the data from Fig. 3, several points were included from the database. A few of the electric vehicles had year information as well as specific power, so the projection also included data points for the 2012 Nissan Leaf traction inverter and the mean specific power for six EV's from 2015-2016. A data point was added in 2021 for the average specific power of the aerospace power converters as well as one more for the rest of the automotive converters. The DC-DC converter database contained mostly converters with very low power and low specific power. The higher power DC-DC converters were more in line with the AC-DC and DC-AC converter specific powers and would be more relevant to the application in an electric powertrain, so also added to the data set used for the projections were the maximum DC-DC converter specific powers from three years in which more than a couple converters were found. The research, industrial, and switch evaluation power converters were not used in the projection because they are not as relevant to the final application. The specific power data used to generate the projections can be seen in Fig. 5. The DC-DC points and the AC-DC or DC-AC points line up well in Fig. 5, but it is important to keep in mind that the DC-DC converter points are maximums of the data set whereas several of the AC-DC and DC-AC points are means. Thus, the projections will necessarily be more aggressive for DC-DC converters than for AC-DC or DC-AC converters. However, there was insufficient data to project DC-DC specific power by itself, and since the principles behind the different types of converters are similar, it was considered that DC-DC specific power would likely fit into an overall power converter specific power trend.

As mentioned previously, it was decided to account for the additional weight required for a high-altitude converter by scaling all specific powers down using a knockdown factor. Ideally to get an estimate of what to set the knockdown factor as, pairs of converters with the same power rating would be compared where one of each pair was designed for high altitude use and the other was designed for sea level use. However, there is scarce data on high power, high altitude power converters, so no estimate was able to be formed this way. In the end, a 30% knockdown factor was chosen as a convenient value that caused the projections in Fig. 7 to line up with a set of goals and projections from a 2016 report [11]. Mathematically, there is no difference in applying the knockdown factor before or after fitting curves to the data, so since the final projections in Fig. 7 show the specific powers after applying the knockdown factor, Fig. 5 also includes the knockdown factor to be consistent. The raw specific powers can be determined Fig. 5 by dividing by 0.7.

The projections were performed by fitting curves to the data in Fig. 5. Logistic curves were used in the fit to give the projections an s-curve shape representing diminished yearly growth as the technology matures. The equation form used is:

$$Specific\ Power = \frac{L}{1 + e^{-k*(y-y0)}} \tag{2}$$

where L is an asymptotic specific power that is approached as time increases, k is a growth rate parameter that correlates to the slope of the curve at the inflection point of the curve, y is the year, and y_0 is the year of the inflection point of the curve where the specific power gains begin to slow. An illustration of a logistic curve with labeled parameters can be seen in Fig. 6.

To provide conservative, nominal, and aggressive projections, three different curves were fit with 2020, 2030,

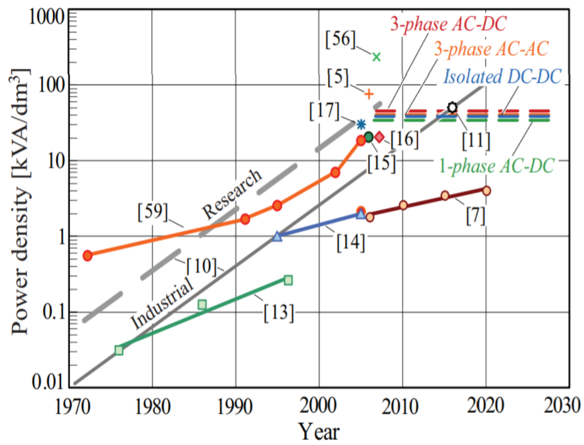

Fig. 3. Historical power converter power density data taken from [10]. Sources in the plot refer to the original paper.

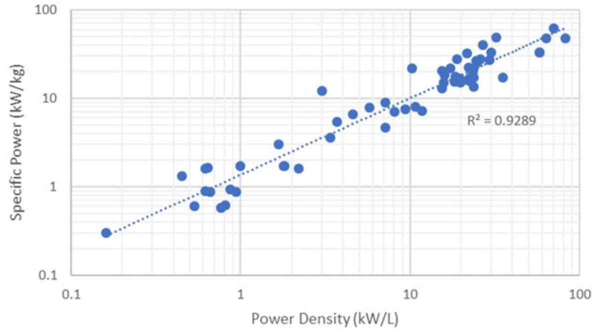

Fig. 4. Relationship between specific power and power density from the converter database [12-38].

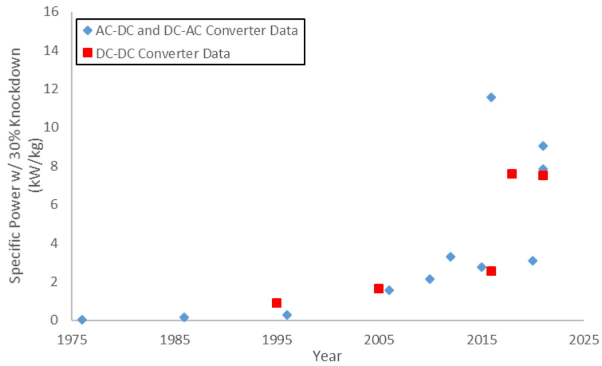

Fig. 5. Converter data used in specific power projections [12-38].

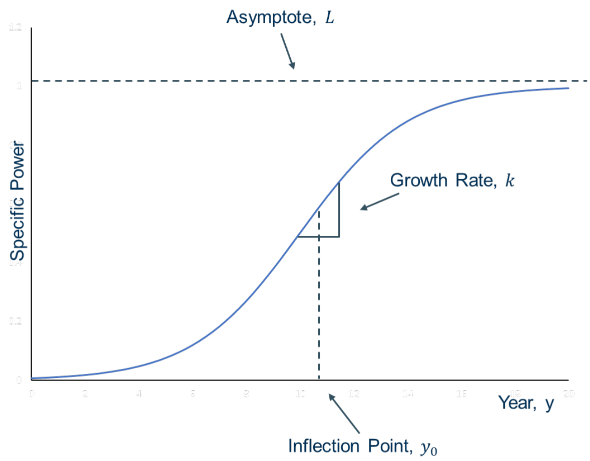

Fig. 6. Nominal logistic curve.

and 2040 inflection points which represent assumptions for the year in which growth begins to slow. The asymptote and growth rate parameters were then tuned while the inflection point parameter remained fixed with the goal of maximizing R2 calculated from the logarithms of the predicted and actual values. The projections can be found in Fig. 7. The parameters defining the logistic curves can be found in TABLE II.

The conservative scenario is mostly predicated on the difficulties of designing a converter for high altitude and for meeting strict certification standards with the assumption that growth achieved by sea level converters cannot be translated to the harsher operating conditions of commercial aviation. The nominal scenario is likely achievable without requiring major breakthroughs to be achieved, relying instead on a full shift to the use of wide band gap materials and improvements to thermal management and topology in order to take advantage of the higher switching frequencies available with the wide band gap materials. For the aggressive scenario to occur, there must not only be continuous improvements made to power converter thermal management and topology, but also further revolutionary improvements to the design including the possible introduction of new materials such as ultra-wide band gap materials to achieve the same jump in specific power allowed by the switch from silicon semiconductors to silicon carbide and gallium nitride. TABLE IV shows the final specific power projections through 2050.

B. *Efficiency*

With significantly less historical data on power converter efficiencies than specific powers, the process of fitting curves to historical data in order to project future performance was unavailable. Instead, a more naïve method was used of simply assuming a yearly rate of improvement, starting with a 2021 efficiency of 98% as defined as the currently achievable efficiency. A larger rate of improvement corresponds to a more aggressive projection whereas a smaller rate corresponds to a more conservative projection. Rates were set in consultation with NASA experts to achieve a reasonable range. The equation used in the projections is:

$$Efficiency = 1 - (1 - 0.98) * (1 - k)^{y-2021} \quad (3)$$

where the 0.98 is the 2021 efficiency, y is the year, and k is the yearly improvement rate. The way the equation is set up, the losses are reduced by k percent each year, so the equation asymptotes towards 1 over time. The efficiency projections can be seen in Fig. 8. The decay rate parameters for the projections can be seen in TABLE III.

C. *Final Projection Results*

TABLE IV shows the projections for specific power and efficiency in 2030, 2040, and 2050 consistent with the methodology described for the projections above. Projecting future performance is inherently uncertain, and specific powers and efficiencies may fall outside of these ranges, but these projections are meant to provide as accurate of a projection as possible based on the existing data.

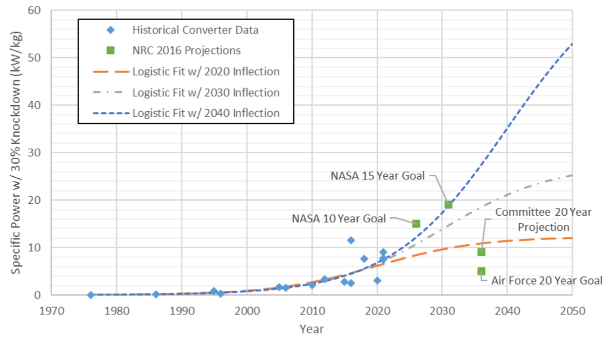

Fig. 7. Specific power projections [12-38].

TABLE II

SPECIFIC POWER PROJECTION CURVE PARAMETERS CORRESPONDING TO (2). THESE CURVES INCLUDE THE 30% KNOCKDOWN FACTOR. THE EQUATIONS WITHOUT THE KNOCKDOWN FACTOR CAN BE DETERMINED BY DIVIDING THE ASYMPTOTE BY 0.7 AND KEEPING THE SAME GROWTH RATE AND INFLECTION POINT.

Confidence Level	Asymptote, L	Growth Rate, k	Inflection Point, y_0
Conservative	12.2	0.1275	2020
Nominal	27.6	0.1165	2030
Aggressive	70.1	0.1119	2040

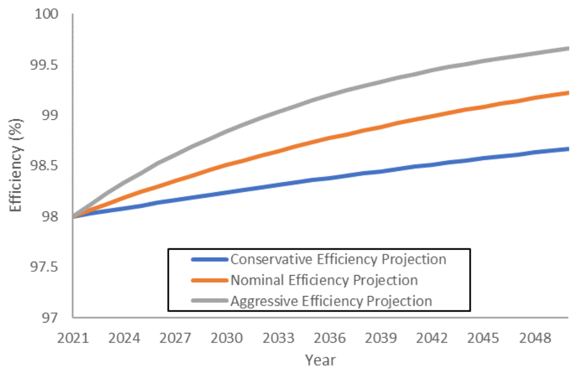

Fig. 8. Efficiency projections.

TABLE III

EFFICIENCY PROJECTION CURVE PARAMETERS CORRESPONDING TO (3)

	Conservative	Nominal	Aggressive
k	0.014	0.032	0.059

TABLE IV

FINAL SPECIFIC POWER AND EFFICIENCY PROJECTIONS THROUGH 2050

Timeframe	Confidence Level	Specific Power (kW/kg)	Efficiency (%)
SoA	—	7.5	0.98
2030	Conservative	9.6	0.982
	Nominal	13.8	0.985
	Aggressive	17.3	0.988
2040	Conservative	11.4	0.985
	Nominal	21.1	0.989
	Aggressive	35.1	0.994
2050	Conservative	12	0.987
	Nominal	25.2	0.992
	Aggressive	52.9	0.997

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