Industrial Drive for Optimization of Electric Motor Driven Systems

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1 Identification and Significance of the Problem or Opportunity

1.1 Opportunity

To achieve near-term and long-term improvement on decarbonization and reach the U.S. goals of 100% carbon pollution-free electricity by 2035 and net-zero GHG emissions by 2050[1] requires energy efficiency improvements for industrial systems. As stated in the DOE Industrial Decarbonization Roadmap[1], "Energy efficiency is a foundational crosscutting decarbonization strategy, and it remains the most cost-effective option for near term GHG emissions reductions. Energy efficiency impacts are delivered through energy-efficient technology development and deployment, combined with a continuing drive to implement strategic energy management (SEM) across all of industry."

Motor applications including pumps, fans, compressed air, materials handling, and others account for 91% of manufacturing electrical energy consumption[2] and 43%–46% of global electricity demand by end use[3] signaling a major opportunity for efficiency improvements. There are over 10 million motors in operation within the industrial sector with an average motor size of 27hp and annual power consumption of 547,000-GWh.

It has been proven that implementation of adjustable speed drives (ASDs) on electric motors can improve system level efficiency by up-to and over 50%. However, 80% of all industrial systems are still fixed speed on/off control. Based on DOE market analysis[3] and multiple published studies, several reasons are identified for this slow adoption rate of ASDs; including 1) slow capital expenditures; 2) inability to effectively retrofit existing systems, 3) efficiency limitations of many ASDs; 4) maintenance costs; 5) limited robustness of the variable speed technology in extreme environments; and 6) limited life of many ASD technologies in industrial applications. Providing an efficient, robust, low-cost, and retrofittable ASD will have a dramatic impact on achieving decarbonization goals. Adoption rate of new ASD technologies is the key to achieving improved energy efficiency.

Orbital has developed a novel mechanical ASD technology that is superior to other commercial technologies in the market including the most common ASD, the variable frequency drive (VFD). Orbital's ASD resolves issues currently identified that limit adoption rates and has the potential to become a dominant ASD solution for retrofitting existing systems and within extreme environments. Orbital's ASD solution for industrial applications can be a key technology in the United States foundational cross-cutting decarbonization strategy.

A 20% improved adoption rate results in 110-GWh annual reduction in power consumption and avoidance of 850 million tons of CO_2 equivalent[4]. This is equivalent to the removal of 168 million gasoline-powered passenger vehicles annually and a financial impact of $158 billion dollars based on latest social costs estimates.

1.2 Significance of the Problem

"Motor applications including pumps, fans, compressed air, materials handling, and others account for 91% of manufacturing electrical energy consumption[2]. When the load is a fraction of maximum available motor output, power savings of up to 80% are available through system level design for energy efficiency. A systems-based approach, applied across entire motor systems, could result in much larger energy savings than individual efforts. For example, a United Nations Industrial Development Organization study shows that the system-level optimization of motor systems like compressed air, pump, and fan systems could result in a total technical electricity saving potential of 27%–57% of the total motor system energy use, depending on the efficiency baseline[6]."

Several terms are used in practice to describe a motor system that permits a mechanical load to be driven at variable speeds, the general term, adjustable speed drives (ASDs) or variable speed drives (VSDs), are often used interchangeably. ASDs are separated into three competitive technologies: mechanical, electrical, and hydraulic drives. Extensive research has been conducted in the various technologies. The technologies are well summarized and reported by the DOE.[7] As detailed in multiple reports, traditionally the most energy-efficient option for control is an electronic ASD, commonly referred to as a variable frequency drive (VFD). The report continues by noting several limitations in many alternatives including form factor, cost, and poor efficiency when compared to traditional electrical variable frequency drives (VFDs).

VFDs have become so ubiquitous in their use that many reports use the term ASD and VSD to refer specifically to VFDs. In a 2002 DOE market assessment, it was found that 9 percent of industrial motor systems and 4 percent of industrial motor system electricity consumption utilized an adjustable speed drive (ASD). The 2002 report describes ASDs as being synonymous with VFDs.

In the 2021 DOE market assessment report, 19 percent of industrial motor systems had some sort of control technology (6 percent have a VFD and 13 percent had another load control technology). Twenty-three percent of industrial motor system electricity consumption was under a load control technology (6 percent utilized a VFD and 17 percent utilized another technology type).[3]

While the report highlights the dramatic uptake in ASD implementation in the past 20 years; the report also highlights and identifies that 80 percent of all industrial motor systems still utilize on/off control.

The need for cost-effective and robust ASDs is clearly stated within the DOE Industrial Decarbonization Roadmap[1] not only as a crosscutting strategy, but also within the five primary industrial sub-sectors. The Industrial Decarbonization Roadmap highlights five energy-intensive industrial subsectors for decarbonization; these include 1) Iron and Steel Industry, 2) Chemical Manufacturing, 3) Food & Beverage Manufacturing, 4) Petroleum Refining and 5) Cement Manufacturing. In these industries, capital expenditure and maintenance costs, extreme environments and ASD form factors play a significant role as barriers to entry for standard VFD implementations.

In the Iron and Steel Industry, the extreme environmental challenges and physical space limitations around the locations of electrical motors limit the ability to implement variable speed drives. However, a Lawrence Berkley National Labs report (Worrell et al),[10] highlights the need and desire for adjustable and variable speed drives for energy efficiency improvements and costs savings in multiple applications including compressors (coke ovens) fans (combustion air, ventilation, turbines) pumps (heat, boiler) and conveyer lines (annealing lines, etc.). In many instances, the environment prevents the utilization of VFDs.

For the Petroleum Refining Industry, capital costs and physical space limitations for system upgrades result in a slow transition to VFDs. According to the report "refineries rarely decommission an existing process unit unless it is no longer needed. And expansion is only driven by market expansion, refinery consolidation, or regulatory changes related to point sources emissions or fuel specifications. Considering the challenge of long equipment lifetimes and strategies that use existing capital and infrastructure (e.g., LCFFES, electrification, energy efficiency) will be crucial for near- and mid-term progress." The ability to provide simple upgrades and retrofit existing units would accelerate implementation of energy efficient solutions.

Other sectors of the Petroleum Industry also have limited adoption to VFD technology due to primarily capital cost and environmental limitations of the existing technology. Upstream Petroleum industry spends over 90% of all expenditures on some form of pumping. Oil production using secondary means of recovery through artificial lift are primarily completed using on/off systems. The authors evaluation of this industry segment suggests that over 90% of artificial lift systems are simple on/off control, representing a significant market opportunity. Customer surveys have confirmed VFDs are not viable due to the motor location in open environments and the capital costs for complete system upgrades.

1.2.1 Significance of the Problem for Centrifugal Pumps

According to the DOE in most industries, centrifugal pumps are identified as the largest consumers of electric motor energy. Also, among all rotating assets in the plant, process pumps had the highest overall potential for electrical energy savings. It was also identified in pumping systems; the electric motor is often oversized during the design phase by an average of 20%. When you consider that every watt of power wasted by over-sized or over-throttled pumps becomes a destructive force that lowers overall process reliability; optimizing pump performance is the key to achieving a triple benefit—lower energy consumption, lower maintenance costs and improved process control.[8]

The higher the pump horsepower (greater than 15- to 30-hp), the more cost-effective the ASD application. Centrifugal loads with variable-torque requirements (such as centrifugal pumps or fans) have the greatest potential for energy savings. ASDs can be cost-effective on positive displacement pumps, but the savings will generally not be as great as with centrifugal loads.[9]

Orbital proposes to utilize its mechanical ASD to develop an industrial pumping system for industrial fluid applications. This application will act as a pilot for the introduction of a small, cost-effective, ASD for extreme environments. This represents a critical area in the Industrial Decarbonization Strategy that will highlight the benefits and value of Orbital's novel solution and future products.

1.3 Orbital's Core Technology:

Orbital's adjustable speed drive (ASD) is a rolling traction variator that uses a variable geometry four-point contact ball bearing, where power transfer to or from the planetary spheres is by means of a roller follower located between the spheres and mounted on a carrier (Figure 1). The result is a mechanism that can be thought of as an unconventional epicyclic (planetary) gearbox with the unique ability to continuously vary the effective pitch diameter of the planets, ring, and sun gears (although there are no gears). The ASD can be better understood by review of multiple published papers on the technology. The technology is covered by more than 50 worldwide patent and patent pending applications across 16 patent families.

The ASD technology was first commercialized as a control system for drilling tools in oil and gas exploration in 2008. Since 2009, Orbital has continued to develop the technology for heavy duty vehicle applications. In addition to the military efforts, Orbital's ASD drives a combination supercharger and turbocharger, which enables downsizing on heavy duty engines without deficiencies experienced by traditional systems. The super-turbo is currently conducting on-vehicle testing.

Orbital has been working extensively with the Department of Defense, since 2015, on the development and use of the technology for advanced power applications and the optimization of heavy-duty diesel engine systems including stationary, mobile and vehicle engines.

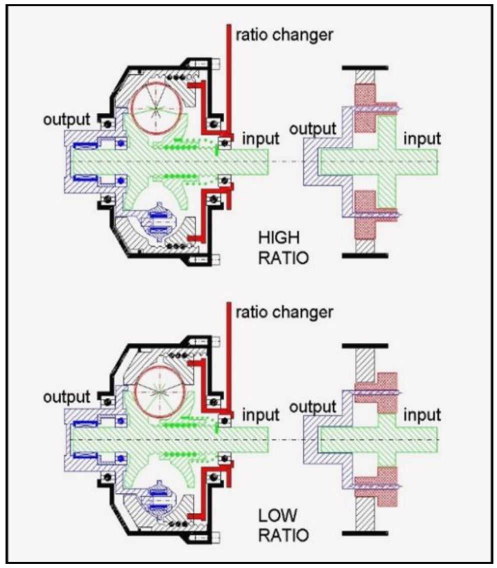

Figure 1: ASD Planetary Ratio vs. Variable Epicyclic

1.3.1 Development of the ASD Technology:

Orbital DoD Contracts: The ASD has been extensively tested in military applications for improving the efficiency and power throughput of accessories on heavy-duty engines. These solutions currently are between TRL 5 and TRL 7. The developed solutions include a drive for rod pumps, portable power generation and several on-engine accessories including a fan drive, water pump, and alternator/generator.

1.3.2 Comparative Analysis of ASD

The wide range of technology solutions for ASDs results in an even wider range of competitors that are often market and application specific. When compared to currently available adjustable speed drives, Orbital's mechanical ASD offers several competitive advantages including: (1) a patented solution based on ball bearing technology, resulting in a self-contained, reliable solution that is simple to manufacture and has a lower comparative implementation cost; (2) a higher power density resulting in an extremely efficient and compact unit with power densities 2-4 times more dense than other mechanical ASDs; (3) direct integration into existing rotating systems with fewer components; and (4) a higher overall system efficiency. Orbital's solution is superior to other mechanical and hydraulic solutions in cost, volume, and efficiency.

Feature	Benefit	Value
Simple Design	Low Manufacturing Cost	• Opens up new market opportunities
Compact	Higher power density	• Smaller and lighter weight • Opens new applications
Simple Shifting	Fewer parts with lower shifting power	• Less energy • Lighter weight • More durable
Fast Shift Response	More precise control	• Energy savings • Smooth operation • Opens up new markets
High Efficiency	Low Power Consumption	• Economic
Robust Design	High Reliability	• Low operating costs

Figure 2: Orbital ASD Benefits

Orbital's ASD vs VFD: As the VFD represents the single most competitive technology, the remainder of this analysis will focus on this comparison. Orbital's ASD will be implemented as a performance optimization drive (POD). The POD provides all the performance benefits of the VFD but has several advantages over VFD technology as shown in Figure 3.

VFD		Orbital
Baseline	Cost	<50% of VFD
2x	Ratio Range	4x
Baseline	Power Density	100x VFD
Requires Enclosure	Environmental	Harsh Environments
Control Required	Torque Dampening	Intrinsic
Requires Site Updates	Retrofit	Easily Retrofit
No	Off-Grid Capable	Yes

Figure 3: Comparison of Orbital ASD to a VFD

The POD is a constant power device. The motor runs at synchronous speed with the full motor power available at all output speeds. A VFD with an AC Motor is a constant torque device. It will provide the same torque as the speed is reduced, but power is reduced in proportion to the speed. At 50% speed, the VFD/motor will only provide 50% power output.

The POD is a compact and environmentally robust device. It is a fraction of the size of a VFD and can be put in-line between the motor and pump in existing installations. The ASD technology is used in a downhole drilling tool that is subject to extreme shock loads and operation temperatures of 175°C. The ASD technology is also qualified for on-engine applications for heavy duty trucks and can withstand the temperature extremes and the environment present in an engine compartment. The POD can be used on any type of motor or rotating drive system. Unlike a VFD, Orbital's ASD can be easily retrofitted on existing motor driven systems without major modifications and at a fraction of the cost of a VFD. Orbital's industrial driveline system can be readily integrated into existing industrial control systems through simple retrofitting the ASD between the motor and load. Orbital's motor drive system is environmentally robust and can be used in most industrial environments without the requirement of additional environmental enclosures. The system will include cost-effective field hardware for remote monitoring, control, automation, and optimization. For systems of 50-hp and greater, the POD is approximately 50% of the price of a VFD when environmental enclosures are required.

The core ASD has a 450% speed range as a speed reducer with an efficiency between 88%-92%. Initial laboratory testing conducted of an industrial driveline, Figure 4, on Orbital's dynamometer, Figure 5, has shown that Orbital's ASD efficiency is similar to and in specific instances more efficient than a VFD when operating the motor significantly below synchronous motor speeds.

Figure 4: Laboratory Mock-up

Figure 5: Orbital Dynamometer

Testing included generating a variable torque load on the system, Figure 6 and controlling output speed to a constant value. System evaluation of efficiency was measured, Figure 7. The results of testing show the benefits at lower speeds. It is well known that a VFD does not perform efficiently below 50% of the synchronous motor speed. Orbital's constant power output keeps efficiency of both the electric motor and the system operating at higher efficiency points ensuring improved overall system efficiency and performance.

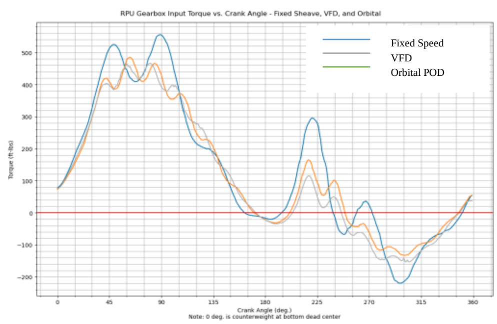

Figure 6: Variable Torque Load

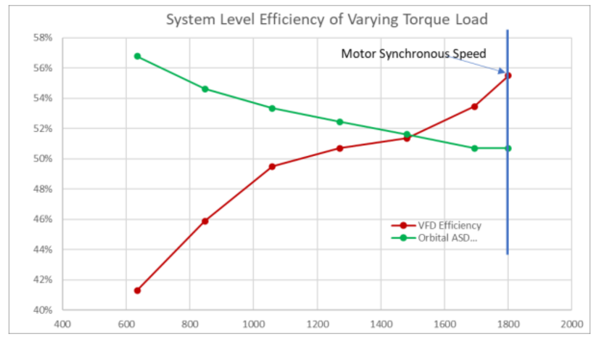

Figure 7: System Performance

1.3.3 Comparative Analysis of Orbital mechanical ASD vs. VFD for Control and Automation

In recent years, industries have been transformed through industrial automation by using advanced technologies facilitated by electronic communications and remote connectivity. These improvements cover a range of advanced technologies including the use of sensors, machine learning, artificial intelligence, automation, advanced control algorithms and novel automated mechanical systems including robotics. This trend encompasses many well-known buzzwords including the industrial internet of things (IIOT) and Industry 4.0.

While the mechanism for actuating Orbital's mechanical ASD is fundamentally different than that of a VFD, the control functions of Orbital's mechanical ASD can be configured such that common controllers and industrial SCADA interfaces will interface with both systems with common signals.

1.4 Orbital's Industrial Drive

Orbital's performance optimization drive (POD) and control system can be implemented to control the speed of the centrifugal pumps and other industrial loads. The ASD is installed between the electric motor and the pump as shown in Figure 8. The system is easily retrofittable on existing pumping systems as well as new installations.

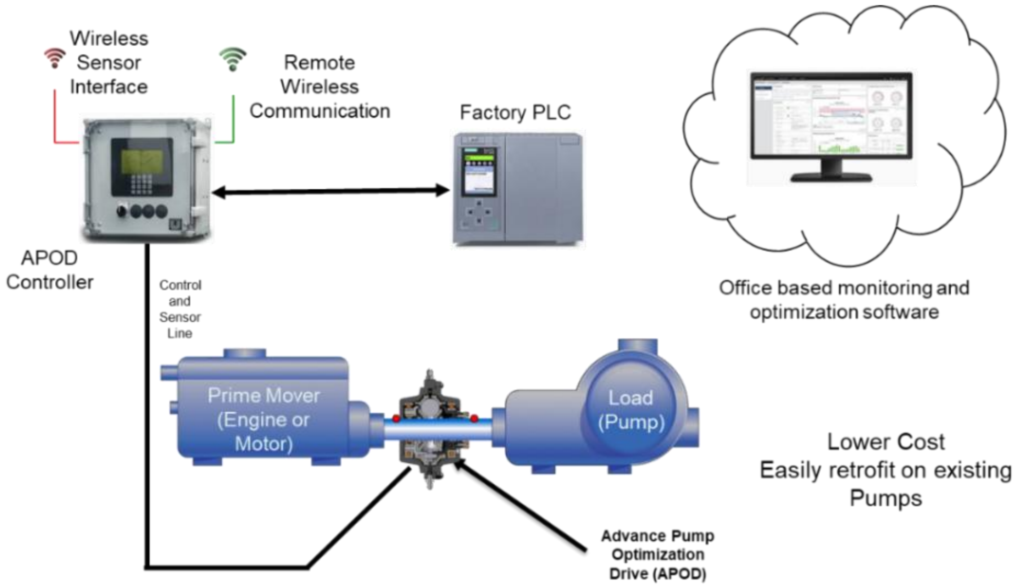

Figure 8: POD (Pump Optimization Drive) System

Orbital's POD Pump Evaluation vs VFD: Orbital utilized a prior analysis provided by the DOE in Pumping Systems Tip Sheet #12, May 2007 as part of the Industrial Technologies Program for throttle vs VFD control. Orbital evaluated the proposed POD design against DOE validated VFD analysis. The four charts, evaluating throttle valve control, VFD control and POD control are found in Table 1, 2, 3, and 4, respectively.

As explained in the tip sheet, "Developing a system curve is the first step in understanding a given pump system's characteristics at various flow rates. Then, process requirements can be displayed in a histogram, flow rate duration curve, or load-duty cycle format. The load-duty cycle is a frequency distribution indicating the percentage of time that a pump operates at each system operating point; it can be useful in calculating potential energy savings." (Table 1)

Load-Duty Cycle for an Existing Centrifugal Pump with Throttle Valve Control					
Operating Point	1	2	3	4	5
Operating Time (hours)	500	1,000	1500	2000	1500
Flow Rate (gpm)	400	600	800	1000	1200
Head (feet)	160	155	145	134	120
Pump Efficiency	63	76	82	83	80
Power (bhp)*	25	31	36	41	45

*Brake horsepower.

Table 1: Load-Duty Cycle with Throttle Valve Control

After establishing values for flow rate and head, you can extract the pump efficiency and shaft horsepower required from the pump curve. Using weighted averages for power at each operating point, factor in the motor's efficiency to calculate weighted input power, Table 2.

Average Power Requirements for a Centrifugal Pump with Throttle Control					
Flow Rate (gpm)	**Duty Cycle (%)**	**Shaft Power (hp)**	**Weighted Power (hp)**	**Motor Efficiency* (%)**	Weighted Input (kW)
1,200	23.07	45	10.38	91.4	8.47
1,000	30.77	41	12.31	91.6	10.02
800	23.07	36	8.30	91.6	6.76
600	15.38	31	4.76	91.2	3.89
400	7.69	25	1.92	90.9	1.58
				Total:	30.72

**Based on a 50-hp, 1,800-rpm, totally enclosed, fan-cooled standard efficiency motor from MotorMaster+ 4.0 data.

Table 2: Average Power with Throttle Valve Control

Perform similar calculations to obtain the average input power for the same pump when using a variable frequency drive (VFD) to control flow rate. Affinity law equations used in conjunction with the system curve can help calculate pump shaft horsepower requirements at each flow-rate point, Table 3.

Average Power Requirements for a Centrifugal Pump with VFD Flow Rate Control					
Flow Rate (gpm)	**Duty Cycle (%)**	**Shaft Power (hp)**	**Drive Efficiency (%)**	**Motor Efficiency****	**Weighted Input (kW)**
1,200	23.07	45.00	95.9	91.4	8.83
1,000	30.77	26.04	94.9	90.9	6.92
800	23.07	13.33	92.1	84.5	2.95
600	15.38	5.62	85.5	70.3	1.07
400	7.69	1.67	53.7	41.1	0.43
				Total:	20.20

**Based on a 50-hp, 1,800-rpm, totally enclosed, fan-cooled standard efficiency motor from

Table 3: Average Power with VFD

Orbital's POD efficiency is entered into the drive column, the motor at synchronous speed has similar efficiency as in Table 4 and the updated weighted input is calculated.

Average Power Requirements for a Centrifugal Pump with Orbital POD Flow Rate Control					
Flow Rate (gpm)	**Duty Cycle (%)**	**Shaft Power (hp)**	**Drive Efficiency (%)**	**Motor Efficiency*** (%)**	**Weighted Input (kW)**
1,200	23.07	45.00	92.5	91.4	9.16
1,000	30.77	26.04	91.9	91.6	7.10
800	23.07	13.33	90.1	91.6	2.78
600	15.38	5.62	85.5	91.2	0.83
400	7.69	1.67	78.8	90.9	0.13
				Total:	19.99

***Based on a 50-hp, 3,600-rpm, totally enclosed, fan-cooled standard efficiency motor from

Table 4: Average Power with Orbital POD

The modelled results of Orbital's control of centrifugal pumps provides similar performance against the VFD, as shown in the mechanical torque analysis, during laboratory testing. The POD demonstrates better efficiency at lower pump rates.

The comparative analysis between the VFD and Orbital POD shows that in theory, the POD can compete directly with a VFD on performance and efficiency. This is a unique finding, in that prior mechanical and hydraulic technologies cannot compete based on efficiency.

The POD will reduce the power of the system by running the pump at the speed required by the load and eliminating power wasting components. The POD allows the motor to run continuously at its synchronous speed which is typically the highest efficiency point of the motor. Comparative testing performed by Orbital has shown that the power savings benefit of a system with an ASD compared to a VFD increases as the speed is reduced from the synchronous speed of the motor. The POD will also reduce the peak power from pumping systems that typically run below maximum load. Utilities implement a power surcharge based on the peak power consumed by the facility. Reducing the peak power load can have a dramatic effect on reducing power costs. In addition to power cost savings, a primary benefit of the POD is that it allows the pumping system to provide the right amount of flow and pressure that is needed by the application that results in a higher overall process performance and efficiency.

The POD system, unlike VFDs, is a constant power device that amplifies torque through a variable gear ratio. The constant power, variable gear ratio and a changing inertial load provide for optimization capabilities not currently available in the commercial market. The technology represents a step-change solution for industrial drives by providing very high torque at low operational speeds. The torque multiplying effect of the POD can allow the use of smaller motors for some applications reducing capital and operating costs as well as power consumption.

2 Anticipated Public Benefits

Using the information for the prior sections, a 20% improved adoption rate using Orbital's ASD results in 110-GWh reduction in annual power consumption and avoidance of 850 million tons of CO2 equivalent[4]. This is equivalent to the removal of 168 million gasoline-powered passenger vehicles annually and a financial impact of $158 billion dollars based on latest social costs estimates.

Environmental Impact: Approximately 40% of global CO2 emissions are emitted from electricity generation through the combustion of fossil fuels to generate heat needed to power steam turbines. The research offered in this proposal makes the availability of ASDs more accessible and economical than that available for VFDs. In short, the use of VFD's has demonstrated the benefits. The POD allows those proven benefits to be extended to more businesses at a faster adoption rate.

Economic Benefits: Development of this product will result in a commercial product offering from Orbital Traction with direct economic benefits. Internal studies indicate that retrofitting just 20% of industrial pumping in the US will create over 100 jobs for a five-year period and Orbital anticipates an 80 million dollar a year business in 2027 from the Orbital industrial drive.

National economic benefits exist through the decrease in CO2, in consumed electrical power and in reduced demand on the grid and power stations. The US goals for decarbonization and energy independence cannot be understated. The electrification of the economy has significant implications for additional power generation capacity and power transmission lines. An implementation of ASDs on 20% of existing industrial motors could result in a reduction in power generation demand of over 50 GW.

Environmental Benefits: Increasing the efficiencies of existing motor driven system with a 50% reduction in power consumption and has the benefits of reducing associated greenhouse gases and reduces the amount of power required from the power grid and power plants.

Global carbon dioxide emissions in 2022 remain at record levels and natural carbon sinks are being impacted by climate change, according to a report published by the Global Carbon Project16. In 2022, fossil CO2 emissions are projected to reach 36.6 billion tons of CO2. A NOAA publication, produced by an international team of more than 100 scientists projects that atmospheric CO2 concentrations will reach an average of 417.2 parts per million in 2022, more than 50 percent above pre-industrial levels. The projection of 40.6 billion tons of CO2 emissions in 2022 is close to the 40.9 billion tons of CO2 noted in 2019, which is the highest annual total ever recorded[17].

Social Cost of CO2: There is a long history of evaluating the social cost of CO2 using the damage per ton of emitted CO2 as the key metric; going back to the Bush II presidency. During the Obama presidency, an interagency working group produced an official number, which was then $42 per ton emitted in 2020 using a 3% discount rate. President Biden in the first month in office put in place a slightly updated SCC, which was $52/ton and ordered a significant update, which was took into account the suggested improvements by the National Academies of Science and Engineering[13,15].

An updated estimate based on a new and extensive model was published in October 2022[16]. This study and the associated model were developed by multiple senior contributors from US based private, public, university and government organizations, including the EPA. The new central estimate from the study is $185 per ton of CO2 which is more than three times the current, official, number of $52. Orbital is using $185/ton CO2 in its evaluation of benefits.

3 Conclusion

The benefits of implementing VSDs on industrial motors are proven. The challenge is to increase the rate of implementation of VSDs to increase the amount of benefit provided by these systems. Orbital has addressed many of the issues that have prevented faster implementation of VSDs with our proprietary technology. The POD system, unlike VFDs, is a constant power device that amplifies torque through a variable gear ratio. The constant power, variable gear ratio and a changing inertial load provide for optimization capabilities not currently available in the commercial market. The technology represents a step-change solution for industrial drives by providing very high torque at low operational speeds. The torque multiplying effect of the POD can allow the use of smaller motors for some applications reducing capital and operating costs as well as power consumption.

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