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Compressed Natural Gas Hybrid Power System for Mobile Vehicles

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research
- Natural Gas-Related Transportation.

Compressed Natural Gas Hybrid Power System for Mobile Vehicles is the final report for the Compressed Natural Gas Hybrid Power System for Mobile Vehicles project (Contract Number: PIR-16-019) conducted by Terzo Power Systems, LLC. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

California provides more than two-thirds of the nation’s consumption of fruits, nuts, and vegetables. Many farming and harvesting activities rely heavily on mechanized equipment to plant, cultivate, and harvest goods. Diesel engines primarily power off-road agricultural vehicles and equipment that contribute 18 percent of the oxides of nitrogen emissions in the San Joaquin Valley. Transitioning off-road vehicles to cleaner and more efficient technologies will therefore improve air quality and reduce greenhouse gas emissions.

This project retrofitted a model year 2018 Shockwave Sprint tree shaker with a hybrid-electric power system consisting of an 87-horsepower Kubota WG3800 compressed natural gas engine, generator, and a 20-kilowatt-hour battery pack. The hybrid-electric power system enables use of lower carbon fuel technology to displace a larger 174-horsepower Caterpillar diesel engine. The combined engine-generator provides sustained power to charge the high-voltage battery pack. The batteries supply the necessary power to electric motors that drive the vehicle propulsion system and hydraulic pumps to perform work functions. By alleviating the need for a large diesel engine to supply high power and torque, the hybrid-electric power system reduced carbon dioxide emissions by 27 percent and fuel costs by 43 percent. By designing the hybrid-electric power system around modular and scalable subsystems, the technology demonstrated in this project can be adapted for use in various types of off-road equipment applications beyond the agricultural industry. The hybrid-electric power system can assist in meeting California’s air quality and greenhouse gas reduction goals while providing a competitive return on investment to end-users.

Keywords: natural gas, heavy-duty engine, hybrid-electric, electro-hydraulic, harvest machine, high-voltage, engine-generator, compressed natural gas, diesel

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EXECUTIVE SUMMARY

Introduction

California has a long-standing commitment to reduce harmful emissions from the production and use of energy in all sectors of the economy, including agriculture, to protect the health and welfare of its citizens. The state has more than 24 million acres of farmland and leads the nation in agricultural production, providing more than two-thirds of consumption of fruits, nuts, and vegetables in the United States. According to the California Department of Food and Agriculture, California delivered an aggregate crop value of $50 billion in farm receipts and nearly $21 billion in international crop exports in 2018.

Many farming and harvesting activities rely heavily on mechanized equipment to plant, cultivate, and harvest goods. These off-road agricultural vehicles and equipment are primarily powered by diesel engines that contribute to 18 percent of oxides of nitrogen (NO_x) emissions in the San Joaquin Valley, an area that is the backbone of the state's agricultural industry. Transitioning off-road vehicles to cleaner and more efficient technologies will improve air quality and reduce greenhouse gas emissions in the region and throughout the state. An efficient hybrid-electric alternative to diesel-powered agricultural equipment that uses low carbon natural gas fuel can improve air quality and reduce greenhouse gas emissions in the San Joaquin Valley while providing economic benefits to the region agricultural industry.

Project Purpose

The goal of this project was to develop a hybrid-electric power system for off-road agricultural equipment that could perform as well as a diesel engine. To achieve additional emission reductions, the hybrid-electric power system included a downsized compressed natural gas engine with lower NO_x emissions, particulate matter, and carbon dioxide (CO_2) than a baseline diesel engine. The project leveraged the hybrid-electric architecture and battery pack to vary operation of the compressed natural gas engine: depending on how it was used, the battery pack could supply all the necessary power to operate the equipment while the compressed natural gas engine was off. The hybrid-electric architecture enables the equipment to run in all-electric mode while using tailored performance tuning to improve efficiency. The project aimed to demonstrate the feasibility and benefits of using a compressed natural gas engine in a hybrid-electric architecture as a cleaner and commercially viable alternative to diesel for off-road agricultural equipment. This project can demonstrate the potential for this technology to displace diesel to original equipment manufacturers, end-users, and regulators.

Project Approach

Terzo Power Systems, LLC, the project leader, has expertise in alternative fuels, high-voltage architecture, electrohydraulic systems, and programming. The company's previous work involving electrification of a snow grooming machine demonstrated the challenges of hybrid power system designs, marketability, and commercialization. The knowledge gained from that effort helped formulate the subsystem architecture in this project. It also highlighted deficiencies in the marketplace for commercial off-the-shelf solutions that can facilitate safer and more flexible methods of designing and integrating high-voltage components into mobile off-road equipment.

To address the barriers previously identified, this project focused on developing a cross-platform compatible solution with scalable performance that could be applied to various equipment types. The researchers divided the compressed natural gas hybrid-electric power system into subsystems required for the machine to perform its duties. The project team designed six subsystems individually to maintain discrete sets of performance metrics:

1. Heating, Ventilation, and Air Conditioning Cab Comfort Subsystem
    a. Electric heat pump with 5-kilowatt (kW) cooling/heating capacity for the operator cab
2. Electrohydraulic Subsystem
    a. 53 kW – 116 kW capable electric motors matched with hydraulic pumps for harvesting functions
3. High Voltage Safety Subsystem
    a. High-low voltage power distribution hub with 12 volts direct current step-down capability and passive and active safety monitoring devices
4. Ruggedized Battery Storage Subsystem
    a. 400 volts direct current, 147 Ampere-hour battery system with 20 kilowatt-hour (kWh) capacity for powering electric motors
5. Compressed Natural Gas Engine and Fuel Storage Subsystem
    a. 87 horsepower (65 kW) compressed natural gas engine with 16 gasoline-gallon-equivalent fuel storage for charging batteries using a mated generator
6. Master Controller Subsystem
    a. Centralized hub for hybrid system diagnostic and real-time performance monitoring and control

Developing the solution in discrete subsystems assisted in the marketability of and education about the new technology. The researchers integrated the subsystems in a commercially available tree shaker as a functional demonstration platform for a compressed natural gas-powered hybrid-electric machine.

The project team tested the main functions of the machine in two different ways: (1) controlled shop transit duty cycle testing and (2) actuation of eccentric weights to gauge power requirements for tree shaking. The controlled transit duty cycle test was a stress test for all components required for machine propulsion. The test entailed driving the machine for 1.1 miles at the Terzo Power Systems facility. The shake testing, also completed at the Terzo Power Systems facility, simulated a harvesting sequence in an orchard by quickly accelerating the machine to travel approximately 10-20 feet then initiating a shake sequence of 8-10 seconds. This event was repeated for repeatability and consistency.

Off-road equipment primarily uses diesel engines due to their high torque capabilities. By decoupling the compressed natural gas engine from the hydraulic pumps using battery storage, the hybrid-electric power system can achieve equivalent high torque performance to diesel engines. Addressing this key barrier to market acceptance of alternative fuels to diesel allows compressed natural gas hybrid-electric power systems to be adopted to reduce emissions from off-road equipment. While the prototype tree shaker machine developed in this project requires an energy- demanding hydraulic system, the team designed the compressed natural gas-hybrid power system to provide enough energy to perform the required harvesting functions. The power system's flexible architecture allows scaling the battery energy capacity up or down to meet any other machine's specific requirements. Also, the flexibility allows for an all-electric design with no internal combustion engine to enable zero-emission operations.

The researchers formed a technical advisory committee consisting of representatives ranging from hydraulics component distributors to large equipment manufacturers. The members were selected to offer a breadth of input ranging from experience interfacing with a regional customer base to having a global impact. The advisory committee included representatives of Western Integrated Technologies, Parker Hannifin, and John Deere. Viewpoints from participating members helped identify project obstacles and challenges in advance. Terzo Power Systems used the advisory committee's input to plan for challenges like commercial acceptance, technology benefits, and duty-cycle optimization. For example, committee members recommended the team remain aware of the high initial cost of implementing alternative fuel and electrified solutions as well as the challenges associated with changing operator behavior. The feedback received resulted in an emphasis on machine efficiency, operational simplicity, and development of a commercialization roadmap.

Project Results

This project demonstrated a compressed natural gas-powered hybrid-electric tree shaker and compared its performance against a commercially available diesel-powered baseline vehicle. The demonstration vehicle was a model year 2018 Shockwave Sprint tree shaker vehicle, manufactured by Orchard Machinery Corporation in Yuba City, California. The baseline vehicle was a standard production model utilizing a Tier 4-compliant Caterpillar 174 horsepower Twin-Turbo diesel engine to power all vehicle functions. "Tier 4" refers to emissions standards established by the United States Environmental Protection Agency for diesel engines used in off-road equipment. The machine relies on a side-mounted shaker arm and propulsion system to travel through orchard rows and quickly harvest from trees. This type of design is common for tree shakers and is consistent across other manufacturer's machines such as Orchard-Rite and COE Orchard Equipment.

The hybrid vehicle used a series-hybrid drivetrain that included a Parker Global Vehicle Motor permanent magnet motor generator coupled to an 87-horsepower Kubota WG3800-G natural gas engine, a ruggedized (designed to be hard-wearing) lithium-ion battery subsystem, an electrohydraulic subsystem, a battery charge and discharge controller, and a master control subsystem. The project team assessed emission and fuel costs to evaluate the functional benefits of the hybrid platform while maintaining expected performance capabilities. To achieve desired results and expand the customer base beyond tree shakers including various off-road equipment, the project focused on finalizing designs of the major subsystems.

Analysis of test results showed that the compressed natural gas hybrid machine enabled a 27 percent reduction in CO_2 emissions compared to the diesel-powered machine. Fuel cost analysis also showed annual cost savings of $3,059 due to the lower cost of compressed natural gas compared to diesel.

In addition, the team identified areas of potential improvement that could benefit from further studies or research:

- Remote compressed natural gas fueling is limited in most orchards. Improving fueling infrastructure availability and speed would increase adoption of systems that use compressed natural gas as a fuel.
- Compression heat and high ambient temperatures limit the complete fueling of compressed natural gas tanks. Because most equipment used in harvesting almond nuts is operated during summer months, compressed natural gas tanks cannot safely achieve a full fill without smart temperature compensation. This limitation leads to decreased effective tank capacity and inefficient use of limited storage space on the vehicle.
- The physical characteristics of the battery pack limited the ability to add battery capacity to the vehicle. The battery pack used in the project was scaled down to 20 kWh from 60 kWh due to space and weight constraints. A distributed battery architecture can assist in achieving higher energy content for working functions. This in turn would allow for increased electric run time and reduced heat of compression and high ambient temperatures in engine use. Coupled with onboard charging, this has the potential to further reduce emissions by using the engine to charge the battery pack at the end of a workday. Although this solution was not feasible with the specific battery system selected for this project, it could be achieved by using a different manufacturer’s battery pack architecture.

Technology/Knowledge Transfer/Market Adoption

Terzo Power Systems’ marketing campaign for the hybrid-electric power system focused on system modularity and scalability to fit various off-road equipment platforms. The marketing campaign began in the early stages of the project to engage and build interest from industry partners in the technologies being developed in the project.

Part of the marketing strategy was attending and exhibiting at trade shows to engage in discussions with the public and like-minded technology innovators. This effort included:

- Terzo Power Systems exhibited at ID Technology Expo in 2017 in the emerging technology category of the exposition. Terzo Power Systems engaged with the public to share the vision for off-road electrification and speak with industry professionals to gain insights on challenges for electrification.
- Through a collaborative effort with AgStart, Terzo Power Systems exhibited at the City of Woodland’s 2018 “Dinner on Main” event, which promotes locally based agriculture through education, community outreach, and networking. The benefits of reduced emissions and equal performance to diesel enabled by the hybrid technology were discussed and shared with the attending public.
- In 2018, Terzo Power Systems was recognized for its efforts and nominated for an award in the Sacramento Region Innovation Awards under the sustainability category. As part of the nomination, Terzo Power Systems gave a presentation on the benefits of low carbon emissions and electrification.

- To further publicly promote the project, in 2018 Terzo Power Systems hosted a site visit for Assemblyman Kevin Kiley and showcased the compressed natural gas-hybrid machine at the Terzo Power Systems facility.
- Terzo Power Systems exhibited the hybrid technology and showcased components of the electrohydraulic subsystem at the 2018 Impact Global Venture Summit in Sacramento, California. This event placed Terzo Power Systems as an exhibitor to engage with the public and communicate how current technology could achieve competitive performance from a non-diesel platform.
- As a founding board member of the California Mobility Center, Terzo Power Systems traveled to Germany in 2019 as an advocate for electrification efforts in California and share how the technology conformed to the goals of the center.
- In 2019, as exhibitors for the Motion+Power Exposition in Detroit, Michigan, Terzo Power Systems promoted the technology to a larger audience and broader industries outside of California. The focus was education about the subsystems approach and how the strategy could be expanded to other applications.
- Terzo Power Systems attended the Tulare Ag Expo in 2019 in Tulare, California as a spectator, which allowed for more informal conversations on the technology with the public. Also, Terzo Power Systems gathered information on other hybrid technology-related research and development activities being conducted by local original equipment manufacturers.

Benefits to California

This project showed that a compressed natural gas hybrid tree shaker machine can perform comparably to a diesel-powered baseline machine while producing 27 percent fewer CO_2 emissions. The researchers accomplished this reduction by developing a hybrid-electric architecture that allows the machine to operate with half the power requirements from the engine. The architecture also enabled use of a downsized compressed natural gas engine with lower emissions. A study conducted by the California Air Resources Board determined that at least 8,845 nut harvesting machines are operating in California; transitioning 10 percent of these machines to the compressed natural gas hybrid technology would reduce CO_2 emissions by 411 metric tons annually.

Due to the modularity and scalability of various subsystems that make up the hybrid-electric architecture, the technology can be adapted to various types of off-road equipment. The same California Air Resources Board study includes inventory numbers for agricultural tractors (117,139), forklifts (241), combine harvesters (3,049), and cotton pickers (948). Around 30 percent of these machines rely on engines that are under 100 horsepower. Depending on the duty cycle, these machines could also transition to hybrid-electric or full-electric architectures.

Introducing an electrified solution for the off-highway market supports California’s ambitious economy-wide decarbonization goals. Electrified architectures can also reduce air quality impacts and improve public health in communities where off-road equipment is operated.

CHAPTER 1: Introduction

Industry Background

The off-highway vehicle market encompasses a large variety of specialized vehicles designed for use away from commuter highways. Industry sectors that use off-road vehicles include agriculture, construction, material handling, and recreation. Many of these vehicles are purpose-built and range from 50 horsepower (hp) to 400 hp and higher. Most of these machines use diesel engines as the primary power source because of their durability, efficiency, and performance. Modern diesel engines use a suite of aftertreatment technologies to reduce harmful emissions such as oxides of nitrogen (NO_x) and particulate matter (PM) to comply with federal Tier 4 emission standards:

- Diesel particulate filters (DPF) reduce PM emissions that contribute to adverse respiratory health effects.
- Selective catalyst reduction (SCR) reduces emissions of NO_x, a precursor to smog, by injecting a reductant agent (urea, otherwise known as diesel exhaust fluid) into the exhaust stream.
- Diesel oxidation catalysts (DOC) oxidize emissions such as carbon monoxide and unburned hydrocarbons, converting these harmful materials into less harmful vapors.

Despite these advancements, diesel-powered off-road equipment contribute considerably to poor air quality and greenhouse gas emissions. Total annual diesel consumption from mobile agricultural equipment in California is approximately 238 million gallons, resulting in 22,500 tons/year of NOx, 1,420 tons/year of PM, and 374,000 tons/year of carbon dioxide (CO_2) emissions.[1] An emissions inventory for agricultural diesel vehicles conducted by the California Air Resources Board estimates that there are 8,845 nut harvesters (the focus of this project) in California.[2] These nut harvesters consume nearly 10 million gallons of diesel annually. This consumption results in 449 tons/day of NO_x, 24 tons/day of PM, and 15,220 tons/year of CO_2 emissions.

Existing Technology and Current Methods

Current State of Technology

Although some upcoming commercially available off-road equipment is powered by alternative fuels, there is limited development of alternative fuel systems for more specialized equipment such as the almond nut harvester developed under this project. Recent developments of alternative fuel tractors and construction equipment include:

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[1] California Air Resources Board. OFFROAD2017 – ORION database.

[2] California Air Resources Board. Emissions Inventory for Agricultural Diesel Vehicles. December 2018. https://ww3.arb.ca.gov/msei/ordiesel/ag2011invreport.pdf.

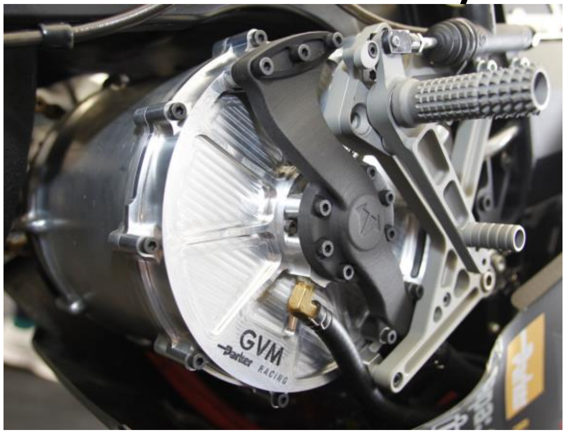
- A Hydrogen Fuel-Cell X Series Excavator developed by the company JCB.[3] Disclosed in 2020, the hydrogen-powered excavator has been under testing and observation for more than 12 months.
- A methane-powered wheel loader from Case Construction rated at 230-hp.[4]
- A versatile power platform architecture from Bomag, the BW 120 AD-5 tandem roller, which can be powered by diesel, propane, or electricity.[5]

These examples represent development efforts of major original equipment manufacturers (OEMs), each producing at least $800 million in revenue a year. Each alternative fuel platform design is proprietary to its own machine and each company's specific product line. Most off-road alternative fuel development efforts have focused on the construction industry, with less activity in the agricultural equipment market. Through this project, Terzo Power Systems, LLC aimed to address this gap to develop a flexible alternative fuel platform and demonstrate it in a piece of agricultural equipment.

Technology Maturity

The technology and components needed to create an alternative fuel platform for off-road vehicles are commercially available off-the-shelf (COTS) packaged solutions. For example, the Parker Hannifin Global Vehicle Motor (GVM) high-voltage traction motors used to power hydraulic pumps and as a generator to charge the battery have been used in various transportation applications including an electric race motorcycle (Figure 1) and an electric bus. The project used these motors because of their high power density, variation in power output, and proven capabilities in mobile systems. These characteristics allowed for optimal electric motor sizing and selection.

Figure 1: Global Vehicle Motor on a Victory Racing Motorcycle



Source: Parker Hannifin

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[3] https://www.jcb.com/en-gb/news/2020/07/jcb-leads-the-way-with-first-hydrogen-fuelled-excavator.

[4] https://www.oemoffhighway.com/trends/equipment-launches/construction/press-release/21063368/case-construction-equipment-case-ce-unveils-methanepowered-wheel-loader-concept.

[5] https://www.forconstructionpros.com/equipment/compaction/product/21118970/bomag-americas-inc-bomag-launches-alternative-fuel-options-for-bw-120-ad5-tandem-roller.

The propulsion inverters, paired with the GVM motors, also have a proven history with ruggedness and robust power electronics derived from experience gained in automotive racing. The project used the PM100 and PM150 propulsion inverters supplied by Cascadia Motion. The project used the PM100 for the auxiliary hydraulic circuit of the electrohydraulic subsystem and dedicated the PM150 units to the higher-powered hydraulic circuits of the machine that includes the hydrostatic drive system for propulsion and the hydraulics dedicated to shaking activities. Testing has shown the power draw for both of those functions to be approximately 30 kW (40 hp) and up to 80 kW (106 hp), respectively.

Figure 2: Propulsion Inverter

Source: Terzo Power Systems, LLC

As a final example, the project used a battery pack supplied by SPEAR Power Systems. The Trident line lithium-ion battery system used a nickel manganese cobalt (NMC) chemistry. To ensure safety, the battery system includes redundant circuitry for overcurrent monitoring and a watchdog printed circuit board responsible for monitoring the status of such circuits. If there is a thermal runaway event, the battery pack has exhaust ports in the rear of each module to guide excessive heat, smoke, and flames in a controlled manner.

Figure 3: Battery System as Installed

Source: Terzo Power Systems, LLC

Challenges to Overcome

There were several challenges to be addressed when combining the technologies used in the project to develop a novel compressed natural gas (CNG) hybrid power system able to compete with proven diesel-powered architecture. To enable the CNG-hybrid power system to operate in full-electric mode, the vehicle required an electrified cab cooling and heating system that did not rely on the engine. The lack of availability of commercial solutions on the market drove Terzo Power Systems to develop a scalable solution to condition the cab interior for operator comfort.

Another challenge stemming from the absence of product availability was a lack of a robust power distribution hub for both low- and high-voltage circuits. The hybrid-electric architecture requires use of high-voltage precharge circuitry. Integrating the necessary high-voltage features and embedded safety systems in a modular architecture can be developed as a marketable solution for this project and other electrified applications.

Developing solutions for the missing links in the electrification effort are a minimum requirement that cannot be ignored. Responding to the various challenges in the project was essential to avoid any compromise to the expected minimum performance of the CNG-hybrid machine to an end-user, which would result in immediate dismissal of the technology.

Lastly, the performance of today’s diesel engines is largely based on power output and efficiencies. Development of an alternative fueled solution must meet the same performance capabilities as a conventional diesel-powered solution while achieving emission and cost reductions to achieve market penetration.

Project Objectives

The goal of this project was to develop a CNG hybrid-electric almond nut harvester (Figure 4) that can compete against a diesel-powered equivalent (Figure 5) in terms of harvesting performance and efficiency. The project analyzed the benefits of using a smaller CNG engine in lieu of a diesel engine and having more flexibility by pairing a CNG engine with a battery pack. Based on these objectives, the project goal was demonstrating:

- Flexible system architecture for cross-platform compatibility: To leverage the work performed and broaden the opportunity to marketability, the CNG-hybrid solution needed to be implemented in a way in which the technology is not applicable only to the almond nut harvesting machine.
- Product development of missing key technology in the marketplace: In the same scope of marketability, complete solutions needed to be developed and made available for missing hardware to fulfill a complete electrification platform.
- Duty-capable alternative system to diesel: For an alternative system to diesel-powered equipment to gain appreciable market share, its productivity metrics at a minimum needed to match that of a diesel system.
- Reduced greenhouse gas emissions: Positively affecting a broader audience, meeting this objective contributed to the health and well-being of the general public, resulting in increased support for the technology.

- Pathway to zero-emission architecture: As the trend continues towards development of fully electric equipment, this project had to address missing elements required to realize zero-emission-capable equipment.

Technical goals for the project included positive contribution towards greenhouse gas reduction from work producing machines. Efforts to achieve those goals materialized in the form of discretized subsystems. The various subsystem development efforts and the emerging sister company of Terzo Power Systems — heavy equipment vehicle integration (HEVI) Hybrids — were ideal platforms for providing OEMs with technical expertise gained from this project. OEMs can then plan their own procurement efforts of proven solutions for integration into their own hybrid power systems of mobile vehicle development projects.

Figure 4: Compressed Natural Gas Hybrid-Electric Almond Nut Tree Shaker

Source: Terzo Power Systems, LLC

Figure 5: Diesel Powered Shaker In Operation

Source: Terzo Power Systems, LLC

CHAPTER 2:
Project Approach

Heating, Ventilation, and Air Conditioning Cab Comfort Subsystem Development

As part of the system integration measurements, the heating, ventilation, and air conditioning (HVAC) cab comfort subsystem was designed to avoid disruptions or modifications to the host vehicle's electrical system or any other vehicle subsystem. The project team exercised special considerations for component selection of the HVAC cab comfort subsystem to meet its two primary functions. Guiding principles included:

- All low-voltage electrical power and fusing must originate from the high voltage safety subsystem to assist with troubleshooting endeavors that remain within the CNG-hybrid architecture.
- Newly specified and procured evaporator/condenser units were designed into the subsystem to meet performance targets and eliminate subsystem dependency on the machine's existing HVAC components.
- Electrical components of the HVAC cab comfort subsystem must have signal and feedback compatibility to integrate with the master controller subsystem. Otherwise, using the machine's existing HVAC controls with the master controller subsystem would place a reliance between the two that prohibits compatibility across other equipment.

Electric Heat Pump Integration

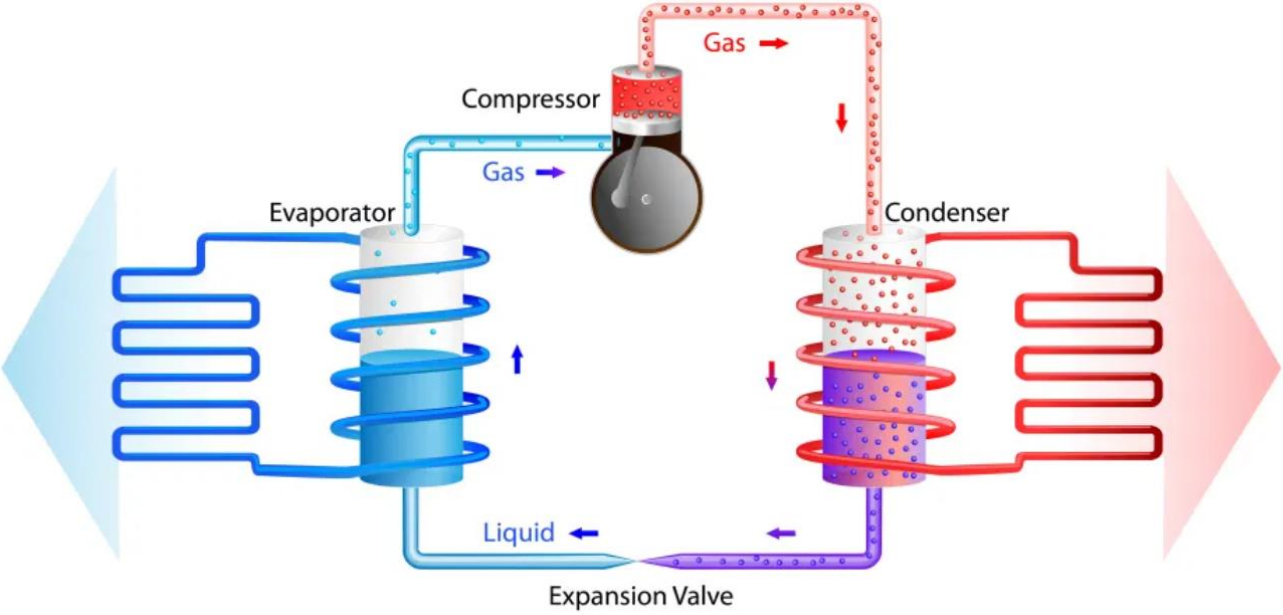
More than half of the energy resulting from the combustion process of an internal combustion engine (spark or compression type) is lost to the atmosphere as heat. Minimizing heat creation (low friction bearings, cylinder deactivation, and so forth) or repurposing heat byproduct (for example, turbos and heated coolant retention) is at the forefront of most internal combustion engine designs.

The most familiar reuse of engine heat is warming vehicle interiors. Warmed engine coolant is typically looped through a heat exchanger located within the vehicle interior. The heat exchanger is paired with a blower (fan) that aids in passing cold interior air through the heat exchanger, resulting in output of warmer air.

As mentioned, one of the design constraints to the deployment of the HVAC cab comfort subsystem was for an integration independent of existing vehicle function support. Hence, the use of the engine's coolant system for heating did not meet the system independence requirement.

To overcome this obstacle, the project used an electric heat pump system architecture to fulfill HVAC duties. Figure 6 is a generic schematic representation of how the heat pump works. A heat pump can function in air conditioning or heating mode by reversing the vapor compression refrigeration cycle, which consists of a compressor, condenser, expansion valve, and evaporator. This approach uncouples the HVAC cab comfort subsystem from the need to use the engine's cooling circuit for reusing expended heat, and results in an engine agnostic system that can be used in any electrified application, including all-electric architectures.

Figure 6: Generic Heat Pump Schematic



Source: www.futureofenergycollege.com

Except for some hybrid vehicles, the compressor is typically directly coupled to the engine crankshaft via a drive belt to use engine power to run the compressor. The project required an electrically powered compressor that could use the high-voltage battery pack in the hybrid-electric system to provide thermal comfort and minimize vehicle invasiveness.

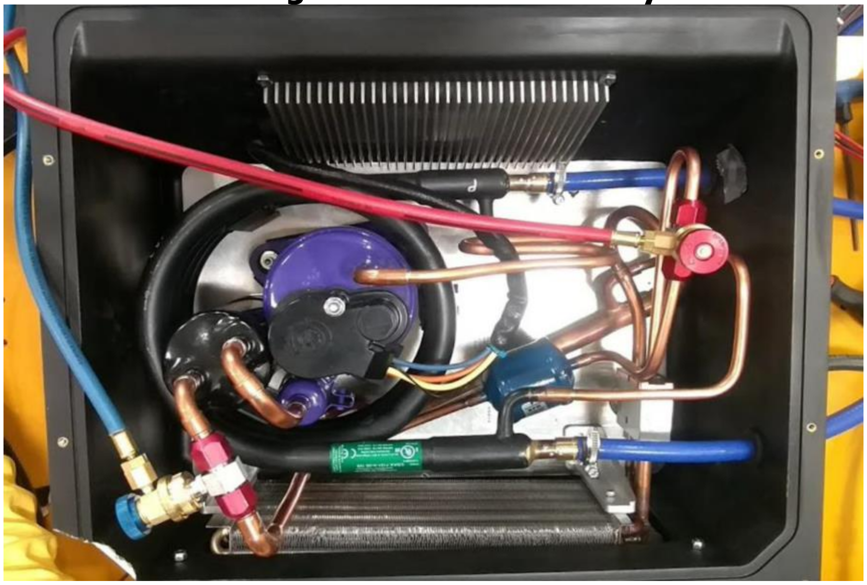
Testing and Validation

After developing a proof-of-concept version of the system, the project team repackaged the variation of the system that would ultimately be used on the machine to fit within a single housing. Containment within a single housing increases the overall efficiency and ease of integration into various other applications. The team integrated all refrigeration components used in the proof-of-concept into the refrigeration section of the HVAC housing (Figure 7 and Figure 8).

Figure 7: Heating, Ventilation, and Air Conditioning Rev 2 Test Setup

Source: Terzo Power Systems, LLC

Figure 8: Heating, Ventilation, and Air Conditioning Rev 2 Refrigeration Line Assembly

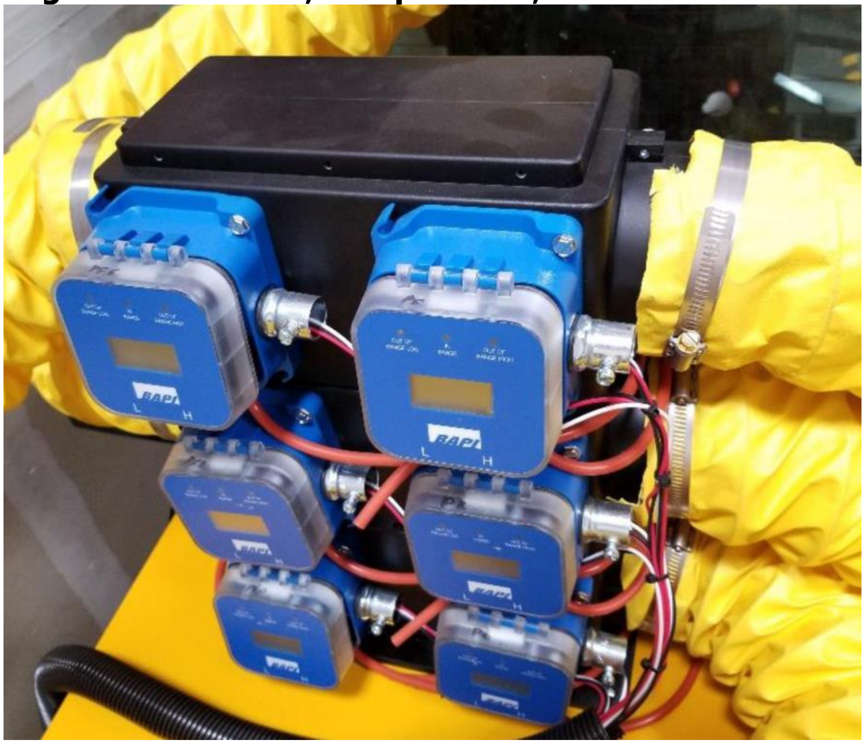


Source: Terzo Power Systems, LLC

To validate the design, the team connected the HVAC cab comfort subsystem to a series of sensor boxes (Figure 9). The boxes allowed for pressure, temperature, and flow measurements to be made during testing. The various ducting allowed for the sourcing of fresh air and recycled air from the test cab, as well as output to the test cab. The researchers performed all preliminary testing on the HVAC subsystem on a dedicated test stand before installing it on the vehicle. Key metrics are described below.

Air flow was tested and measured since the flow rate of any HVAC system has a major effect on the rate the that the system can heat or cool an area, as well as provide the conditioned area with fresh air. Preliminary testing yielded a maximum flowrate of 430 cubic feet per minute (CFM) as measured by the output sensor box (Figure 9). This value of 430 CFM is towards the higher end of the blower fan's performance output. As the HVAC subsystem is continually developed and tested, the blower may be resized to ensure that the system operates in its most efficient state. If more or less airflow is necessary in the cab, the blower can be replaced with a larger or smaller version. The HVAC subsystem's scalable architecture is consistent with the flexible modularity of the other subsystems that make up the hybrid power system.

Figure 9: Pressure, Temperature, Flow Sensor Boxes



Source: Terzo Power Systems, LLC

Minimum temperature was also a key metric. After validating full compressor functionality and verification of no refrigerant leaks, the team measured and recorded minimum cooling temperature. Minimum temperature reached was 47 degrees F while consuming a maximum power of 1700 watts.

Considering that the HVAC cab comfort subsystem as designed did not go through a secondary revision, progressive revisions are warranted to fully optimize performance. Some untested areas for improvement include noise and decibel levels, heating load, cab pressurization (eliminating dust ingress into the cab), and durability testing.

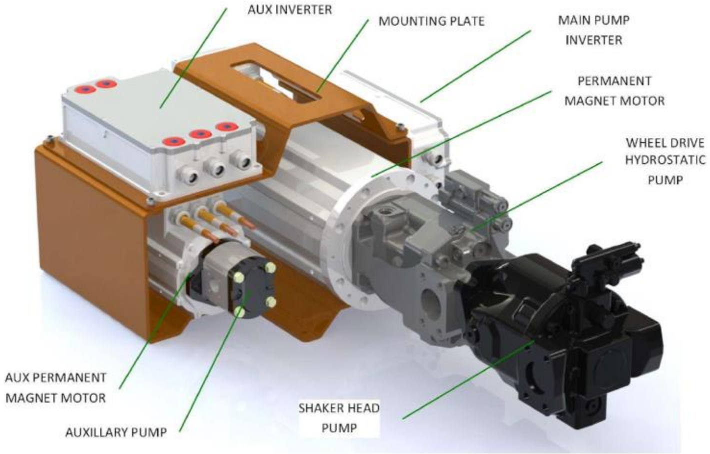
Electrohydraulic Subsystem Development

As with most off-road equipment, hydraulic systems are essential to the equipment's ability to perform work functions. Almost all agricultural equipment use a direct-drive hydraulic system powered by the prime mover (typically a diesel engine for off-road machinery). Diesel engines are the preferred engine type for heavy equipment hydraulic applications due to their inherent efficiencies and high torque output.

This project's hybrid-electric power system uses a CNG engine at around half the power output of the diesel engine it replaces. Because of the hybrid-electric architecture, a hydraulic pump cannot directly mate with the CNG engine. Instead, the CNG engine is mated to an electric motor operating as a generator to charge the battery pack.

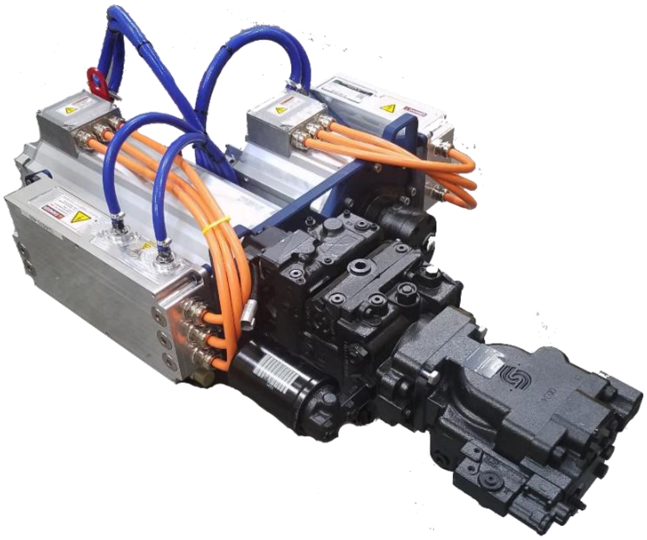
The electrohydraulic subsystem consists of permanent magnet electric motors mated to the machine's hydraulic pumps. The electric motors are from Parker Hannifin's GVM product line and offer a low-inertia, high efficiency package capable of achieving idle to full flow rpm quicker than a diesel engine. This type of system is called a "drive controlled pump system" and is significantly more energy efficient than a standard induction motor driven alternative.

Figure 10: Initial Proposed Concept



Source: Terzo Power Systems, LLC

Figure 11: As-Installed Final Design



Source: Terzo Power Systems, LLC

Table 1 shows the models and power ratings of the GVM motors and inverters used in the electrohydraulic subsystem. The larger GVM motor was mechanically coupled to the tandem pumps used for propelling the machine and actuating the shaker arm. The smaller GVM motor was affixed to an auxiliary pump for the smaller hydraulically powered machine functions, such as steering the front wheel and rotating the undercarriage sweepers. Each motor was fed controlled volts direct current (VDC) power from its own dedicated inverters supplied by Rinehart Motion Systems.

By employing a drive-controlled pump architecture on the CNG-hybrid nut harvester, the project capitalized on the torque and speed control capabilities of permanent magnet motors. Although additional efficiency gains can be achieved by selecting application specific pumps, this method makes use of the vehicle's existing pumps that come standard on the Shockwave Sprint to have the ideal performance benchmark. Efficiency gains by revisiting pump selection in an application comes from the premise that in retrofits, the existing hydraulic systems originate from the design philosophy that pumps are directly driven from a combustion engine. In instances where electric motors are the prime movers, pump selection is no longer limited to those that operate within the rpm available from a combustion engine to provide pressures and flows for a given actuator. For example, electric motors can operate well beyond 3,000 rpms. This enables a new dynamic for selecting pumps and rethinking hydraulic circuits.

Table 1: Subsystem Main Components

Component	Manufacturer	Model	Power
Main Motor	Parker-Hannifin	GVM210-300	113 kW
Auxiliary Motor	Parker-Hannifin	GVM142-200	53 kW
Main Motor Inverter Drive	Rinehart Motion Systems	PM150DX	150 kw
Auxiliary Motor Inverter Drive	Rinehart Motion Systems	PM100DX	100 kW

Source: Terzo Power Systems, LLC

High Voltage Safety Subsystem Development

High-voltage safety is paramount when it comes to the design, development, and implementation of any electric system operating above 48 VDC. Component selection, design, testing, and validation are key to creating an architecture that can be successfully commercialized. There are inherent risks when working with or around high-voltage systems that must be addressed by following protocols for high-voltage work. These protocols range from communicating the specific tools to be used to using the proper procedures when operating such systems. As part of the proposed hybrid architecture, a high-voltage battery pack is the source of power and energy for all electrification needs. The cells of the battery pack are arranged to provide working voltages up to 400 VDC. At these voltage levels, the propensity for air ionization and the degree of arcing is greatly increased. The individual components that make up the various high-voltage safety circuits were designed into a singular "safety module." Table 2 lists components housed inside the module.

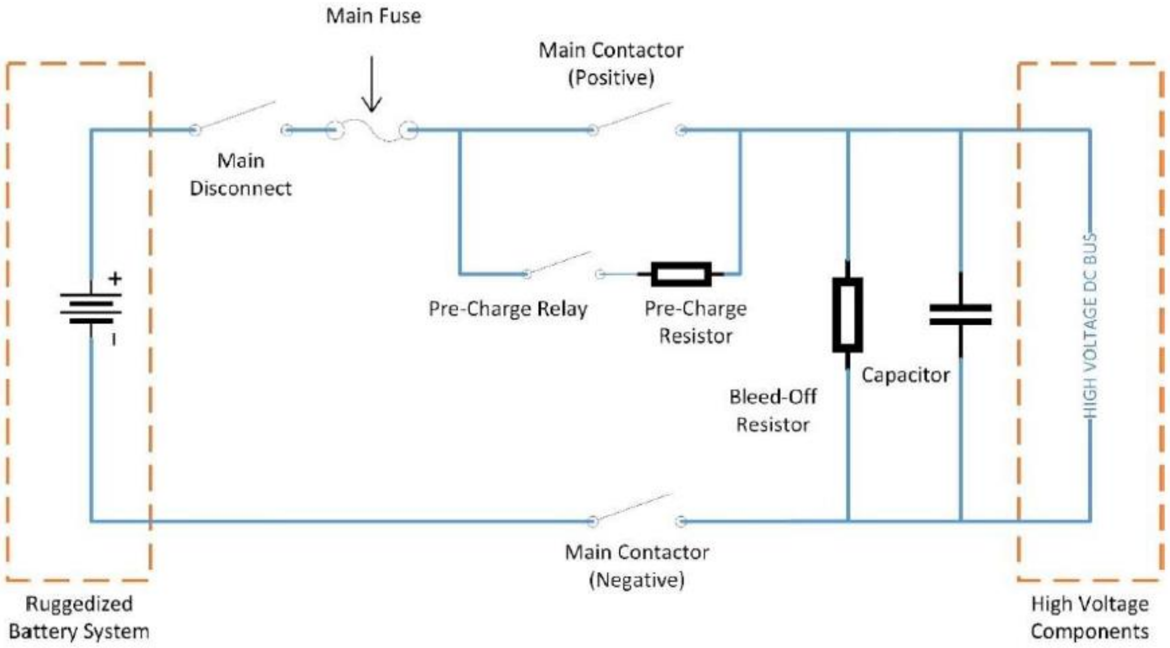
Table 2: High Voltage Safety Subsystem Function and Performance

Component	Description
Main disconnect	Switch used for complete shutdown of the high-voltage system.
Main contactors	Electrically controlled switch designed for high current applications.
Bleed-off resistor	Properly discharge any stored energy in a given capacitive circuit.
Precharge circuit	Properly charge the capacitive circuits to the proper operating level before main operation.
Isolation barrier	Safety and certification barrier between high-voltage features and low voltage auxiliary features.
DC/DC conversion	Generate low-voltage power from high-voltage battery.
Manual service disconnect	Disconnect used when vehicle is undergoing service. Integrated with fuse to protect against overcurrent.

Source: Terzo Power Systems

The high-voltage safety subsystem represents an instance where development of a product was driven by the lack of a solution in the marketplace. There are no practical COTS products that can act as a hub for high-voltage power distribution while meeting project requirements. For example, requirements for high to low voltage power conversion and precharging capabilities further reduced the already minimal solutions available. Figure 12 shows a schematic of the critical components listed in Table 2.

Figure 12: High Voltage Safety Subsystem Schematic



Source: Terzo Power Systems, LLC

The most critical function of the high-voltage safety subsystem is enabling safe interaction between the user and the high-voltage components. This places safety and expected performance as high priorities. To achieve success in operation, the project team tested every listed component shown in Table 2 to ensure it met minimum and maximum criteria. Two elements of the high-voltage safety subsystem were tested to the point of failure to understand and document failure modes that could occur in the field. Table 3 lists the methods for features tested.

Table 3: High Voltage Safety Subsystem Evaluation Characteristics

Function	Engineering Requirement	Unit of Measure	Ideal Value
High Voltage Interlock Loop	No voltage on high voltage bus	V	0
Power up/down	Unit exhibits operational characteristics	P/F	P (PASS)
Under voltage and reset	No temporary or permanent malfunctions when subjected to lower than optimal supply voltage	P/F	P (PASS)
Over voltage	No temporary or permanent malfunctions when subjected to higher than optimal supply voltage	P/F	P (PASS)
Bleed resistor circuit	Verify voltage discharge after controlled and emergency system shutdown	V	<5
Precharge circuit	Verify proper operation of the precharge circuitry	P/F	P (PASS)
Main disconnect	Zero functionality of any subsystem	P/F	P (PASS)

Source: Terzo Power Systems

Examples of such failure mode tests included rapid energize/de-energize of the high-voltage safety subsystem's main positive and negative contactors. The contactor's role is to switch close its internal terminals to allow high-current to pass through to the components downstream. Replicating a scenario in which the operator would turn on the high-voltage safety subsystem and decide to immediately turn it off, the test to failure consisted of cycling on/off at 2 Hz. Initial tests yielded a contact arcing failure mode. This results in the contact terminals fusing together creating a permanent path for current. To remedy that phenomenon, the high-voltage precharge circuit was designed for an increased three second delay. The master controller subsystem was also involved in monitoring voltages before and after the contactors before triggering a "close" command for the contactors.

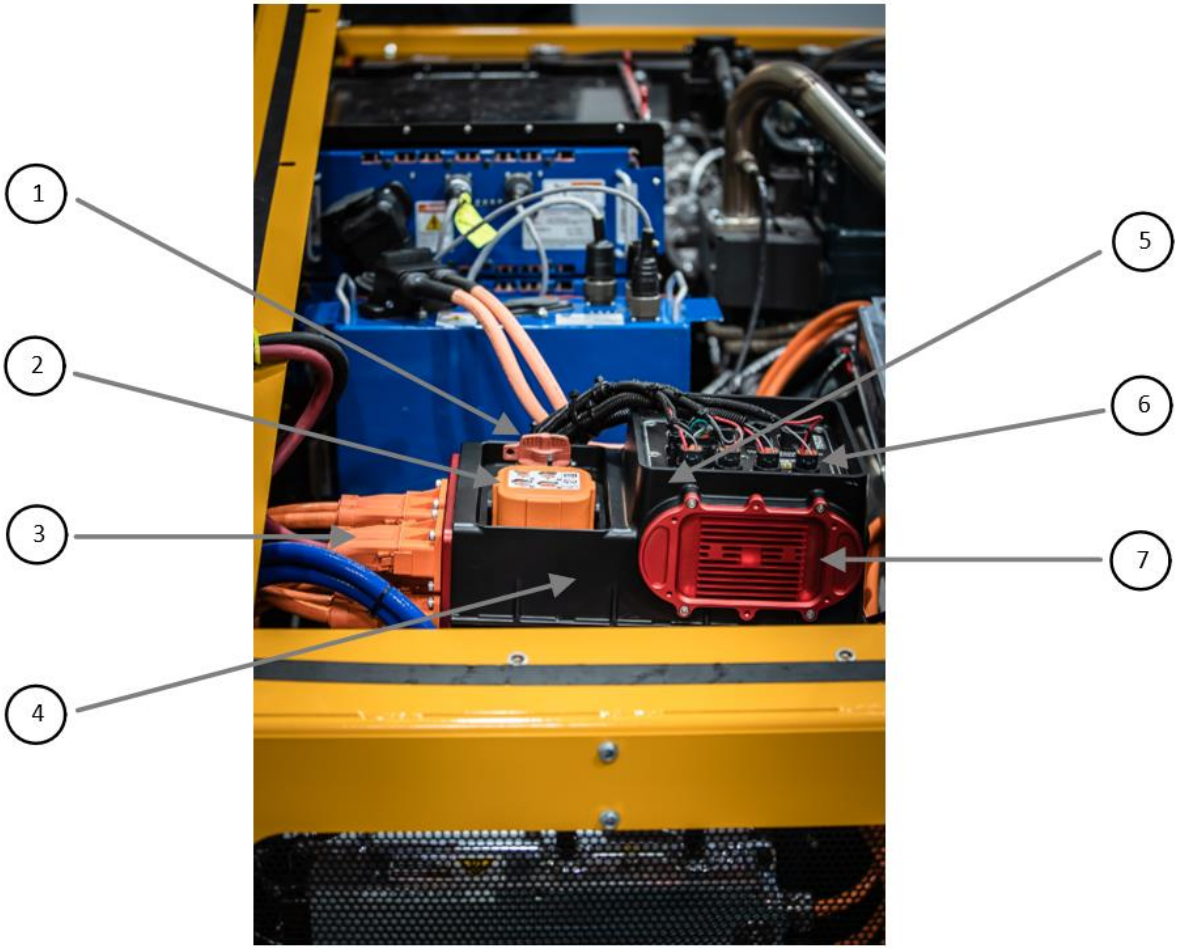
The second element tested was the precharge circuit itself. Root cause of failure is like the contactors: repeated on/off switching of the circuit components. Part of the design process for the precharge circuit involved adequately selecting an appropriate precharge resistor. A key feature of a precharge resistor is the ability to dissipate the heat energy associated during the precharge timeframe. Repeated on/off switching of the precharge circuit exposes the precharge resistor to an increased amount of energy dissipation. The failure mode here is an overheated resistor and, thus, a failed precharge circuit exposing high-capacitance components downstream to highly elevated in-rush currents, causing them to fail. In conjunction with oversight from the master controller subsystem, the result was selection of a high-powered resistor capable of up to five times the energy dissipation capabilities required.

Figure 13: High-Voltage Boards Under Test

Source: Terzo Power Systems

The team ultimately mounted the final design of the high-voltage safety subsystem towards the rear of the machine to keep the high-voltage safety subsystem near all main high voltage components (batteries, electric motors, and inverters) and access to liquid cooling for the DC-DC conversion. Like the HVAC cab comfort subsystem, proximity to connected components takes advantage of shorter connections to reduce electrical resistance and enhance electrical efficiency. Figure 14 identifies the major components of the high-voltage safety subsystem as well as their location with respect to the housing.

Figure 14: High-Voltage Safety Subsystem



(1) Master On/Off safety switch; (2) High current/high voltage primary safety fuse; (3) Common high-voltage connection region; (4) Thermally/electrically insulating engineering-plastic housing; (5) 'Internal' – Precharge safety circuitry; (6) Individually fused low voltage/high power outputs; (7) Liquid cooling interface for low voltage/high power auxiliary output circuitry.

Source: Terzo Power Systems

Ruggedized Battery Storage Subsystem Development

The researchers designed the ruggedized battery storage subsystem to be flexible and scalable in voltage and energy capacity. Adequate pairing of a high-voltage battery system to the application's energy demands is essential for a cost-effective solution because the battery system has a large procurement cost and space claim in this type of hybrid architecture.

The project originally sought a 60-kWh energy storage battery solution, but a battery pack of this size using this manufacturer's architecture would require too much space to integrate effectively and safely within the existing Shockwave Sprint chassis. The initial approach was to divide the pack's individual modules into three separate locations, but this solution was unfeasible using this specific battery architecture. Adding more battery modules (x8) and additional string controllers (x2) for the 60-kWh solution would pose volumetric challenges. Dedicated string controllers are intrinsic to the battery pack design architecture from Spear Power Systems. Continued efforts to house the originally proposed 60 kWh battery pack would entail custom machine fabrication to mount and sustain the added weight. Ultimately, the team selected a 20-kWh capacity and the integration result is shown in Figure 15, outlined by the yellow box at the bottom of the figure.

Figure 15: Ruggedized Battery Pack Location

Source: Terzo Power Systems

The advantage to mounting the battery pack in this location was the lateral orientation of the pack with respect to the machine. This allowed for the high voltage connectors to be directly situated in the region of the system’s high voltage components, reducing voltage drop by shortening connections. Adding to this, the battery pack enclosure rested close to the high-performance radiator fans of the high-voltage electronics cooling circuit. This adaptation aided in convection cooling by routing warm compartment air out and replacing it with cooler ambient air.

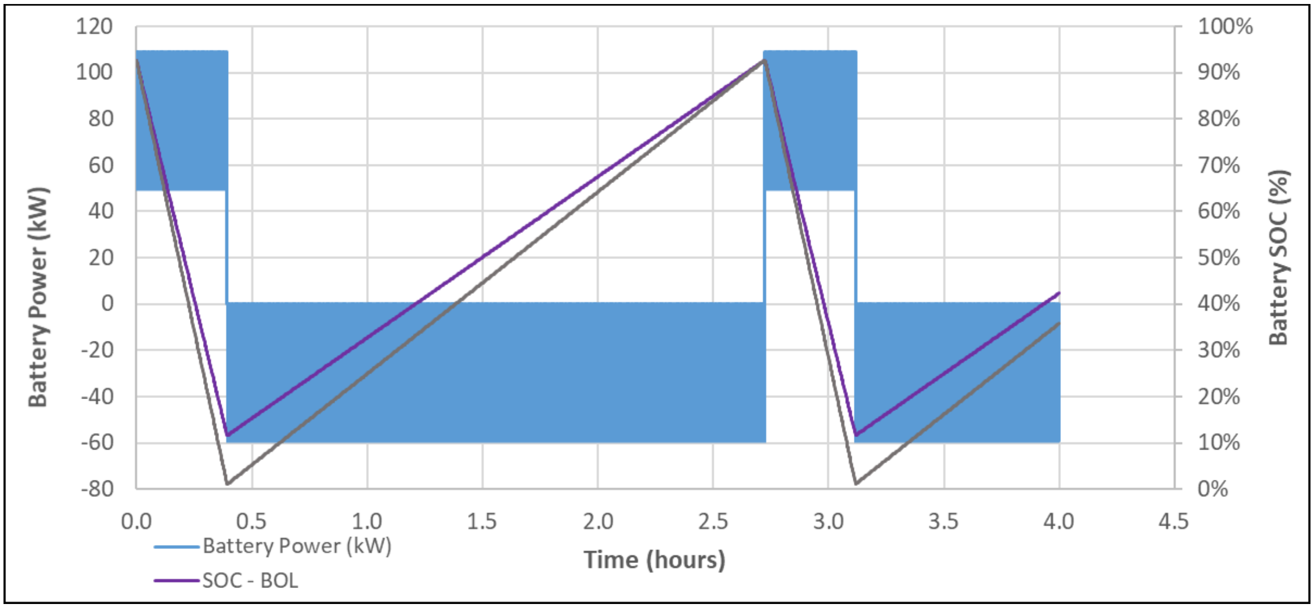
Terzo Power Systems partnered with Spear Power Systems to develop a robust and capable battery solution. Spear Power Systems has more than a decade of large format lithium-ion battery pack performance analysis and design. The Trident product line has a history of raised efficiency profiles resulting from smart thermal design practices. Spear’s modules integrate high conductivity thermal spreading materials to efficiently extract generated heat from the cell face to the heat exchanging surfaces on the sides of the module to maximize cell performance during high-rate discharges.

The overall activity of almond nut harvesting is an energy demanding, aggressive, and jarring activity. Understanding this, Terzo Power Systems requested a battery system capable of having a minimum service life of 10 years and discharge rates capable of satisfying the power draw of the electric motors to actuate the hydraulics.

Three main factors accelerate cell aging and reduce the useable lifetime of the battery system: average cell voltage, operating/storage cell temperature, and the number of cycles. The higher the average cell voltage and storage/operating temperatures, the greater the calendar aging effects. Over the life of the battery system, the relative capacity is expected to fade based on the cycle count. Enough capacity must be embedded at the beginning of life to ensure the battery can support the usage profile at the end of life (EOL). The cell's DC internal resistance is also expected to grow over the life of the system. As the cell's internal resistance increases, the battery voltage under periods of peak loading must also be considered to ensure that it supports the conversion input voltage range at EOL.

Spear Power Systems considered these elements to ensure all electrical requirements are met at EOL. Through initial project discussions with Spear Power Systems, Terzo Power Systems assessed energy consumption. Estimates on how much power was needed for the hydraulic functions were based on the baseline machine's published hydraulic system details. Based on consideration of the expected duty-cycle of harvesting activities and estimates for all-electric runtimes, Spear Power Systems suggested a charging and discharging profile that would promote a balance of performance while adhering to the 10-year service life of the batteries. Figure 16 shows the charge/discharge profile of the battery system as specified by Terzo Power Systems to Spear Power Systems to reflect the CNG-hybrid machine's duty cycle while adhering to the 10-year battery service life expectancy.

Figure 16: Charge/Discharge Duty-Cycle Profile



Source: Spear Power Systems

Compressed Natural Gas Engine and Fuel Storage Subsystem Development

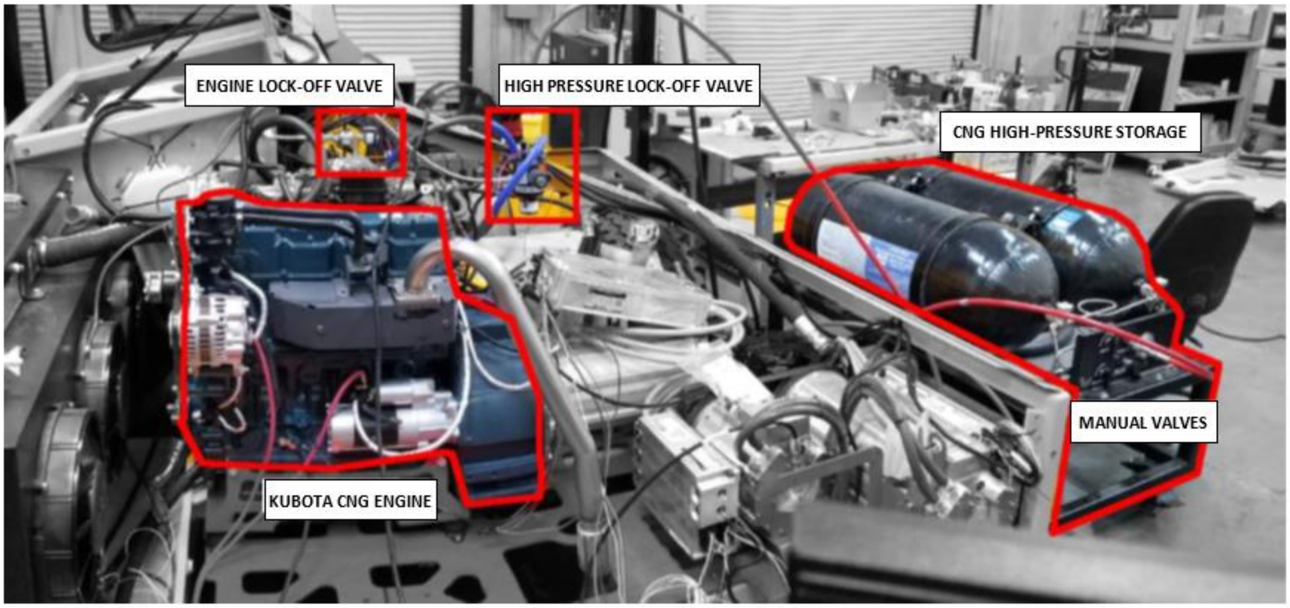
CNG engines operate much like conventional gasoline engines. A moving piston compresses a mixture of natural gas and air, and a spark catalyzes the combustion processes. CNG engines emit lower greenhouse gas emissions and fewer toxic pollutants compared to diesel engines.

The team selected a Kubota WG3800, 3.8-liter engine to be paired with a GVM motor generator. The CNG variant used in the project is capable of 87 hp (65 kW) of power output. Industry standard CNG on-board storage pressure is 3600 psi. The Kubota WG3800 engine has a design requirement of 120 pounds per square inch (psi) as part of its fuel supply system. The engine is equipped with a pressure regulator to bring the storage pressure down to the design pressure of the fuel supply system.

Unlike a liquid fuel engine, the engine's heated coolant is used to circulate through the pressure regulator to avoid freezing when dropping from high pressure (3,600 psi) to low pressure (120 psi), which creates a significant drop in temperature. Figure 17 shows the initial test setup used to verify full operation of the system.

During refueling, CNG is pumped into a cylindrical pressure vessel at 3,600 psi. With all pressure vessels, there are inherent risks regarding safety and damage. To circumvent the risk of such events from occurring, the CNG fuel storage system was designed and integrated to meet various stringent vehicle safety standards. The tanks were designed against rupture damage caused by heat or direct fire impingement as well as meet post-crash leakage and physical damage limits. The complete CNG storage system (fuel storage, delivery, and so on) was designed in accordance with the following safety standards and regulatory codes and regulations: NFPA 52: Vehicular Gaseous Fuel Systems Code, California Title 13, Chapter 8 NGV 1 -NGV 4.8, FMVSS 304, and SAE J1616 Theory of Operation.

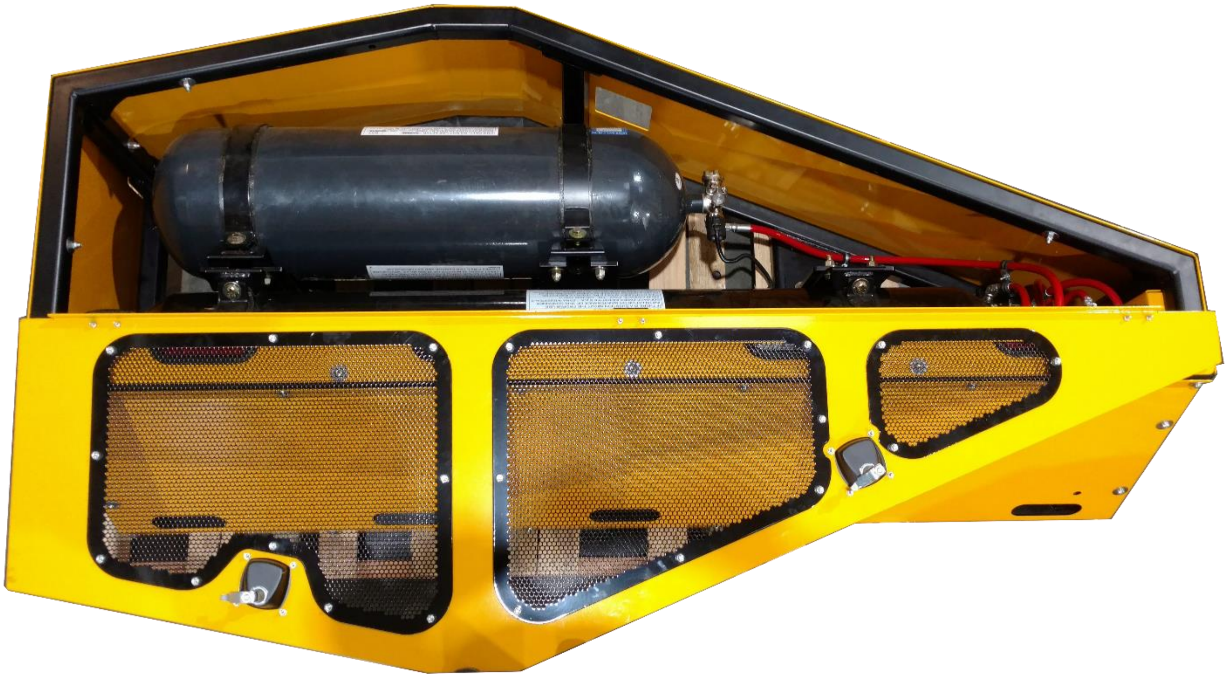
Figure 17: Compressed Natural Gas Engine and Storage Test Setup



Source: Terzo Power Systems

A-1 Alternative Fuel Systems supplied the CNG fuel storage tanks (Figure 18) for this project. The set of two differently sized tanks enabled integration into the machine with consideration of space constraints while providing an overall capacity of 16 gasoline gallon equivalents (GGE) of CNG. The tanks were enclosed in a steel frame with a matching profile to the rear of the machine. The complete frame assembly extended the machine's overall length by 24 inches.

Figure 18: Fuel Storage Tanks



Source: Terzo Power Systems

A-1 Alternative Fuel Systems provided the turn-key solution using:

1. Two (2) tanks with combined capacity of 16GGE
2. Manual valves
3. Instrument panel
4. Fill receptacle
5. Quarter-turn manual shut-off valve
6. High-pressure gauge
7. Offload receptacle
8. Three-way valve

Master Controller Subsystem Development

The Parker Hannifin's MD4-7 was selected as the human-machine-interface (HMI) to identify and interact with the hybrid system and its various subsystems. The HMI originates from Parker Hannifin's electronic controls IQAN product line. Widely used in industry, the J1939 compliant IQAN system was selected for its reliability, simplified design process, and integrated diagnostics measurements and adjustments. The MD4-7 is a ruggedized 7" touchscreen-capable display designed for markets such as construction, transportation, agriculture machinery, and material handling equipment.

Prominent performance features of the MD4-7 (herein referred to as simply the MD4) includes the ability to integrate up to four (4) separate CAN-buses (Controller Area Network). With multiple CAN buses available, it allows for an increase in data bandwidth between other J1939 components by separating high traffic bus loads from each other. This increases the reliability of each CAN network by not overloading the bus with excess data streams. Each GVM/Inverter combination benefits greatly from a singular CAN bus topology.

To further enhance the capability of the master controller subsystem (MCS), the HMI includes up to 10 inputs for sensor status and/or data collection. Additionally, up to 4 outputs are available to trigger additional functions. Table 4 summarizes the MD4-7's most pertinent feature set.

Table 4: High Voltage Safety Subsystem Evaluation Characteristics

Manufacturer	Product Code	# of Inputs	# of Outputs	IP Rating	Working temp range	Communication Interface
Parker Hannifin	MD4-7-T1	Up to 10	Up to 4	65	-30C – 60C	CAN (x4)

Source: Terzo Power Systems

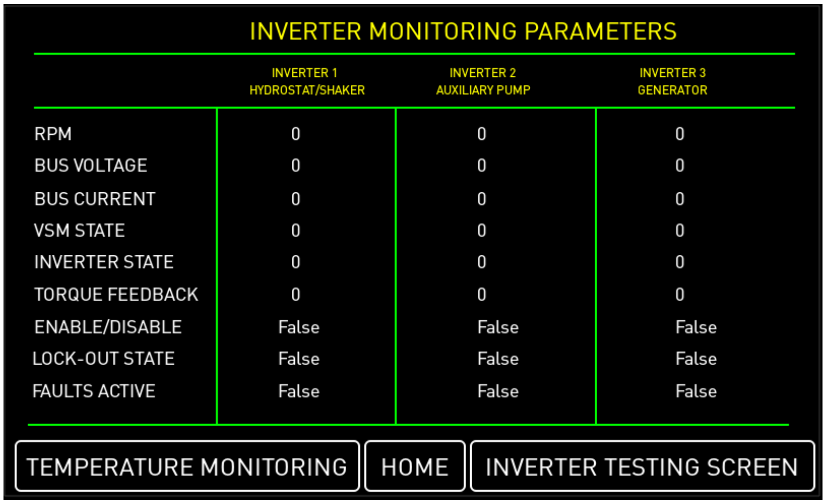
The project also implemented custom programming specific to the application that grants quick user access to the real-time status of various subsystems monitored by the MD4-7. To further address the safety risks associated with high-voltage systems, the program also allowed immediate communication of any faults during operation to the user along with a description of the hazard. The operator can immediately distinguish from the four standard precautionary statements (See ANSI 535):

1. NOTICE: Statement including nature of hazard and possible fault
2. CAUTION: Description of hazard that could result in minor or moderate injury
3. WARNING: Description of hazard and possible resulting injuries or death
4. DANGER: Description of imminent hazard and failure to avoid hazard will result in death

The master controller subsystem also enabled measurement of performance characteristics for various components throughout the bench testing process. The subsystem was used heavily during the development of the HVAC cab comfort subsystem for measuring air flow and temperatures. Another example is use during the development of the high-voltage safety subsystem. In this instance, it was used to trigger the high-voltage contactors during testing of the power electronics boards.

Figure 19 and Figure 20 are example screenshots of "pages" developed for visualizing the status of the inverter and CNG engine for the operator. Similar pages exist as well for the CNG engine generator, high-voltage safety subsystem contactor status, and temperature monitoring of the inverters and GVM motors.

Figure 19: Inverter Performance Page



INVERTER MONITORING PARAMETERS

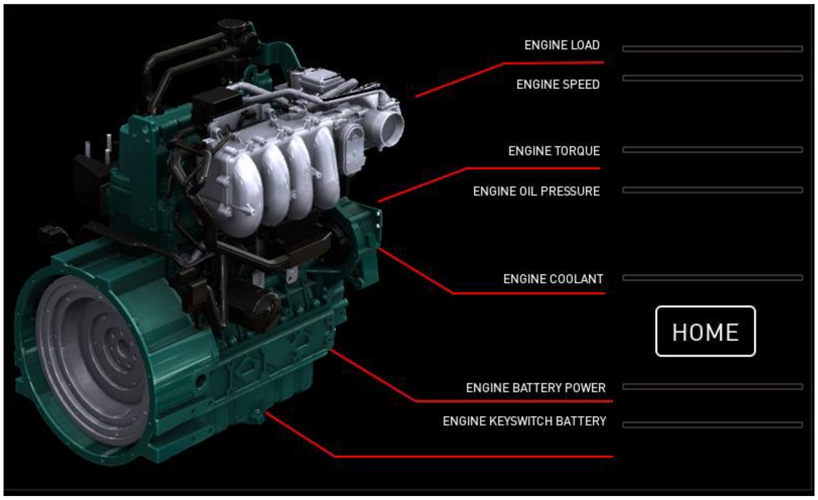
	INVERTER 1 HYDROSTAT/SHAKER	INVERTER 2 AUXILIARY PUMP	INVERTER 3 GENERATOR
RPM	0	0	0
BUS VOLTAGE	0	0	0
BUS CURRENT	0	0	0
VSM STATE	0	0	0
INVERTER STATE	0	0	0
TORQUE FEEDBACK	0	0	0
ENABLE/DISABLE	False	False	False
LOCK-OUT STATE	False	False	False
FAULTS ACTIVE	False	False	False

Source: Terzo Power Systems

The inverter performance page in Figure 19 displays the conditions of the three inverters that make up the machine’s battery charging scheme and electrohydraulic subsystem. The operator can observe any active inverter faults, real-time voltage and current use, and revolutions per minute. The page also enables optimization for power-on-demand profiles of the electrohydraulic subsystem.

Much like the inverter performance page, the CNG engine monitoring page shown in Figure 20 displays a list of typical engine parameters including engine load, speed, and torque.

Figure 20: Compressed Natural Gas Engine Monitoring Page



Source: Terzo Power Systems

The master controller subsystem is important because it is the primary means of interacting with every component in the CNG-hybrid system. The subsystem’s effectiveness and capacity for monitoring, governing, and broadcasting data to the operator depends solely on the logic behind it. In its current state, it can provide a vital and basic level of information collection and control for each component. Along with the rest of the subsystems, future development work is needed to assist in further optimizing the CNG-hybrid architecture.

CHAPTER 3:
Project Results

Compressed Natural Gas Engine and Hybrid-Electric Architecture Performance

Unlike the baseline diesel machine, the CNG engine in the hybrid-electric power system is only used to charge the battery pack as its energy gets depleted. As the battery supplies power to the hydraulic system for vehicle propulsion or shaking activities, the CNG engine generates electricity to sustain the battery pack state of charge (SOC).

As the various subsystems were introduced into the machine, the project team performed intermediary tests to validate their functionality. After the researchers successfully integrated and validated the subsystems, testing regimes moved to data collection, observation, and quantification of metrics. The following describes the charging metrics.

The generator portion of the CNG engine and fuel storage subsystem is primarily an electric motor acting in the capacity of a generator. This lends itself to a few modes of operation unique to a hybrid energy source architecture. During times when the CNG engine operates in generation mode, the project team gauged the process and specifics of how the hydraulic system worked and gathered data on the correlation between the charging profiles and fuel consumption. The team also assessed CNG engine use and emissions per charge time and calculated baseline engine diesel emissions per use.

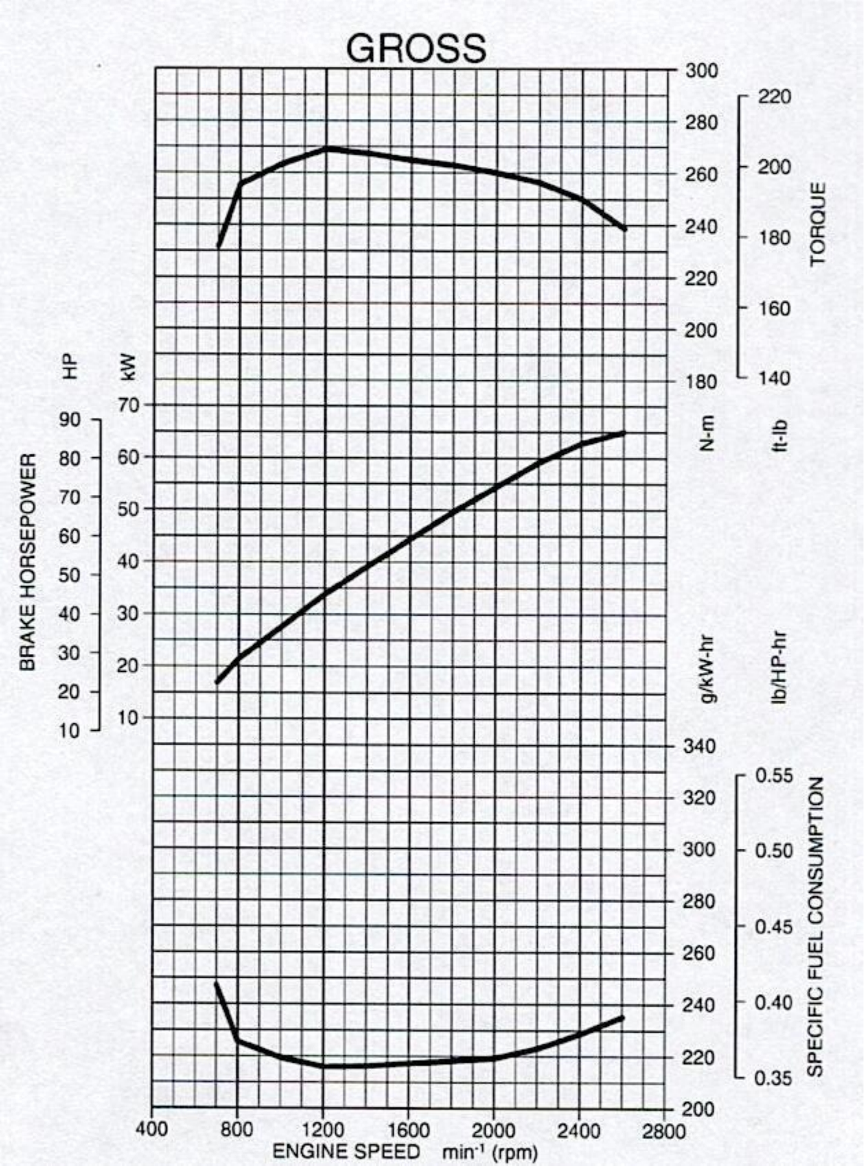
The battery pack from Spear Power Systems has a nominal voltage of 400 VDC. To increase the chances of the battery pack to reach its intended design life, Spear Power Systems recommended keeping battery voltage at or above 320 VDC. With a maximum voltage of 451 VDC, the lower voltage threshold represents a 73 percent state of charge. There is an absolute lower limit voltage of 260 VDC that represents a definitive 53 percent state of charge. The state of charge is limited by cell chemistry and the point at which irreparable cell damage may occur. Although the batteries have the capacity for a higher charge voltage, the limiting factor is the inverter’s 420 VDC maximum voltage rating. Based on the communicated design specifications of 5,400 charge and discharge cycles over the course of 10 years, analysis by Spear Power Systems showed that limiting discharge voltage to a lower limit of 320 VDC allows the battery cells to hold a charge for continued energy output.

Each electric motor is paired with a separate inverter. The inverter’s role is to change the electrical current from DC to AC and vice-versa. When operating alongside a generator, the inverter converts 3-phase AC from the motor/generator to DC type. The inverter allows direct control of the load or “resistance” to the electric motor from turning. The engine in turn reacts by overcoming that resistance in the form of torque. The two opposing forces permit the GVM motor to generate electric current that then charges the battery pack, allowing the motor to continue to run while the battery is being charged by the engine-generator.

Figure 21 shows the performance curves of the Kubota WG3800 natural gas engine from Kubota’s engine specification journal. For the most power output and regeneration capabilities, the engine operates at its maximum allowed engine speed limit of 2,600 rpm. The graph shows specific fuel consumption as about 0.44 lbs/hp-hr under peak horsepower conditions

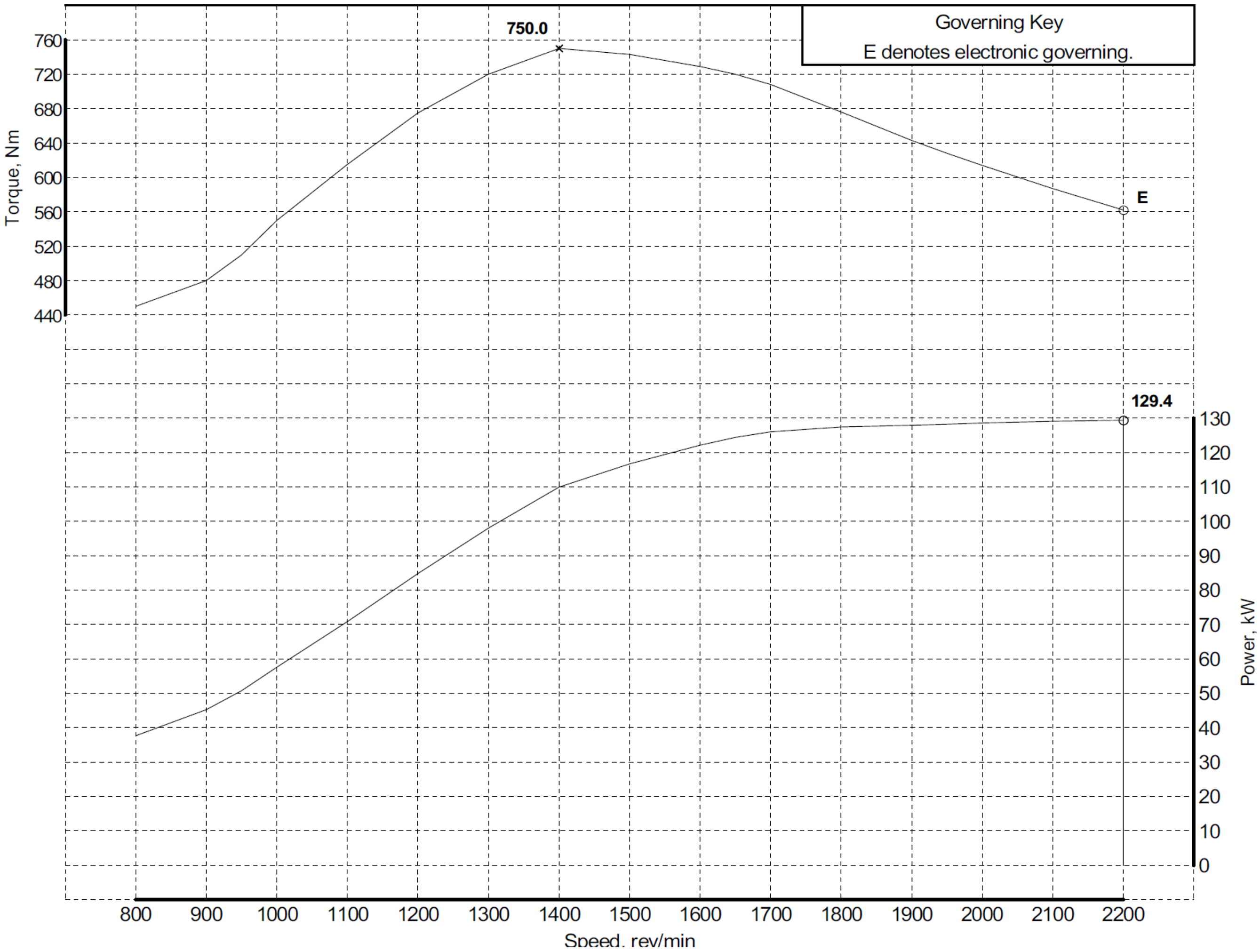
(87 hp). From these two variables, it takes approximately 28.6 lbs of CNG to produce 87 hp continuously for one hour. Figure 22 shows the baseline machine's diesel engine performance curve for reference.

Figure 21: Kubota WG3800 Performance Curves



Source: Kubota

Figure 22: Caterpillar 4.4-Liter Diesel Engine Performance Curves



Source: Caterpillar Engine Specification Manual

Table 5 presents well-established energy content data to provide an initial frame of reference between fuel types. As previously shown, the Kubota CNG engine consumes 28.6 lbs of CNG, which translates to 576,576 Btu, when operated under peak horsepower conditions at 2,600 rpm for one hour. The Caterpillar C4.4 diesel engine used in the baseline vehicle consumes 9.16 gal/hr under full load (174 hp) at 2,600 rpm. This equates to 1,176,950 Btu consumed over an hour of full load conditions. After applying a load factor of 0.44 (the proportion of maximum horsepower an engine produces on average for a nut harvester use case), resulting consumed Btu is 517,858.

Table 5: Energy Content

	Lower Heating Value
CNG	20,160 BTU/lb
Diesel	128,488 BTU/gal

Source: Terzo Power Systems

Additional CO_2 emission reductions were achieved due to CNG's lower carbon content compared to diesel. A gallon of combusted diesel fuel emits approximately 10.23kg (22.5lbs) of CO_2, while natural gas has a CO_2 emissions factor rate of 0.05444 kg (0.12 lbs) per standard cubic foot (scf).

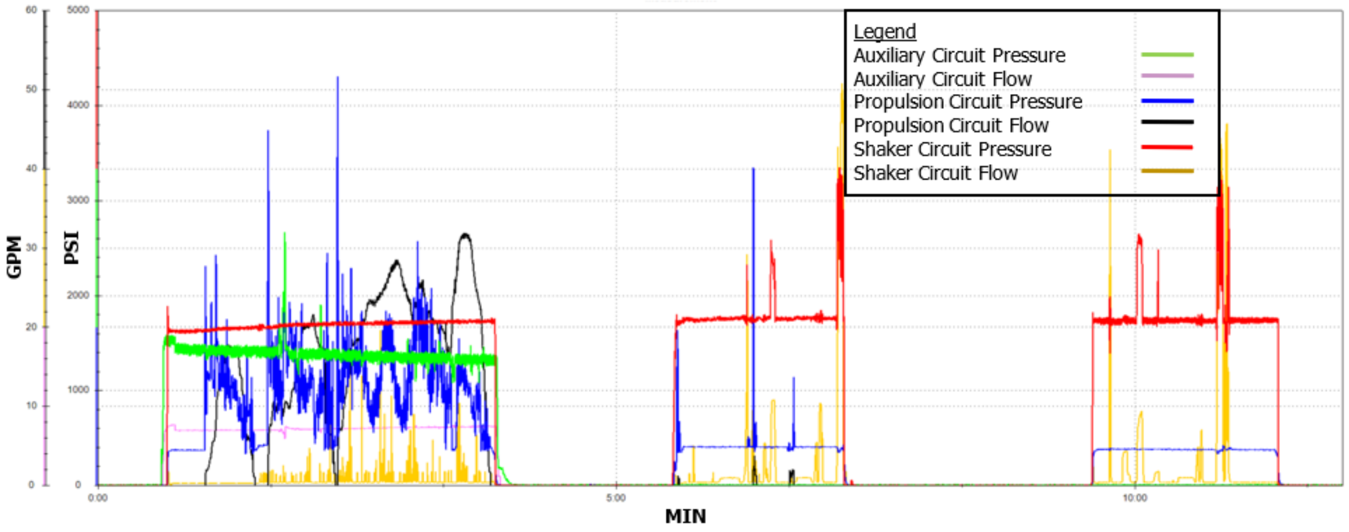
Applying the diesel CO_2 emissions factor to the fuel consumption rate results in the diesel engine output of 90.68 lbs of CO_2 emissions during one hour of nut harvesting activities. In contrast, the CNG engine only emits 66.13 lbs of CO_2 during the same timeframe and full load conditions. This represents a possible 27 percent reduction in CO_2 emissions when using the CNG-hybrid machine over the baseline diesel machine.

Compressed Natural Gas-Hybrid Machine Power Demand

The machine was outfitted with a data acquisition system designed for hydraulic performance data collection. Initial data collection activity was targeted to familiarize data collection workflow and navigation through the SensoWin software, which is Parker Hannifin's proprietary Windows software for the Service Master Plus data acquisition unit system. In general, all subsystems were enabled for the general test and the team collected data while the machine traveled one-eighth of a mile using various hydraulic functions. The data collection exercise actuated functions associated with the electrohydraulic subsystem to confirm working data collection system and to establish which connected sensor was associated with which hydraulic circuit. This effort included the hydrostatic transmission, shaker, and steering hydraulic circuit.

Figure 23 represents the hydraulic data collected for the session. The data directly reflected the amount of hydraulic power required for each particular function. Hydraulic power in horsepower units was derived from the gathered flow rate (measured in gallons per minute [GPM]) and pressure (measured in pounds per square inch [PSI]) using the formula: HP = PSI x GPM/1714.

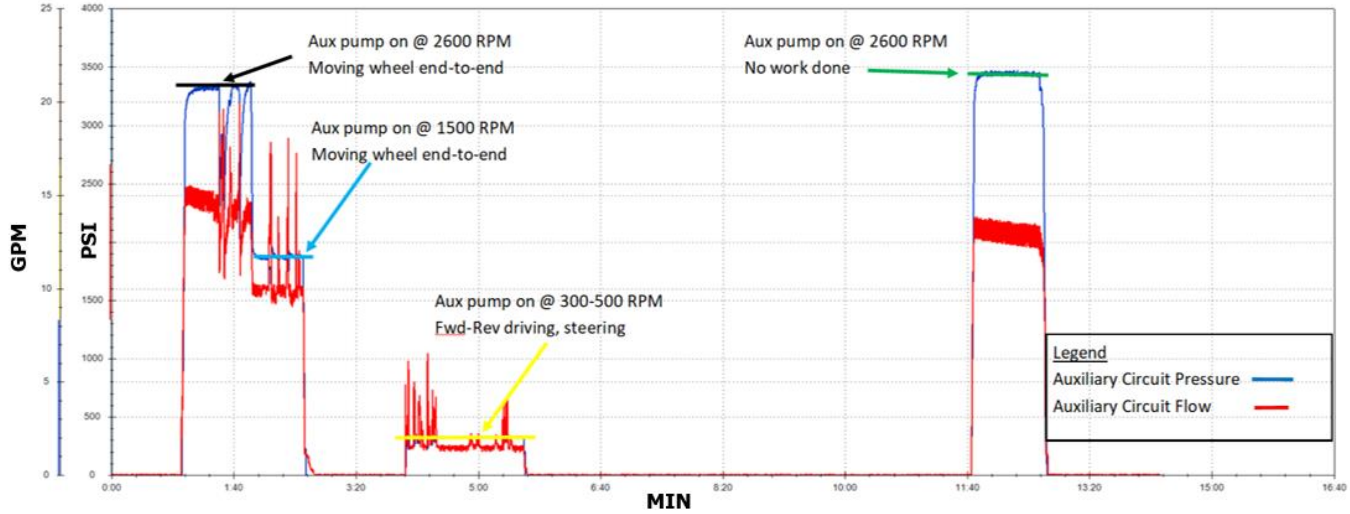
Figure 23: First – General Data Collection



Source: Terzo Power Systems

Following the general testing activity, the project team developed a targeted scope of data collection for each hydraulic system. The purpose of the data collection exercise was to narrow initial expectations of work functions and associate the correct sensor output to the appropriate hydraulic circuit. To start, the team isolated the auxiliary hydraulic circuit — which has the primary function of steering the front of the triwheeled harvester — for observation. An important consideration was the type of pump used for this circuit; the gear pump driving this function actually detracts from the overall efficiency of the machine. Future efforts should investigate alternative pump options for this circuit to improve machine efficiency. Figure 24 shows the results of this exercise.

Figure 24: Auxiliary Circuit – Isolated



Source: Terzo Power Systems

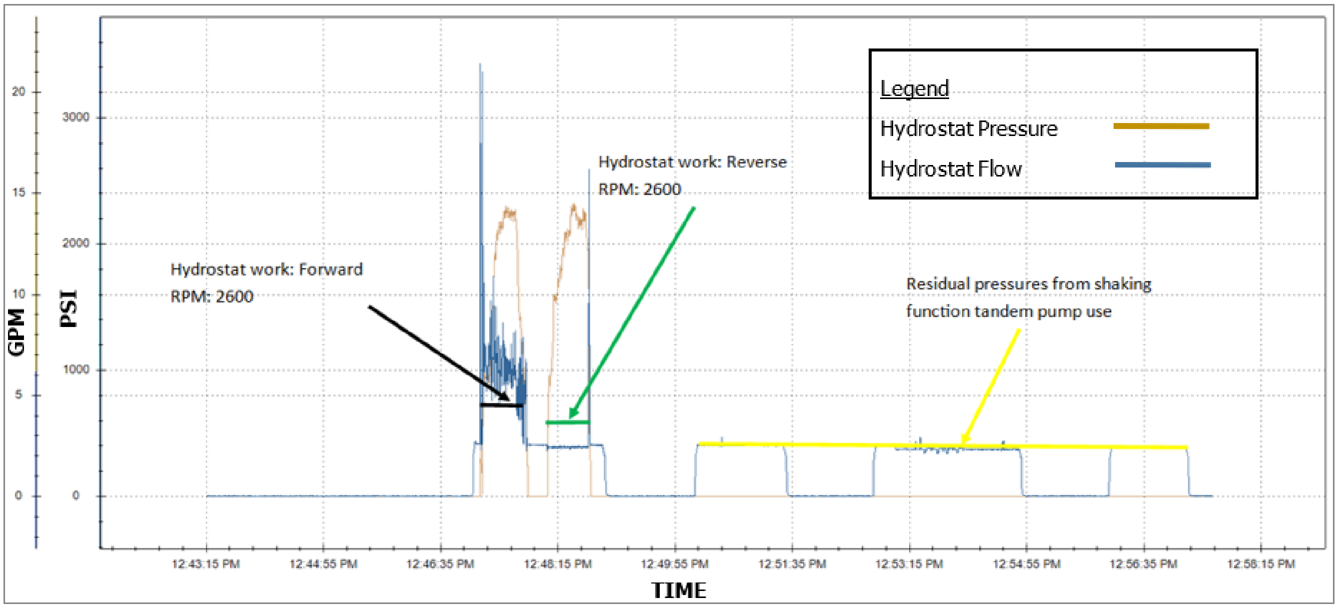
The setup for this session involved enabling the inverter for the auxiliary circuit and confirming operational speed. The initial speed setting was 2,600 rpm, typical of a diesel-powered machine’s engine speed during harvesting activities. The steering wheel turned lock-to-lock for the initial portion of the test. This action is shown in Figure 24 as the initial peaks starting 16 seconds into the test. Afterwards, the engine speed was lowered to 1,500 rpm and the same actions were performed. By gauging hydraulic output at varying speeds, the physical outcome of the hydraulic function can be associated with reduced pressures and flows, which translate to reduced power requirements. This activity opens a path to additional efficiency improvement efforts of the overall system by introducing variable speed architectures to the hydraulic systems. These initial two events took place while the machine was static. This ensured no other hydraulic functions would affect the data collected by introducing residual pressures into the auxiliary circuit.

Figure 25 shows the isolated hydrostatic drive circuit. Machine driving occurred at approximately 12:47 pm, with the data collected for this session at a new pump speed of around 400 rpm. The various peaks indicated by yellow designators in the figure are small corrections of the wheel as the machine was driven forward. Lastly, to show the most prominent areas for improved efficiency, at 12:55 pm the pump speed was increased to 2,600 rpm and the machine was left to idle. The auxiliary pump consumed 27 hp to continuously run without performing work. This is shown and labeled in the last peak shown in Figure 24.

At the same instance, the hydrostatic drive was logged while the machine was driven. To duplicate the operating conditions that would be seen in a standard baseline machine, drive pump speed was adjusted to 2,600 rpm. Dark blue lines in Figure 25 are recorded pressure readings, while brown peaks display flow demand while in motion. In this case, the two flow peaks are associated with driving forward (first peak) and reversing (second peak). Because of the nature of a hydrostatic drive circuit and the location of the data collection instruments, there would be zero pressure readings from the sensor when driving the vehicle in reverse (which is seldom in actual harvesting functions) This is evident in the flat 350-400 psi pressure reading for the second peak associated with reversing the machine.

The interesting features of the collected data in this exercise are the “residual pressures” indicated by the horizontal yellow line for the remaining session. While no actual work from the hydrostatic drive was performed during this timeframe, the data collection did detect induced pressures while the shaker head was being used. Further insight here is warranted, but this presents an improvement opportunity for increased hydraulic component life if residual pressures could be eliminated.

Figure 25: Hydrostatic Drive Circuit – Isolated

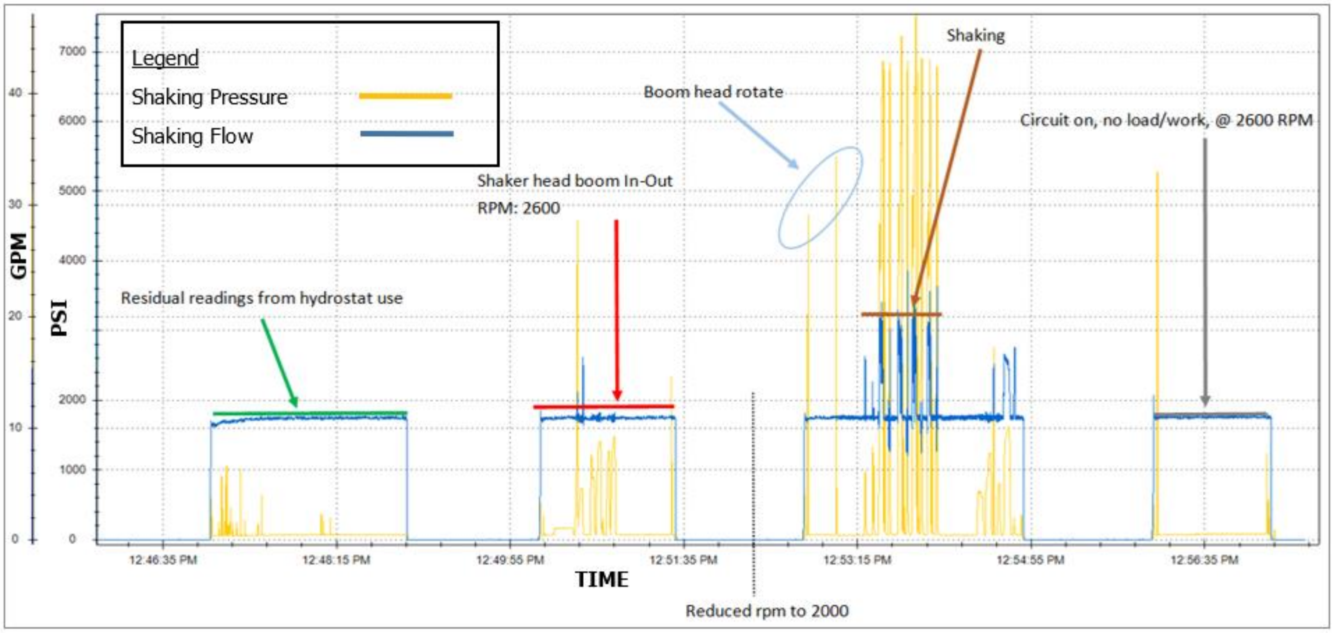


Source: Terzo Power Systems

Figure 26 shows the isolated hydraulic circuit associated with boom manipulation and shaking. Initial review of the data showed increased activity throughout this validation exercise. The first event showed residual pressure behavior similar to when the machine was propelled using the hydrostatic pump. These pressures, in both previous isolated tests, are attributed to the tandem pump setup consisting of the hydrostatic and shaking hydraulic circuits. The second point of activity occurred at 12:50 pm. The shaker arm (boom) has various actuators to articulate three primary movements: (1) linear motion of the boom to extend the shake clamps and grip a tree, (2) rotation of the boom from an axis parallel to the ground, and (3) shake sequence to release nuts from a tree. Performing the shake sequence movement consumes the most power. Applying the hydraulic power equation HP = PSI x GPM/1714 using maximum flow and pressures of 43 GPM and 3,200 PSI respectively results in an estimated maximum 80 hp required for the shake sequence.

The articulation of the boom and the time it is in use is negligible compared to the rest of the functions. Depending on operator manipulation, the boom extension, including retraction, can be anywhere from six to eight seconds per tree shaking session. Three seconds of staging over a one-hour harvesting session takes approximately 0.13 kWh.

Figure 26: Shaking Circuit – Isolated

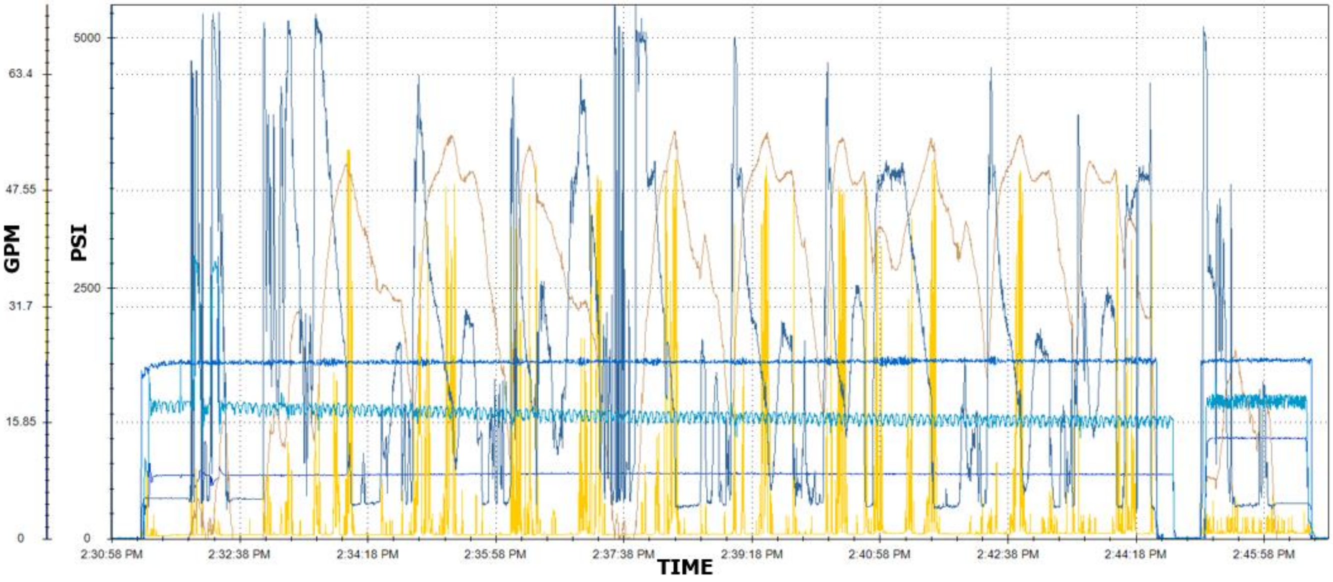


Source: Terzo Power Systems

As a final data collection test, the machine was driven for two laps of 1.3 miles each for a total transportation distance of 2.6 miles. As an inclusive test for the overall functionality of all subsystems, the 2.6-mile mobility event included observation of propulsion circuit as well as continuous battery charging to gauge power required (hydraulics) and power generated (battery charging). This test provided the groundwork for gauging the benefits of the CNG-hybrid power system over conventional diesel versions.

Figure 27 shows the full data set for the test sequence mentioned above.

Figure 27: Mobile Transport Data



Source: Terzo Power Systems

The primary purpose of this test was to expose the machine to a loading scenario that had not been performed before and empirically observe the stress response of all subsystems. The machine used nearly 8 kWh of energy for propulsion and steering during the 36-minute transport test. During the test, the CNG engine was operating continuously to supply energy to charge the batteries. The engine was able to provide enough energy to deliver a surplus to the battery, resulting in a positive net battery voltage change by the end of the test.

Emissions Benefits

The results with the most impact for this project were the reduced greenhouse gas emissions enabled by the CNG-hybrid power system. Machine testing and fuel consumption analysis showed a 27 percent reduction improvement in this category. Table 6 compares operation of the CNG and diesel engines.

Table 6: Compressed Natural Gas-Hybrid and Diesel Engine Comparison

	Diesel	CNG
Per-hour fuel consumption	4.03 gal/hr	4.48 DGE/hr
BTUs per hour	517,858 BTUs/hr	576,576 BTUs/hr
Capable run-time	17.36 hrs	3.13 hrs
Fuel consumption vs diesel	-	+4.35%
CO_2 emissions	90.68 lbs	66.13 lbs

Source: Terzo Power Systems

With a baseline understanding of emissions output for both engine types, the advantages are evident for the use of CNG rather than diesel. Using a base operation of one-hour run-time for each engine, the following assessments were gathered.

An immediate observation is the 4.35 percent increase in fuel consumption of the CNG engine (in DGE units) compared to diesel. For cost comparison, the price of CNG currently is 44 percent that of diesel. At a conservative use of 500 hours of operation a year, 4.03 gal/hr * 500 hrs = 2,015 gallons of diesel fuel is used. At current average diesel prices in California of $3.507/gallon, 2,015 gallons of diesel costs $7,066. For CNG, 2,240 DGE of CNG would be used in 500 hours of operation. Using 1.155 as a conversion factor from DGE to GGE yields 2,587 GGE (CNG is dispensed and priced using GGE units). The current average price for 1 GGE of CNG is $1.549. This amounts to $4,007 to operate the CNG engine for the same amount of time, with the difference in savings equating to 43 percent of the cost of using diesel.

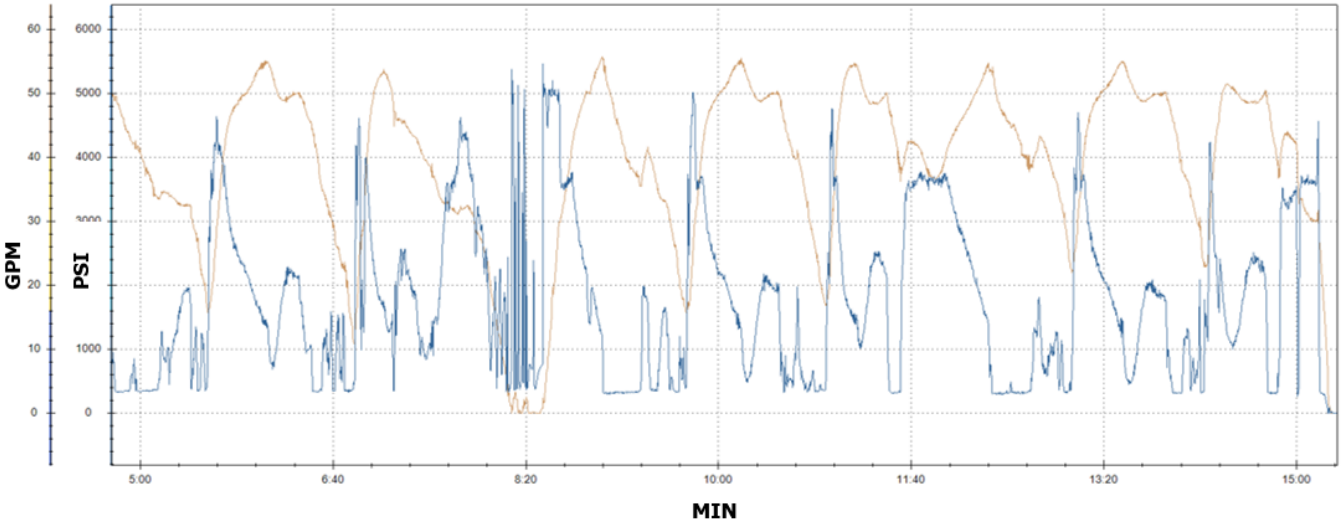
A key element that allows for the agnostic selection of engine fuel type stems from the decoupling of the engine from a machine’s hydraulic systems. Instead of the hydraulic pumps normally rotated by the engine’s crankshaft, there is an electric generator used to charge a high-voltage battery. The batteries now drive electric motors coupled to the individual hydraulic pumps. This architecture enables the machine to operate using a smaller and lesser-powered engine to perform the same amount of work as an engine with twice the power.

Data acquisition equipment installed on the hybrid machine during the demonstration enabled observation of power draw from each hydraulic circuit. Of the three main functions, derivation of energy will be discussed for the two prominent circuits: propulsion and shaking.

Vehicle propulsion demanded the most power. Figure 28 shows the pressure and flow data for 10 minutes of driving the machine for the purpose of extracting power and energy consumption numbers. During the 10 minutes, the vehicle propulsion demanded an average of 44.68 kW (59.57 hp). Power was averaged due to the difficulty in maintaining a constant speed.

Typical shaking activity in an almond orchard involves shaking four trees a minute with 3 seconds of propulsion between shakes (3/3,600 of an hour), taking 44.68 kW to move the machine. The time to move from one tree to the next uses 0.0373 kWh. Multiplying this amount by 4 trees per minute and by 60 minutes in an hour yields 8.94 kWh needed for vehicle propulsion for one hour of typical operation.

Figure 28: Mobile Transport - Propulsion

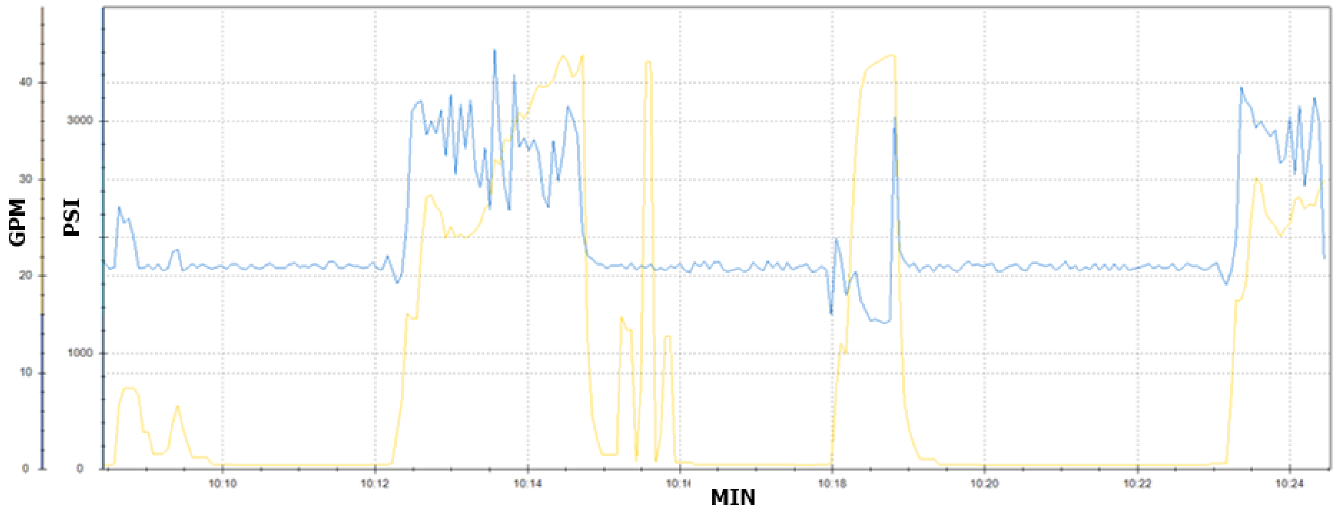


Source: Terzo Power Systems

Figure 29 shows a 3-second shake cycle for the purpose of establishing energy use. Average hydraulic pressure and flow numbers are 2,973 psi and 31.29 GPM. Following the hydraulic power formula yields 50.98 hp (38.2 kW). Shaking times vary by tree maturity and operator experience, but a 10-second shake time is used in the following example. A 10-second shake time corresponds to 1/360 of an hour. Utilizing the same harvesting goal of 4 trees per minute, 38.2 kW * 1/360 = .1061 kWh of energy for a 10-second shake. One hour at this pace requires 25.46 kWh.

In this case, the combined total energy used for propelling the machine to stage for a shake and the shake activity itself for an hour of continuous activity is 34.4 kWh based on a harvesting rate of four trees per minute. As described previously, the battery capacity was scaled down from 60 kWh to 20 kWh because of space constraints. Due to manufacturer recommendations to keep the battery at or above a 320 VDC to prolong battery life, the battery pack can hold up to 16 kWh of "useful" energy. The battery can sustain approximately 30 minutes of harvesting duties before reaching the 320 VDC threshold and requiring recharging. This is the equivalent of shaking close to 110-120 almond nut trees. In future efforts, early design phases can include battery capacity optimization studies to achieve a more optimal level of all-electric capability.

Figure 29: Harvest Activity – Shaking



Source: Terzo Power Systems

Total energy output required for one hour of sustained harvesting activities was calculated to be 34.4 kWh. This represents hydraulic energy based on the collected pressure and flow data. At the point of collection, there had been five different upstream energy conversions at the following estimated efficiencies:

1. Chemical (fuel) converted to engine (mechanical, 38.46 percent)
2. Engine (mechanical, 38.46 percent) converted to electrical (inverter/generator, 92.6 percent)
3. Electrical (inverter/generator, 92.6 percent) converted to chemical (battery, 85 percent)
4. Chemical (battery, 85 percent) converted to electrical (inverter/electric motor, 92.6 percent)
5. Electrical (inverter/electric motors, 92.6 percent) converted to mechanical (hydraulic motor, 60.69 percent)

These efficiency percentages yield an overall fuel-to-hydraulic energy output efficiency of 17 percent. To produce 34.4 kWh of useful energy, 202.15 kWh of energy must be supplied by the CNG fuel. The CNG engine has a 38.46 percent efficiency, leaving 77.75 kWh of energy available originating at the engine. Since the maximum power output of the engine is 65 kW, the battery pack must supply the remaining 12.75 kWh of energy. Furthermore, this shows that the engine is highly likely to be operating at full load during harvesting activities to keep battery voltage above the required capacity.

This chapter shows some key advantages of using a CNG-hybrid as a power platform in lieu of diesel, including lower greenhouse gas emissions and fuel costs. The hybrid configuration can also enable flexibility in engine run-time, which may compound these benefits with further optimization.

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

Terzo Power Systems is committed to innovation continuous product improvement based on interaction with members of the public ranging from OEMs to product users. Terzo Power Systems designed the hybrid-electric power system for this project to provide a commercialized solution for the off-highway market that will benefit the public and relevant regulatory agencies by enhancing quality of life and sustainability practices. The research team engaged in the following technology and knowledge transfer activities during the course of the project.

- Terzo Power Systems exhibited at ID Technology Expo in 2017[6] in the emerging technology category of the exposition. Terzo Power Systems engaged with the public to share the vision for off-road electrification and speak with industry professionals to gain insights on challenges to electrification.
- In 2018, Terzo Power Systems collaborated with AgStart and exhibited at the City of Woodland's "Dinner on Main" event,[7] which promotes locally based agriculture through education, community outreach, and networking. The benefits of reduced emissions and equal performance to diesel enabled by the CNG-hybrid technology were discussed and shared with the attending public.
- Terzo Power Systems' efforts and exposure with the CNG-hybrid project led to recognition and nomination for an award in the 2018 Sacramento Region Innovation Awards in the sustainability category.[8] As part of its nomination, Terzo Power Systems gave a presentation on the benefits of low carbon emissions and electrification.
- Also in 2018, in an effort to further communicate this project's work to the public Terzo Power Systems hosted a site visit for Assemblyman Kevin Kiley and showcased the CNG-hybrid machine at the Terzo Power Systems facility.
- Terzo Power Systems exhibited the hybrid technology and showcased components of the electro-hydraulic subsystem in the 2018 Impact Global Venture Summit in Sacramento, California.[9] As an exhibitor, Terzo Power Systems was able to engage with the public and communicate how the technology could achieve competitive performance from a non-diesel platform.

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[6] IDTechEx Show. IDTechEx Launchpad. https://www.idtechex.com/electric-vehicles-usa-17/show/en/launchpad.

[7] Terzo Power. Terzo Hits "Dinner on Main". https://terzopower.com/terzo-hits-dinner-on-main.

[8] Sacramento Innovation Awards. 2018 Sacramento Region Innovations Awards – SUSTAINABILITY Finalists. https://www.sacramentoinnovationawards.com/winners.

[9] YouTube. 2018 Impact Global Venture Summit. https://www.youtube.com/watch?v=I71o31GBmnI.

- As a founding board member of the California Mobility Center (CMC), Terzo Power Systems traveled to Germany in 2019[10] to advocate for electrification efforts in California and shared how the CNG-hybrid technology conforms to the goals of the CMC.
- In 2019, as exhibitors for the Motion+Power Exposition in Detroit, Michigan,[11] Terzo Power Systems promoted the technology to a larger audience and broader industries outside of California. The focus was education about the subsystems approach and ways to expand the strategy to other applications.
- Terzo Power Systems attended the Tulare Ag Expo in 2019[12] as a spectator and conducted informal conversations on the technology with the public. Also, Terzo Power Systems gathered information on other hybrid technology-related research and development activities being conducted by local original equipment manufacturers.

Efforts to commercialize the technology have been underway throughout the course of the project. Plans for commercialization have evolved to target the market in two ways. First, Terzo Power Systems' sister company, HEVI Hybrids, aims to support future direct sales of the subsystems in addition to third party hardware integration (HMIs, logic controllers, joysticks). HEVI Hybrids was created to provide a platform and one-stop solution for all heavy equipment electrification needs. It was primarily under this name that the outreach efforts listed above were performed.

Focusing on impacting broad transportation electrification efforts, Mike Terzo, CEO and Founder of Terzo Power Systems, is one of a twelve-member board of directors to the CMC. As a board member, Terzo Power Systems is poised to be a voice in communicating where the off-highway industry is headed in terms of the performance of hybrid-electric systems and the technology now available to assist in providing complete scalable solutions.

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[10] Twitter. PEM Motion. https://twitter.com/pem_motion/status/1151422285292724224.

[11] Terzo Power. Hydrapulse Hits the Motion+Power Tradeshow. https://terzopower.com/hydrapulse-hits-the-motionpower-tradeshow/.

[12] Terzo Power. Tulare Farm Show 2019. https://terzopower.com/tulare-farm-show/.

CHAPTER 5: Conclusions and Recommendations

The CNG-Hybrid Power System for Mobile Vehicles project addressed challenges that required the development of a technology not present in the marketplace at the time. The results of such development provide answers and knowledge to common barriers for both technology adopters and to OEMs interested in electrified off-highway solutions. Prior to the project, there were no single-purchase options for an integrated safety hub and power conversion solution or a stand-alone high-voltage HVAC system. While the project categorized six subsystems, the researchers identified three of those subsystems as missing or underdeveloped in the current market and necessary for development of a complete hybrid architecture:

1. HVAC cab comfort subsystem
2. High-voltage safety subsystem
3. Electro-hydraulic subsystem

With the concurrent development of the above three subsystems completed and integrated with the other subsystems, Terzo Power Systems can provide a seamless experience for machine operators interested in adopting hybrid-electric architectures. Terzo Power Systems also demonstrated that performance expectations can be maintained when transitioning from traditional diesel power plants to a hybrid-electric architecture.

Recommendations

The project faced several obstacles related to the use of CNG that have the potential to hinder adoption of the technology. Solutions to the following major details were outside the scope of this project and further consideration should be given to gather wider acceptance.

There is a lack of onsite fueling capability for CNG tanks in agricultural environments. In certain uses, such as almond nut harvesting, multiple fill-ups of CNG are needed to be performed to provide equal run-time to a diesel engine. In this project, the baseline machine 70-gallon diesel tank had an estimated run time of 7.6 hours, while the CNG engine only had 3 hours of run time before needing to fill up. The inconvenience of increased refueling frequency to keep pace with uninterrupted diesel run time is a critical barrier. The lack of mobile, quick refueling of high pressure CNG detracts from the competitiveness of CNG as a fuel for agricultural applications.

The project was limited to a 16 GGE CNG fuel tank due to limited available space on the machine because additional storage capacity would have required heavy modifications. Future improvements in high density CNG fuel storage technology should be pursued to improve the competitiveness of CNG with diesel in the off-road equipment market. For example, “conformable storage” solutions (Figure 30) can increase CNG storage capacity for the tree shaker by 23 percent to 40 percent by more closely integrating with the machine’s envelope.

Figure 30: Conformable Storage Example

Source: NVG Global

Thorough understanding of hydraulic system loading during real-time harvesting activities will allow for improved control algorithms from the master controller subsystem. For example, room for improvement lies in the actuation of the electric motors responsible for engaging the hydraulic pumps. By only engaging the pumps needed to accomplish certain tasks, a power-on-demand control scheme would contribute to the efficient use of battery energy and a decreased duty-cycle of the CNG engine. Currently, the electrohydraulic controls are performed manually to operate similarly to the baseline machine. To effectively carry out these improvements, a robust and comprehensive data set of harvesting activities would be needed for extensive analysis. The data set would need to represent harvesting activities from both the experimental machine and baseline diesel version as used in an authentic harvesting environment. For increased accuracy of energy expenditure, additional instrumentation is recommended to be installed to measure battery output power. In-use data collection on engine loading should be pursued for expanded understanding of emissions output from both types of engines and architectures.

In addition, the project also identified potential opportunities for further efficiency improvements enabled by the hybrid-electric architecture. For example, variable speed hydraulic architectures can lead to additional efficiency improvements. Complimentary technology developed by Terzo Power Systems, called Hydrapulse® (Figure 31), has the potential to address this need and raise the efficiency ceiling of a compact electro-hydraulic solution. The Hydrapulse[13] technology was not ready for use in this project, but the approach to integrate the electric motor, inverters, and thermal management equipment into a compact system addresses many of the unfavorable characteristics such as weight, overall cost, integration complexity, and space claim related to the electro-hydraulic subsystem solution in the hybrid machine.

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[13] Terzo Power. Hydrapulse. https://terzopower.com/hydrapulse/.

Figure 31: Hydrapulse Product Line

Source: Terzo Power Systems

CHAPTER 6: Benefits to Ratepayers

The CNG-hybrid machine developed and demonstrated in this project represents an electrified, low-emission alternative to conventional diesel-powered off-highway equipment. In severe air quality nonattainment areas — like the San Joaquin Valley — where the majority of land is agricultural, the importance of a solution to improve air quality and reduce adverse respiratory health in the region is high. San Joaquin Valley is surrounded by mountains, resulting in trapped air pollutants, and emissions from diesel-powered heavy equipment, irrigation pumps, and tractors in the agricultural sector exacerbates air quality issues.

This project showed that a CNG-hybrid tree shaker machine can fulfil the same functions as a diesel-powered baseline machine while emitting 27 percent fewer CO_2 emissions. This reduction was accomplished by developing a hybrid-electric architecture that allows the machine to operate with half the power requirements from the engine. The architecture also enabled use of a downsized CNG engine with lower emissions. Transitioning 10 percent of the 8,845 nut harvesting machines to this CNG-hybrid technology will result in 411 metric tons of reduced CO_2 emissions annually.

Due to the modularity and scalability of the various subsystems that make up the hybrid-electric architecture, the technology can be adapted to various types of off-road equipment. The same CARB study includes an inventory of agricultural tractors (117,139), forklifts (241), combine harvesters (3,049), and cotton pickers (948). An estimated 30 percent of these machines rely on engines that are under 100 hp. Depending on the duty cycle, these machines can also transition to hybrid-electric or full-electric architectures.

Introducing an electrified solution for the off-highway market supports California's ambitious economy-wide decarbonization goals. Electrified architectures can also reduce air quality impacts and improve public health in communities where off-road equipment is operated.

With increasing efforts to develop electrified variants of equipment powered by combustion engines, improving on the benefits of using alternative fuels is a natural next step. The combined benefits of using an alternative fuel engine in a hybrid-electric architecture in applications where a high-powered diesel engine can be displaced, further add to the number of emissions reductions numbers.

At current fuel rates, CNG costs 44 percent less than diesel. Standardizing a baseline working time of one hour with a load factor of 0.44 applied, the diesel engine consumes 4.03 gallons of fuel while the CNG engine consumes 4.48 DGE * 1.155 = 5.17 GGE. With the current fueling rates referenced in Chapter 3, that equates to $14.13/hr to operate the diesel engine and $8.01 for its CNG counterpart. Table 7 shows that a machine operator can see an approximate 43 percent fuel savings amortized over a year with the assumption of 500 hours of operation per year by switching from diesel to the CNG-hybrid system.

Table 7: Compressed Natural Gas versus Diesel Fuel Savings

	Diesel	CNG
One-year amortization	$7,066	$4,007

Source: Terzo Power Systems

By addressing key barriers related to converting a diesel-powered harvester to a CNG-hybrid architecture, the project demonstrated the potential emissions and cost benefits of electrification and use of alternative fuels. Further development of technology needs to continue to add variability and increase competitiveness for electrified power systems in the off-highway market. Increasing scale across multiple types of equipment will reduce capital costs and enable broader market adoption due to lower operating expenses.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
Ah	Amp hour – Current of one ampere flowing for one hour.
CFM	Cubic Feet per Minute – Air flow unit of measure describing how much cubic feet can be moved or exchanged in one minute.
CMC	California Mobility Center – California institution aiming to support, fund, and assist to commercialize new future mobility technologies.
CNG	Compressed Natural Gas – Comprised of methane, it is one of the cleanest burning fuels. Also used in its liquid form.
CO_2	Carbon Dioxide – A colorless natural greenhouse gas.
COTS	Commercial Off-the-Shelf – Items and services available in the commercial marketplace that can be bought and used.
DOC	Diesel Oxidation Catalyst – Catalyst promoting chemical oxidation of carbon dioxide and hydrocarbons of diesel particulates.
DPF	Diesel Particulate Filters – Exhaust aftertreatment device to trap particulate matter like soot or ash.
EOL	End of Life – Describes the product lifecycle at the end of its useful life.
GGE	Gas Gallon Equivalent – Amount of alternative fuel to equal the energy content of one gallon of gasoline.
GPM	Gallons Per Minute – standard unit for hydraulic flow rate
FMVSS	Federal Motor Vehicle Safety Standard – U.S. federal vehicle regulations specifying design, construction, performance, and durability requirements for motor vehicles.
HMI	Human-Machine Interface – a user interface or dashboard that allows a user to interact with a device.
HVAC	Heating Ventilation and Air Conditioning – Technology for conditioning indoor air quality for comfort.
kW	Kilowatt – Measure of 1,000 watts of electrical power.
kWh	Kilowatt Hour – Measure of electrical energy equivalent to a power consumption of 1,000 watts for 1 hour.
NFPA	National Fire Protection Association – Nonprofit organization devoted to eliminating death, injury, property, and economic loss due to fire related hazards.
NGV	Natural Gas Vehicle – Abbreviation for natural gas vehicle.
NOx	Oxides of Nitrogen – Poisonous gases derived from nitrogen and oxygen and contribute to smog and acid rain.

Term	Definition
OEM	Original Equipment Manufacturer – Organization that makes devices from component parts bought from other organizations.
PM	Particulate matter – Comprises of solid and liquid particles suspended in air.
PSI	Pounds per Square Inch – Pressure resulting from a force of one pound-force applied to an area of one square inch.
RPM	Revolutions Per Minute – Number of turns occurring in one minute.
SAE	Society of Automotive Engineers – Globally active professional association and standards developing organization for engineering professionals in various industries.
SCR	Selective Catalyst Reduction – Active emissions control technology responsible of converting nitrogen oxides into diatomic nitrogen and water.
VDC	Volts Direct Current – Single directional flow of electric charge.

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