FINAL REPORT

Waste Gasification System for Fixed Installation On-site Distributed Generation

ESTCP Project EW-201334

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Energy and infrastructure security are a key part of the DoD's mission. Fixed installations that do not have independent energy supply may be exposed to interrupted service should civilian energy grids fail. Alternative baseload power sources are needed to mitigate this risk. Fixed installations that procure energy from commercial grids are also subject to changing cost, and this can cause budget overruns.
Sierra's FastOx® gasification waste to energy platform is designed to provide baseload power and has the added advantage of eliminating the need to transport waste to landfills. It also can allow DoD facilities to control energy costs by generating on-site power.
The objective of this demonstration project was to validate that FastOx gasification is an environmentally sustainable and economic solution to energy security issues both on DoD installations and in the broader civilian market.

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ACRONYMS AND ABBREVIATIONS

ADG	Anaerobic Digestion Gas
AFB	Air Force Base
APCD	Air Pollution Control Device
ATC	Authority to Construct
ATSI	Andco Technical Services Incorporated
ATSM	American Society for Testing and Materials
BOP	Balance of Plant
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COTS	Commercial Off-The-Shelf
CP	Cost Performance Report
DP	Demonstration Plans
EA	Environmental Assessment
EIR	Environmental Impact Report
EPCM	Engineering, Procurement and Construction Management
FHL	Fort Hunter Liggett
FOB	Forward Operating Base
GHG	Greenhouse Gas(es)
H&MB	Heat and Mass Balance
IC	Internal Combustion
ISBL	Inside Battery Limits
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LFG	Landfill Gas
LDP	Landfill Diversion Percentage
MSW	Municipal Solid Waste
MTPD	Metric Ton (tonne) Per Day
ND	None Discovered
NIST	National Institute of Standards and Technology
NO_x	Oxides of Nitrogen
OM&R	Operations, Maintenance, and Repair
OSBL	Outside Battery Limits

PM	Particulate Matter
ppm	Part Per Million
ppmv	Part Per Million Volume
PO	Performance Objective
PTO	Permit to Operate
PV	Present Value
QA	Quality Assurance
QC	Quality Control
QRP	Quality Recycling Program
RETC	Renewable Energy Testing Center
SCADA	Supervisory Control and Data Acquisition
SO_x	Oxides of Sulfur
SSP	Steady State Period
TG	Test Group
Tonne	Metric Ton
VOC	Volatile Organic Compounds
%vol	Percent by Volume

ACKNOWLEDGMENTS

The Sierra Energy team thanks the Department of Defense (DoD) for its crucial funding and support via the Environmental Security Technology Certification Program (ESTCP). This partnership with the DoD enabled SE to design, build, and commission a first-of-a-kind FastOx® gasification system to demonstrate utilization of waste as an alternative energy resource. The US Army and Fort Hunter Liggett (FHL) has created the ideal testing ground for the system and both were excellent partners and contributors to this project.

Sierra also thanks the California Energy Commission (CEC) for its co-funding via the Alternative and Renewable Fuel and Vehicle Technology Program (ARFVTP). The CEC was instrumental in developing the demonstration plant and the production capability of renewable Fischer-Tropsch liquid fuel from clean synthesis gas.

ESTCP and CEC's participation has greatly increased the speed at which Sierra could develop its first plant and has helped leverage additional commercialization developments, including renewable electricity and renewable hydrogen production from waste at the current location and for future plants.

The team also thanks its entire hard working and innovative team of engineers, business development managers, administrative professionals, consultants and vendors who have worked diligently to develop and implement this first commercial demonstration project.

The Sierra project team would finally like to acknowledge and thank the many individuals who provided guidance and direct assistance in bringing this technology and project to fruition. These include, but are not limited to:

- Todd Dirmeyer, CEM – former FHL Engineering Chief/Energy Manager
- Greg Vallery, PE, CEM – former FHL Director Public Works
- Glenn Woodson – Resource Efficiency Manager, FHL DPW
- Dr. Jim Galvin, PhD – former Program Manager, Energy & Water, SERDP-ESTCP
- Tim Tetreault, PMP, CEM – Program Manager, Energy & Water, ESTCP

ABSTRACT

INTRODUCTION AND OBJECTIVES

Energy and infrastructure security are a key part of the DoD's mission. Fixed installations that do not have independent energy supply may be exposed to interrupted service should civilian energy grids fail. Alternative baseload power sources are needed to mitigate this risk. Fixed installations that procure energy from commercial grids are also subject to changing cost, and this can cause budget overruns.

Sierra's FastOx® gasification waste to energy platform is designed to provide baseload power and has the added advantage of eliminating the need to transport waste to landfills. It also can allow DoD facilities to control energy costs by generating on-site power.

The objective of this demonstration project was to validate that FastOx gasification is an environmentally sustainable and economic solution to energy security issues both on DoD installations and in the broader civilian market.

TECHNICAL APPROACH

Sierra Energy was selected to design, fabricate, install and operate its first commercial scale waste gasification system at U.S. Army Garrison Fort Hunter Liggett to generate on-site energy products and mitigate waste disposal costs at the facility. After onsite preparation, the individual fabricated sections of the plant arrived on-site and were installed. Several phases of commissioning and testing followed each portion of the install. All subsystems were connected to the controls and monitoring system and a full plant commissioning was completed in 2018.

Testing on wood waste was conducted over several short campaigns to create baseline data and further understand the plant operating envelope. The final test of the demonstration phase was completed in February 2019.

RESULTS

Sierra Energy completed the design, fabrication and installation and initial operations of the first FastOx gasification demonstration plant. Sierra Energy compared the results of the operations to the existing baseline case - electricity procured from the local civilian utility and waste collected and disposed of by regional waste hauler. If implemented at FHL again without cost overruns and assuming 100% of the syngas is converted to electricity, the system would provide on-site distributed power at a lower cost and eliminate waste.

BENEFITS

The FHL facility successfully produced syngas and anticipates producing electricity and liquid fuels on-site during future operations. The plant will continue to operate for the expected lifespan of the equipment to mitigate waste on-site and generate baseload power.

This ESTCP funding has enabled Sierra Energy to build its first commercial unit. The project moves the gasification industry forward with both Life Cycle Analysis and Techno Economic Analysis reports, and progress on a new Low Carbon Fuel Standard pathway, and by advancing public knowledge and improving the standard greenhouse gases, regulated emissions and related knowledge bases.

EXECUTIVE SUMMARY

INTRODUCTION

Sierra Energy in partnership with the Department of Defense's Environmental Security Technology Certification Program and the California Energy Commission, installed and demonstrated a commercial scale gasification plant at Fort Hunter Liggett in Monterey County, California. This system is designed to convert municipal solid waste and waste wood generated on base into electricity and ultra-low sulfur clean, renewable Fischer-Tropsch Liquids.

The plant is the pilot of Sierra Energy's patented FastOx® gasification thermochemical conversion process, which breaks waste down at the molecular level without burning. The system utilizes oxygen and steam as catalysts to heat the waste and drive off gases using concentrated oxygen injection. The gas generated by the FastOx gasifier, consisting mostly of H2 and CO, is sent through a gas cleaning isle where impurities such as particulate matter; acidic compounds and other unwanted organic compounds are reduced to acceptable levels. The clean syngas is then sent to a low-pressure header, from which it can flow to a generator to produce electricity or a separate isle to produce liquid fuels.

If utilizing this technology to produce baseload renewable sustainable energy, this DoD installation will gain additional self-sufficiency and reduce vulnerability by operating independent of the civilian power grid. The data collected during the completed and future operations will allow for cost savings calculations and for project managers to interpret the avoided costs of landfilling and energy purchase, as well as environmental impacts.

Sierra Energy is currently in the early operations and demonstration phase. This final report will discuss all significant activity and outcomes that have occurred during the project to this point.

OBJECTIVES

This project tests the hypothesis that the demonstration plant at Fort Hunter Liggett will prove that the FastOx gasification system is a robust, net-energy-producing and cost-efficient way to eliminate waste by converting to baseload electricity, in comparison to the existing practice of waste hauling to landfill and electricity being pulled from the local utility.

Military readiness is compromised when an installation experiences power failure. The DoD's current strategy of obtaining energy from fragile commercial energy grids involves inherent risks. Commercial energy grids are susceptible to service interruptions resulting from natural disasters, fluctuating prices and competition for resources. Though solar energy is a viable source of energy during the day, it does not adequately supply nighttime energy needs. Available options do not provide the resiliency required for the security of installations [1].

A key driver of this project was President Obama’s 2007 Executive Order 13423 [4] that strengthens federal environmental and energy management. This includes provisions to increase renewable energy and landfill diversion and reduce greenhouse gas emissions. Federal agencies were directed “to improve the energy efficiency and reduce greenhouse gas emissions through reduction of energy intensity by (i) 3% annually through the end of fiscal year 2015, or (ii) 30% by the end of fiscal year 2015 relative to the baseline of the agency’s energy use in fiscal year 2003” [4]. The Department of Defense developed a program to address this order that involved inter agency partnerships to “speed innovative energy and conservation technologies from laboratories to military end users” [7], culminating in programs such as ESTCP that are providing funding for this demonstration.

The DoD’s 2011 Strategic Sustainability Performance Plan sets goals for renewables in the military. The targets of this plan are directly addressed by this project including solid waste and construction waste landfill diversion [5]. The primary objective of the project is to help facilitate FHL’s mission of a net-zero waste facility.

TECHNICAL APPROACH

To test the hypothesis stated above, the existing FHL waste and energy operations are measured to provide a baseline. The project equipment is then designed, shipped and installed on-site. The final phase is to test the full plant via operational campaigns according to the demonstration plan. Data acquisition tools and instruments are used throughout the system to ensure adequate data is collected for each objective and phase. Through detailed analysis of operations data, the impact of the FastOx process will be compared to the baseline and conclusions made, which will ultimately measure the potential operational benefits of this renewable energy technology for federal entities.

The project is divided into several test phases and related milestones, and these objectives are further broken down and organized by tasks. Tasks were completed by the project team and managed by Sierra Energy. This team also established phases based on performance objectives reached. Major tasks in this demonstration project are described below.

- Engineering – All major equipment and engineering tasks were divided between the assembled project team that comprised of Sierra Energy and various sub-contractors and outside laboratories. A responsibility matrix ensured the completion of tasks on parallel tracks by the project manager. The core technology design was the first stage of the project in parallel with site specific engineering prior to construction.
- Permitting – This task included air, water, waste, building and facility use permitting. The onsite Fire Department also performed several quarterly inspections and the project team coordinated with Cal OSHA and separately Monterey Country Department of Health to ensure regulatory compliance.
- Construction and Installation – This task included site preparation by the local contractors, off-site fabrication of containerized equipment modules, and delivery and installation of all equipment and utilities connections.
- Operations during Commissioning – There are four phases to this commissioning process. Site Acceptance Testing confirmed that the equipment and subsystems arrived per the original mechanical design specifications. Independent subsystem testing in the middle of its operating envelope was then followed by performance qualification to verify that equipment was functioning across an expanded operating envelope. The last step is ongoing full system testing of the lower and upper limits, and overall plant performance testing that verifies that all subsystems are working in line during full plant operations.
- Operations during Demonstration – Sierra Energy followed a test schedule that included several operating campaigns. This leads into ongoing testing at the facility past the project timeframe and is the final stage of the demonstration portion of the project.
- Transfer of Equipment – When the FastOx gasification testing phase is complete and the system is optimized and proven beneficial, the plant will continue to be operated by Sierra Energy staff in collaboration with Fort Hunter Liggett.

Performance Objectives were established to guide the project and measure the potential benefits of the technology as a renewable energy source. The following is a summary of each performance objective and a description of success criteria.

- Peak Specific Renewable Electricity Generation – An objective value of 700 [kWhe (net)/tonne (into gasifier)], was determined as the baseline for operations on post-recycling residual waste in California.
- Specific Operating Cost – The system operation can achieve unlevelized cost parity or be less expensive than the existing average costs of electricity the installation is paying ($0.176/kWhe in FY18).
- Environmental Benefit – Compare the specific emissions of the project to those of the ‘mixed fossil fuel portfolio’, to validate the environmental benefits of using syngas fuels. The aim is not only to meet the specific emissions of fossil fuels but see significant reductions in each.
- System Turndown – At the reduced 1/10th capacity operations, the SNEP will not drop by more than 25% from the designed value (of 700 kWhe/tonne).

- Landfill Diversion Percentage – At full operations a minimum the goal is set at 75% landfill diversion.
- Total Mass of Material Gasified – minimum of 275 tonnes of material should enter the FastOx gasifier to ensure the system evaluated with satisfactory sample size.
- System Uptime – To exceed 75% online and available status.
- Seasonal Operations Robustness – No major, operationally disruptive qualitative affects observed.
- Odor and Noise – No complaints for either odor or noise.

The objectives were further divided into test groups so that the metrics related to specific success criteria could be collected and analyzed. For each test group, independent, dependent and controlled variables were defined. The operating parameters and campaign goals were designed for system optimization and to meet successful criteria for the performance objectives.

RESULTS AND DISCUSSION

Sierra Energy completed the design, permitting, fabrication, installation, commissioning and early operations-demonstration of a first-of-its-kind oxygen-blown waste gasification system, that as a future technology platform will provide various DoD entities and managers the ability to diversify their waste disposal and energy procurement portfolios, while subsequently increasing energy resiliency, decreasing environmental footprint, and decreasing overall levelized costs. The Sierra Energy team produced syngas at Fort Hunter Liggett during the demonstration campaigns and expects to produce electricity and liquid fuels in 2020. Sierra Energy plans to work with the U.S. Army to ensure that power production can continue for at least 10 years after steady state operations begins, and ideally for the 25-year expected life of the equipment.

Quality assurance and quality control procedures were in place during all operations that included confirmation of major instrumentation calibration such as gas analyzers and flow meters, data analysis to remove outliers and obtain steady state averages and best practices for working with independent laboratory vendors.

Although the plant is still in early operations-demonstration, data was collected from the campaign's steady state FastOx operations on waste wood to syngas. While a major goal is operating the system at steady state and generate electricity, the electrical generator is yet to be operated, so there is not enough empirical data to validate the success criteria relative to actual operations and electricity metrics. In the absence of empirical data, the team used computer simulated data to estimate potential electricity generation, as follows. When 10 metric tons of waste wood feedstock with 20% moisture is introduced into the FastOx gasifier computer simulation model created on Aspen Plus, it predicts a gross electric power output of 521 kWe.

One product of the system is a stone material composed of inorganic materials that is tapped out the bottom of the gasifier vessel. This is a salable product and potentially a revenue source. A sample of this vitrified slag from waste wood gasification was collected after one of the operating campaigns and sent to a lab for analysis for the presence of metals and EPA non-hazardous waste confirmation testing. The results confirmed its determination as 'non-hazardous'.

The following table summarizes the results to date for each performance objective.

Performance Objective	Summary of Results
Peak Specific Renewable Electricity Generation	Current calculations incorporating preliminary plant operating data shows an expected specific net export of 674 kWh_e/tonne, with the goal of 700 kWh_e/tonne at a minimum. This is expected to increase with optimization of the plant and process.
Specific Operating Cost	Current calculations for a repeat 10 MTPD project show an unlevelized Operating Cost of \$0.005/kWh_e.
Environmental Benefit	Without operations on the syngas genset, the manufacturer's own conservative emissions profile guarantees must be used as a placeholder. CO < 5.93 g/kWh_e, NO_x at 2.80 g/kWh_e and NMHC < 1.12 g/kWh_e.
System Turndown	Calculations extrapolated from early operations-demonstration at 2.3 MTPD capacity, shown the SNEP should not drop more than 19.7% at 10:1 (1.0 MTPD) operations.
Landfill Diversion Percentage	Unable to validate on MSW feed materials due to absence of operating data with MSW, but on wood waste is in the 95–99%wt. LDP range.
Total Mass of Material Gasified	7.5 tonnes of materials gasified in early operations-demonstration. At 5 MTPD (50% throughput capacity), will require 54 days of operations to reach success criteria of 275 tonnes.
System Uptime	Insufficient data to evaluate given limited operations beyond commissioning.
Seasonal Operations Robustness	Initial environment-related equipment failures have been resolved. However, increased waste material moisture content will lower overall operating efficiency. This can be mitigated with a waste pre-dryer that reutilizes waste-heat from the system.
Odor and Noise	No complaints to-date and would likely not be an issue for most semi-industrial DoD installation settings, especially with mitigation measures readily available.

A simple cost model for the FastOx gasification facility was also completed. The cost included leveraged funds from stakeholders other than grants, including Sierra Energy and Fort Hunter Liggett. Based on this costing analysis, a repeat project without cost-rework and design would be economical. The following costing elements were considered: permitting, site preparation, installation, consumables, operations and maintenance, hardware and salvage value. This information was further assessed through a Life Cycle Cost Assessment, which compares the baseline case that uses the civilian electrical utility provider and waste disposal service providers and the FastOx gasifier system case. The study determined that the FastOx gasification system provides the lower cost indicating that it is the preferred solution with net savings of \$3.2 million over the conventional baseline approach over the 20-year analysis period.

IMPLICATIONS FOR FUTURE RESEARCH AND BENEFITS

ESTCP funding has enabled Sierra Energy to build its first commercial system in California and demonstrate the FastOx process with a full balance of plant. The project also moves the gasification industry forward in terms of knowledge and operating data. In addition to the project specific objectives, Sierra Energy and the project team have advanced several ancillary studies as a result of this plant. A Life Cycle Analysis and Techno Economic Analysis report was generated in collaboration with our university partners, a new Low Carbon Fuel Standard (LCFS) pathway was discovered, and several public and private research entities have communicated with Sierra Energy on future studies.

Sierra Energy and the project team will continue to collect and evaluate the operations data to further

Future applications for the DoD include operations at both domestic and foreign operating bases. At different scales FastOx can be applied at a wide range of existing installations serving diverse populations. There are considerable benefits to adopting the FastOx technology as a deployable solution for overseas missions, to supplement existing generators and offset diesel and JP-8 requirements. This technology implementation in foreign territories would also mitigate the need for convoys to transport waste, resulting in further reduction of risk during missions [1].

1.0 INTRODUCTION

Sierra Energy is currently in the early operations and demonstration phase (operations-demonstration) of the FastOx® waste gasification technology at U.S. Army Garrison Fort Hunter Liggett (FHL). This final report will discuss all significant activity and outcomes that have occurred during the project to this point.

1.1 BACKGROUND

Security is the DoD's primary mission; however, reliance on fragile civilian energy grids puts that mission at risk by weakening the fixed installation's security. Such reliance also burdens the DoD with increasing energy costs at homeland facilities, not just due to the trend in local rate/price increases, but also when the DoD reduces its military presence outside the U.S. and troops return to homeland facilities, thereby increasing power consumption at these facilities.

Increased Energy Security and Resiliency: Military readiness is compromised when an installation loses power. The DoD's current strategy of obtaining energy from fragile commercial energy grids involves inherent risks. These risks include competition with civilian communities for limited energy supplies, increased peak energy costs, and the risk of brownouts or blackouts that can leave installations without power. Commercial energy grids are also susceptible to natural disasters that can interrupt energy supplies for extended periods. Though solar energy can provide needed electricity during the day, it does not adequately address nighttime energy needs without significant energy storage capacity. Current options alone do not provide the resiliency required for the secure operation of these [1]. Alternative baseload energy sources that can provide power, such as waste to energy, decrease dependence on any one energy resource.

Reduced Waste Disposal Costs: Sierra's FastOx gasification platform has the added advantage of reducing waste disposal costs. It disposes of waste without the high parasitic loads, capital expenses, and ash disposal problems that plague other waste conversion technologies.

Reduced Energy Costs: Fixed installations that obtain energy from commercial energy grids incur fluctuating and ever-increasing energy costs that can not only be prohibitively expensive but can also make budgeting difficult. Sierra's FastOx gasification platform helps alleviate these problems, putting the DoD facilities in greater control of their energy supply.

Reduced Greenhouse Gases: Every tonne of waste disposed in a landfill emits approximately one tonne of Greenhouse Gases (GHGs) [2]. These emissions diminish the DoD's efforts to meet its waste [3] targets. The DoD's initiatives are further hampered by the carbon footprint of the non-renewable energy sources that power the commercial energy grids used by most DoD installations.

1.2 OBJECTIVE OF DEMONSTRATION

The objective of the demonstration is to verify that a FastOx gasifier is a cost effective, environmentally beneficial way to achieve energy resiliency and security. Results from the demonstration project are expected to help DoD, and other potential users, make informed decisions on the deployment of future systems, identify optimal locations and quantify the potential benefits. An enhanced data acquisition system will track material throughput, energy production, maintenance and repair costs, and outputs.

In addition to increased energy security and reduced energy costs, the FastOx gasifier will reduce greenhouse gas and other pollutant emissions compared to conventional operations. By diverting a single tonne of waste from a landfill to the FastOx system, 1 tonne of CO_2 equivalents (mainly from methane gas) is prevented from release into the atmosphere [2]. When combusted in a genset, syngas produced by the FastOx gasifier produces lower criteria pollutant emissions compared to fossil-derived diesel or JP8.

During commissioning and early operations-demonstration phase, policymakers, energy managers, scientists within the DoD and consultants have had the opportunity to visit FHL and see the FastOx system in operation. When coupled with the results from the long-term operations, this firsthand experience is expected to accelerate the acceptance of FastOx technology throughout the DoD.

1.3 REGULATORY DRIVERS

The principal driver for this demonstration was President Obama's 2007 Executive Order 13423 [4] which strengthens federal environmental and energy management and includes provisions to ensure that renewable energy production is increased, greenhouse gas emissions are reduced and an increase in solid waste diversion from landfills is achieved. The heads of each Federal agency were directed "to improve the energy efficiency and reduce greenhouse gas emissions through reduction of energy intensity by (i) 3% annually through the end of fiscal year 2015, or (ii) 30% by the end of fiscal year 2015 relative to the baseline of the agency's energy use in fiscal year 2003" [4].

The DoD's 2011 Strategic Sustainability Performance Plan [5] sets objectives for the military to provide alternate renewable energy sources and cut greenhouse gas emissions. These targets are specifically addressed by Performance Objectives (POs) 1 and 3 of this project. Performance Objective 4 of this project targets solid waste landfill diversion at 50%, and construction and demolition waste landfill diversion at 60% [5]. The goal of the project is to help facilitate FHL's mission of a net-zero waste facility. Building on this approach, the DoD's Integrated (Non-Hazardous) Solid Waste Management Policy also sets forth a plan that includes waste volume reduction via conversion to energy [6].

The DoD also responded to the aforementioned E.O. 13423 [4] with an intent to partner with other agencies, such as the Department of Energy, to "speed innovative energy and conservation technologies from laboratories to military end users" [7], culminating in programs such as ESTCP that are providing funding for this demonstration.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

Sierra's FastOx gasifier deployed at FHL is a 10-tonne-per-day ("MTPD") waste-gasification system that efficiently converts virtually any form of waste into renewable energy.

Sierra's compact and integrated FastOx gasification system consists of many modularized major equipment items including a waste pre-processing unit, an air-separation unit ("ASU") for oxygen generation, a FastOx gasifier, a polisher to breakdown condensable hydrocarbons, gas conditioning equipment, a control, utility skid, and an electrical genset. Shown below in Figure 1 is a process flow diagram for a generic FastOx waste-to-electricity system. Streams shown in red were originally proposed integrations that were not incorporated due to final system design constraints, however, could be added and implemented in the future to improve system performance and efficiency.

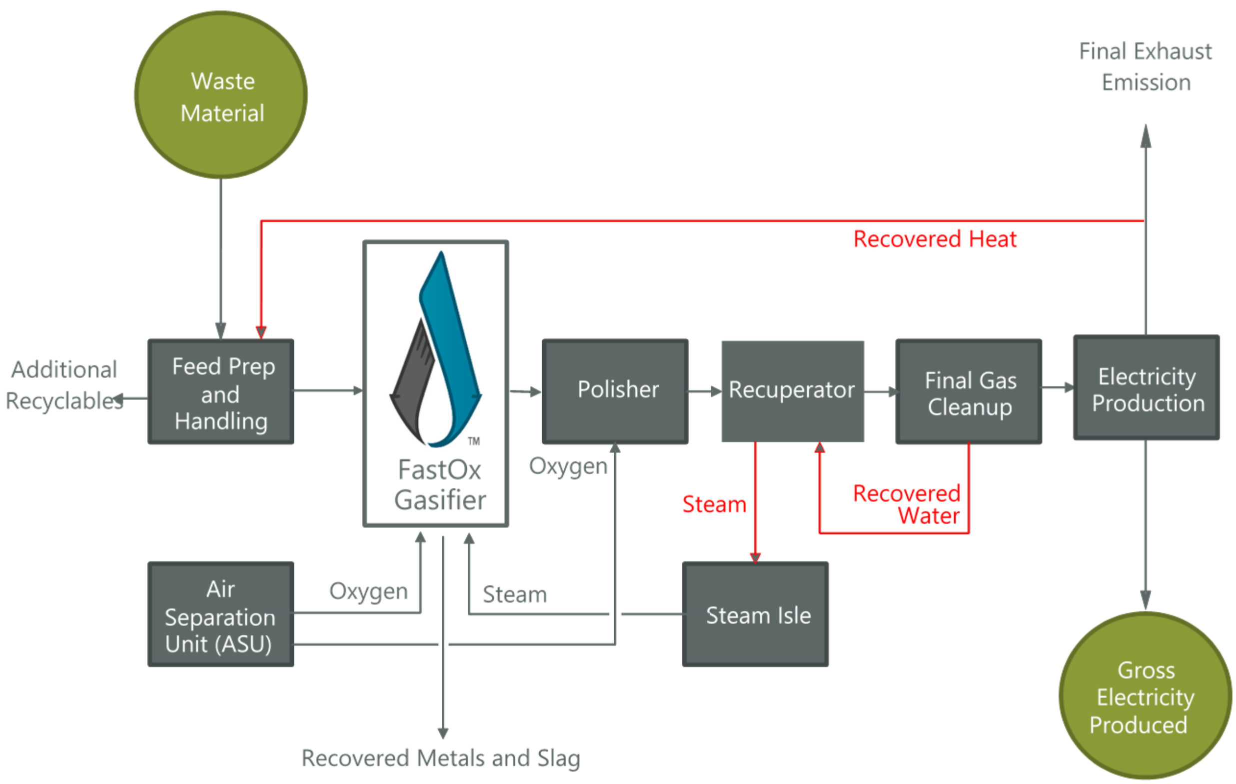

Figure 1. Generic Process Flow Diagram

Waste that is received at the facility gates is sorted by the Feed Prep & Handling section. As directed by environmental permits, recyclables are removed and the remaining waste is fed into the top of the refractory-lined gasifier, while oxygen and steam are injected at the bottom. Here, Sierra's [8] high-temperature thermochemical conversion process breaks down waste at the molecular level to produce synthesis gas or syngas – a mixture of mainly carbon monoxide and hydrogen. The design allows the entire process to occur within a single vessel, with no internal moving parts, minimizing maintenance and increasing uptime.

Syngas produced by the FastOx gasifier flows to a polisher where it is heated to a minimum of 1,500°F to break down condensable hydrocarbons and organic compounds into additional, usable syngas. This gas is sent to the gas cleaning module where any trace contaminants are removed to meet genset and local air permit requirements.

Finally, the genset combusts the cleaned syngas to produce electricity. In the genset, FastOx syngas is anticipated to combust cleaner than conventional atomized liquid fuels. Oxides of sulfur (SO_x) emissions should also be reduced since the syngas contains minute levels of sulfurous compounds after cleaning. Because syngas has a lower energy density compared to conventional fuels, the combustion takes place at lower in-cylinder temperatures, which is expected to lead to a decrease in the formation rate of oxides of nitrogen (NO_x).

Future applications for the DoD include operations at both homeland and foreign facilities. Due to the inherent scalability of the system, FastOx can be applied at a wide range of existing installations of various populations. There is considerable benefit with the integration of the FastOx system into forward operating bases to power gensets already in place, or to offset diesel and JP-8 requirements. The offset results in reducing high-risk convoys in enemy territory, effectively diminishing soldier exposure from what is considered to be one of the most dangerous and enemy-targeted missions abroad [1].

2.2 TECHNOLOGY DEVELOPMENT

Sierra Energy has been constructing and operating various prototypes of its FastOx gasifier (the Mk1, Mk2, Mk3, and Mk4) since July 2009 at the DoD-funded Renewable Energy Testing Center (RETC) located at the former McClellan Air Force Base (AFB) in Sacramento, CA. These efforts resulted in a whitepaper written by the RETC in August 2010 [9].

Sierra built the Mk4 gasifier in September 2010 to test the conversion of multiple waste streams compositions, determine the composition of the resulting syngas and troubleshoot operational logistics. With the addition of significant design updates in 2012, Sierra's Mk4 processed a variety of wastes including shredded tires, sterilized medical waste, biomass, oil shale, coal, synthesized Municipal Solid Waste (MSW) and metals. The gasifier also proved that it recovers molten metals and a non-leachable slag that can be sold as a construction material to replace cement clinker and road base.

In a second RETC whitepaper written in September 2012 [10], preliminary Mk4 data satisfied the following technical objectives:

- Verification of the Mk4's operability with numerous waste materials, all varying in ash and moisture content.
- Validation of increased syngas quality through real-time gas analysis, demonstrating a 118% increase in the dry syngas energy density when compared with conventional air-blown operations.
- Confirmation of the non-leaching character of the vitrified slag coproduct, in accordance with EPA TCLP and TTLC standards, qualifying the slag to be sold as a construction material to replace cement clinker and road base.

- Analysis of the Mk4's performance metrics, indicating a 116% increase in operational productivity and a 185% increase in oxidant productivity.

Shown below is a project timeline beginning the third quarter of 2011 up to the first quarter of 2019 covering major technology developments from feasibility studies until final commissioning phases of the FastOx gasification system (present day).

Table 1. Project Timeline Summary

Year	Quarter	Activity
2011	Q3	Feasibility Study for 50 tons/day FastOx system to be installed at Port of West Sacramento (POWS) near several identified feed stock sources.
2012	Q3	Front End Engineering & Design (FEED) performed. The FastOx process takes a lot of technology from existing blast furnace design, decreasing novel equipment development.
	Q4	Funding award issued by ESTCP, that required the pilot plant be installed at FHL.
2013	Q1	Demonstration project is relocated to FHL; funding from CEC requires project to be located within California and DoD funding requires location to be on Army base.
	Q3	DoD Contract received and finalized.
	Q4	FEED is restarted (with a focus on a smaller, 10 tons/day, pilot plant for FHL). System was designed to be modular and more readily deployable (for DoD requirements).
2014	Q2–Q3	FEED complete (full plant): 1) chemical engineering, 2) control engineering, 3) vessel design, 4) full CAD
		Air Permit 'Authority to Construct' (ATC) application package submitted to Monterey Bay Air Resources District (MBARD)
2015	Q1	Air Permit ATCs received from MBARD
		Wastewater and Water Use permit applications submitted to Central Coast Regional Water Quality Control Board
		Engineering Package completed and used to initiate the process of selecting a modular fabrication shop
	Q2	SE now files Solid Waste Permit documents with the Local Enforcement Agency (LEA) Monterey County Dept. of Health & Sanitation
	Q3	Modular Fab shop selected to build and deliver the modular equipment
2016	Q1–Q2	FHL Directorate of Public Works (DPW) took lead on ASME pressure vessel standards compliance
		LEA provides the required final environmental permit for this project
	Q3–Q4	Major equipment arrivals at FHL
2017	Q1	Major equipment arrivals at FHL
	Q2	Site Acceptance Testing (SAT) begins
	Q3	SAT and Subsystem Operational Testing (SOT) continues
		Wiring and electrical work completed
	Q4	SAT and SOT continues
2018	Q1	PPT Commissioning begins – issues with burner subsystem identified
		Burner modifications and testing to accept premix initiated
	Q2	Polisher refractory cure completed
	Q3	Gasifier refractory cure completed with modified burners
	Q4	Campaign with waste wood materials
		Campaign with pre-loaded feedstock & waste wood materials
2019	Q1	PPT Commissioning continues and system operated in 'FastOx Mode'.

Where: FAT = Factory Acceptance Testing
SAT = Site Acceptance Testing
SOT = Subsystem Operational Testing
PPT = Plant Performance Testing

Currently the system is in early operations-demonstration phase, each major subsystem has been individually tested, some key components have been identified as requiring future upgrades, after which the project team will move to completing the operations-demonstration phase (including process optimizations via Design of Experiments (DOX) methodologies). Plant Performance Testing (PPT) of the entire facility is ongoing where the interaction between individual pieces of equipment or unit operations is being tested. The system deployed at FHL reached 'FastOx' mode in January 2019 where operations at a consumption rate of ~2 metric tons per day of waste wood feedstock were achieved.

The next big milestone is operations at 10 metric tons per day of waste wood and then operations with MSW. Sierra Energy expects that this will be achieved in Q1 2020. Many of the POs of this project can then be fully assessed as per the testing procedures summarized in this report.

After the successful testing and optimization of the plant, Sierra Energy anticipates cooperating with the US Army and FHL to ensure that operation of the FastOx gasification system can continue not only for assisting FHL with their energy and environmental goals, but also providing a platform for educating and training various branches of the DoD and for Sierra Energy to acquire data on various feedstocks and operating parameters. These continued demonstration findings and briefings – generated even after the close-out of the ESTCP contract – will continue to be available for presentation back to the ESTCP committee and other interested DoD entities.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Advantages

Scale-Up: while Sierra Energy's FHL system is a 10 MTPD unit, Sierra expects that its FastOx technology can accept thousands of tonnes per day in a single vessel since the technology shares the same basic design as the proven industrial iron-making blast furnace. Future scale-ups of Sierra's FastOx system present a relatively risk-free exercise of increasing the volume of major reactor vessels and auxiliary equipment while retaining most operating procedures and control algorithms.

Figure 2. Sierra Energy's Gasifier, Polisher & Recuperator Nearing Mechanical Install Completion in 2017

Simple, Robust Design: FastOx gasifiers are designed for continuous operation with few moving parts. The simple design translates into low maintenance costs, efficient processing of waste and high system up-time.

Thorough Waste Conversion: The ultra-high temperature at which FastOx gasifiers operate breaks down waste efficiently. Organic material is vaporized and collected as a clean syngas while inorganic material melts and is collected as metal and non-leaching inert stone. No toxic ash is leftover.

Flexible Waste Processing: FastOx gasifiers can handle nearly any waste with minimal pre-processing. Depending on the design for a complete system, suitable wastes include MSW auto shredder residue (ASR), construction and demolition (C&D) waste, medical waste, hazardous waste, industrial waste and biomass. Current exceptions are radioactive or explosive wastes.

Minimal Land & Water Use: A FastOx system occupies far less land than other renewable energy technologies. For the same amount of energy, a FastOx system requires a fraction of the space needed for a solar array. While some water is needed to create steam and cool the system, moisture in the waste materials processed can be recovered and reused, and in certain instances the plant can be a net-producer of water, a very valuable feature for certain DoD operational areas.

Production of High Value Products: Due to the low diluent and inters content, FastOx syngas can be converted into a wide range of valuable end-products including renewable electricity, diesel, hydrogen, and ammonia. FastOx systems are designed to be flexibly configured to meet specific customer needs.

Reduced Emissions: FastOx gasification uses purified oxygen instead of air which reduces the availability of nitrogen to form unsatisfactory byproducts, and with smaller total volumes of syngas makes the gas cleaning isles more efficient and cost effective. Incinerators form and re-form toxic dioxins and furans when feedstock is burned; these toxins then end up in exhaust by decomposition, re-forming or passing through the system without undergoing any change. Gasification technologies have been found to have significantly lower emissions than direct combustion systems.

Disadvantages

While Sierra's FastOx technology can be applied to projects at very large scales (1,000 MTPD and above using a single gasifier), Sierra's FastOx gasification system at 10 MTPD is the smallest anticipated commercial unit for common medium-value waste streams. This implies that smaller communities that do not produce that much waste will not be able to take advantage Sierra Energy's technology. (Note, Sierra has been approached by some DoD entities about designing smaller 1–3 MTPD systems for highly-hazardous waste mitigation, which is a potentially-economically viable application for small-volume, high-value waste streams where the focus is on waste mitigation, not efficient energy generation).

The biggest disadvantage of the FastOx gasification system deployed at FHL is the relatively high cost of the first system. Engineering costs for future systems are going to be significantly lower due to the major one-time design costs associated with the FastOx gasification platform at FHL. Optimization of the system at FHL will also help to keep operating costs down – both at FHL and at future FastOx sites.

Compared with conventional landfilling practices, potential barriers for acceptance by operators, maintenance staff and management may arise from the increased operator skill level required, and upfront capital costs. FastOx gasification systems require O2 (typically from an onsite oxygen generator), which does increase the capital cost, however, the system's return on investment (ROI) is improved compared with non-FastOx thermochemical conversion processes. Another disadvantage with FastOx that impacts upfront capital costs is the syngas is typically high in hydrogen (H2), which requires the procurement of expensive European-built internal combustion engine gensets to convert to electricity. Sierra Energy completed an SBIR Phase 1 contract [11] for the Defense Logistics Agency (DLA) to investigate the techno-economic benefits of separating H2 from the FastOx syngas, allowing the production of fuel-cell quality H2, and the H2-depleted syngas could then be utilized in conventional US-built IC engine gensets for lower-cost electricity.

Competing Technologies

Technologies that compete with FastOx gasification as waste conversion solutions include incineration (mass burn), pyrolysis, anaerobic digestion, low-temperature gasification, and plasma arc gasification. These technologies have various limitations, as indicated in Figure 3.

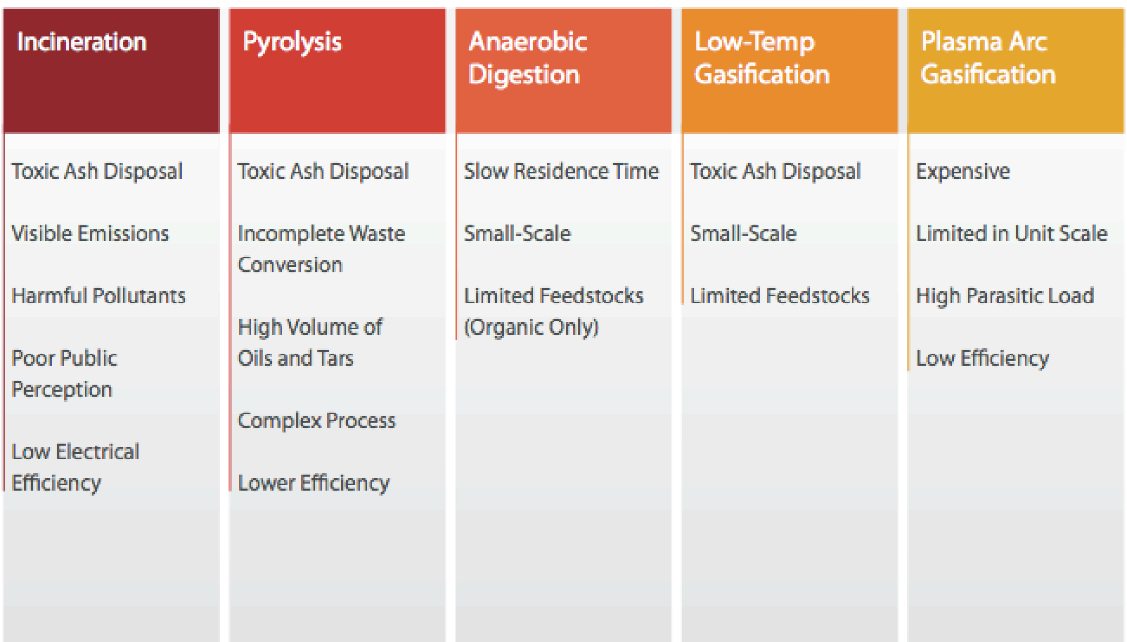

Figure 3. Disadvantages of Existing Waste Conversion Methods

(source: Sierra Energy)

Moreover, most other technologies within the 'thermochemical conversion of waste' category will have lower Landfill Diversion Percentage (LDP) compared to FastOx.

- Pyrolysis – operates at low temperatures in the absence of oxygen, which results in the production of large volumes of ash and char (carbon left over). Typically, the mixed char and ash will not meet toxic metals leachability requirements for reuse and must be landfilled at a significant cost to the operation.

- Low Temperature Gasification – operates at medium temperatures with limited oxygen available, which results in the char being converted into additional syngas. However, the temperatures are not high enough to melt the inorganic ash components, resulting in a volume of ash that will not meet toxic metals leachability requirements for reuse and must be landfilled at a significant cost to the operation.
- Anaerobic Digestion – only converts the non-cellulosic organic material (i.e. food waste) resulting in a large volume of waste material still going to the landfill.
- Incineration – produces toxic ash that requires costly specialized landfilling.
- Plasma – has many of the benefits of FastOx gasification (complete conversion of carbon, conversion of ash to safe slag) but requires significant amounts of electricity to operate.
- FastOx – operates at high temperatures with limited oxygen which results in the complete conversion of char into syngas. At the high operating temperatures, the ash will melt and be recovered as a non-leaching, inert vitrified coproduct. If there are any bulk metals in the waste materials, they will also melt and be recovered as a separate coproduct from the FastOx gasifier. Given that both the recovered metals and slag are safe for reuse and have a market value, they can be sold back into the recycling and bulk materials markets and therefore are completely diverted from the landfill, at significant environmental and economic benefit to the project.

3.0 PERFORMANCE OBJECTIVES

The POs of this project help to measure the potential operational benefits of this renewable energy technology for DoD entities. If utilizing this technology to produce baseload renewable, sustainable energy, this DoD installation self-sufficiency will allow for reduced vulnerability compared to the civilian power grid. The data collected would allow for cost savings calculations to interpret the avoided costs of landfilling and energy purchase, as well as environmental savings.

Table 2 below is the list of performance metrics and the current status.

Table 2. Performance Objectives

PO #	Qualitative Performance Objective	Metric	Data Requirements	Success Criteria	Results
1	Peak Specific Renewable Electricity Generation	[kWh_e/tonne (material into FastOx gasifier)]	In hourly summations: electricity produced by genset, electricity consumed by process equipment, tonnes of materials entering FastOx gasifier.	Specific net export of electricity of at least 700 kWh_e/tonne (material into FastOx gasifier)	Current calculations incorporating preliminary plant operating data shows an expected specific net export of 674 kWh_e/tonne, though it is expected to increase with optimization of the plant and process.
2	Specific Operating Cost	[$/$kWh_e$]	Complete system stream data to formulate empirical 'mass and energy balances. Logging of maintenance events. FHL's average costs of electricity and waste hauling and disposal during testing period.	Operation costs achieve parity with FHL's electricity costs: $0.176/$kWh_e$ (average annual cost FY18)	Current calculations for a repeat 10 MTPD project show an unlevelized Operating Cost of $0.005/$kWh_e$. Including the Total Installed Capital Cost (provided the equivalent of a Levelized Cost of Electricity (LCOE)), this would increase to $0.091/$kWh_e$.
3	Environmental Benefit	[g(pollutant)/kWh_e]	Real-time exhaust analyzer data as well as a single third-party EPA-approved stack testing to measure release of the selected criteria pollutants from IC genset exhaust (the only emission point from the enclosed FastOx system during normal operations). The gross power output of the genset.	Criteria emissions to meet or exceed: • CO: 2.918 g/kWh_e a 45% decrease* • VOC: 0.462 g/kWh_e a 20% decrease* • NO_x: 1.262 g/kWh_e a 90% decrease* • SO_x: 0.001 g/kWh_e a 65% decrease* • PM: 0.214 g/kWh_e a 10% decrease*	Without operations on the syngas genset, the manufacturer's own conservative emissions profile guarantees must be used as a placeholder. • CO: $<$ 5.93 g/kWh_e • NO_x: 2.80 g/kWh_e • NMHC: $<$ 1.12 g/kWh_e The actual emissions profile is anticipated to be significantly improved over the manufacturer's guaranteed minimums.
4	System Turndown	[%]	Complete system stream data to formulate empirical 'mass and energy balances' when operating system at different throughput rates with the same feed material.	A turndown of 90% of system throughput/capacity (1.0 MTPD) without a greater than 25% reduction in specific net electricity output. i.e., specific net electricity production should remain above 525 kWh_e/tonne (into FastOx gasifier).	Calculations extrapolated from early operations-demonstration at 2.3 MTPD capacity, shown the SNEP should not drop more than 19.7% at 10:1 (1.0 MTPD) operations.

PO #	Qualitative Performance Objective	Metric	Data Requirements	Success Criteria	Results
5	Landfill Diversion Percentage	[kg(waste diverted from landfill using FastOx system)/ kg(waste that was destined for landfill)]	Logged data of mass of waste material received by the FastOx system and mass of any waste material that still must be landfilled after FastOx processing.	Landfill diversion will be a minimum of 75% weight of material received by the FastOx system.	Unable to validate on MSW feed materials due to absence of operating data with MSW, but on wood waste is in the 95–99%wt. LDP range.
6	Total Mass of Material Gasified	[tonnes (material into gasifier)]	Logged data of mass of material placed into the FastOx gasifier	At least 275 tonnes of material gasified over the duration of the demonstration program.	7.5 tonnes of materials gasified in early operations-demonstration. At 5 MTPD (50% throughput capacity), will require 54 days of operations to reach success criteria.
7	System Uptime	[%]	Hours the FastOx system is operational and consuming waste materials. Hours of maintenance conducted on FastOx system when it's scheduled to be operational.	Greater than 75% System Uptime	Insufficient data to evaluate given limited operations beyond commissioning.
8	Seasonal Operations Robustness	Satisfactory System Operation	Operational log of operators and quarterly visitations and observations by expert culminating in a report.	No qualitative adverse effects of operating the system during different weather and seasonal conditions.	Initial environment-related equipment failures have been resolved. However, increased waste material moisture content will lower overall operating efficiency. This can be mitigated with a waste pre-dryer that reutilizes waste-heat from the system.
9	Odor and Noise	N/A	Survey base personnel	No complaints.	No complaints to-date and would likely not be an issue for most semi-industrial DoD installation settings, especially with mitigation measures readily available.

*Decrease in the criteria pollutants before emissions control equipment relative to a mixed portfolio of conventional fossil fuels usage (diesel, gasoline and natural gas).

PO1: Peak Specific Renewable Electricity Generation

Definition: The net amount of electrical energy that can be generated per unit mass of waste material converted.

Purpose: Peak specific electricity generation is an operational parameter that can be used to compare technologies within the same solid material conversion technology class. This metric also allows future DoD installations to determine an initial estimate of the electrical energy generation potential if they were to convert their waste materials (assuming a similar waste composition to FHL).

Metric: This parameter provides the efficiency of the entire installed system by providing net electricity output (kWh_e (net)) divided by the mass of solid waste feed material (tonne wet material into gasifier).

For other 'solid material conversion technologies', the net specific electricity production is [12]:

- Combustion/Incineration: 525 kWh_e(net)/tonne (into process)
- Low Temperature Gasification: 400–650 kWh_e(net)/tonne (into process)
- Plasma Gasification: 400–1250* kWh_e (net)/tonne (into process)
  - *assumes prepared fuel including tires

Data: An empirical mass-energy balance for the system operation while at steady state (i.e. the process is operating stably and there are no major fluctuations in process parameters) is required for the calculation of this parameter. In hourly summations:

- Total gross electricity produced by genset (kWh_e),
- Total electricity consumed by process equipment,
- Total tonnes of materials entering FastOx gasifier.

Analytical Methodology: The Supervisory Control and Data Acquisition (SCADA) system includes a main terminal that will control and record gasification plant operations. The software at the main terminal will have historical data logging capabilities and will record major process parameters.

The mean-averaged, post-processed data values for the selected Steady State Period (SSP) will then be placed in the following equation:

$$SNEP = (GEPG - ERP)/(MMEG)$$

Where:
SNEP = Specific Net Electricity Production [kWh_e (net)/tonne (into gasifier)]
GEPG = Gross Electricity Produced from Genset [kW]
ERP = Electricity Required by FastOx Plant [kW]
MMEG = Mass of Material Entering Gasifier [tonnes (into gasifier)/hr]

The syngas-to-electricity generator set (built and delivered by Siemens-Guascor) has yet to be operated at the FHL plant. For the purpose of this report, a different methodology using computer modelling results will be substituted. The results from the computer model, which have been validated against empirical data from the Mk4 gasifier, along with estimates for *ERP* can be used to obtain a theoretical *SNEP*. This calculation is shown in Section 6.

Success Criteria: Sierra selected an objective value of 700 [kWh_e (net)/tonne (into gasifier)] as this is the theoretical value calculated by Sierra's engineers for operations on typical post-recycling residual waste in California. It is difficult to compare FastOx to other conversion technologies operating on waste materials due to the highly heterogeneous nature of MSW and the challenge in obtaining detailed mass-energy balances for private companies.

PO2: Specific Operating Cost

Definition: Specific Operating Cost calculates the simple cost of operation per unit of electricity generated.

Purpose: Specific operating cost allows for comparison to alternative electricity generation options based on the operating cost alone (excluding the environmental and baseload power resiliency benefits of the FastOx technology that are difficult to quantify). The simple (not levelized) operating cost excludes cost of equipment or capital borrowed also.

Metric: This parameter calculates the cost to produce a unit of electrical energy. If the material the gasification system converts into syngas is a 'cost' to the operation (i.e., a purpose-grown agricultural crop at $40/tonne delivered to site) this will increase the cost of producing the unit of electrical energy. Conversely, if the material the system accepts is offsetting a 'cost' to another department within the installation, this 'avoided cost' is incorporated into the operating cost calculation, decreasing the overall cost to produce the unit of electrical energy and making the system even more cost-competitive with the existing local utility.

Data: To calculate this parameter, the investigator requires the following data:

- All system inputs and outputs as described by the empirical heat and mass balance of the entire system including oxygen injection, parasitic energy loads (if applicable), water input, weight of reclaimed products (metal and slag) etc.
- Average cost of electricity for FHL during the demonstration period. The average cost is used to simplify the complex tiered pricing schedule that exists for most commercial and industrial utility clients. Most recent prices for FHL hover around $0.189/$kWh_e$
- Waste hauling and disposal costs prior to and during the demonstration period.
- Logged maintenance (scheduled) hours and costs deemed to be consistent with average operation (not associated with corrections with initial design or equipment selection).
- Market potential or actual sale price for metal and slag.
- Labor accrued for operation and normal maintenance during specified test plan TG2 (see Section 5 of this report for details).
- Electrical energy generated during operation hours in TG2 (see Section 5).

Analytical Methodology: To calculate the cost per kWh_e (net) of Sierra's FastOx gasification system over a selected time period (1 week during TG2), the following formula will be used:

$$SSOC = (CDL + CDI + CM + CDO)/NEPS$$

Where:
SSOC = Specific Simple Operating Cost [\$/kWh_e (net)]

CDL = Cost of Direct Labor for FastOx system operations [$]
CDI = Cost of Direct Inputs (including avoided waste disposal costs) [$]
CM = Cost of Maintenance (both labor and parts/equipment) [$]
CDO = Cost of Direct Outputs (including sales of metals, inert slag) [$]
NEPS = Net Electricity Produced from System [kWh_e (net)]

Success Criteria: System operation can achieve cost parity or less than the existing average costs of electricity.

PO3: Environmental Benefit

Definition: The specific mass of pollutants produced from the genset per unit electrical power produced by the genset.

Purpose: This PO will provide a metric to directly compare the local air-quality environmental benefits of electricity production via syngas compared to conventional fossil fuel methods of producing power on homeland and foreign DoD installations.

Metric: The environmental performance of a technology is typically derived and displayed in terms of the concentration of pollutants per unit volume of exhaust flow released to atmosphere. For example, a reading of 25 ppmv (CO) is calculated as 0.0025 %volume concentration of CO in the exhaust. However, this metric does not consider the actual total mass flow rate of emission, nor does it include the actual beneficial output produced by the technology (in this case the electricity output).

Example: if two technologies both have an exhaust pollutant concentration of 25 ppmv (CO) and both have a dry gas flow rate of 200,000 Nm^3/hr, this would be 5 Nm^3(CO)/hr emitted for both technologies. If one of these technologies, *A*, produces twice as much net electricity output as *B*, it makes environmental sense to use technology *A*, as the 'specific emissions' will be half of those of *B*. Therefore, specific emissions are a rational way of comparing and selecting technologies as it combines the emissions concentration along with the net beneficial output.

Most genset and power plant installations will require the final exhaust emissions to atmosphere to meet local, state or federal regulations (dependent on the site's requirements). To meet the stringent air quality standards, post-combustion air pollution control devices (APCD) are typically required, at significant initial capital cost and operational cost.

Because the operation of a conventional IC genset with syngas is calculated to be significantly cleaner than conventional fossil fuels, several options become available to operators of the FastOx gasification technology:

- For the same final emission to atmosphere levels amounts as produced by conventional fossil fuels, a significantly smaller and therefore less expensive APCD would be needed to meet the same air quality standards.
- Alternatively, the same-sized APCD that would be used on the higher-polluting fossil fuel units could be installed and operated at the same cost but given the cleaner exhaust stream from the syngas fuel, the final emission to atmosphere would be significantly lower than the fossil fuel emission.

Data: To calculate this PO, one requires the empirical mass-energy balance for the system operations while at steady state operation (the process is operating stably; there are no major fluctuations in process parameters). In hourly summations:

- Total gross electricity produced by genset (kWh_e)
- Total volume flow rate of the genset exhaust
- The concentration of criteria pollutants in the genset exhaust

Analytical Methodology: As described in the analytical methodology for PO1, the Supervisory Control and Data Acquisition (SCADA) system's main terminal will control and record the entire gasification plant operations from which the logged data will be retrieved and placed in a spreadsheet that is set-up to automatically graph the major process parameters. The investigator will use these process overview graphs to select an SSP as a representative data group.

The emissions in the genset exhaust will be obtained via a real-time exhaust gas analyzer (in ppmv and %vol ranges) and logged by the SCADA system, as well as the temperature and volume flow rate of the exhaust.

The mean-averaged, post-processed data values for the selected SSP are then placed in the following equation for each emission component:

$$SE(x) = (CE(x) * VFE/22.4 * MW(x))/GEPG$$

Where:
SE(x) = Specific Emission of component *x* (where *x* is CO, VOC, NO_x, SO_x, or PM) [g(*x*) /KWh_e (gross)]
CE(x) = Concentration of Emission *x* in the exhaust [ppmv or %vol.]
VFE = Volume Flow rate of Exhaust [Nm^3/hr]
MW(x) = Molar Weight of component *x* [kg(*x*)/1kmol(*x*)]
GEPG = Gross Electricity Produced from Genset [kWh_e/hr]

Emissions data provided by the generator manufacturer has been used to evaluate this PO. These results will be verified with real time emissions analysis once the generator is operational.

Success Criteria: Currently, the production of primary and back-up electrical power used on DoD installations is derived from mainly fossil fuels. Given that the exact breakdown of the fuel types used within the DoD's portfolio is not known, an evenly mixed portfolio is estimated at 33.3% diesel (and JP-8), 33.3% gasoline and 33.3% natural gas (and propane).

This PO will compare the specific emissions of the project to those of the mixed fossil fuel portfolio to prove the environmental benefits of using syngas fuels. The aim is not only to meet the specific emissions relative to fossil fuels, but see significant reductions in each:

- CO: 2.918 g/kWh_e (a 45% decrease targeted)
- VOC: 0.462 g/kWh_e (a 20% decrease targeted)
- NO_x: 1.262 g/kWh_e (a 90% decrease targeted)
- SO_x: 0.001 g/kWh_e (a 65% decrease targeted)
- PM: 0.214 g/kWh_e (a 10% decrease targeted)

PO4: System Turndown

Definition: System turndown is the ability of any system to be able to function satisfactorily when operating below the designed capacity which can be expressed as a ratio. For example, 10:1 would be a system that can function adequately at operation down to 10% of the designed 100% capacity.

Purpose: This PO will provide a metric that allows the assessment of system viability for a fixed FastOx gasification system size for future DoD installations. For example, if the fixed system size is 10 MTPD, and the turndown ratio of the equipment is determined to be 20:1, this would mean a minimum of 10 MTPD/20 = 0.5 MTPD of material would need to be generated at the DoD installation to have a functioning system.

Metric: 'Satisfactory system operation' has been defined to be operations where the Specific Net Electricity Production (SNEP) [kWh_e (net)/tonne (into FastOx gasifier)] does not drop below the system's designed capacity by more than 25%.

For the post-recycling FHL waste materials, the full-capacity SNEP is determined to be 700 [kWh_e (net)/tonne (into FastOx gasifier)]. Therefore, 'satisfactory system operation' will occur when this parameter remains above 700 * (100% – 25%) = 525 kWh_e (net)/tonne (into FastOx gasifier)].

Data: Same as PO1.

Analytical Methodology: During the last campaign of operations at FHL, steady state operation was achieved for a period at a feed rate of approximately 2.3 metric tons per day – a turndown of 10:2.3. Although this cannot be considered demonstration, the data obtained from the campaign can be used to provide a rough system turndown SNEP result.

This is done using the measured syngas composition and flow rate. This data in conjunction with the predicted efficiency of the generator can be used to predict the theoretical *SNEP* that could have been produced had the generator been operational. See section 0 for details and results.

Success Criteria: At the reduced 1/10th capacity operation (current operating material consumption = max designed operating material consumption capacity * 10%), the SNEP will not drop by more than 25% from the designed value.

PO5: Landfill Diversion Percentage

Definition: Landfill Diversion Percentage (*LDP*) measures the amount of material that was destined for landfill that was repurposed and ultimately avoided landfilling.

Purpose: The *LDP* is a useful metric to compare similar technologies' effectiveness at reducing landfilling requirements and allows the DoD to assess the use of the FastOx technology at other DoD installations. The DoD would be able to concurrently calculate the total tonnes of material (if any) that would still need to be landfilled. A high *LDP* helps increase the longevity of any existing onsite landfills.

Metric: With the FastOx system installed in conjunction with existing FHL recycling practices, the landfill diversion rate should approach 100% during demonstration testing.

Data: To calculate this PO, the empirical mass balance for the system operations is required. In daily summations:

- Total tonnes of materials arriving at the project boundary of FastOx system.
- Total tonnes of recyclable materials (including coproduct slag and metals) recovered from the FastOx system and returned to FHL's Qualified Recycling Program (QRP).
- Total tonnes of materials still requiring landfilling after being processed by the FastOx system (if required).

Analytical Methodology: The main solid material mass flows (movements across the project boundary) will be measured by the operators using industrial scales and logged.

- The materials arriving at the project boundary will be weighed on arrival every time there is a receipt of materials (which could be multiple times per day).
- Any recyclable materials generated by the FastOx system will be stored in large containers until there is enough material to warrant a transaction (material movement) to the FHL QRP group.
- If required, any materials that must still be landfilled after processing by the FastOx system will be stored in large containers until there is enough material to warrant a transaction (material movement) to the collection contracted, which is currently Midstate Waste.

Success Criteria: When the FastOx system is operational, Sierra Energy has set the goal of obtaining a minimum of 75% LDP. The reason this goal is not higher is because the actual materials received at the project boundary may be determined to be unsuitable for processing with the FastOx system (example: environmental permits require that large volumes of hazardous liquid waste be removed) in which case this material will be dealt with via conventional strategies.

PO6: Total Mass of Material Gasified

Definition: This is the summation of the mass of material converted in the FastOx gasifier over the testing phase of this ESTCP project.

Purpose: This is a PO will ensure that an adequate amount of material is processed by the FastOx system to evaluate the equipment with enough sample size and variation of material types generated at FHL.

Metric: The total tonnes of material into gasifier: [tonnes (into gasifier)].

Data: To calculate this PO, the empirical mass balance for the system operations is required. In daily summations:

- Total tonnes of materials entering the FastOx system.

Analytical Methodology: See PO5.

Success Criteria: A minimum of 275 tonnes of material should enter the FastOx gasifier to ensure the system evaluated with satisfactory sample size.

PO7: System Uptime

Definition: The number of hours of actual operations divided by the total number of hours the system should have been operational.

Purpose: This metric allows for the comparison of the FastOx gasification system to other similar technologies. It also allows for future planning of resources (cost and labor) for operation of the equipment at other installations.

Metric: System uptime (sometimes called the 'availability' for large industrial processes) is typically a ratio of the number of hours a plant is operational (and above some operating capacity factor) divided by the total number of hours in a year.

Given that during the demonstration, the operations of the system will follow a predetermined campaign-based operating schedule and that the amount of waste generated at FHL will fluctuate, the uptime of the FastOx system will not be evaluated over the typical hours in a year of operations. Instead, the PO will be evaluated by looking at the total number of operating hours when the system is consuming solid materials compared to the total number of hours required for scheduled maintenance (cleaning and replacing filters, lubrication etc.).

Additions or modifications to the FastOx System during the testing period will be excluded. Should a piece of equipment require in-field modifications, these hours will not be included in the PO evaluation, as the resulting 'upgraded equipment' design would be included in all future FastOx systems, and thus it would not be necessary for future systems to also require downtime to solve the same operational problems.

Data: To evaluate this PO, the system operational and maintenance log summary is required. In summation over the entire testing phase:

- The total hours the FastOx gasifier is operational and consuming solid materials.
- The total hours the FastOx gasifier is offline due to typical scheduled maintenance (that would be expected in all near-future system installations).

Analytical Methodology: The operational and maintenance logs (kept daily by the system's operators) will be reviewed daily and weekly by the lead project engineer to ensure the correct selection of category for the logging of hourly operations and maintenance activities and a detailed explanation of activities is completed.

$$SU = (TGO)/(TGO + TTM)$$

Where:
SU = System uptime [%]
TGO = Time Gasifier Operational (and consuming solid materials) [hr]
TTM = Time for Typical Maintenance (Gasifier is offline – not consuming solid materials due to typical/scheduled maintenance) [hr]

The lead project engineer will calculate the SU weekly, monthly and over the entire ESTCP project testing phase.

Success Criteria: The System uptime will exceed 75%. Qualitatively, this means the hours of typical maintenance required will not be greater than 33% of the time the gasifier is operational.

PO8: Seasonal Operations Robustness

Definition: The system should be designed for all seasons and conditions expected in typical operational theaters. The 'robustness' should be represented by evidence that the operations of the system are not greatly affected (as defined by the investigators), even if the ambient temperatures and moisture content of the waste materials fluctuate greatly.

Purpose: Different geographical locations can have a noticeable effect on equipment operations. For example, problematic locations can include operation of compressors at high altitudes (low ambient pressure) or the operation of ambient heat exchangers in high temperature climates. Many of the geographical affects can be mitigated during the design and engineering phase to ensure equipment compatibility and optimization.

Metric: Should local conditions affect equipment operation; the effects are typically observed in a change in efficiency of operation. It is expected any local fin-fan effects on the FastOx system be observed in the SNEP, assuming the same feedstock composition between the compared operating phases. It is likely equipment maintenance and malfunctions observed by the operators may also be attributed to local ambient conditions.

While the main metric being evaluated is qualitative, (including qualitative notes and logs from the operators) the total dataset will be evaluated qualitatively for visible trends over the entire testing phase.

Data: To evaluate this PO, system operational and maintenance log summary and some quantitative data are required. In summation over the entire testing phase:

- Qualitative notes and operational logs.
- The average daily SNEP.
- The local ambient conditions (temperature, pressure, humidity), averaged daily.

Analytical Methodology: For similar feed materials, the SNEP results and qualitative logs summary will be compared across the seasons to observe any correlations with local ambient conditions.

Success Criteria: There should be no major, operationally disruptive qualitative affects observed. The FastOx system should still perform satisfactorily, converting the waste material, but potentially at a lower overall efficiency (SNEP).

PO9: Odor and Noise

Definition: Odor and noise are considered unpleasant smells and excessive sound levels respectively.

Purpose: It is important for the safety of operators of the FastOx system to not be exposed to odor and noise levels for extended periods of time above certain regulatory standards. It is important to ensure neighbors and visitors are not exposed to anything that could limit the future adoption of the FastOx technology.

Metric: For odor – N/A. For noise – N/A

Data: To evaluate this PO, one requires qualitative documents and a quantitative measurement:

- Qualitative notes and operational logs from system operators
- Questionnaire responses from FHL employees

Analytical Methodology: Periodic questionnaires will be collected from key stakeholders, and the base will be informed of methods of directly alerting the system operators at any point in time should an odor or noise issue arise. Any alert will be logged in the master summary spreadsheet.

Surveys will be compiled during the operation period and given to the FHL environmental division, as well as FHL employees neighboring this project to evaluate the project on noise and odor. The response options for each will be as follows: ‘Not noticeable’, ‘Slightly noticeable’, ‘Very noticeable’, ‘Considerable nuisance’.

Success Criteria: No complaints for either odor or noise.

4.0 SITE DESCRIPTION

4.1 SITE LOCATION AND OPERATIONS

The project site is located on US Army Garrison Fort Hunter Liggett (FHL) in Monterey County, California. The facility address is

Sierra Energy at Fort Hunter Liggett
Bldg 339, Infantry Road,
Jolon, CA 93928

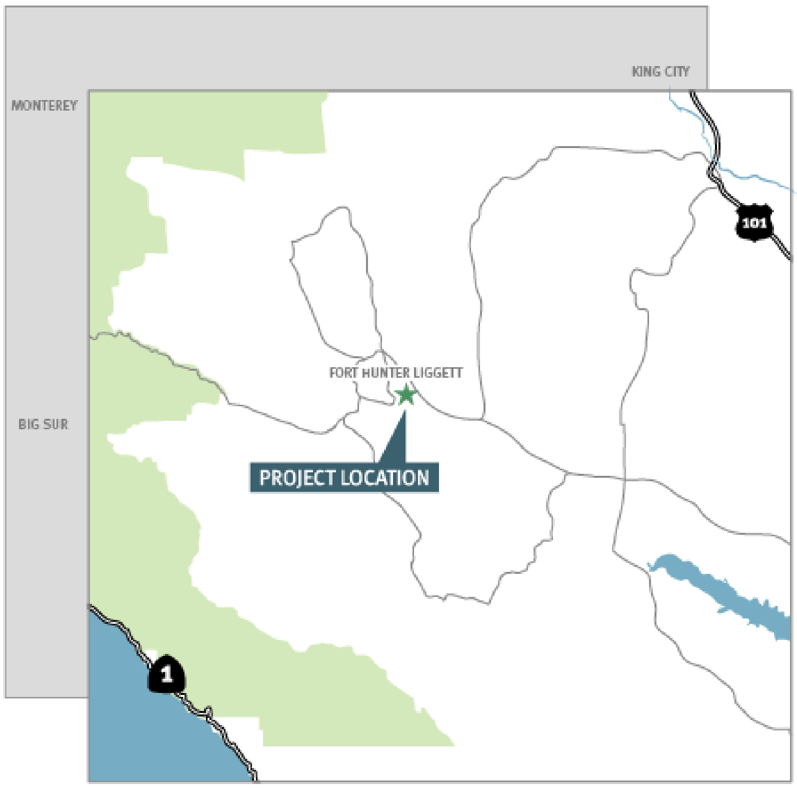

Figure 4. Map of FHL

FHL continues to see growth of its training operations and plans to expand in the future. This will result in an increased volume of waste disposal and energy demands. Like other small-population installations, FHL is in a rural area. While this makes FHL an ideal training area, the installation does not have the benefits of the same infrastructure that urban installations have available such as convenient civilian waste disposal and energy generation systems.

FHL currently has 3MWe of solar photovoltaic capacity and a 1MWHr Li-Ion battery storage system, however both are still not enough for FHL to be completely secure and islanded from the civilian grid. As a result, FHL still relies on grid electricity, and a grid outage could leave the installation unable to support its mission, which is a serious concern at FHL. Historically, the installation experiences four to six grid outages per year. Short-term generation exists for critical operations (from LPG-powered back-up gensets and some uninterruptible power supplies), but the back-up capacity is insufficient to support most operations at the military base for extended periods of time.

This project aligns with FHL's designation as a pilot installation for the DoD's Net-Zero Waste and Net-Zero Energy initiatives [10]. Strategies that are proven successful over adequate demonstration periods at FHL will likely be adopted by other installations.

4.2 SITE CONDITIONS

Demonstration Site Description: FHL is in a Mediterranean-analog climate zone – i.e. hot and dry summers with cool winters with some rainfall. It is at an elevation of 1,000 ft.

FHL provided the following infrastructure for the project:

- An existing building (Bldg. 339) for waste pre-processing and lab space
- Utility connections for water, sewer and electricity
- Concrete pad for the installation of the major biorefinery modules outside

Shown below is a picture from 2016 of site preparation work being completed at FHL. Bldg. 339 is shown on the right.

Figure 5. Site Preparation Work in 2016

The building itself serves as the waste pre-processing center. The rest of the gasification facility is sited outdoors in the area south of Bldg. 339.

Key Operations: FHL is responsible for training combat support soldiers, with military operations occurring year-round. Sierra's FastOx gasification project will not adversely impact any of these operations. If Sierra's FastOx gasification platform is deemed applicable to foreign sites, the experience and familiarity with the technology gained at FHL will be valuable to locations where FHL-trained personnel are deployed.

Command Support: FHL's command endorsed this project and found Sierra's FastOx technology to be fully supportive of FHL's Net-Zero initiatives.

Communications: The POC at FHL determined that the FastOx facility can have access to communications without being connected to DoD or Army communication facilities such as cell phone modems or cell phones.

Other Concerns: Sierra's FastOx gasification project is considered in positive terms by the FHL community, both on-base and off. The base plans to continue to communicate the benefits of the project being complementary to FHL's net-zero goals and to celebrate the completion of the FastOx gasification system operations-demonstration program.

5.0 TEST DESIGN

This project set out to generate baseline operational data for FastOx gasification at a commercially viable scale. The data and operations experience are critical for determining the feasibility of future plants and scaled up systems. This demonstration will continue to produce key data beyond the early operations-demonstration phase that will be used to design and develop future FastOx gasification units. This project will also generate data needed for other federal facilities to assess the applicability of the FastOx gasification technology for their locations.

5.1 CONCEPTUAL TEST DESIGN

The POs listed in **Table 2** are grouped together into campaigns or 'testing groups' (TG) with similar testing specifications. For example, the PO testing the maximum capacity of the installed system is in direct conflict with the PO for testing the turndown (minimum capacity) of the system. Grouping the PO's testing specifications together also makes for a more-efficient test program by reducing the total number of individual test campaigns required to obtain all the data to assess the POs.

The POs are grouped into four TGs, as detailed in **Table 3**, with their respective test specifications.

Table 3. Testing Group Summary Table

<table>
<tr><th>Test Group #</th><th>PO #</th><th>PO Title</th><th>Test Specifications</th></tr>
<tr><td>TG1</td><td>PO4</td><td>System Turndown</td><td>Reduced Capacity Operation:
10hrs per operation at consumption rate of 1.0 MTPD. Minimum of 6 discrete operations.</td></tr>
<tr><td rowspan="3">TG2</td><td>PO1</td><td>Peak Specific Renewable Electricity Generation</td><td rowspan="3">Maximum Capacity Operation:
12hrs per operation at consumption rate of 10 MTPD. Minimum of 6 discrete operations.</td></tr>
<tr><td>PO2</td><td>Specific Operating Cost</td></tr>
<tr><td>PO3</td><td>Environmental Benefit</td></tr>
<tr><td rowspan="3">TG3</td><td>PO5</td><td>Landfill Diversion Percentage</td><td rowspan="3">Continuous Observation & Evaluation Throughout the Entire Testing Phase:
The key parameters for each PO are logged and evaluated continuously throughout the main test groups TG1 and TG2.</td></tr>
<tr><td>PO6</td><td>Total Mass of Material Gasified</td></tr>
<tr><td>PO7</td><td>System Uptime</td></tr>
<tr><td rowspan="2">TG4</td><td>PO8</td><td>Seasonal Operations Robustness</td><td rowspan="2">Periodic Observation Throughout the Entire Testing Phase and Post-Testing Evaluation:
The key parameters for each PO are obtained periodically during the main test campaigns TG1 and TG2 but are not evaluated until the end of TG2.</td></tr>
<tr><td>PO9</td><td>Odor and Noise</td></tr>
</table>

Variables are described below for each TG with reference to the corresponding PO which is utilizing the collected data:

TG1 – Reduced Capacity Operation

Independent variable(s):	• Mass flow rate of waste material entering the FastOx gasifier is set to 1.00 MTPD. [PO4] • Burden height of waste material within the FastOx gasifier is reduced to the predetermined level for the lower consumption rate. [PO4] • The overall flow rate of injectants will be reduced to the predetermined level for the lower consumption rate. [PO4]
Dependent variable(s):	• Electrical power (gross) generated by the IC genset. [PO4] • Electrical power consumed by the entire system [PO4]
Controlled variable(s):	• Unless it has been selected as an Independent Variable, all other operational set points for the entire plant will be maintained by the plant automation software. [PO4] • The type/composition of the waste material feed to the gasifier will be selected so its effect on the test is minimized. [PO4]

TG2 – Maximum Capacity Operation

Independent variable(s):	• Mass flow rate of waste material entering the FastOx gasifier is set to 10 MTPD. [PO1,2,3] • Burden height of waste material within the FastOx gasifier is increased to the predetermined level for the maximum consumption rate. [PO1,2,3] • The overall flow rate of injectants set to the predetermined level for the maximum consumption rate. [for PO1,2,3]
Dependent variable(s):	• Electrical power (gross) generated by the IC genset. [PO1,2,3] • Electrical power consumed by the entire process. [PO1,2,3] • Criteria Pollutants in the exhaust from the genset. [PO3] • Labor requirements. [PO2] • Non-Electricity utility requirements (if utilized). [PO2]
Controlled variable(s):	• Unless it has been selected as an Independent Variable, all other operational set points for the entire plant will be maintained by the plant automation software. [PO1,2,3] • The type and composition of the waste material feed to the gasifier will be selected so its effect on the test is minimized. [PO1,2,3]

TG3 – Continuous Observation & Evaluation for Entire Testing Phase:

Independent variable(s):	• N/A
Dependent variable(s):	• Total material accepted at the boundary of the FastOx project. [PO5,6] • Total recovered recyclable material delivered from the FastOx project to the FHL QRP recycling center. [PO5,6] • Total material leaving the FastOx project boundary destined for collection and landfill. [PO5] • Total hours while the FastOx gasifier is consuming solid materials. [PO7] • Total hours of maintenance performed on the main FastOx processing equipment while FastOx gasifier is operational. [PO7] • Total hours of maintenance performed on the main FastOx processing equipment while FastOx gasifier is non-operational. [PO7]

Controlled variable(s):	• N/A – this TG3 is conducted concurrently with main testing campaigns and is meant to assess the overall long-term performance of the equipment throughout the various testing campaigns of the ESTCP project.

TG4 – Periodic Observation for Entire Testing Phase and Post-Testing Evaluation:

Independent variable(s):	• N/A
Dependent variable(s):	• Mass flow rate of material entering the FastOx gasifier. [PO8] • Electrical power (gross) generated by the IC genset. [PO8] • Electrical power consumed by the entire system. [PO8] • Operator's qualitative log of system operations and maintenance. [PO8] • Operator's qualitative log of system operations. [PO8] • Operator and FHL Personnel qualitative log of questionnaire responses concerning noise and odor issues. [PO9]
Controlled variable(s):	• N/A – this TG4 is conducted concurrently with main testing campaigns and is meant to assess the overall long-term performance of the equipment throughout the various testing campaigns of the ESTCP project.

Hypothesis: The demonstration will prove that the FastOx gasification system is a robust, net-energy-producing and cost-efficient way to eliminate waste by converting to baseload electricity, in comparison to the existing practice is waste disposal via hauling and landfilling and electricity being pulled from the external local utility.

Test Design: To test the hypothesis, the existing FHL waste and energy operations are measured to provide a baseline. The project equipment is operated according to the demonstration plan. Finally, through detailed analysis of the individual POs, the impact of the FastOx process will be compared to the baseline.

Data acquisition tools and instruments will be installed so that adequate data required for analyzing the cost and POs will be obtained during the demonstration and operations phase.

Test Phases and Tasks

Major milestones in the path towards demonstration are described in this section.

Task 1. Engineering (completed)

- Task 1a. Division of Responsibilities. All major equipment and engineering tasks were divided between the assembled project team (including Sierra, engineering firms, design-build fabricators, consultants, local contractors, and representatives from FHL). A responsibility matrix ensured parallel design tracks, allowing accelerated project deployment.
- Task 1b. ISBL Engineering. Inside of Battery Limits ("ISBL") engineering involved the detailed design and specification of the equipment that make-up the FastOx gasification system.

- Task 1c. OSBL and Site-Specific Engineering. Prior to construction, this project needed final civil and Outside of Battery Limits ("OSBL") engineering design for site-specific utility connections, grading, foundations, and tying-into existing electrical interconnects.

Task 2. Permitting (principally completed)

This task ran concurrently with Task 1 and included permitting (air, water, waste, building, facility use) and the related task of obtaining the electrical utility interconnect. A list of all the permits obtained by Sierra Energy for the project can be found below.

In addition to regular inspections by FHL Fire Department and separately FHL DPW Environmental Division, Sierra Energy has hosted several annual and quarterly inspections from Cal OSHA and separately Monterey Country Department of Health.

Table 4. Permit Summary

Topic	Agency	Requirement	Date Obtained
Air permit – Authority to Construct (ATC)	Monterey Bay Unified Air Pollution Control District	Permit to Procure and install equipment per the Air Board's requirement	5-Feb-2015 and updated 9-Jun-2017 and 1-Feb-2018 and 5-Dec-2018
Air Permit – Permit to Operate	Monterey Bay Unified Air Pollution Control District	Permit to operate the system continuously	In progress
Solid Waste Permit Exemption	Monterey County Dept. of Health	Ensure system meets all state and local requirements	1-Mar-2016
Water	FHL Dept. of Public Works (DPW)	Ensure backflow preventers meet all state and local requirements	12-Jul-2017
Wastewater (Discharge to FHL)	CCRWQCB	Confirmation that system does not require FHL to obtain new permit	8-Apr-2015
CEQA/NEPA	CEC (CCRWQCB, MBARD and FHL DPW)	Project needs to be CEQA compliant given the funding sources requirement	1-Jun-2015
Cal/OSHA	Cal/OSHA	Confirmation that the system does not trigger PSM (Process Safety Management)	24-Jan-2018
SPCC	FHL DPW	Double-wall tanks and concrete tertiary spill containment areas	Coordinated with FHL DPW
Pressure Vessels	Cal/OSHA Pressure Vessel Division and FHL DPW	Meets CA Dept. of Industrial Relations requirements	7-Jun-2016 – 9-Mar-2017
Boiler	Cal/OSHA Pressure Vessel Division	Permit to operate steam boiler	29-Jun-2017
Fire	FHL Fire Department	Inspections to confirm equipment, and layout meets FHL FD, California and Federal requirements	4-Apr-2017
Structural	FHL DPW	Meets CA requirements	27-Apr-2016 – 24-Feb-2017

Task 3. Construction and System Installation (principally completed)

This task included site preparation by the local contractors, off-site construction of the ISBL containerized equipment modules, and delivery and installation of all ISBL and OSBL equipment (including utilities connections).

All equipment is currently in place and interconnections have been completed as per the original design. Other than the PG&E interconnect wiring and agreement documentation, all electrical work has also been completed.

Task 4. Operations–Commissioning (in progress)

There are four phases to this commissioning process

- Site Acceptance Testing (SAT): Confirming the equipment and subsystems have arrived to-site per the original mechanical designs and specifications, include all required components and can be installed satisfactorily (including catalyst loading). This step has been completed.
- Subsystem Operational Testing (SOT): The equipment or isle is 'bump tested' and operated individually (in the middle of its operating envelope) to ensure the installation was completed correctly, that the overall plant controls system can communicate effectively with the subsystem etc. This step has been completed for all equipment constituting the FastOx gasification system except for the syngas electrical generator. The generator SOT will be likely be completed in Q1 2020.
- Performance Qualification (PQ): Verification that equipment or isle is working as per design/per specifications, across its entire operating envelope. This process is ongoing. The gasifier reached steady state operation with waste wood materials at a low feed rate in early 2019 at a 1:5 turndown. The PQ will be considered complete once the system is run on 10 MTPD of MSW for a predetermined number of hours.
- Plant Performance Testing (PPT): Verification that all the equipment isles work in conjunction with the rest of the plant. This task is being completed in parallel with the PQ since in most cases, it is not possible to test the performance of individual unit operations without the upstream and downstream systems being operational.

Task 5. Operations–Demonstration (in progress)

This task will execute the detailed demonstration plan via the test groups identified in section 5.1 above and recording data per the project POs.

Task 6. Transfer of Equipment (in progress)

Once the FastOx gasification system is fully operational and optimized, and proven beneficial to FHL's operations, the system will continue to be operated by Sierra Energy operators in collaboration with FHL DPW. The FastOx gasification system will also be used as a training facility for FHL and external DoD employees for future FastOx gasification platform installation and operation at other facilities and locations.

For Sierra and FHL DPW personnel to continue to operate the FastOx gasification system, maintaining the existing permits is all that is required, which involves quarterly inspections and annual compliance testing (at the expected cost of $30,000 per annum). The reason no new permits are required when the equipment is transferred from ESTCP to FHL, is because the air quality and water quality permits were provided assuming 24:7 year-round operations. The Solid Waste Permit (SWP) exemption will also not need to be updated as the existing Standard Operating Procedures (SOPs) comply with the California Minimum Standards for Solid Waste Handling and Disposal as per Articles 6.1 to 6.35 of Title 14, California Code of Regulations.

For future system locations, all typical environmental (air quality, water quality, waste handling and disposal etc.); facility-use and safety permits would need to be obtained before construction and maintained periodically as-required. Given that this first-demonstration has occurred within Monterey County, California (a territory with high stringency on environmental impacts), the permitting pathway and permit clauses themselves can be used for future permitting entities, accelerating the acquisition of environmental permits greatly. The list of permits that would need to be reviewed for applicability and obtained (as needed) can be found in Table 4.

Should waste need to be brought-in to a DoD facility for conversion via gasification (if the host facility did not produce enough total volume, or enough adequate volume of waste materials), the system operators would need to evaluate and obtain permits to the transfer of waste (potentially across county and state borders), in addition to receiving approval and clearance from the certain DoD units having jurisdiction over this facility (Army Reserve Installation Management Directorate (ARIMD) for example).

5.2 BASELINE CHARACTERIZATION

Reference Conditions

- Currently no baseload power is being produced from the waste materials generated onsite at FHL.
- All post-recycling residual material along with the non-recyclables stream is sent offsite to landfill. The hauler (previously Waste Management, and since Q1 2018 has been Midstate Waste) measures the mass of these materials being collected from FHL. See **Figure 6** for a schematic of the current practices.

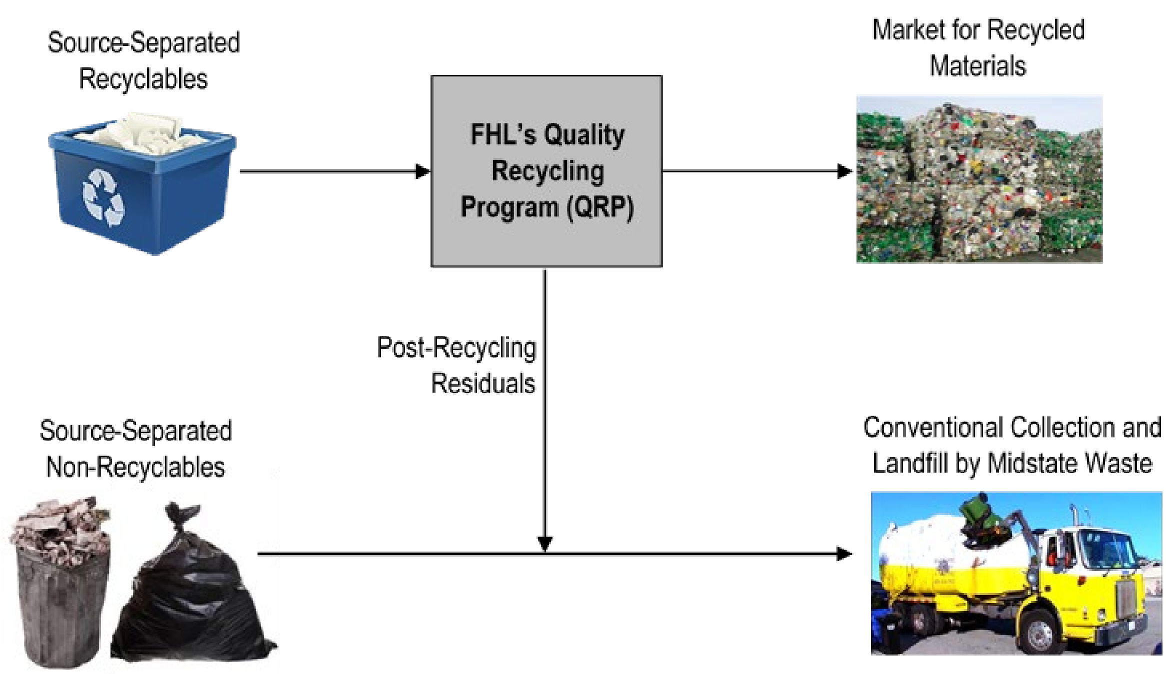

Figure 6. Existing FHL Waste and Recycling Program

Baseline Collection Period:

As the amount of waste generated at FHL (within the cantonment area, and the in-field training & exercise waste) varies especially given FHL's expansion, previous year's data cannot be utilized as a 'baseline' for this project. Instead, it is evaluated in real-time from the data acquired during the operations-demonstration period.

FHL's electricity consumption onsite has the same issue as the waste generation records; vast changes to the infrastructure have occurred within the last few years (new solar photovoltaic installations, battery storage additions and energy efficiency improvements) and are planned for the coming years while changes in total electricity required continue as new buildings are brought online.

Therefore, instead of measuring the existing practices at FHL over a period to obtain baseline conditions (before the installation of the FastOx technology), the 'before and after' comparison is completed in real-time during operation.

- Baseline electricity – there are currently no secure, onsite, distributed production of baseload electricity from the waste materials, therefore any net electrical power produced will offset an equal amount of power currently being pulled from the local utility.

- Baseline waste disposal – any mass of material that the FastOx demonstration project receives at its 'boundary limits' is material that would have been directly hauled and disposed of in landfill. Therefore, the demonstration project can obtain the 'baseline' by comparing the mass of the received materials. Other than materials that Sierra Energy's environmental permits do not allow conversion of (and must be removed from the incoming waste stream), all residuals coming from the FastOx demonstration project should be of recyclable value. If there are materials that still do require landfilling even after FastOx gasification processing, the net diversion (mass of material accepted by FastOx demonstration plant minus mass of material still ultimately landfilled) will determine performance. See **Figure 8** for proposed integration of project within existing FHL operations.

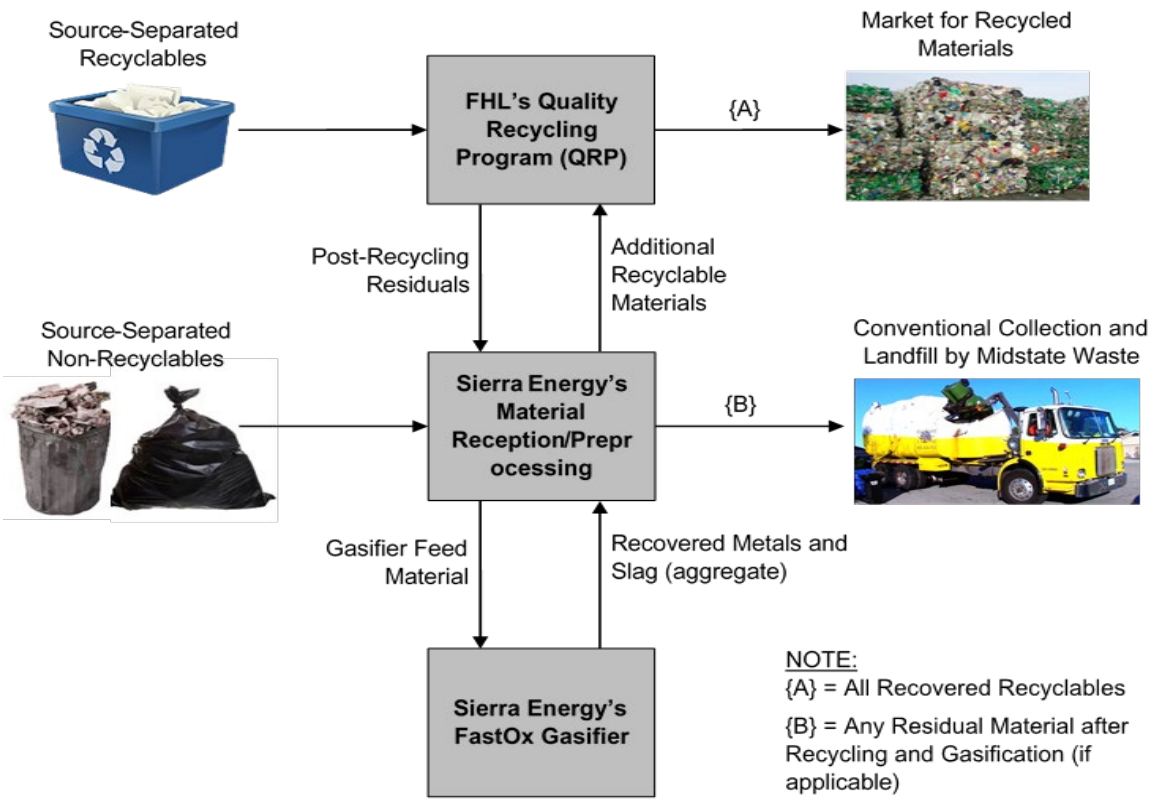

Figure 7. Proposed Integration of Project Within Existing FHL Procedures

Existing Baseline Data:

- The specific emissions analysis [PO3], or the actual emissions coming from the IC genset within the FastOx demonstration project, will be compared to industrial and academic empirical data for gensets of a similar size while operating on the fuels that are present for the back-up generators at most DoD installations (JP8, diesel, natural gas and propane).
- For the specific operating cost analysis [PO2], the costs that FHL pay for waste removal and average electricity price will be obtained from on-base personnel or National Labs who are assisting FHL personnel with the Net-Zero Waste Initiative [13] and the Net-Zero Energy Initiative [3, 13], and have access to all of the FHL utility operating data.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

Sierra's relatively compact and streamlined FastOx gasification platform consists mainly of pre-packaged modules and skids including a waste pre-processing isle, an air-separation unit ("ASU") for oxygen generation, a FastOx gasifier, gas conditioning equipment, a utility skid, the controls system, an electrical genset, and various other pre-packaged major equipment items.

Of the major unit operations, the core enabling and novel technologies the integrated system builds around is Sierra Energy's FastOx gasifier and the downstream syngas polisher unit. The rest of the equipment selected and assembled into the subsystem modules is generic or customizable commercial off-the-shelf (COTS), which has already been proven independently, but not integrated together in a complete system.

A plot plan of the entire facility can be found in Appendix A.

<u>Waste Handling and Charging System</u>

The waste wood materials generated by FHL are stored in manageable outdoor stockpiles (typically after shredding with a tub-grinder that FHL DPW owns) within 300 yards distance of Bldg. 339. Municipal Solid Waste (MSW) is delivered directly to Bldg. 339 where it is sorted inside the building.

Whether waste wood or MSW, after the recyclable materials and hazardous materials have been separated (per the environmental permitting requirements), the remaining materials are shredded into pieces less than two inches nominal dimension by a quad-shaft shredder. The shredding process increases surface area, makes the feedstock more homogeneous and shortens the residence time in the gasifier.

The shredded waste is loaded onto a conveyor system that carries the waste into the gasifier charging system. The charging system has two main sections: the weigh hopper and the airlock.

Figure 8. Feed Operator Shredding Waste Wood Feedstock in Bldg. 339.

Conveyor system up to the top of the FastOx Gasifier module can also be seen.

The weigh hopper has loadcells that measure the amount of waste fed into the gasifier. The weigh hopper is loaded via the feed conveyor until a desired weight or maximum volume is reached. Then the conveyor is stopped.

The airlock system prevents the escape of syngas to atmosphere (a potential fugitive emission, which would also decrease the volume of renewable end-products yielded), while simultaneously preventing air being drawn into the process which would slightly dilute the syngas.

Air Separation Unit

The air separation unit (ASU) is designed to separate oxygen from air. This is achieved using a vacuum swing adsorption (VSA) system which consists of several vessels of adsorbent material that has high affinity for nitrogen – the other major component of air. When pressurized air is passed through the vessels, the nitrogen is selectively adsorbed while oxygen passes through unimpeded. This oxygen can then be used for the FastOx gasification and FastOx polishing processes.

When the adsorbent beds are 'saturated' with nitrogen, pressure in the vessel is released causing the nitrogen to be 'desorbed' and the adsorbent is 'regenerated'. By having one set of adsorbent beds under pressure adsorbing and another set of beds regenerating simultaneously, a continuous stream of oxygen can be produced.

FastOx Gasifier

The FastOx gasifier vessel shell is made of high-quality carbon steel and houses a refractory lining, a cooling jacket and tapping equipment for the removal of the molten, vitrified stone and metals.

The FastOx gasifier vessel is constructed to withstand the thermochemical reaction temperatures, the harsh chemical and mechanical environment that take place during the conversion process, allowing for 95% uptime, or 347 days of continual operation between regular maintenance periods.

As the solid waste enters the gasifier from the top of the vessel, oxygen and steam are injected at highly concentrated and rapid rates in the lower regions using FastOx lances. This supersonic injection of oxygen and steam dramatically increases process efficiency and syngas yield. This injection process also prolongs refractory life and the life of the lances as it forces the primary reactions to occur towards the center of the gasifier rather than around the perimeter.

The high-temperature exothermic reaction of oxygen with the residual carbon (char) present within the feed material produces bulk syngas – a mixture of mainly hydrogen and carbon monoxide.

Sierra Energy is responsible for the primary innovations and design surrounding the FastOx Gasifier unit operation; the rates and injection amounts of oxygen and steam, the physical vessel and injection apparatus design and the controls architecture.

Figure 9. FastOx Gasifier Module Arriving On-site

Solid waste descends through the gasifier by gravity, passing through four reaction zones, including:

1. *Drying:* occurs when hot syngas produced at the bottom of the gasifier rises and passes through the waste in the top zone of the unit, drying the waste as it passes. The operating temperature of this zone is between 82 °F – 302 °F.
2. *Devolatization:* is where most of the volatile organic matter is driven off into syngas. The operating temperature of this zone is between 302 °F – 932 °F.
3. *Partial oxidation:* when carbon-containing materials in the waste react with the injectants of steam and oxygen. This reaction creates high temperatures allowing for the thorough conversion of residual carbon into syngas. The operating temperature of this zone is approximately 3632 °F – 4000 °F
4. *Melting* of the inorganic compounds results from the high temperatures occurring in the partial oxidation zone. These inorganic compounds collect at the bottom of the unit and are continuously removed as molten stone that contains recycled metals, silica and other inorganics. The operating temperature is between 2732 °F – 3272 °F.

Figure 10. Reaction Zones **Figure 11. Inputs and Outputs**

Polisher and Recuperator

The purpose of the FastOx Polisher is to further react condensable hydrocarbons in the gas stream produced by the FastOx gasifier into additional syngas. This not only removes the possibility of the compounds condensing out in low-velocity and low-temperature zones within the system, but also increases the volume of usable syngas available for conversion to renewable end-products.

High temperature syngas from the polisher is sent to the recuperator – a system designed to cool the gas down to a temperature that can be handled by the primary gas cleaning systems, while subsequently recovering heat from the hot syngas (for reuse within the plant in future improvements and augmentations of the FHL system).

Gas Cleaning Module

Gas from the recuperator then enters the gas cleaning isle which has five (5) main components:

- Venturi scrubber
- Packed bed scrubber
- H_2S guard bed
- Syngas blower
- Carbon bed

Figure 12. Primary Gas Cleaning Modules at FHL

Venturi Scrubber

The venturi scrubber subsystem receives a low-temperature (<212°F) syngas and washes the gas with the primary purpose of particulate matter removal.

The scrubber fluid pH and conductivity are closely monitored. To maintain the pH of the scrubbing fluid, a pH control loop and metering pump is used to add NaOH to the system as necessary. A conductivity loop automatically drains scrubber water from the vessel and adds fresh water when required.

Figure 13. Venturi Scrubber Module at FHL

Packed Bed Scrubber

This subsystem receives the post-venturi scrubber syngas and further removes acidic compounds and moisture (excess water) from the syngas utilizing a chilled solution over a packed bed.

The heat exchanger is needed to remove the heat that is absorbed by the scrubbing fluids from the incoming syngas and the heat of reaction. Constant temperature is maintained by varying the cooling water flow to the heat exchanger.

The caustic solution pH and conductivity is closely monitored. To maintain the pH of the scrubbing fluid, a pH control loop and metering pump is used to add NaOH to the system as necessary. A conductivity loop automatically drains saturated scrubber water from the vessel and adds fresh water when required.

H_2S Guard Bed

Due to the presence of sulfur compounds in waste streams, hydrogen sulfide (H_2S) is a highly undesirable component of the syngas produced by the gasifier. If not removed, it can corrode lines and equipment and become SOx emissions from the electrical genset. The H_2S Guard Bed removes this compound using an adsorption process.

A bed of Iron Oxide housed within the vessel has a high affinity for H_2S. As the syngas passes over this porous material, the H_2S attaches onto adsorbent sites on the FeO bed and is thus removed from the syngas stream.

Syngas Blower

The syngas from the gasifier needs to pass through several pieces of equipment before it eventually reaches the syngas header. Each of these individual pieces of equipment imposes a backpressure on the system which needs to be overcome by the syngas. A rotary lobe type gas blower is used to boost the pressure of the syngas coming from the H_2S Guard Bed. A pressure control loop varies the motor speed of the blower in order to maintain a steady 3 PSIG at the syngas header.

Carbon Bed

This subsystem provides a final guard to remove any organic compounds that have not already been converted or removed. This bed is meant to adsorb any final carbon compounds in the syngas.

Finally, the syngas enters the syngas header from where it is sent to the generator to produce electricity.

Electrical Generator Set

The generator being used is an internal combustion engine capable of utilizing high-hydrogen content, medium-BTU syngas of varying composition to produce electric power.

Syngas-to-Liquid Fuels

The FHL FastOx Demonstration plant was also selected for demonstration of a gas-to-liquids system, that can take the low-pressure syngas (primarily CO and H2) and convert to straight-chain Fisher-Tropsch liquid (FTL) fuel derivatives. While this is not the focus of the original ESTCP demonstration, leveraging funding from the California Energy Commission (CEC) assisting with permitting, procurement and operations of the core FastOx-to-Syngas system, and as-such these goals were complementary to the ESTCP project. Any produced low-carbon, low-sulfur, high-cetane FTL will be tested to confirm it meets basic DoD specifications and will potentially be utilized by FHL's existing diesel-powered vehicular fleet.

5.4 OPERATIONAL TESTING

Operational phases of the project have been described in section 6.1. This section details which tasks have been completed and which are currently in progress.

A table showing the dates of completion of project specific milestones can be found in section 3.2.

5.5 SAMPLING PROTOCOL

<u>Data Collection Diagram</u>: The schematic in Figure 14 identifies a key selection of major unit operations, and associated key 'streams' or material and energy flows. The FastOx gasification system at FHL logs many thousands of parameters simultaneously. For the purposes of evaluating the POs of this ESTCP project, only a key selection of the large array of measured parameters are utilized directly – these streams are marked below.

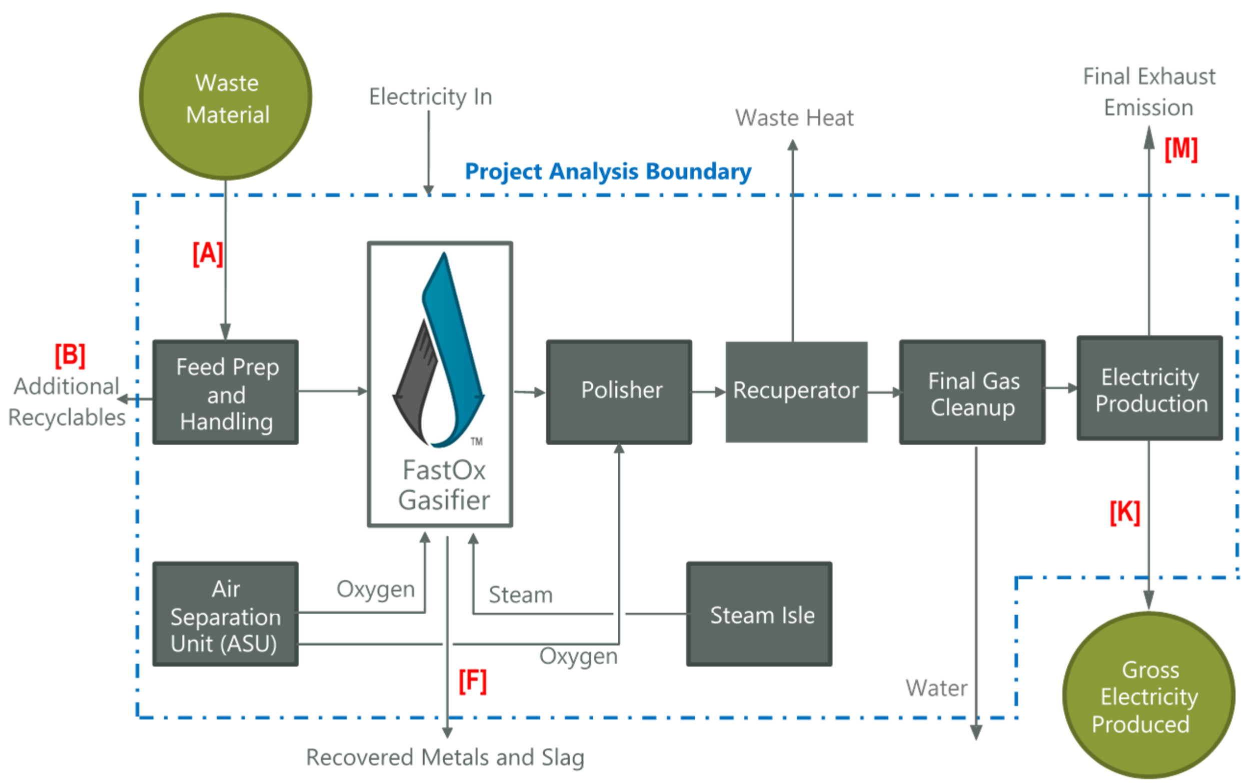

Figure 14. Schematic of FHL Analysis Boundary

Table 5 below shows all the key parameters to be utilized to evaluate the POs of this ESTCP project.

Table 5. Data Acquisition Table

Parameter	Measurement Equipment and Instrument	Standard Protocol	Responsible Party
[A] Waste Material Received at Project Boundary			
Mass	Industrial Scale	SE procedure	SE Operators
Bulk Composition	Laboratory Scale	Lab procedure	SE Operators
Moisture Content	Oven	Lab procedure ASTM	SE Operators
Proximate Analysis	Lab Equipment	ASTM D-5142	Outside Lab
Ultimate Analysis	Lab Equipment	ASTM D-5373	Outside Lab
Heating Value	Calorimeter	ASTM D-5865	Outside Lab
Bulk Density	Laboratory Scale	Lab procedure	SE Operators
[B] Additional Recyclable Materials Recovered by Preprocessing Isle			
Mass	Industrial Scale	SE procedure	SE Operators
Bulk Composition	Lab Scale	Lab procedure	SE Operators
[F] Vitrified Slag and Recyclable Metals Recovered from FastOx Gasifier			
Mass Flow Rate	Lab Scale	SE procedure	SE Operators
Temperature	Laser Pyrometer	SCADA Logging	SE Operators
Bulk Composition	Lab Equipment	EPA SW6020	Outside Lab
Leachability	Lab Equipment	EPA TCLP	Outside Lab
[K] Electrical Output from Genset			
Gross Power	Genset onboard meter	SCADA Logging	Automated
Frequency	Genset onboard meter	SCADA Logging	Automated
Power Factor	Genset onboard meter	SCADA Logging	Automated
[M] Final Exhaust Emission to Atmosphere			
Velocity of Exhaust	Pitot Tube	SCADA Logging	Automated
Temperature	Thermocouple	SCADA Logging	Automated
CO	Exhaust Gas Analyzer	SCADA Logging	Automated
CO_2			
NO_x			
SO_2			
Particulate Matter	Isokinetic Sampling	EPA Method-5	Outside Lab
Standard Utilities Used by Every Major Component Isle			
Electrical Power	Power Meter	SCADA Logging	Automated
Water In	Water Meter	Meter reading	SE Operators
Wastewater Discharged	Water Meter	Meter reading	SE Operators
Fuel Gas	Electronic Gas Meter	SCADA Logging	Automated

Survey Questionnaires: Once commissioning is completed, surveys will be given to the FHL environmental division, as well as employees at neighboring facilities to evaluate the project for noise and odor.

Equipment Calibration: There are several sensors and analyzers incorporated into the FastOx gasification system, most of which are designed for long life in harsh industrial environments. For ensuring high quality of data, it will be necessary to perform scheduled calibration of most major sensors.

- Gas analyzers. There are several real-time gas and exhaust analyzers that require weekly ‘cal-checking’ (to confirm they are within calibration specifications). Certified calibration gases from outside industrial gas companies are be used for cal-checks and calibration of analyzers.
- Temperature and pressure sensors both have high repeatability (precision) but usually do not all zero initially (inaccurate). The SCADA software includes an algorithm that ‘zeros’ all applicable sensors before a new system operation is undertaken.
- Mass Flow Meters. Given the reliance on obtaining an accurate mass balance for many of the POs, where possible, the system incorporates equipment redundancies on certain critical streams. Different technologies types are sometimes used in series (for example a differential pressure device is placed in series with a thermal-mass meter to obtain two independent readings of a syngas mass flow in different locations of the system). Calibration of all mass flow meters is designed into the SCADA system’s Calibration Subroutine, which is initiated by the operator and conducted automatically thereafter by the system.
- Any outside laboratories or outside subcontractors brought onsite to conduct testing will utilize their in-house calibration protocols.

Quality Assurance Sampling: Quality assurance and quality control ("QA/QC") procedures used with previous FastOx testing and validation operations is maintained for this demonstration including: confirmation of major instrumentation calibration before and after operational campaigns, rejection of anomalous data (typically due to instrument error or failure), statistical averaging of raw data to obtain a time-averaged steady state mass-energy balance, and use of outside approved laboratories and contractors.

A heat and mass balance is completed for each testing run – that obtains a satisfactory ‘steady-state’ operation – using inputs from data collected empirically and compared to previous empirically validated H&MB simulations for evaluation.

Outside laboratories will utilize their own in-house calibration and QC/QA protocols that are typically adopted from established EPA, ASTM and NIST methods.

5.6 SAMPLING RESULTS

Although the plant is still in early operations-demonstration, some data collected from the previous campaign’s steady state FastOx operations on waste wood is presented in this section.

[A] Waste Material Received at Project Boundary

Shown below is the ultimate and proximate analysis of the waste wood feedstock used in the commissioning process. It is mainly C&D and waste wood. The ultimate analysis is an elemental breakdown of the waste once water has been completed removed leaving five elements, C, H, N, O, S and ash. The ash consists of metals and other compounds with high melting points like metal oxides and silicates. The proximate analysis of the waste determines what percentage of the waste is volatile and how much fixed carbon is available. Fixed carbon is main source of energy for the FastOx gasification process.

Table 6. Wood Waste Ultimate Analysis (Dry Basis)

Component	Weight%
Carbon	53.8%
Hydrogen	5.6%
Nitrogen	0.6%
Oxygen	38.5%
Sulfur	0.04%
Ash	1.4%

Table 7. Waste Wood Proximate Analysis (As Received)

Component	Weight%
Moisture	14.3%
Volatile Matter	70.2%
Fixed Carbon	14.2%
Ash	1.2%

[F] Vitrified Slag Coproduct Recovered from FastOx Gasifier

Shown below is a picture of the vitrified slag from waste wood gasification collected after one of the operating campaigns at FHL. A sample was sent to a lab for analysis for the presence of metals and EPA non-hazardous waste confirmation testing. The results confirming it's determination as 'non-hazardous' (so it can be reused or sold for revenue) are presented in Table 8.

The project's Solid Waste Exemption permit letter confirms, "Prior to disposal or reuse the slag will be tested for toxicity per both federal and California regulations [(Toxicity Characteristic Leaching Procedure (TCLP); Total Threshold Limit Concentration (TTLC) and Soluble Threshold and Limit Concentration (STLC)], as outlined in Titles 22 and 26 of the California Code of Regulations."

Sierra Energy will be storing each batch of recovered slag, conducting these three (3) lab tests, and on receipt of confirmation that the material is indeed non-hazardous will be transferring accordingly (worst-case it can be landfilled), or preferably reused by FHL DPW for construction aggregate.

Figure 15. Vitrified Stone Co-product Example

Table 8. Slag TTLC, STLC and TCLP Test Results

	TTLC					STLC			TCLP		
Elements (Symbol)	Regulatory Limit Limit	Result	Haz. Waste?	STLC Test req?	TCLP Test req?	Limit	Result	Haz. Waste?	Limit	Result	Haz. Waste?
	mg/Kg	mg/Kg	Yes / No	Yes / No	Yes / No	mg/L	mg/L	Yes / No	mg/L	mg/L	Yes / No
Antimony (Sb)	500	ND	No	No	--	15	ND	No	--	ND	No
Arsenic (As)	500	0.76	No	No	No	5	ND	No	5	ND	No
Barium (Ba)	10,000	960	No	No	No	100	5	No	100	0.59	No
Beryllium (Be)	75	0.86	No	No	--	0.75	ND	No	--	ND	No
Cadmium (Cd)	100	ND	No	No	No	1	ND	No	1	ND	No
Chromium (Cr)	2,500	160	No	Yes	Yes	5	1.1	No	5	ND	No
Cobalt (Co)	8,000	3	No	No	--	80	0.068	No	--	ND	No
Copper (Cu)	2,500	280	No	Yes	--	25	0.054	No	--	0.046	No
Lead (Pb)	1,000	ND	No	No	No	5	0.2	No	5	0.054	No
Mercury (Hg)	20	ND	No	No	No	0.2	ND	No	0.2	ND	No
Molybdenum (Mo)	3,500	11	No	No	--	350	0.15	No	--	ND	No
Nickel (Ni)	2,000	54	No	No	--	20	1.3	No	--	0.096	No
Selenium (Se)	100	0.71	No	No	No	1	ND	No	1	ND	No
Silver (Ag)	500	0.48	No	No	No	5	ND	No	5	ND	No
Thallium (Tl)	700	0.99	No	No	--	7	ND	No	--	ND	No
Vanadium (V)	2,400	12	No	No	--	24	0.081	No	--	ND	No
Zinc (Zn)	5,000	2	No	No	--	250	ND	No	--	ND	No

The average bulk gas composition of the syngas produced by unoptimized FastOx operations of the waste wood is presented below. This data was gathered in real time by Sierra's gas analyzers. Collection of this data is the first step towards DOX-based optimization of syngas quality by modifying operating parameters.

Part of this DOX optimization strategy includes minimizing the amount of nitrogen in the syngas. Nitrogen is used as a purge gas to keep sampling lines clear of condensable hydrocarbons and particulates in the system and is present in the air-premix to Oxy-Fuel burners (used as a temporary measure to address burner system issues with the LPG fuel, see Section 8.0). The second column in **Table 9** shows the theoretical syngas composition when the presence of nitrogen is corrected for.

Table 9. Unoptimized Bulk Syngas Composition from Waste Wood Gasification

Component	Measured Syngas [vol%]	Measured Syngas (corrected for N_2) [vol%]
CH_4	3.9%	4.9%
CO	27.7%	35.4%
CO_2	27.6%	35.2%
H_2	19.3%	24.6%
N_2	21.6%	0.0%

6.0 PERFORMANCE ASSESSMENT

PO1: Peak Specific Renewable Electricity Generation

Success Criteria: Sierra selected an objective Specific Net Electricity Production (*SNEP*) value of 700 [kWh_e (net)/tonne (into gasifier)], as this is the theoretical value calculated by Sierra's engineers for operations on typical post-recycling residual waste in California. It is difficult to compare FastOx to other conversion technologies operating on waste materials due to the highly heterogeneous nature of MSW and the challenge in obtaining detailed mass-energy balances for private companies.

Results: Since the plant is still early in its operations-demonstration stage and the electrical generator is yet to be operated, there is not enough empirical data to validate this success criteria relative to actual operations. In the absence of empirical data, the predicted *SNEP* based on computer simulations is shown below.

When 10 metric tons of waste wood feedstock with 20% moisture is introduced into the FastOx gasifier computer simulation model created on Aspen Plus, it predicts a gross electric power output of 521 kW_e. Based on initial empirical data gathered during the commissioning process, the Electricity Required by FastOx Plant (*ERP*) at full operating capacity has been estimated to be 240 kWe.

$$\text{Gross Electricity Produced by Genset, } GEPG = 521 \text{ kWe}$$

$$\text{Electricity Required by FastOx Plant, } ERP = 240 \text{ kWe}$$

$$\text{Mass of Material Entering Gasifier, } MMEG = 10 \ {}^{\text{tonnes}}/_{\text{day}} = 0.42 \ {}^{\text{tonnes}}/_{\text{hr}}$$

$$\text{Specific Net Electricity Production, } \boldsymbol{SNEP} = \frac{(521 \text{ kWe} - 240 \text{ kWe})}{0.42 \ {}^{\text{tonnes}}/_{\text{hr}}} = \boldsymbol{674} \ {}^{\boldsymbol{kWhe}}/_{\boldsymbol{tonne}}$$

While the calculated *SNEP* of 674 kWh_e (net)/tonne is lower than the success criteria of 700 kWh_e (net)/tonne, this number can be significantly improved upon. Once the plant is fully operational, several systems will be optimized to reduce the *ERP* on the plant. Test engineers will continuously improve upon the control scheme of the plant – adjusting parameters based on factors such as ambient conditions and the type of waste being used as feedstock. Improvements are also expected as field operators become more familiar with the plant. These enhancements are achieved without any extra capital expenditure, merely optimizing the existing equipment within its existing operating envelope.

Besides the optimizations that are expected during normal operation of the plant, it would also be possible to recover waste heat from around the plant and feed it back into the process with the addition of some equipment. This would further improve the *SNEP*.

Once the demonstration begins, the actual *SNEP* will be calculated using data logged by the SCADA system.

PO2: Specific Operating Cost

<u>Success Criteria:</u> If the system operation can achieve unlevelized cost parity or be less expensive than the existing average costs of electricity the installation is paying (\$0.176/kWh$_e$ in FY18).

<u>Results:</u> Since the plant is still early in its operations-demonstration stage and the electrical generator is yet to be operated, there is not enough data to validate this success criteria. However, in the absence of empirical data and using the calculations presented in Section 8.3 (**Table 12** and **Table 13**), when the waste disposal savings and sales of coproducts is removed from the FastOx system O&M cost, the approximate 'Operating Cost' (or Cost of Electricity (*COE*)) is calculated as \$0.005/kWh$_e$ using Net Present Value (NPV) calculations over 20-yrs with a discount rate of 2%. This calculation is equivalent to those presented in Section 3.0 for the Specific Simple Operating Cost (SSOC).

COE = (*O&M_NPV* + *CPS_NPV* – *WDS_NPV*)/(*NEP_20*)

= (\$16,106,000 + \$144,000 – \$15,648,000)/(3,035,000 * 20)

= **\$0.005/kWh$_e$**

Where:
O&M_NPV = Operations and Maintenance Costs over 20-years, converted to NPV
CPS_NPV = Co-Product Sales over 20-years, converted to NPV
WDS_NPV = Waste Disposal Savings over 20-years, converted to NPV
NEP_20 = Net Electricity Produced (and exported) over 20-years

Including the CAPEX, the levelized Operating Cost (or Levelized Cost of Electricity (*LCOE*)) is still far below the current average electricity procurement price of \$0.176/kWh$_e$ at FHL.

LCOE = (*TICC_NPV* + *O&M_NPV* + *CPS_NPV* – *WDS_NPV)*/(*NEP_20*)

= (\$5,200,000 + \$16,106,000 + \$144,000 – \$15,648,000)/(3,035,000 * 20)

= **\$0.091/kWh$_e$**

Where:
TICC _NPV = Total Installed Capital Cost, converted to NPV (though all incurred in Yr-0 anyway)

PO3: Environmental Benefit

<u>Success Criteria</u>: Currently, the production of primary and back-up electrical power used on DoD installations is derived from mainly fossil fuels (LPG at FHL, Nat. Gas and Diesel/JP-8 at other locations). Given that the exact %–MWe breakdown of the fuel types within the DoD's portfolio is not known and varies per location, an evenly-mixed portfolio is estimated at 33.3% diesel (and JP-8), 33.3% gasoline and 33.3% natural gas (and propane).

This PO will compare the specific emissions of the project to those of the 'mixed fossil fuel portfolio', to validate the environmental benefits of using syngas fuels. The aim is not only to meet the specific emissions of fossil fuels, but see significant reductions in each:

- CO: 2.918 g/kWh$_e$ a 45% decrease*
- VOC: 0.462 g/kWh$_e$ a 20% decrease*
- NO_x: 1.262 g/kWh$_e$ a 90% decrease*
- SO_x: 0.001 g/kWh$_e$ a 65% decrease*
- PM: 0.214 g/kWh$_e$ a 10% decrease*

*over the assume mixed-electricity portfolio of 33.3% diesel (and JP-8), 33.3% gasoline and 33.3% natural gas (and propane).

Results: Since the plant is still early in its operations-demonstration stage and the electrical generator is yet to be operated, there is not enough empirical data to validate this success criteria relative to actual operations. Shown below is the guaranteed emissions profile provided by the generator manufacturer Siemens-Guascor. Predictions and guarantees are not provided for SO_x, VOC or PM.

CO: < 5.93 g/kWh$_e$
NO_x: 2.80 g/kWh$_e$
NMHC: < 1.12 g/kWh$_e$

While these emissions parameters are greater than the proposed PO success criterion, the genset deployed to FHL is smaller than originally anticipated during the in 2011 and 2012 project application (300 kW$_e$ instead of the original 500 kW$_e$) and being less efficient, there's a corresponding increase in the specific emission factors. In addition, the manufacturer is conservative with emissions profiles until actual syngas is generated and tested. Therefore, the actual emission factors measured in the field are still expected to near or exceed the success criterion.

Once demonstration begins with the genset online, real-time emissions data from the generator exhaust stack will be obtained using an exhaust gas analyzer. Additional testing will be completed by a third-party inspector to verify results obtained by Sierra. This testing is a permit requirement for the Monterey Bay Air Resources District (MBARD).

PO4: System Turndown

Success Criteria: At the reduced 1/10th capacity operations, the *SNEP* will not drop by more than 25% from the designed value (of 700 kWh$_e$/tonne).

Results: During the last operations-demonstration campaign at FHL (in January 2019), steady-state operation was achieved for a period at a feed rate of approximately 2.3 metric tons per day – a turndown of 10:2.3. Although this was not with optimized process operations, the data obtained from the campaign can be used to provide an approximate *SNEP* impact due to system turndown.

The average steady state gas composition is shown below in **Table 10**.

Table 10. Average Steady State Gas Composition from Jan 2019 Campaign

Component	Volume %
CH_4	3.87%
CO	27.71%
CO_2	27.56%
H_2	19.25%
N_2	21.64%

$$\text{Calculated LHV} = 177.7\ {}^{Btu}/_{SCF}$$

$$\text{Average Measured Syngas Flow Rate} = 105\ \text{SCFM}$$

$$\text{Efficiency of genset (engine plus dynamo)} = 33.7\%$$

$$\text{Theoretical Gross Electricity Produced by Genset}, GEPG = 33.7\% * 177.7\ \frac{Btu}{SCF} * 105 \frac{SCF}{min} * \frac{kWe}{56.92\ {}^{Btu}/_{min}} = 110.5\ kWe$$

$$\text{Electricity Required by FastOx Plant}, ERP = (240\ \text{kWe}) * \frac{2.3\ \text{tonnes/day}}{10\ \text{tonnes/day}} = 55.2\ kWe$$

$$\text{Mass of Material Entering Gasifier}, MMEG = 2.29\ {}^{tonnes}/_{day} = 0.095\ {}^{\text{tonnes}}/_{\text{hr}}$$

$$\text{Theoretical Specific Net Electricity Production}, SNEP = \frac{(110.5\ \text{kWe} - 55.2\ \text{kWe})}{0.095\ {}^{\text{tonnes}}/_{\text{hr}}} = 582\ \text{kWhe/tonne}$$

Decrease in *SNEP* as a result of reduced system operating capacity =
= (700 – 582)/700 = 16.8%.

The calculation shows that the system's relative efficiency decreases by 16.8% at 10:2.3 turndown. Assuming a linear relationship, it can be estimated that **at 10:1 turndown, the *SNEP* would drop by 19.7%, which is less that the Success Criteria of max *SNEP*-drop of 25%.**

Note, in the absence of empirical data, the above calculations assume linear electricity requirement as a function of O2 generator output.

PO5: Landfill Diversion Percentage

Success Criteria: When the FastOx system is operational, Sierra has set the goal of obtaining a minimum of 75% *LDP*. The reason this goal is not higher, is due to the actual materials received at the project boundary may be determined to be non-suitable for processing with the FastOx system (for example large volumes of hazardous liquid waste streams that must be removed as required by our environmental permits), in which case this removed material will be dealt with via conventional strategies.

Results: Since the plant is still early in its operations-demonstration stage, there is insufficient empirical data to evaluate this PO on MSW materials. From initial operations on waste wood, it is observed that the ***LDP*** **with waste wood and biomass is in the 95–99%wt. range.**

PO6: Total Mass of Material Gasified

Success Criteria: A minimum of 275 tonnes of material should enter the FastOx gasifier to ensure the system evaluated with satisfactory sample size.

Results: Since the plant is still early in its operations-demonstration stage, only 7.5 tonnes of predominantly waste wood has been gasified during the commissioning process. To meet the success criteria, another 54 days of operations at an average capacity of 5 MTPD would be needed, or approximately 9 more months of demonstrations.

PO7: System Uptime

Success Criteria: The system uptime will exceed 75%. Qualitatively, this means the hours of typical maintenance required when the system is meant to be 'online and available' will not be greater than 33% of the time the gasifier is operational.

Results: Since the plant is still early in its operations-demonstration stage, there is insufficient empirical data to evaluate this PO especially given the maintenance and rework hours completed to-date are mainly corrective actions (would not be expected on future systems), and the hours haven't been satisfactorily logged and attributed to individual activity types (something that will be improved going forward).

PO8: Seasonal Operations Robustness

Success Criteria: There should be no major, operationally disruptive qualitative affects observed. The FastOx system should still perform satisfactorily, converting the waste material, but potentially at a lower overall efficiency (Specific Net Electricity Production).

Results: Since the plant is still early in its operations-demonstration stage, there is insufficient data to validate this PO quantitatively. However, below are a few qualitative observations to-date:

- The altitude and dust content in the area has not caused issues with the equipment and operations.
- FHL weather typically follows a Mediterranean climate with dry hot summers and wet winter months. Temperature range from freezing conditions in the 20s to 110 °F during the summer. With equipment field-deployed, it was identified that freeze protection (equipment and procedures) was inadequate, while additional cooling was also required for some equipment that was overheating when reaching 104 °F (a common maximum working temperature for certain electrical components).
- There were several issues in early commissioning with rainwater ingress into electrical components and equipment, partly due to OEM's equipment not meeting manufacturing specifications, and partly due to poor electrical subtracting workmanship not meeting

code. This is not expected to be an issue for future systems if the equipment specification and selection, and separately electrical subcontracting selection and oversight is improved.

PO9: Odor and Noise

Success Criteria: No complaints for either odor or noise.

Results: Since the plant is still early in its operations-demonstration stage, there is insufficient data to evaluate this PO.

Noise within the plant is monitored periodically using a decibel meter to ensure that plant personnel are exposed to levels that are detrimental to their health. Based on the results observed during early plant commissioning stages, certain sections of the plant have been designated as areas where hearing protection is mandatory (commonly encountered with these types of equipment and processes). As of today, no noise complaints have been lodged by any FHL staff.

Odor has yet to be an issue on-site with waste wood operations, however the more-odorous MSW operations in the coming months may require mitigation.

7.0 COST ASSESSMENT

7.1 COST MODEL

A simple cost model for the FastOx gasification facility is shown below. The costs displayed include leveraged funds from stakeholders other than ESTCP, including Sierra Energy, FHL and the CEC. In the final column, estimates for a repeat project (without cost-rework and equipment replacement and with cost-impacting design improvements incorporated (heat recovery and reutilization), and a larger electrical genset to make use of all generated syngas) are displayed.

Table 11. Cost Model for FastOx Gasification Systems

Cost Element	Data Tracked During the Demonstration	Total Cost Incurred at FHL	Expected Cost for Repeat Project
Permitting costs	Expenses incurred for application fees and consultants.	$100,000	$50,000
Hardware capital costs	Expenses paid on custom and COTS equipment, costs to modularize, and overhead. (For FHL, this category also includes costs to rework or replace inferior equipment and subsystems in the field.)	$6,600,000	$4,500,000
Site Preparation costs	Expense associated with design, engineering and subcontracting to prepare site for system delivery.	$1,250,000	$250,000
Installation costs	Expenses paid on construction management, equipment installation, system commissioning and labor hours spent on these activities.	$660,000	$400,000
Consumables	Amount of materials used during the testing operations, including the unit cost of materials. (Total over 12 months)	$200,000	$50,000
Facility operational costs	Operating and admin labor (inc. consultants). Monthly equipment rentals. (Total over 12 months)	$2,800,000	$825,000
Maintenance	Record of non-commissioning-related typical maintenance (scheduled and minor unscheduled events) including labor, material and subcontractor expenses. (Total over 12 months)	$110,000	$110,000
Hardware lifetime	Hours of active operations (hours/month), date when a part or component required replacement, both expected and unexpected occurrences.	Lifetime of components at FHL	6-9 Months for key high-wear components
Salvage value	Gains from sale of system equipment and expenses paid on uninstalling the system will be reported at the end of the project demonstration.	N/A	N/A

Several items listed in the costing model will be significantly reduced in future systems due to design and fabrication costs being highest for a first system. Example include the one-time engineering cost associated with initial design and rework and cost overrun due to inefficiencies during construction in the absence of an experienced Engineering Construction and Procurement (EPC) company to lead the project. As the first deployment, there were also equipment items or subsystems that, during commissioning, were identified for replacement with better quality or more efficient components, which will be incorporated into future systems (so the costs of two components would not be incurred).

There is also a significant economy of scale with respect to labor requirements that larger deployed systems. For example, almost all systems irrespective of capacity will require Environmental, Health & Safety coordinator and various admin personnel, at significant expense to small operations. These costs can be reduced if the facility's existing personnel can cover these responsibilities.

In general, the larger a system or equipment item, the more efficient it is, as there is generally reduced heat loss, increased motor efficiency etc.

- Permitting
  - Description: Required pre-construction and annual permits and approvals for air, water, waste, facility-use and safety.
  - Interpretation and Scaling Considerations: Permitting costs are generally consistently high irrespective of scale (unless the system is under some 'trigger threshold') and irrespective of location.
    - If a host facility's DPW Environmental Division can cover some of these permitting and management aspect, a potential decrease in costs of 25-50% may be possible, but outside consultants will generally be needed for complex air emission modeling, and for determining and negotiating waste-related permit requirements and restrictions.
  - Location considerations: Certain high-sensitivity states (California, New York etc.) may require additional long-lead and high direct cost environmental analyses (for example the California Environmental Quality Act (CEQA)) that can add $-millions to the cost and 12–18 months to a project timeline.

- Hardware Capital Costs:
  - Description: These represent the main capital expenses incurred by procuring a FastOx gasification system. Every piece of equipment, whether they were custom or COTS, has a total cost associated with it. This cost includes the engineering, procurement, fabrication and management costs incurred by the developer.
  - Interpretation and Scaling Considerations: Costs will be lower for future systems as most of the engineering will not need to be repeated (assuming equipment doesn't change significantly). Also, as the system scales, major equipment generally follows a "0.6 power law" (see below) whereby there is a significant economy of scale that can be leveraged, so a vessel or equipment package that doubles in capacity, only increases by ~52% in cost.

$$C\_LS = C\_SS * (Cap\_LS/Cap\_SS)\verb|^|0.6$$

Where:
C_LS = Cost at Larger Scale
C_SS = Cost at Small Scale
Cap_LS = Capacity (of equipment) at Larger Scale
Cap_SS = Capacity (of equipment) at Small Scale

In the future, DoD entities maybe able to lease equipment like this, rather than carry the upfront cost or debt-service which may improve the economic proposition for higher-CAPEX systems.

– Location Considerations: the CAPEX for major equipment and modules won't vary significantly, as all equipment meets US-wide safety and design codes and are generally built in the lowest-cost modular fabrication shops.
– Hardware Summary:

Equipment Isle	Unique to SE or COTS	Cost
Waste reception and pre-processing isle	COTS	$350,000
FastOx Gasifier and Valving	Unique to SE	$1,450,000
FastOx Polisher	Unique to SE	
FastOx Recuperator	Unique to SE	
Gas Cleaning	COTS (but needs to be specified carefully by SE)	$415,000
Syngas Genset	COTS	$550,000
O_2 Generator	COTS	$350,000
Controls/E-House	COTS (but includes SE's IP and controls algorithms)	$550,000
Enclosed Flare	COTS	$175,000
Misc. Balance of Plant Equipment	COTS	$630,000

- Site Preparation Cost:
  – Description: Required design, engineering and sub-contracting to have the site prepared with utilities brought to the equipment boundary (electricity, water, sewer), buildings, roads, fencing etc.
  – Interpretation and Scaling Considerations: Given the footprint of a system doesn't increase linearly (larger-capacity systems are relatively smaller than smaller capacity systems), the relative site preparation costs will decrease with increasing system scale. For example, whether the system is 10 MTPD or 100 MTPD, the facility will still need the same support facilities (office building, roadways, fire water back-up storage etc.).
    - Note, the DoD seems to pay significantly more for basic civil and mechanical contracting work (buildings, site work, electrical etc.), especially when compared to similar regional projects in the private sector. This negatively affects the economics for these types of novel systems when compared to business as usual (waste collection and landfilling offsite) that doesn't require civil works on DoD facilities.

- Location considerations: Projects in states with lower-cost labor and materials rates will see savings, potentially up to 30%.

- Installation Cost:
  - Description: Once the major equipment arrives on-site, it needs to be installed as per manufacturer recommendations (where applicable) and interconnected with existing equipment and site utilizes.
  - Interpretation and Scaling Considerations: The installation costs are relatively stable with respect to scale (if all the equipment remains pre-modularized minimizing on-site work).
  - Location considerations: As with the Site Preparation costs, projects in states with lower-cost labor and materials rates will see savings, potentially up to 30%.

- Consumables:
  - Description: Consumables include all materials required by the FastOx Gasification system for day-to-day operations. Examples include limestone, fuel gas such as natural gas or LPG for system startup, caustic solution for the gas cleaning process etc. Electricity is not considered a consumable since the facility produces more than it consumes (is a net-exporter). If the end-product produced from the FastOx syngas is not electricity, then electricity would become and input/consumable.
  - Interpretation and Scaling Considerations: Generally, the efficiency of a system will increase with increasing scale, with a corresponding decrease in consumables required.
  - Location considerations: Due to site conditions (elevation and weather), there may be subtle differences in consumables due to increased heat loss, increased compression power requirements etc.

- Facility Operational Cost:
  - Description: Any expenses required for the day-to-day operations of the facility that are not covered under the 'consumables' cost elements are included here. The primary operational cost is labor and start-up fuel gas.
  - Interpretation and Scaling Considerations: As noted previously, at all scales there are minimum staff responsibility requirements that need covering (EH&S, admin etc.), which can be prohibitively expensive at small operating scales.
    - The FHL system is less optimized and doesn't have as much automation as could be incorporated in future systems, resulting in the requirement for increased personnel.
    - The FHL system, being a test and validation demonstration system is currently staffed with almost entirely engineers and oil & gas (O&G) field operators, at significant expense.
    - In the future, with additional automation and a refined operating envelope, the operator skill-level requirement can be reduced so non-engineering and non-O&G operators can operate the simplified system, saving significant OPEX, especially for remote locations (where support costs (transportation, accommodation, per diem etc.) can become significant).
    - The requirements of the FastOx system on the FHL DPW personnel are minimal, and for the foreseeable future it is expected that the Sierra team will continue operating the equipment at-cost to Sierra, especially given Sierra's interest in retaining the FHL system operating for continued R&D, test and validation programs.

- Maintenance:
  - Description: Both scheduled preventative and unscheduled corrective maintenance have costs associated with them. In addition to the direct cost repairs entail, indirect costs associated with facility down-time may also need to be considered.
  - Interpretation and Scaling Considerations: The costs in this category do not include the one-time rework or replacement costs for equipment, as these are included in the Hardware Capital Costs category.
    - The cost of high-wear replaceable components such as injectors and oxy-fuel burners, are included in this category.
- Hardware Lifetime:
  - Description: This data is used in conjunction with the capital expenditure to evaluate the true cost of an equipment item.
  - Interpretation and Scaling Considerations: A main goal of this test and validation project is to establish and confirm the longevity of critical components to provide replacement intervals for operators, and Mean Time Between Failures metrics. In industries such as O&G, coal gasification and iron & steel, it is common for core high-wear critical components to last 6–9 months.
- Salvage Value:
  - Description: Any money expected to be recouped from sale of equipment at the end of the expected lifetime of the facility is listed here.
  - Interpretation and Scaling Considerations: At FHL and for next units, it is expected that the equipment will remain operational well beyond the 15- to 20-year planned operating life. Equipment will not be scrapped at the end of the initial operating window, but instead maintained, upgraded and operated for the determined contract length.

7.2 COST DRIVERS

Cost drivers are those factors that significantly affect the overall system economics and vary considerably with project site location.

The primary cost drivers when determining the feasibility of a FastOx system in a specific area is the waste disposal cost and electricity procurement cost. These waste gasification systems are likely to be most financially viable in parts of the world where waste disposal costs are high (due to the unavailability of space for landfills or due to the high environmental cost of landfilling waste) or where electricity prices are higher.

Other factors to consider include:

- Waste availability: If the immediate area around a new gasification facility does not produce enough waste to run the gasifier continuously, additional sources of waste will need to be established.
- Labor cost: As stated previously, labor is a significant factor; 30–70% of the annual operating expenses depending on scale and regional labor markets.

7.3 COST ANALYSIS AND COMPARISON

Sierra Energy looked at the existing baseline case, electricity procured from the local civilian utility and waste collected and disposed of by regional waste hauler and compared it with the alternative which is a FastOx gasification system. If implemented at FHL again without all the 1-time cost overruns and assuming 100% of the syngas is converted to electricity, the system would provide on-site distributed power at a low cost and eliminate waste, which helps to reduce disposal costs and budget shortfalls.

Sierra has quantified these advantages through the Life Cycle Cost Assessment (LCCA). Most cost data for this LCCA are estimated using the current costs incurred at FHL, updated to assume a second identical project is implemented. Sierra's method converts prices and costs at the current date to prices and costs at the future date. Sierra assumes that the basic supply conditions for all the materials and services required for the operation remains the same as those for most other goods and services. Hence, Sierra assumes that the prices and costs will change at roughly the rate of general price inflation and average national wages.

The discounting approach is the Present Value (PV) at the base date, while the cash flow convention is at end of calendar year basis. The discount rate used in this analysis is 2% [14]. The life-cycle cost (LCC) timeframe is one-year period for planning, construction and commissioning and 20-year service period.

This LCCA compares between the baseline case and the FastOx gasifier system case. The baseline case uses the civilian electrical utility provider (Pacific Gas & Electric (PG&E)) and waste disposal service providers (Midstate Waste and previously Waste Management). The LCC of $24.4-million for the conventional approach (**Table 12**) serves as a baseline against which the LCC of the energy-saving and cost-effective alternative system will be compared.

Table 12. Cost Data Summary for Conventional Operations at 10 MTPD

Cost Items	Base Date Cost	Year of Occurrence	Present Value
Initial investment cost	$0	Yr 0	$0
Residual value	$0	Yr 20	$0
Electricity cost:			
3,035 MWh at $0.176/kWhe	$534,000	Annual	$8,732,000
Waste disposal cost:			
3,468 tonnes at $276/tonne	$957,000	Annual	$15,648,000
LCC for Conventional Operations			$24,380,000

The LCC of the alternative approach – the FastOx gasification system – is shown in **Table 13**.

Table 13. Cost Data Summary for FastOx Gasification Solution at 10 MTPD

Cost Items	Base Date Cost	Year of Occurrence	Present Value
TICC for FastOx Gasification System	$5,200,000	Yr 0	$5,200,000
Residual value	$0	Yr 20	$0
O&M	$985,000	Annual	$16,106,000
Sale of secondary product, slag:			
220 tonnes at $15/tonne	($3,300)	Annual	($54,000)
Sale of secondary product, metals:			
110 tonnes at $50/tonne	($5,500)	Annual	($90,000)
LCC for FastOx System			$21,162,000
LCC for Conventional Operations			$24,380,000
Net Savings			**$3,218,000**

According to the results of the LCC tables above, the FastOx gasification system provides the lower LCC indicating that it is the preferred solution with net savings of $3.2 million over the conventional baseline approach over the 20-year analysis period.

To account for different potential project site locations, a sensitivity analysis is completed (and displayed in **Table 14** below) for the major cost drivers – waste disposal cost and electricity procurement cost. All other assumptions (CAPEX, labor, consumables etc.) are held constant.

Table 14. 'Net Savings' (over conventional Operations) Sensitivity Analysis for 10 MTPD FastOx Vs Baseline

	$0.03/kWhe	$0.10/kWhe	$0.176/kWhe	$0.25/kWhe	$0.40/kWhe
$25/tonne(waste)	-$18,251,000	-$14,768,000	-$11,007,000	-$7,328,000	$112,000
$50/tonne(waste)	-$16,845,000	-$13,362,000	-$9,601,000	-$5,922,000	$1,518,000
$100/tonne(waste)	-$14,000,000	-$10,517,000	-$6,756,000	$3,077,000	$4,363,000
$276/tonne(waste)	-$4,026,000	-$543,000	**$3,218,000**	$6,897,000	$14,337,000
$550/tonne(waste)	$11,508,000	$14,991,000	$18,752,000	$22,431,000	$29,871,000
$900/tonne(waste)	$31,359,000	$34,842,000	$38,603,000	$42,282,000	$49,722,000
$3,000/tonne(waste)	$150,430,000	$153,913,000	$157,674,000	$161,353,000	$168,793,000

It should be noted that some of the waste disposal cost and electricity procurement cost options shown in Table 14 while higher than typically observed for larger facilities located closer to population centers, are indeed in line with remote, small-scale facilities. For example, FHL paid $540/tonne for average waste disposal in FY18, and this number has since increased to $895/tonne in FY19. Hazardous wastes can also cost up to $3,000/tonne to dispose of at FHL.

It is not advisable to utilize this technology where the economics are not supportive and robust, however there still exist many locations where the DoD has highly-sensitive and costly waste streams that requiring mitigation, and locations where the cost of energy procurement is far in excess of $0.30/kWhe. In these locations, a small FastOx gasification system can make significant improvements to the facility's operating expenses and energy resiliency.

Assumptions for the LCC and Sensitivity Analysis calculations above are listed below.

Table 15. **Operating and Financial Assumptions**

Description	Value
Gross Electricity production	521 kWh_e/tonne of feedstock
Parasitic Electrical Load	30%
Average system availability	95%
Avoided waste disposal fee	$276/tonne of waste[1]
Cost of direct and indirect labor	$800,000/year[2]
Cost of system maintenance	$110,000/year
Total operating expenses	$985,000/year
Discount Rate	2%/year

[1]At FHL, the average base-wide waste disposal cost (including housing cans, large commercial bins and roll-off containers) was $540/tonne in FY18 and $895/tonne in FY19 for ~1,100 TPY collected.

Sierra has been conservative and assumed that for a remote facility that has 10+ MTPD of waste requiring disposal (after recycling, composting etc.) that the $/tonne would be lower than those encountered at FHL currently. Therefore, Sierra uses an averaged number for FHL waste disposal from FY12: 98.5 percent of total waste amount is municipal solid waste (MSW) which costs $235 per tonne to be hauled to landfills of and 1.5 percent of total waste amount is hazardous waste which costs $3,000 per tonne to be dispose of. The weighted average of waste disposal cost per tonne is (98.5% *235) + (1.5% * 3,000)] = $276/tonne.

[2]Assumes eight FTE (full-time equivalent) operations-related personnel with an average annual cost of $100,000/yr. Also assumes EH&S and other admin roles are covered by on-post DPW personnel, so that headcount and costs are not double-counted.

These analyses also did not take into account the increased energy-resiliency afforded to the host facility due to the baseload power being produced by FastOx onsite; or didn't account for the benefits to the local economy (by creating direct jobs and the associated indirect jobs) than paying an external company to merely remove this energy resource from the facility.

These analyses also assumed that the capital costs were absorbed by the project in their entirety in Yr-0, and grants and tax credits are not included. These financial aids are readily available for projects that decrease the carbon intensity of operations, increase energy security and lower LCC.

These analyses also did not take into account the receipt and sale of carbon credits, that in certain states (CA, CT, DE, MA, ME, NH, NJ, NY, RI and VT) are available for projects of this nature that decrease the carbon-intensity of operations. In 2019, UC Davis (UCD) completed a Life-Cycle Assessment (LCA) study on the FastOx Gasification technology deployed at FHL (10 MTPD) and at the larger 50 MTPD scale. UCD calculated that the FastOx system significantly lowers the carbon-intensity of operations, and would be able to receive significant Low Carbon Fuel Standard (LCFS) credits, significantly improving the economics of the system even further, see **Table 16**.

It shows that for the FHL project (rows 1 and 2), FastOx operations would generate an additional \$0.18–\$0.22/kWhe in LCFS credits, which would increase the relative electricity revenue and offset from \$0.176/kWhe to \$0.356–0.396/kWhe. Again, this LCFS credit was not included in the LCC analysis, but the qualitative affect can be observed in Table 14, improving the 20-yr Net Savings from \$3.2 million to approximately \$14.3 million (NPV).

Table 16. Carbon Intensity of FastOx and LCFS credits applicable (Source: UCD)

Configurations	EER	Carbon Intensity	LCFS credit
FHL-E-1	3.4	51 $g_{CO_2\,eq.}/MJ$	0.18 \$/kWh
FHL-E-2	3.4	-85 $g_{CO_2\,eq.}/MJ$	0.22 \$/kWh
E-1	3.4	-42 $g_{CO_2\,eq.}/MJ$	0.24 \$/kWh
E-2	3.4	-65 $g_{CO_2\,eq.}/MJ$	0.25 \$/kWh

The above analyses (the LCCA and the subsequent Sensitivity Analysis) were completed for a very small, 10 MTPD system, as deployed at FHL. The system and project economics improve greatly with increasing scale, and Sierra's next commercial deployment (at 50 MTPD) will confirm these improved economics, especially with respect to the baseline cases or 'business as usual'.

8.0 IMPLEMENTATION ISSUES

This waste gasification plant at FHL is the first large-scale demonstration of an oxygen-based solid waste gasification system in California. This project also represents the first time that Sierra Energy worked with commercial vendors to modularize a fully integrated system combining COTS equipment with Sierra Energy's novel technologies. The team overcame several hurdles that were not initially anticipated. These challenges resulted in excellent learning and advancements to the current system and for future systems.

Proposals and deployments of future projects have already improved, commercial customers are nearing the point of purchase, and implementation of future projects will proceed more smoothly based on the learnings of this FHL-based ESTCP project.

8.1 PERMITTING PATHWAY

At the onset of this project, Sierra Energy found there to be no previously defined pathway for permitting commercial gasification systems in California. Gasification is currently defined in a restrictive way in the Public Resource Code creating roadblocks to installing gasification projects beyond demonstration. This is a California-specific barrier to commercialization; there are fewer issues with permitting outside of the state as evidenced by other technologies having built and operating gasification plants in other locations in the United States such as Fulcrum in Nevada, Ineos-Bio in Florida etc.

Sierra Energy initiated permitting (environmental, building use and occupancy etc.) for this FHL project with the Department of Public Works (DPW) at FHL in 2013. Given the nature of this type of waste conversion system and the lack of predecessors and examples of fielded waste gasification projects in California, a clear environmental permitting pathway was not established and had to be developed with all the local and state agencies – a significant challenge and resource burden for a small, emerging technology company.

After three (3) years, all the pre-construction environmental permitting had been established and received.

The Sierra Energy team hopes that this project sheds light on these environmentally beneficial emerging technologies available to efficiently and cleanly convert wastes to energy, helping ease regulatory pathways for commercialization of this beneficial FastOx technology and related industry offerings.

FastOx is a new technology with benefits that span different California agencies (CARB, local AQMDs, CEC, CalRecycle) and addresses various state needs (waste diversion, air and water improvements, GHG reductions, economic development) and produces various end-products (renewable diesel, electricity, hydrogen and sustainable co-products). Given the complexity and numerous potential Waste-to-X system configuration options, communication with stakeholders is more involved than for a simpler technology with a simpler mix of stakeholders.

8.2 SUBSYSTEM ISSUES

As had been relayed back to the ESTCP committee in Quarterly Progress Reports (QPR) online and annual In-Progress Review (IPR) meetings, there were a number of issues with vendor-supplied subsystems, that had to be resolved (sometimes without the support of the original equipment manufacturer (OEM)) by the project team before the core FastOx Gasification technology could be fully commissioned, tested and then optimized.

Some examples of subsystem issues identified and resolved included:

- Oxy-fuel burners were operating outside of the provided specifications (producing too much soot due to incomplete reactions)
- Level instruments in the airlock and charging system unable to operate with the feed material
- Controls algorithms had major fundamental issues, plus operator alarm overload
- Instrumentation grounding issues in the main Control panel
- Leaks on water jacket welds on pressurized process vessels

8.3 PG&E INTERCONNECT ISSUES

It is not only complicated and expensive to parallel to the grid for a demonstration project, but the utility is typically inefficient and has a general dislike of small renewable and intermittent power projects. It was also complicated further as FHL already has 3 MWe of photovoltaic solar, a 1 MWhr battery system, and a 1 MWe export limit from the facility (which requires a complicated 'curtailment' SCADA to ensure FHL cuts-off power and connection to power sources onsite to avoid exceeding that 1 MWe export limit). The curtailment SCADA is custom and was designed for 2 MWe of the 3 MWe of solar, the 1 MWhr battery and the Sierra syngas genset were never able to be incorporated into the scheme or PG&E interconnect agreement, as FHL has changing goals, changing budgetary requirements and ultimately is planning to add additional battery storage, additional solar and form a microgrid (island themselves from the PG&E grid) in the coming years.

It is recommended for other demonstration projects where the injection of power into the local grid is not a primary goal, to instead focus on producing the electricity and putting directly into a load bank to avoid the cost, logistics and timeline impacts.

8.4 PROJECT DEVELOPMENT AND MANAGEMENT

Given the financial constraints for this first-of-its-kind FastOx gasification deployment, Sierra Energy was forced to 'self-perform' (act as the lead contractor and project developer) and bid-out and manage all subcontracts. Not only did this pre-qualification, bid solicitation and contract negotiation effort take a long time for a small, project-inexperienced, resource-constrained company, the subsequent delays (due to some subcontractors underestimating cost and time expectations) and cost overruns impact smaller companies who have less cash flow and are less likely to acquire reputable industry contractors to bring projects back on-track.

The project at FHL trailed behind initial schedules, due to several key reasons, including:

- The length of time it took to officially relocate the project for the Port of West Sacramento, to the US Army's FHL, took approximately three years.
- The length of time for permitting to be completed for this project, due in part to the determination of the permitting requirements and pathway between the stakeholders and regulators, which took three years in total.
- The design team and suppliers experienced delays delivering equipment to the project site, due to numerous design revisions, and complexities of fabricating this first-of-its-kind system.
- Electrical work took longer than proposed, as several issues were discovered after the initial contract was complete, requiring SE to bring in a separate electrical contractor to correct the issues to meet California code.
- The I/O Checkout, an essential part of early commissioning, took three months instead of the proposed three weeks.
- The controls firmware, software coded specifically for the FastOx gasification unit operations, was not implemented to the specified requirements, and required many onsite changes which took over six months to complete.

Despite all the issues encountered during the project, the strong support of the FHL and ESTCP personnel allowed Sierra Energy to continue to focus on the important task at-hand; the design, permitting, fabrication, installation, commissioning and early operations-demonstration of a first-of-its-kind oxygen-blown waste gasification system, that as a future technology platform will provide various DoD entities and managers the ability to diversify their waste disposal and energy procurement portfolios, while subsequently increasing energy resiliency, decreasing environmental footprint, and decreasing overall levelized costs.

This patience and long-term vision and foresight of the FHL and ESTCP personnel may not be present at all future deployment locations, and this should be taken into account when selecting host facilities for demonstrations, as invariably these types of complex pilot testing projects (that include the integration of a large number of COTS and novel technologies) typically encounter permitting, cost and timeline pressures.

8.5 TECHNOLOGY OUTLOOK

Sierra Energy's overall company focus is on working with engineering and technology partners to optimize and ruggedize the 50 MTPD commercial package and deploy widely within the United States to public and private entities.

Sierra Energy will continue 10 MTPD operations and validations at FHL, as this will be the primary test facility for the FastOx platform. Future testing will include data acquisitions for technology scale-ups and downs, optimizations to enable decreased CAPEX and OPEX, the testing of different feed materials and providing the demonstration of the production of different end-products from FastOx syngas.

The FHL FastOx plant will also become a training facility for DoD and other governmental personnel, whose organization is acquiring a FastOx Waste-to-X system.

9.0 REFERENCES

[1] C. Hammock, *Keynote: Energy Programs of the Army, presented at the Defense Energy Summit,* Austin, TX, 2013.

[2] "EPA Warm Model," 2013. [Online]. Available: http://epa.gov/epawaste/conserve/tools/warm/Warm_Form.html.

[3] S. Booth, J. Barnett, K. Burman, J. Hambrick and R. Westby, "Net Zero Energy Military Installations: A Guide to Assessment and Planning," NREL, 2010.

[4] Office of the President, *Executive Order (EO) 13423: Strengthening Federal Environmental, Energy, and Transportation Managements,* Federal Register, 2007.

[5] DoD Senior Sustainability Officer and Under Secretary of Defense, *Department of Defense Strategic Sustainability Performance Plan,* 2011.

[6] Office of the Under Secretary of Defense, *DoD Integrated (Non-Hazardous) Solid Waste Management Policy,* Washington, DC, 2008.

[7] "Memorandum of Understanding between U.S. Department of Energy and U.S. Department of Defense," 22 July 2010. [Online]. Available: http://energy.gov/sites/prod/files/edg/media/Enhance-Energy-Security-MOU.pdf.

[8] Patent 6,030,430.

[9] ""Preliminary Experiments to Examine Steam and Oxygen as Injectants in a FastOx Gasification Process – US Army Contract W15QNKN-05-D-0030", Renewable Energy Testing Center, McClellan, CA," McClellan, CA, 2010.

[10] *Developments in the FastOx™ Gasification Technology - U.S. Army Contract W15QKN-05-D-0030: 1604-111,* Renewable Energy Testing Center, McClellan, CA, 2012.

[11] Sierra Energy, "“Contract Summary Report: Phase I Final Report (Contract No. SP4701-15-C-0103)"," 2016.

[12] Alternative Resources to CIWMB, "Evaluating Conversion Technology for Municipal Waste Management," October 2008. [Online]. Available: http://www.calrecycle.ca.gov/organics/conversion/Events/MunicipalWst/Presentation.pdf.

[13] "Army vision for Net-Zero," June 2013. [Online]. Available: http://army-energy.hqda.pentagon.mil/netzero/default.asp.

[14] A. Rushing, J. Kneifel and B. Lippiatt, "Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis, Annual Supplement to NIST Handbook 135 and NBS Special Publication 709 - 2013," Prepared for U.S. Department of Energy, June 2013. [Online]. Available: http://nvlpubs.nist.gov/nistpubs/ir/2013/NIST.IR.85-3273-28.pdfv.

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APPENDIX B PLOT PLAN