ESTCP
Cost and Performance Report

(EW-200940)

Modular Biopower System Providing Combined Heat and Power for DoD Installations

December 2013

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ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

COST & PERFORMANCE REPORT
Project: EW-200940

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ACRONYMS AND ABBREVIATIONS

Btu	British thermal unit
Btu/SCF	British thermal units per standard cubic foot (at 60°F and 30 in. Hg)
CARB	California Air Resources Board
CFR	Code of Federal Regulations
CHP	combined recovered heat and electrical power
CO	carbon monoxide
CO_2	carbon dioxide
CPC	Community Power Corporation
DoD	Department of Defense
dP	differential pressure
dscf	dry standard cubic foot
EO	Executive Order
EPA	U.S. Environmental Protection Agency
EPACT 2005	Energy Policy Act of 2005
ESTCP	Environmental Security Technology Certification Program
EW	Energy and Water
g/hp-hr	grams per horsepower hour
gpm	gallons per minute
H_2	hydrogen
HHV	higher heating value
ISO	International Organization for Standardization
ITC	investment tax credit
kW	kilowatt
kW_e	kilowatts of electrical energy
kW_eh	kilowatts of electrical energy per hour
kW_{th}	kilowatts of thermal energy
$kW_{th}h$	kilowatts of thermal energy per hour
lb/hr	pounds per hour
lbs/mwhr	pounds per megawatt hour
LHV	lower heating value
m^3/hr	cubic meters per hour
mg barium/L	milligrams of Darium per liter
MMBtu	million Btu
MTBF	mean time between failure
MTTR	mean time to repair
MW	megawatt

MW_eh	megawatts of electrical energy per hour
MWhr	megawatt hour
N	nitrogen
NDAA 2007	National Defense Authorization Act of 2007
NIST	National Institute of Standards & Technology
Nm^3/h	Normal meters cubic per hour
NOx	nitrogen oxide
O&M	operations and maintenance
PGM	Power Generation Module
PM	particulate matter in air emissions
PPM	Power Production Module
ppm	parts per million
ppmdv	parts per million dry volume basis
psia	pounds per square inch absolute
RCRA	Resource Conservation and Recovery Act
SCFM	standard cubic feet per minute
SNL	Sandia National Laboratory
SO_2	sulfur dioxide
TCLP	Toxicity Characteristic Leaching Procedure
THC	total hydrocarbon
TQG	Tactical Quiet Generator
VOC	volatile organic compound
W.C.	water column

ACKNOWLEDGEMENTS

The authors, King Browne and James Diebold, wish to acknowledge the contributions made to this program by Fort Carson, the Fort Carson Directorate of Public Works, its Utility Programs Manager, Vince Guthrie, and the exceptional team at Fort Carson who assisted in making this site demonstration successful.

We want to thank the Environmental Security Technology Certification Program (ESTCP) for providing the funding for this project and the guidance provided by Dr. Jim Galvin, Energy and Water (EW) Program Manager, and his team.

We also wish to acknowledge Community Power Corporation (CPC) personnel who played an integral role in the project success: John Steele, Carl Peterson, Andrew Freeman, Art Lilley, Mark Stewart, Chad Cooper and Kevin Splant.

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

The Department of Defense (DoD) has been mandated to increasingly derive energy from renewable resources. A review of DoD installations revealed that 170 of them had access to significant amounts of woody biomass materials within a 25-mile radius and an interest in alternative energy. It was also recognized that this first prototype system would need continuing technical support from Community Power Corporation (CPC), so a field-test site close to CPC was desirable. It was rationalized that the data generated at one DoD site could be extrapolated to a large number of other DoD sites, taking into account differences in feedstock costs, local energy costs, local labor costs, etc. For these considerations, the selected test site was at Fort Carson, Colorado, which was relatively near to CPC's headquarters and one that had personnel dedicated to increasing the use of alternative energies. Woodchips salvaged commercially from beetle-killed pine were selected as the feedstock.

TECHNOLOGY DESCRIPTION

The technology uses a downdraft gasification process to convert the energy trapped in biomass into a synthesis gas that is cooled, filtered and utilized to power gensets, which create electrical and thermal energy. The BioMax® 100 system is highly automated, moving feedstock from a walking floor trailer, through the dryer and into the gasifier based upon the electrical load needs of the site. The system can alert the operator of alarm conditions via computer, tablet or smart phone.

DEMONSTRATION RESULTS

During the field test, the BioMax® 100 had a steadily increasing monthly availability for the system that was approaching the program goal of 80%. The highest monthly availability attained was 74%, occurring in the last month of the field test. On a weekly basis, there were 4 weeks where the availability exceeded 80%, but only two of them were consecutive.

A life-cycle cost analysis was performed for the BioMax® 100 system operating as a base-load provider, which showed the small system had a relatively high capital cost, but a relatively low fuel cost assumed to be $40/dry ton (about $3.50/million British thermal units [Btu] [MMBtu], if the wood were burned in a boiler operating at 80% efficiency). Feedstock cost varies from a negative, avoided disposal cost to over $100/dry ton based upon the site, transportation logistics, etc. The assumed $40/dry ton is reasonable average based upon CPC's experience with BioMax® Systems at various locations in the contiguous U.S. A BioMax® System cannot compete economically with grid power in most DoD locations, except in Hawaii and other remotely located facilities having very high fossil fuel costs.

For the case of generating electricity at sea level (assuming no recovery of waste heat) with the BioMax® 100 system, the electricity produced must be valued at over $0.335/kilowatts (KW) of electrical energy (kW_e) per hour (kW_eh) to result in a simple payback period of 7 years or less. With recovered waste heat, 7-year simple payback periods can be achieved with lower electrical values, which depend upon the value of the displaced fuel used for heating. For example, with a heating fuel cost of about $4.65/MMBtu (contiguous U.S. industrial average 2013 for natural gas), the electrical value needs to be over \$0.29/kW_eh. For with the displaced heating fuel cost of \$4.10/gal of fuel oil, the electrical value can be near zero with waste heat recovery for a simple payback period of seven years. Operating the BioMax® 100 system at higher elevations results in engine de-rating and consequently lower levels of electrical generation and recovered waste heat levels, both of which impact negatively on the economic projections,

The BioMax® 100 has difficulty competing with electrical grid power and natural gas in the contiguous U.S. However, for remote locations that are not served by the grid or by natural gas, the BioMax® 100 is very competitive with long term generation of electrical power and recovered waste heat, compared to generating the same amount of power with two 60 kW Tactical Quiet Generators (TQG's). Operating the BioMax® 100 over an assumed 15-year life with biomass at \$40/dry-ton is projected to have a life cycle present value of +\$323,904, compared to producing the same amount of electrical power using two 60-kW TQG's, fueled with diesel at an assumed average contiguous U.S. price of \$4.10/gallon having a negative present value of -\$3,308,559. Over the long run, the lower cost of biomass, compared to JP-8, more than compensates for the initial high capital cost of the BioMax® system.

IMPLEMENTATION ISSUES

Prior to shipping to Fort Carson, exhaust emission testing showed that the system had extremely low levels of emitted pollutants in the exhaust gas. The projected maximum yearly air emissions were so small, that it appeared that a permit to operate the BioMax® 100 was not required by the State of Colorado. None the less, Fort Carson required a Colorado permit to operate the system on its premises, which resulted in a significant program delay.

After a short period of operation, the custom-designed engine developed mechanical problems, which resulted in its replacement with two General Motors spark-ignited engines that CPC had modified slightly to accommodate fueling with gasoline, producer gas, or a combination of the two during startup of the gasifier. Fueling with gasoline only occurs during startup of the system. This required new gaseous emission testing and a new operating permit, which delayed the field testing several months.

The commissioning period at Fort Carson lasted much longer than planned before unattended operation was attained. This prototype system required numerous control code changes and some minor equipment changes. Nearly all of the program goals were met or exceeded. For example, the maximum sustainable, net electrical power at Fort Carson's elevation was 83 kW (104 kW net at sea level), compared to the goal of 75 kW at an unspecified altitude. The maximum sustainable recovery of waste engine heat was 180 kW thermal, which extrapolates to 226 kW thermal at sea level, compared to the goal of 150 kW thermal recovered.

1.0 INTRODUCTION

The Department of Defense (DoD) has 170 facilities that have large land areas containing significant biomass resources. Typically biomass is left onsite to decompose or is land-filled at great expense, but not used as fuel. Converting this biomass resource to heat and/or electricity lowers an installation's dependency on fossil fuels and directly contributes to the DoD's energy goals.

1.1 BACKGROUND

Gasification of biomass was widely practiced in the past. Producer gas was generated for municipal use before the local availability of natural gas and in World War II in Europe and Japan due to fossil fuel shortages. The old gasification technology that was used to make the producer gas was labor intensive, because process automation had not yet been developed. Producer gas contains large amounts of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and nitrogen (N). The old technology also co-produced large amounts of tars and tarry water that had to be removed prior to using the gas as fuel in efficient engines. The environmental disposal of these tars and tarry water is an unacceptable burden today and has precluded the widespread use of biomass gasification, especially in small scale systems.

Recent advances in gasification technology by Community Power Corporation (CPC) have resulted in the ability to gasify biomass to produce a clean fuel gas containing low amounts of water vapor and negligible residual particulates and tars. The gas is used to fuel internal-combustion engines to produce heat and power. CPC has coupled this new gasification technology with modern automated-process controls in their BioMax® systems that provide the ability for one operator to safely operate multiple systems unattended and remotely 24/7 via the internet.

Due to the distributed nature of the biomass resource, CPC believes that the optimal size of the biomass gasifier system should be relatively small, compared to typical power plants making megawatts of electrical power, to enable the use of locally available biomass and to keep the biomass transportation costs low. CPC modular gasifier systems are factory built and can be transported and commissioned near to where the biomass is located. These sustainable, modular systems use locally grown waste biomass to produce electrical power and heat, which can be utilized very efficiently on-site without traditional utility transmission losses.

The combustion of biomass is considered to be environmentally neutral with respect to greenhouse gas emissions, because it is viewed as recycling contemporary carbon. However, if burning biomass results in the displacement of fossil fuels, then it would be preventing the emission of fossil-derived CO_2 into the atmosphere and be "carbon negative." For example, one 100-kilowatts (kW) of electrical energy (kW_e) net modular biopower system operating at 80% availability can convert 778 tons of biomass (0% moisture or bone-dry basis) per year into over 700 mega watts of electrical energy per hour (MW_eh) and 5,300 million British thermal units (Btu) (MMBtu) of recovered thermal energy. If the electricity from the modular biopower system were used to displace grid power, each 100-kW system would reduce CO_2 emissions by 300 tons per year.[1] If the recovered waste heat is used to displace the use of natural gas, then an additional 363 tons of CO_2 would be avoided. Conversely, if the biomass were landfilled, much of it would decompose to form methane, which has a greenhouse effect 21 times stronger than CO_2 in the atmosphere.[2] Landfilling is recognized as the largest source of anthropogenic methane emissions in the U.S.[3]

The use of char made from biomass as a soil amendment has recently received considerable interest as “terra preta” (black earth). This biomass derived char, or “biochar,” contains nearly all of the mineral content of the biomass, including potassium, calcium, phosphorous, trace elements, etc. Depending upon the biomass used and the thermal processing used, biochar can have the physical properties of activated carbon and have a slow release of its mineral and nitrogen content over time. Biochar is a very stable material, can remain in the soil for extended periods of time and result in the sequestration of carbon for hundreds of years. The market for Biochar is relatively new with scarce sales data, so the char may provide a revenue stream in the future.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of the demonstration was to generate data under realistic conditions on a DoD facility to allow preliminary, meaningful analyses of the technical and economic viability of the BioMax® technology for widespread deployment at specific DoD facilities in the future. These necessary data include the system’s carbon footprint, payback period, biomass drier performance, producer gas quality (heating value and the levels of tars and particulates of the producer gas), operational availability, reliability, ease of use (labor to operate), recurring costs, net power and heat production, emissions quality (CO, nitrogen oxide [NOx], and total hydrocarbon [THC]), and byproduct char quality, usage or disposal (heavy metal content and Toxicity Characteristic Leaching Procedure [TCLP]).

The objectives of the demonstration were met or were on the way to being met by the end of the demonstration period. The objectives associated with carbon footprint, biomass drier performance, producer gas quality, ease of use, net production, emissions quality and char quality were all met. The operational availability and reliability goals were not met, but operations during the final weeks of the demonstration indicated these goals were within reach. The payback period objective was met, but only when considering the technology against high-cost alternatives.

1.3 REGULATORY DRIVERS

The DoD has increasingly recognized that its energy use at installations and in operations is occurring at levels that must be comprehensively reduced and must be increasingly derived from a greater percentage of renewable energy sources. The DoD must strive to meet the requirements of Congressional legislation and Executive Orders (EO), which mandate change in our nation’s energy consumption and production. The Energy Policy Act of 2005 (EPACT 2005) requires Federal agencies to purchase 7.5% of their energy from renewable sources by 2013; EO 13423 requires that half of this renewable energy come from new sources; and the National Defense Authorization Act of 2007 (NDAA 2007) requires that 25% of DoD’s total electricity come from renewable sources by 2025.

The legislated energy mandates and cultural initiatives support DoD-wide goals of improving its resiliency and endurance as a military force. These include:

1. Surety: preventing loss of access to power and fuel sources;
2. Supply: accessing alternative and renewable energy sources available at the installation;
3. Sustainability: promoting support for DoD’s mission, its community, and the environment;
4. Sufficiency: providing adequate power for critical missions; and
5. Survivability: ensuring resilience in energy systems.

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2.0 TECHNOLOGY DESCRIPTION

CPC's BioMax® autonomous gasification technology converts surplus or waste biomass to heat and electrical power, transforming a waste-disposal liability into an energy asset.

2.1 TECHNOLOGY OVERVIEW

CPC's autonomous BioMax® advanced-state-of-the-art technology is based on down-draft gasification with recently developed and patented secondary-air injection to convert tars and char into a usable producer gas with an unusually low residual tar content in the gasifier. This ultra low-tar producer gas are cooled in a uniquely stress-relieved, high-temperature tube-and-shell heat exchanger, and then filtered to remove fine char and ash particulates.

The heat from cooling the hot producer gas is recovered as hot air that is used, as needed, to dry the wet raw feedstock down to a suitable level for gasification in the range of about 8% to 18% (wet basis). The energy content of biomass is proportional to the weight of the bone-dry (0% moisture) material. Any moisture in the wood will be evaporated during the gasification process and result in lower energy efficiency. It is therefore misleading to state the weight of biomass consumed in an alternative energy process, without also specifying the moisture content of the biomass. There are two different bases used to express the moisture content of wood, the "wet" basis and the "dry" basis. The dry basis is defined as the weight of water per weight of dry biomass. This report uses the wet basis, which is the weight of water per weight of wet biomass.

The innovatively high level of automation of the BioMax® system alerts the operator of problems by texting, with the operator able to remotely change settings via the internet or by advanced mobile phones.

The clean producer gas contains about 18% CO, 16% H_2, 3% methane, 10% CO_2, 9% water vapor, and 44% N, and readily burns in conventional spark-ignited internal combustion engines.

Figure 1 shows that after the producer gas and the entrained char pass through the reciprocating grate and leave through the bottom of the gasifier, the coarser char drops out between the gasifier and the heat exchanger.

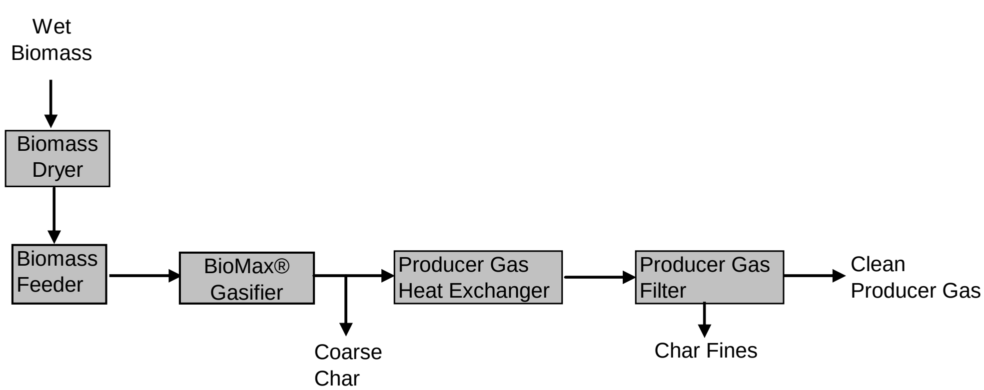

Figure 1. Block flow schematic of BioMax® gasifier.

The cooled producer gas and the entrained fine char then pass to the filter to remove the particulates at controlled temperatures well above the dew point to keep the water vapor from condensing. These chars are cooled as they are augered out of the system, and stored in large plastic drum liners for disposal or preferably sold as a fertilizer. Alternatively, the char can be utilized as a carbon adsorbent replacing activated carbon, depending upon the feedstock used and on the local market for char.

The cleaned producer gas then is mixed with a controlled amount of combustion air and fed to a spark-ignited internal combustion engine. The engines turn generators to produce electrical power. The emissions in the exhaust gases are greatly reduced as they pass through 3-way catalytic converters, in the same manner as with an automobile engine.

Waste heat is removed from the engine block and exhaust gases and is transferred to the client's heat-transfer fluid. This thermal energy can be used in water heating or space heating applications.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The advantages of CPC's advanced-state-of-the-art gasification technology are:

1. The negligible level of residual tars in the producer gas that otherwise would require the disposal of accumulated tars as hazardous waste and increased maintenance;
2. The clean burning nature of our producer gas appears to extend engine life compared to using liquid fossil fuels based on previous CPC BioMax® unit operations;
3. The lack of a condensed water by-product, which would require expensive treatment prior to disposal;
4. Recovery of waste heat from cooling the producer gas to dry feedstocks having excessive moisture;
5. The automation that permits safe, unattended operation to minimize labor costs; and
6. The self-dumping gasifier grate, the two char-removing subsystems, and the self-cleaning filters that extend the periods of operation between routine maintenance.

The advantages of the BioMax® systems' modularity are:

1. Minimal environmental impact – system is intended for relatively small scale distributed heat and power applications, which minimizes the local environmental impacts and makes them easier to permit;
2. Parallel installation – multiple systems can be installed in parallel to permit better load following;
3. Self-contained – systems need no new facilities to house them; and
4. Easy to re-deploy to a new site, because the system operates within the International Organization for Standardization (ISO) shipping containers.

Current limitations of this new technology are:

1. A low number of operational hours in the field with wood chips at this scale; and
2. High capital cost because prototype units are not yet benefitting from the economies of mass production.

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3.0 PERFORMANCE OBJECTIVES

Table 1 shows the performance objectives for this project. The results of this demonstration are discussed in detail later in Section 6.0 Performance Assessment.

Table 1. Performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Carbon footprint reduction	Tons CO_2 per year and tons/MWhr	CO_2 emissions of fossil fuel generators and BioMax® used to produce electricity and heat; kW of delivered heat and power	300 Ton CO_2/MW_eh	Fossil CO_2 emissions only briefly during system startup; projected displacement of 0.912 ton of fossil CO_2/MW_eh
Payback	Years to payback	System efficiencies, availability, energy costs and usage, capital and recurring costs	<7-year payback as per NIST Building Life Cycle Cost Program	Need to displace high energy costs to meet this goal. In a Hawaiian Industrial setting the payback would be 3 to 5 years.
Drier performance	Moisture content and throughput	Feedstock weight and moisture measurements	Dry feedstock to less than 18% moisture (wet basis). Ability to successfully gasify dried feed	The feedstock drier was able to dry woodchips to below the 18% moisture requirement for successful gasification.
Producer gas quality	Lower heating value of gas; tar and particulates	Producer gas composition; CPC's tar and particulate protocol	>115 Btu's per Btu/SCF <25 parts per million (ppm) tars <10 ppm particulates Long life of filter media and clean engine intake valves	135 Btu/SCF; No tars noted; no tar related operational problems; Particulates were only 0.000313 grain/ dscf, significantly less than the 10 ppm goal
Operational availability	% of time system is operational	Monthly operational log	>80%	Was steadily increasing to end at 74%
Ease of use	Number of operators, skill level and training requirements	Time of assisted operation, operational support requirements, factory support requirements	One operator trained and maintaining required availability within 1 month after field commissioning	Trained operator supplied by CPC, but not able to achieve desired availability
Reliability of BioMax® system technology	Maintenance requirements, MTBF, MTTR	Documentation of maintenance, failures causing system shutdown and repairs	Maintenance < 3 days/month MTBF > 21 days MTTR < 2 days	Last month of demo: MTBF = 4.33 days MTTR = 0.27 days

Table 1. Performance objectives (continued).

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives (continued)				
Gross power and heat production	kW_e; kW_{th}	Electrical power meter; hot water temperature and flow rate	>100 kW_e >500,000 Btu/hr (150 kW_{th}) thermal	Achieved 83kW_e at 5830 ft elevation, extrap. to 100 kW_e at sea level Achieved 614,000 Btu/hr (180 kW_{th}) thermal
Emissions quality	lbs/MWhr of combined heat and power	Engine exhaust gas analysis for CO, NOx, THC emissions; exhaust gas flow rate	CARB 2007 for waste gas <0.5 lb NOx/MWh <6.0 lb CO/MWh <1.0 lb VOC/MWh	0.49 lb NOx/MWh 0.20 lb CO/MWh 0.013 lb VOC/MWh, based upon sea-level system performance
Qualitative Performance Objectives				
Bio-char quality and usage	Elemental analyses of bio-char and its leachate	Heavy metal analysis, TCLP	Environmental Protection Agency TCLP Non-Hazardous Designation for disposal	No toxic levels of heavy metals. Only some benzene in filter char leachate

Mwhr=megawatt hour
NIST=National Institute of Standards & Technology
SCF=Standard cubic foot
ppm=parts per million
dscf=dry standard cubic foot
MTBF=mean time between failure
MTTR=mean time to repair
lbs/Mwhr=pounds per megawatt hour
CARB=California Air Resources Board
Voc=volatile organic compound

4.0 FACILITY/SITE DESCRIPTION

Sandia National Laboratory (SNL) was given the responsibility in this project to survey DoD facilities for the potential siting of BioMax® systems. SNL compiled a list of 170 potential DoD sites with the contact information, apparent interest in alternative energy, size of the facility in acres, local sustainable biomass resource available in the local county area, and the local cost of electricity and of heating fuels.

Fort Carson was selected to host the demonstration of the BioMax® 100 system. The unit was installed on the north side of Building 8030. It provided electricity to Fort Carson's distribution grid and thermal energy for the seasonal space heating loads of the building. Use of the recovered heat in the warmer months of the year could be to make hot water or to power an absorptive cooling system, but this was outside the scope of this demonstration.

Fort Carson's energy costs are relatively low: electricity at $0.060/kWh and natural gas at likely less than $6.00/MMBtu. This site would not normally be chosen to demonstrate a large energy-cost savings. It was selected because it's within an hour's drive from CPC's headquarters and was therefore cost-effective field support during the demonstration.

4.1 FACILITY LOCATION AND OPERATIONS

Fort Carson is located approximately one-hour south of CPC's headquarters, just south of Colorado Springs, Colorado. Fort Carson comprises approximately 137,000 acres and ranges from 2 to 15 miles from east to west and up to 24 miles from north to south.

Figure 2 shows a rough outline of Fort Carson's boundaries, with the cantonment area located along the northern boundary of the installation, where the BioMax® 100 was located.

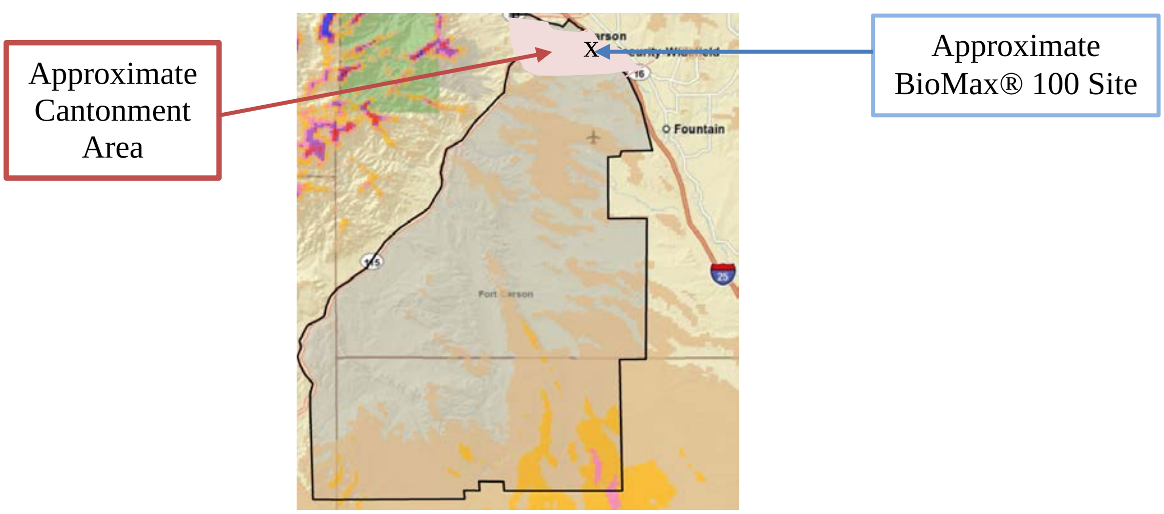

Figure 2. Fort Carson installation boundaries.

4.2 FACILITY/SITE CONDITIONS

The climate at Fort Carson is a combination of Great Plains and Rocky Mountain weather. Summers are relatively mild and short, with day-time high temperatures seldom above 95°F. The humidity in this semi-arid climate is relatively low, which contributes to low moisture contents occurring naturally in biomass feedstocks. The altitude at the Fort Carson cantonment is about 5,830 ft above sea level, with an average barometric pressure of about 11.9 pounds per square inch absolute (psia), compared to sea level with 14.7 psia.

Local feedstock exists for the Fort Carson site. Beetle kill trees from nearby forests and commercial processing capabilities provided the biomass necessary for system operations.

5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

The demonstration test period commenced at Fort Carson after the installation of the BioMax® 100 system at Fort Carson in August 2011. The environmental permitting process delayed the commissioning for six months until February 2, 2012. The Commissioning period lasted until the system was grid tied, and the system debugged and operable. The delivery of electricity to the grid first occurred on March 7, 2012. The Controlled Testing period began immediately after Commissioning was completed, with the first run of around-the-clock system operation at Fort Carson occurring April 24 through 25, 2012 for about 41½ hours.

The original, custom designed 9.2-L engine began using excessive quantities of oil; testing was halted until the engine could be replaced. A replacement power module consisting of two 8.1-L Vortec engines was developed; installation of the new power generation module was completed in January 2013. Reliable operation of the new system was attained in the latter part of May 2013. The Operation period began after the successful completion of the Controlled Testing in the latter part of May and extended through the end of July 2013. The on-site presence of the operators was decreased until remote monitoring and operation were the norm. The reliability and ease of operation steadily increased during the last three months of operation, as minor adjustments and improvements were made to the system.

Data was automatically logged by the computer that also controls the BioMax® system. From these data are calculated the producer gas flow rate, gross power produced, and parasitic power consumed every minute. Most of these data were used to verify that the modules were all operating properly and to predict when maintenance will be required for acceptable operation.

Only a few of these data had significance to the technical and economic evaluation of the BioMax® 100 system. For example, the total hours of operation, time between maintenance or failures, percent availability, and total kilowatts of electrical energy per hour (kW_eh), and kilowatts of thermal energy per hour ($kW_{th}h$) delivered were all summarized at the end of each month. These parameters are presented as a function of time to reflect the benefits of experience gained and expected improvements made to the system during the field demonstration.

5.2 BASELINE CHARACTERIZATION

The baseline testing at CPC was designed to provide quantitative data on the performance of the BioMax® 100 system that were needed to determine the technical and economic viability of the technology. These data were necessary for the valid comparison and prioritization of applicable alternative energy concepts, when making deployment decisions.

Fort Carson Test Location

The baseline characterization of Building 8030 was not necessary to determine, because CPC directly measured the electrical and thermal energy delivered by the BioMax® 100 system. All of this delivered energy displaced grid electricity and natural gas that would otherwise be consumed. Whether or not the facility saw a decrease in their fossil-fuel derived utilities depended heavily upon factors outside of our control, e.g., the weather and the energy conservation behavior of the facilities manager. The BioMax® 100 was designed to automatically release any unused recovered waste heat as hot air to avoid overheating the engine.

BioMax® 100 System Testing at CPC

Engine-exhaust emissions were measured by AIRTECH Environmental Services, Inc., on August 7, 2012 at CPC, with the new 8.1-L, Vortec, spark-ignited, internal combustion engine. Measurements were obtained while at steady-state “rich-burn” conditions, fueling first with commercial gasoline and then later just with producer gas from the BioMax® gasifier being fed softwood chips. The test protocols used were those specified by 40 Code of Federal Regulations (CFR) Part 60 JJJJ and other Federal regulations.

The emission results are summarized in the Table 2 and compared to the existing Federal regulations and currently permitted emissions. Table 2 shows the total engine-exhaust emissions from two 8.1-L Vortec engines fueled with gasoline on 8/7/12 with an average of 0.05% oxygen in the exhaust gases (assuming 1 hr/start, 1 start/day, 365 day/yr).

Table 2. BioMax® 100 dual-engine exhaust emissions fueled with gasoline (8/7/12).

Units	PM	NO_x	SO_2	THC	CO
Parts per million dry volume basis (ppmdv) (0.05% O_2)	NA	13.3	<0.2	3.14	10.4
lb/hr	0.000146	0.01214	<0.000254	0.00274	0.00576
ton/year	0.000026	0.00222	<0.000046	0.00050	0.00106
g/hp-hr	**0.00223**	**0.185**	**<0.00384**	**0.0418**	**0.0876**
40 CFR Part 1054 Table 1 g/hp-hr	**NA**	**8 (incl. THC)**	**NA**	**8 (incl. NO_x)**	**610**

PM = particulate matter in air emissions
SO_2 = sulfur dioxide
ppmdv = parts per million dry volume basis
lb/hr = pounds per hour
g/hp-hr = grams per horsepower hour
NA = not applicable

Comparing these measured values to those allowed by 40 CFR Part 1054 Table 1 (as directed by 40 CFR Part 60 JJJJ for engines with small power outputs) in the bottom two rows of Table 2 shows that the emissions from the CPC-modified engines are orders of magnitude less than the maximum allowable emissions levels in the JJJJ regulations for New Stationary Emission Sources when burning gasoline, which defer to 40 CFR Part 1054 Table 1 due to the small power level attainable with the small gasoline injectors.

Producer-Gas Fueled Engine Exhaust Emissions

There is no category specifically for producer gas in the Federal regulations for the Emissions of New Stationary Sources (40 CFR 40 Part 60 JJJJ). It is assumed that producer gas will be viewed as a fuel in the same category as natural gas. Table 3 shows that the emission data for the BioMax® 100 engines operated in lean-burn mode with producer gas easily meet this requirement while using producer gas.

Alternatively, the allowable upper limits in the exhaust gas (corrected to 15% oxygen on a dry basis in 40 CFR Part 60 Table 1 Part 60 JJJJ) are:

1. 82 ppmdv NO_x;
2. 60 ppmdv VOC; and
3. 270 ppmdv CO.

It is seen from Table 3 that the measured emissions were well below these volumetric limits for New Stationary Emission Sources (40 CFR Part 60 JJJJ).

Table 3. BioMax® 100 emissions in dual engines with producer gas (8/7/12).

Units	PM	NO_x	SO_2	VOC	CO
ppmdv (15 % O_2)	NA	25.9	2.32	0.717	17.9
lb/hr	0.00058	0.1412	0.0178	0.00366	0.0582
ton/year	0.00254	0.6184	0.0780	0.01603	0.2549
g/hp-hr	0.00185	0.449	0.0566	0.0117	0.185
40 CFR Part 60 JJJJ Table 1 g/hp-hr	NA	1.0	NA	0.7	2.0

Baseline characterization was established during testing at CPC, due to the availability at CPC of more instrumentation and personnel than in the field. The Baseline testing was performed using the same source of woodchips as to be used at Fort Carson, after the initial shakedown of the new system and it was operating properly.

Tests that were not repeated in the field demonstration include:

1. Analyses of the producer gas composition, including tar and particulate levels; and
2. Feedstock consumption rate as a function of producer-gas flow rate (feedstock consumption as a function of electrical output is a more relevant statistic – BioMax® Systems use 200 lbs of 0% moisture feedstock to produce 100 kWh_e at sea-level atmospheric conditions).

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The BioMax® 100 system is housed in five 20 ISO shipping containers that serve both as the shipping containers and as the housing for the system when operating on site. Figure 3 shows the conceptual layout of the BioMax® 100 system.

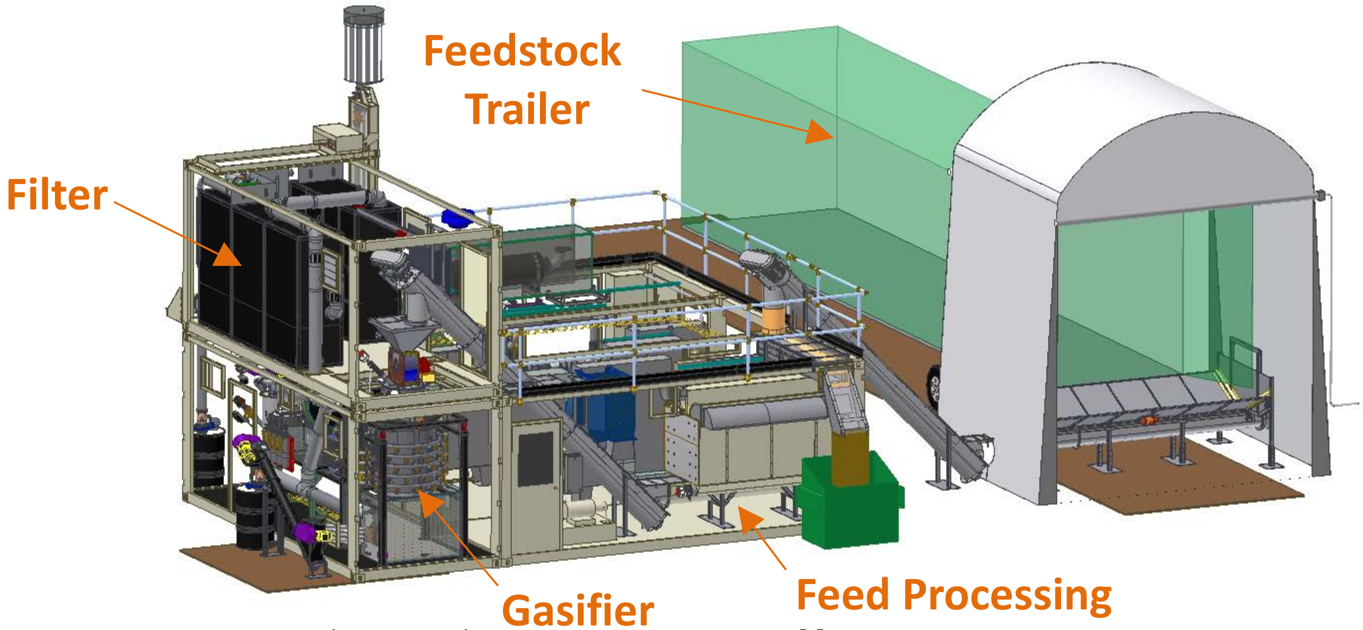

Figure 3. BioMax® 100 – conceptual layout.

Woodchips were delivered in a walking-floor trailer. The trailer was left on site to slowly off-load itself on demand, with its hydraulically operated moving floor using system generated power. This demonstration required a bit less than two woodchip deliveries per week, when operating 24/7 at full power. The woodchips fall off the back end of the trailer into a trough, from which they were conveyed into the dryer.

From the dryer, the dried chips were sorted to remove the excessively fine and coarse chips before the usable chips are fed into the gasifier. The fine material typically contained a lot of dirt and is landfilled or better used for composting. The coarse chips could be re-chipped if they were in sufficient quantity to economically justify this extra step. These unwanted materials should have been removed primarily by the woodchip supplier, minimizing the amount of out-of-specification materials for disposal or re-work.

After gasification, the producer gas and char fines passed through the heat exchanger to cool and then were filtered to remove the particulates. The cool, clean producer gas was then used to fuel the spark-ignited engines to power the generator. Waste heat was recovered from the engine coolant and the engine-exhaust gases and was available as hot water.

The BioMax® 100 system is completely automated to allow for unattended, autonomous, and safe operation. The computer controls were programmed to respond in the same manner as a constantly alert expert operator to broken sensors, variable moisture contents in the feedstock, abnormal temperatures and pressures, stalled engine, etc. In the event that the controls are unable to keep the system within established limits of operation, the system will safely shut itself down automatically.

5.4 OPERATIONAL TESTING

After the controlled testing was completed, we began: operating the system unattended; monitoring the system from CPC; and attending to any problems that arose on an as-needed basis. These problems, which required the system to automatically shut down or which required maintenance and/or repair, were documented in a permanent log book or file with respect to the date, time of day, total cumulative operational hours, subsystem, the part of the subsystem, what was required to remedy the problem, the number of man-hours involved, and the number of hours of down time that resulted.

During the demonstration period, the goal was to operate the BioMax® 100 continuously to accumulate the maximum possible number of hours of availability at high rates of electricity production and waste heat recovery. In March, total run time on both engines was 121 hours. Energy generation for the month was 4967 kW_eh.

Total run time and energy generation for April (3/31-4/27) was 126.3 hrs and 4,590 kW_eh respectively. Availability (19%) and performance were low for two reasons: the system was being run on a daily shift duty cycle (8 hrs/day) and the system struggled with feedstock issues (a malfunctioning feedstock screen sorting system and very dry feedstock). The resulting high fines content and dry feedstock created gasification control issues, including high temperatures and high pressure drops across the bed. Aggressive grate action to try to lower the gasifier bed differential pressure (dP) resulted in a grate mechanism failure. The failure was traced to a design problem and the mechanism was replaced. The sorting screen was retuned and the system returned to normal operation.

Total run time for May (4/28-6/1) was 384.4 hrs and energy generation for the month was 21,861 kWhrs. Availability (46%) and performance improved as the operators started to allow the system to run unattended from one day to the next.

In May, the combined recovered heat and electrical power (CHP) system was finally commissioned following delays in final wiring. It was operated for several days before hot weather prevented further heat delivery into the building. However, the heat load of the building varied considerably. From June 4 to June 7, it was operated at full power for the high altitude at Fort Carson (90 kW_e gross). During the period of 0800 to 2300 hours on June 5, the CHP system delivered an average of 177 kW_{th} (600,000 Btu/hr) to the vehicle maintenance facility. During this same period, the exhaust gas heat exchanger was reducing the temperature of the exhaust gases from 474°C down to 126°C (884°F to 259°F); Engine #1 coolant's temperature was 82°C (180°F) and that of Engine #2 was 70°C (158°F). The average temperature of the hot water leaving the BioMax® system was 69°C (156°F) and returning was 66°C (151°F), with a water flow rate of 56 cubic meters per hour (m^3/hr) (250 gallons per minute [gpm]).

Total run time for June (6/2-6/29) was 461.6 hrs and energy generation for the month was 26,666 kWhrs. Monthly availability (70%) and performance continued to improve due to consistency in feedstock quality and dedicated operations and maintenance (O&M) support.

Total run time for July (6/30-8/1/13) was 575 hrs and energy generation for the month was 27,862 kWhrs. The longest continuous run lasted 105 hours (about 4.4 days). Monthly availability (74%) and performance continued to improve due to consistency in feedstock quality and dedicated O&M support.

5.5 SAMPLING PROTOCOL

During the testing at CPC, the logged data was reviewed for its completeness to generate the operational insights required to meet the objectives of this program. Additional data were taken as determined by the review.

Feedstock – At CPC, several grab samples were randomly taken from several locations in the receiving bin at least 3 inches below the surface of each load of wood chips at least once during each four hours of testing. The grab samples taken at the same time were combined, mixed, and a sample of approximately 5 grams of usably sized woodchips were randomly selected for moisture determination in the ADL Infrared Moisture Determination Balance Model 4714A. Grab samples of the feedstock taken between the drier and the gasifier were taken in a similar manner, but once an hour. Woodchip samples that could not be immediately analyzed were temporarily placed in "Ziploc"-type plastic bags and analyzed as soon as possible. These data were used to verify the performance of the dryer and to determine the relationship between moisture in the dried feedstock and system efficiency.

Producer Gas – A slipstream of producer gas was taken at CPC after the safety filter and passed through a NOVA gas analyzer after drying to determine the percentages of O_2, CO, CO_2, methane, and H_2 in the dry gas. This data was recorded manually and the gas compositions corrected for an average amount of water vapor before the lower heating values (LHV) were calculated.

Although there is a tar and particulate protocol developed in Europe, it reports all volatile organics, e.g., gasoline components, to be tars and is, therefore, not appropriate for our purposes. The purpose of testing for tars and particulates is to predict the suitability of the producer gas for use in an internal-combustion engine, but the meaningful test is the demonstration of long-term engine operation without tar-related problems, such as sticky intake valves, excessive wear, etc. CPC has confidence in its gasifier design to result in a producer gas having such low tar and particulate values that they do not adversely affect the engines during extended operation. Consequently, determination of tars and particulates in the producer gas was not performed. The extremely low particulate and VOC values measured in the exhaust gases substantiated the effectiveness of the producer-gas filtration to remove particulates and tars.

Bio-Char – Grab samples of bio-char made from the Rocky Top softwood chips from the two char drums were taken and subjected to testing to determine the plant nutrient, heavy metal content, and the leachable components of interest in the U.S. Environmental Protection Agency's (EPA) TCLP test protocol. This was done to verify that disposal of the char made from this type of feedstock may be a non-hazardous material.

Net Power and Heat Production – The levels of net power and waste heat recovery were sampled once every 15 seconds of operation by the data acquisition system. The data were analyzed for trends, consistency and reasonableness between the various sensors to identify potentially invalid data and the need for corrective action. Mass and energy balances were made to verify that the data reflects expected results with good closures.

5.6 SAMPLING RESULTS

5.6.1 Char Characterization

Samples of the woodchips used as the feedstock and the resulting chars recovered from just after the gasifier and from the filters were submitted to Hazen Research, Inc., to determine their ultimate, proximate, Btu values, as well as, their mineral content. As expected, Table 4 shows a very large increase in the ash content of the char, compared to the feedstock. A mass balance on the ash content of the feedstock entering and of the chars leaving suggests that these levels of ash in the recovered chars correspond to a char yield of about 2%. If the feedstock has a lot fines or dirt in it, the char yields will be a bit higher, especially if the gasifier's grate is regularly dumped to control the pressure drop through the gasifier.

Table 4. Ultimate, proximate, and Btu values.

Values	Woodchips	Gasifier Char	Filter Char
Proximate			
Ash, %	0.87	32.3	44.79
Volatile, %	84.92	7.51	21.59
Fixed C, %	14.21	60.19	33.62
Ultimate			
Carbon, %	51.31	66.57	53.68
Hydrogen, %	6.03	0.23	0.39
Nitrogen, %	0.14	0.44	0.98
Sulfur, %	0.02	0.04	0.37
Ash, %	0.87	32.30	44.79
Oxygen*,%	41.63	0.42	<0.01
Btu			
HHV, Btu/lb	8077	9402	7398
LHV, Btu/lb	7518	9382	7362

The remaining volatiles in the gasifier char reflect the presence of some partially gasified char that had been dumped from the gasifier to correct high pressure drops. The even higher volatile content of the filter char is thought to reflect the tars that had been adsorbed onto the fine filter char during cooling and filtering of the producer gas. The higher sulfur and nitrogen content of the Filter Char is thought to be from their capture from the producer gas, e.g., as H_2S and ammonia, by the adsorption onto the large surface area of the Filter Char.

The results of the char testing showed that both char samples were non-corrosive and non-ignitable. Of the Resource Conservation and Recovery Act (RCRA) heavy metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver), only barium was detected in the two chars at 1.6% to 3.9% of the allowable 100 milligrams of barium per liter (mg barium/L) of leachate in the TCLP test. In contrast, some commercial "green" fertilizers have significant amounts of heavy metals in them, e.g., Down to Earth's Acid Mix 4-3-6 All Natural Fertilizer, which has 10 ppm arsenic in it.[4]

The TCLP of the gasifier char showed no volatile organic compounds or semi-volatile compounds in the leachate, whereas, the TCLP of the filter char released 1.37 mg benzene/L of leachate (exceeding the 0.5 mg benzene/L allowable) and allowable trace amounts of cresols. This level of benzene in the leachate was unexpected and was the first instance of excessive benzene levels in the TCLP test of filter char made from clean woody biomass, although it has been previously reported by us for filter char made from feedstocks containing cardboard and plastics.

CPC demonstrated in a previous DoD project[5] that when the gasifier char and filter char are physically mixed together, benzene is immobilized in the char mixture by the activated-carbon nature of the gasifier char, resulting in acceptably low levels of benzene in the TCLP leachate. In the future BioMax®100 GEN2 systems, the two chars are collected by the system as one mixed-char by-product that is non-hazardous in nature.

Studies at the University of California, Davis have shown that BioMax® char is an excellent adsorbent for heavy metals and organic compounds.[6] The two chars were also tested for their potential as a fertilizer. Table 5 shows the mineral and nitrogen content of the ash of the two chars and of the chars calculated from the ash composition and the ash content of the beetle-killed pine woodchips. For comparison, a commercial fertilizer such as Vigaro contains 12% N, 5% P_2O_5, and 7% K_2O., The two chars have considerable merit as fertilizers; in particular, the potassium levels in the chars correspond to commercial levels in more dilute fertilizers designated as "non-burning." The calcium, sodium, and potassium content increase the pH of the soil and the ability to retain ammonia fertilizer. These chars can be used for carbon sequestration and for improving the quality of poor soils (i.e., biochar or terra preta). However, the market for this biochar is quite new and of unknown size, so no credit was claimed for the biochar in the economic analyses.

Table 5. Nitrogen and mineral content of BioMax® 100 chars (8/1/13).

Values	Gasifier Char Ash	Filter Char Ash	Gasifier Char	Filter Char
SiO_2, %	42.26	40.79	13.65	18.27
Al_2O_3, %	11.07	10.78	3.58	4.83
TiO_2, %	0.35	0.36	0.11	0.16
Fe_2O_3, %	3.41	4.03	1.10	1.81
CaO, %	14.90	20.50	4.81	9.18
MgO, %	3.64	4.74	1.18	2.12
Na_2O, %	0.90	0.79	0.29	0.35
K_2O, %	8.80	90.2	2.84	4.04
P_2O_5, %	1.53	2.15	0.49	0.96
SO_3, %	0.43	1.25	0.14	0.56
CL, %	0.07	0.42	0.02	0.19
CO_2, %	4.07	1.47	1.31	0.66
N, %			0.44	0.98

5.6.2 Combined Heat and Power

Figure 4 shows the steady-state energy flows in the BioMax® 100 measured at 1400 hours on June 5, 2013, at Fort Carson. The 244 normal meters cubic per hour (Nm^3/h) (1070 standard cubic feet per minute [SCFM] at 0°C and 1 atmosphere) of producer gas at that time were delivering a calculated 368 kW_{th} to the engines, based on the nominal gas composition and its lower heating value. The energy meter in the heat-transfer fluid (coolant) measured 180 kW_{th}. Of this useful recovered waste heat, 71 kW_{th} was from the Exhaust-Gas Coolant (estimated from the flow rate of producer gas, and temperatures of the engine-exhaust gas entering and leaving the Exhaust-Gas Cooling heat exchanger). Subtracting the exhaust-gas contribution of 71 kW_{th} from the 180 kW_{th} total amount of recovered energy in the CHP Coolant, leaves 109 kW_{th} that was recovered from the engine by the Engine Coolant. This waste heat was recovered, while the generator produced 90 kW_e gross. The parasitic electrical loads averaged 7 kW_e, leaving 83 kW_e for export from the system.

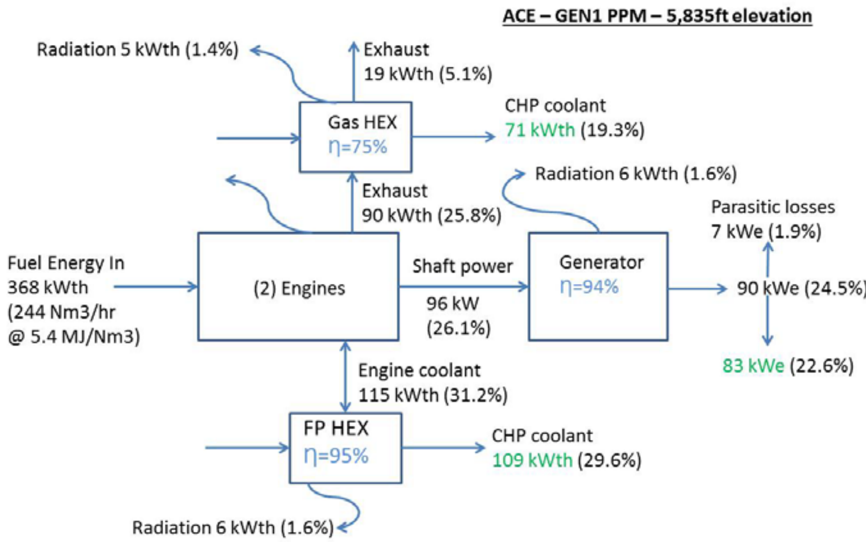

Figure 4. Energy flow diagram for the BioMax® 100 CHP system at Fort Carson.

By difference, 79 kW_{th} was lost by radiation and convection from the engine and the generator and most of the 7 kW_{th} parasitic power into the interior of the Power Generation Module (PPM); these heat losses were dissipated by the flow of air generated by the radiator fan. This is about 28% of the energy in the producer gas going into the engine that leaves the PPM as warm air at about 52°C (~126°F). During severely cold weather, this warmed air could be used as pre-heated Producer-Gas cooling air to provide additional energy for drying the feedstock or directly for local space heating (but only with careful attention to monitoring the CO levels in the warm air).

Figure 5 shows the net electrical and thermal power delivered on June 5, 2013 after 0600 hours. The electrical output delivered to the Fort Carson grid is relatively constant with time. The available thermal energy should be as constant, but the actual thermal energy exported depends upon the demand of the building. This causes the exported thermal energy to vary considerably, but appears to reach a steady state value of 180 kW_{th} at 1400 hours, about 40 minutes after peaking at about 195 kW_{th} at about1320 hours.

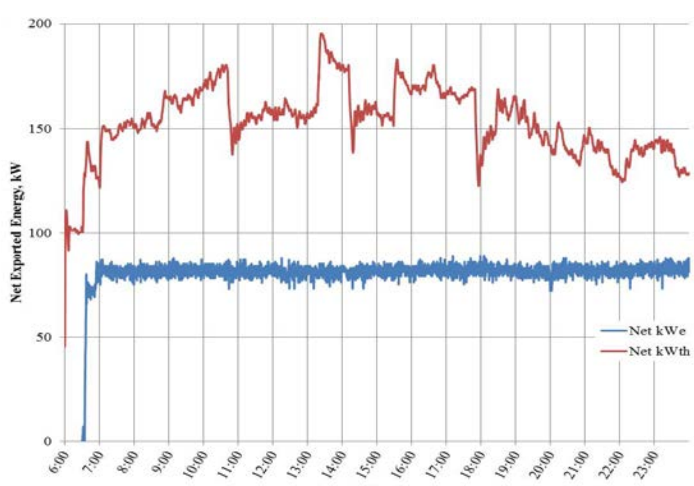

Figure 5. Net electrical and thermal power delivered to Fort Carson on 6/5/2013.

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6.0 PERFORMANCE ASSESSMENT

After the demonstration was completed and CPC had a significant number of operational hours, the performance of the system was assessedto update the inputs necessary for the technical and life cycle cost evaluations, including feedstock input rates, net electrical and recovered thermal power, availability of the system, recurring operating costs, labor for maintenance, overhead, exhaust emissions, etc.

Carbon Footprint: The reduction in carbon footprint is based on the electrical power output and the amount of waste heat recovered. We considered that the CO_2 emitted by the BioMax® system is from contemporary CO_2, rather than from fossil sources and not included in these calculations. Thus, the carbon footprint reduction will be equivalent to the carbon footprint of the fossil fuel required to produce the same amount of energy displaced by the BioMax® system.

EPA lists the amount of CO_2 emitted from the generation of electricity as 1135 lbs CO_2/MWh from natural gas, 1672 lbs CO_2/MWh from oil, and 2,249 lbs CO_2/MWh from coal.[7] The average value in the U.S. is 1216 lbs CO_2/MWh, although in Colorado it is 1829 lbs CO_2/MWh.[8]

Using EPA's Carbon Footprint Calculator for electricity generation and space heating with electricity, fuel oil, propane, or natural gas,[9] with an availability of 80% at sea level, a net of 104 kW_e is equivalent to 359 tons of fossil CO_2 per year and the recovered 226 kW_{th} is equivalent to 488 tons of fossil CO_2 from fuel oil per year. The total reduction in CO_2 emissions is 847 tons CO_2/year. These reductions are equivalent to 0.5 tons of CO_2 per MW_eh and 0.3 tons of CO_2 per MW_{th}h.

Payback: The years for simple payback were calculated using the values generated in the field demonstration for system availability (but extrapolated to 80% availability at sea level), net electrical output, waste heat recovery, feedstock consumed, cost of consumables, labor, etc. A range of energy and feedstock costs were considered to provide guidance for the prioritization of potential sites for the BioMax® 100 system. Energy value and feedstock costs were determined that yield a variety of simple payback periods, which are discussed in detail in the section 7.0 Cost Assessment. In addition, a NIST Life Cycle Cost Present Value analysis was performed using a more realistic system life of 15 years, which is also discussed in Section 7.

Dryer Performance: During the baseline characterization of the BioMax® 100 system at CPC, the performance of the dryer was characterized. This required measuring the feedstock fed over a period of time, initial and final moisture contents of the feedstock, the time elapsed, and the local air temperature and relative humidity. The ability of the drier to keep up with the demands of the gasifier was crucial to achieving high system availabilities and high energy outputs. The feedstock moisture was reported on a wet basis (lbs water/100 lbs wet biomass, expressed as a percentage). The gasifier works best with feedstocks having between 8 and 18% moisture on a wet basis. The criteria for success was to be able to reduce the moisture content from its initial moisture content down to less than 18% moisture, while sustaining high power outputs.

Figure 6 shows a sampling of the dryer's performance in 2012, which all met the demonstration. The feedstock received in 2013 was much drier and did not need drying except on two occasions when the moisture content exceeded 15%. In the relatively dry Colorado climate, the moisture content of the delivered woodchips was rarely above 25%, so the dryer was not tested at its maximum performance capability during the field demonstration period. Some problems were encountered with feedstock that was a bit too dry for optimal gasifier operations, which suggests that adding a little water to an overly dry feedstock could be helpful. Excessively high moisture in the feed was only experienced with a small quantity of feedstock in a storage bin that had not been adequately protected from rain (not shown in Figure 6).

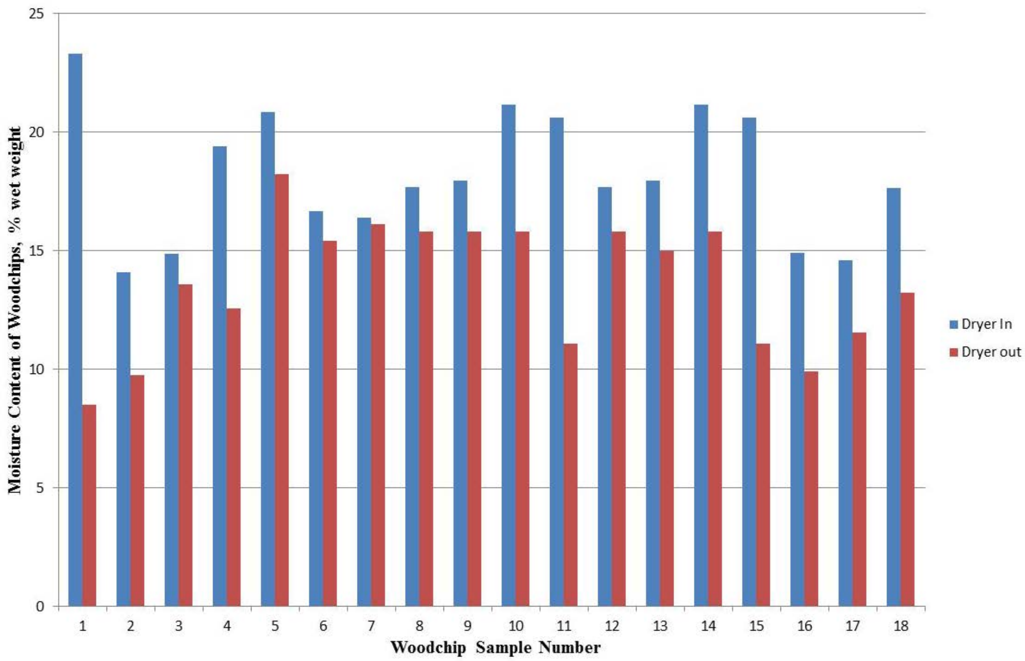

Figure 6. Performance of BioMax® 100 Dryer.

Product Gas Quality: During the Shakedown and baseline characterization of the BioMax® 100 at CPC, we measured the dry producer-gas composition. We used the nominal wet gas composition to estimate the LHV of the producer gas at 5.4 MJ/Nm^3 (138 Btu/SCF), using the well-established LHV values of the individual gases from the literature. An LHV greater than 115 Btu/SCF (60°F and 4 in. water column [W.C.]) is desirable in order to have good combustion characteristics.

The 8.1-L Vortec engines performed well during the entire field operation period with this producer gas, during which each engine logged over 1400 hours of operation on producer gas. There were no indications of tar accumulations during field operation, so good quality in the producer gas sent to the engines was demonstrated. The measured particulates and VOCs in the exhaust gases were extremely low due, to the removal of the char fines by the producer-gas filters and the low residual levels of tar vapors in the producer gas, as discussed later in this section under "Emissions Quality." Consequently, we did not quantify the tar and particulate levels in the clean producer gas using CPC's tar and particulate protocol.

Operational Availability: Operational availability is defined as the ratio of the time the BioMax® 100 was functioning during a month to produce power and recovered waste heat at design levels divided by the total time elapsed during that month, expressed as a percentage. When the system was otherwise operational, the system availability was not penalized for any downtime due to the following problems outside of the control of CPC:

1. Delayed feedstock shipment due to inclement weather, i.e., closed highways;
2. Inability of the grid to accept the full output of electricity; and
3. Inability of the building to accept recovered waste heat.

Because these three problem areas affect the potential income stream, these site specific items will need to be considered and estimated in any detailed economic evaluation of the BioMax® 100 system at a particular site.

Figure 7 shows the percent of time the BioMax® 100 system was operating and producing power. Integration of the new PPM into the system and other system integration problems with this prototype gasifier system combined to keep the monthly availability of the system quite low until May 2013. The longest continuous run was made starting on June 30 and ending on July 4, 2013, for 104 hours. Although we did not achieve the goal of 80% monthly availability, CPC was within a few per cent of that goal and getting closer each month.

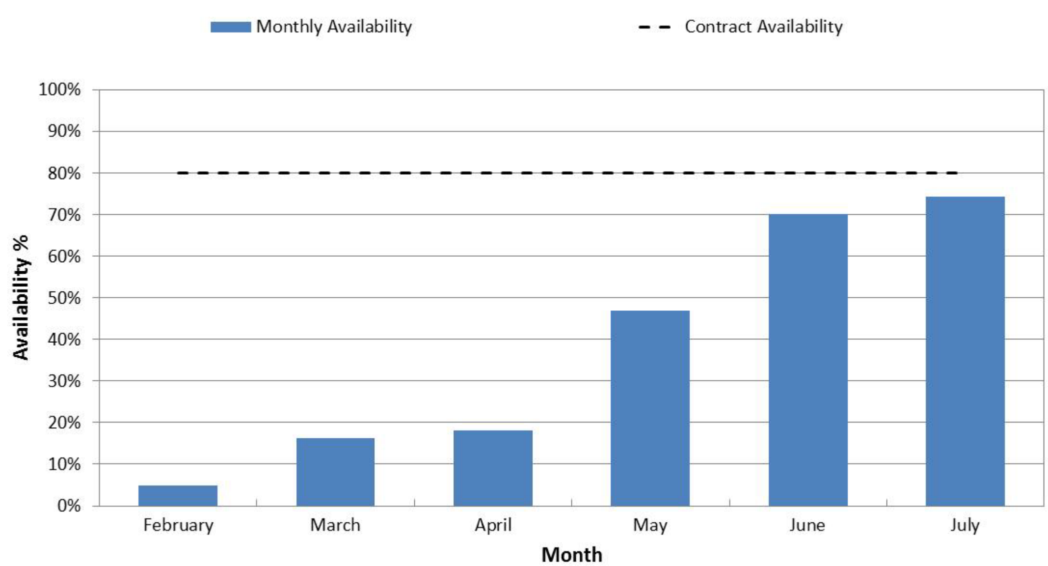

Figure 7. Monthly availability of the BioMax® 100 at Fort Carson.

Figure 8 shows the distribution of the problems that affected the monthly availability after May 23, 2013. Figure 9 shows the total length of time of the shutdowns by their causes. Problems with the gasifier typically resulted in the longest downtime per occurrence, because the gasifier must cool down for most of a day before it can be opened and fixed.

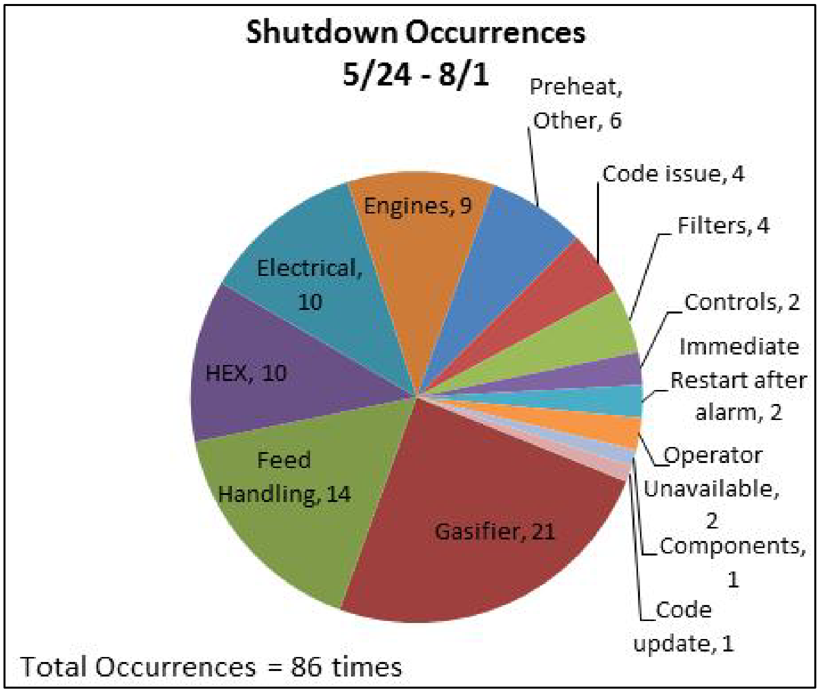

Figure 8. Reasons for BioMax® 100 shutdowns.

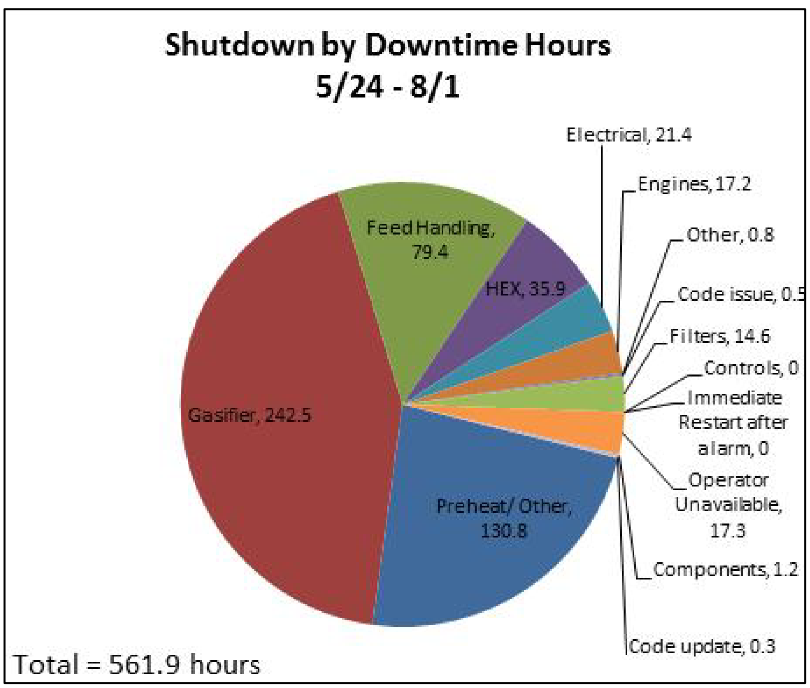

Figure 9. Severity of shutdowns by cause.

Ease of Use: The criterion for success was to be able to operate the system on a basis of 24 hours per day and 7 days per week with a total of one operator after the first month of commissioning and controlled testing. CPC was able to run 24 hours per day (unattended after the day shifts) and achieved up to 104 hours (4.6 days) of continuous operation.

Reliability of Technology: The reliability of this first prototype BioMax® 100 system steadily improved during the field demonstration, but did not reach the goals of MTBF of more than 21 days. However, the average downtime required to repair or maintain the BioMax® 100 was only an elapsed time of 6.5 hours, easily meeting the goal of less than an average of 48 hours per occurrence.

Figure 10 shows the dates, causes, and length of duration of the system shutdowns after May 23, 2013. It is seen that the Engines and the Feed Handling were problems initially, but were resolved by late June. The gasifier was initially not a problem, but was thereafter a common issue causing a system shut down for maintenance primarily, as expected. The severity of the gasifier-caused shutdown is pronounced due to the time required to cool the gasifier before it can be maintained.

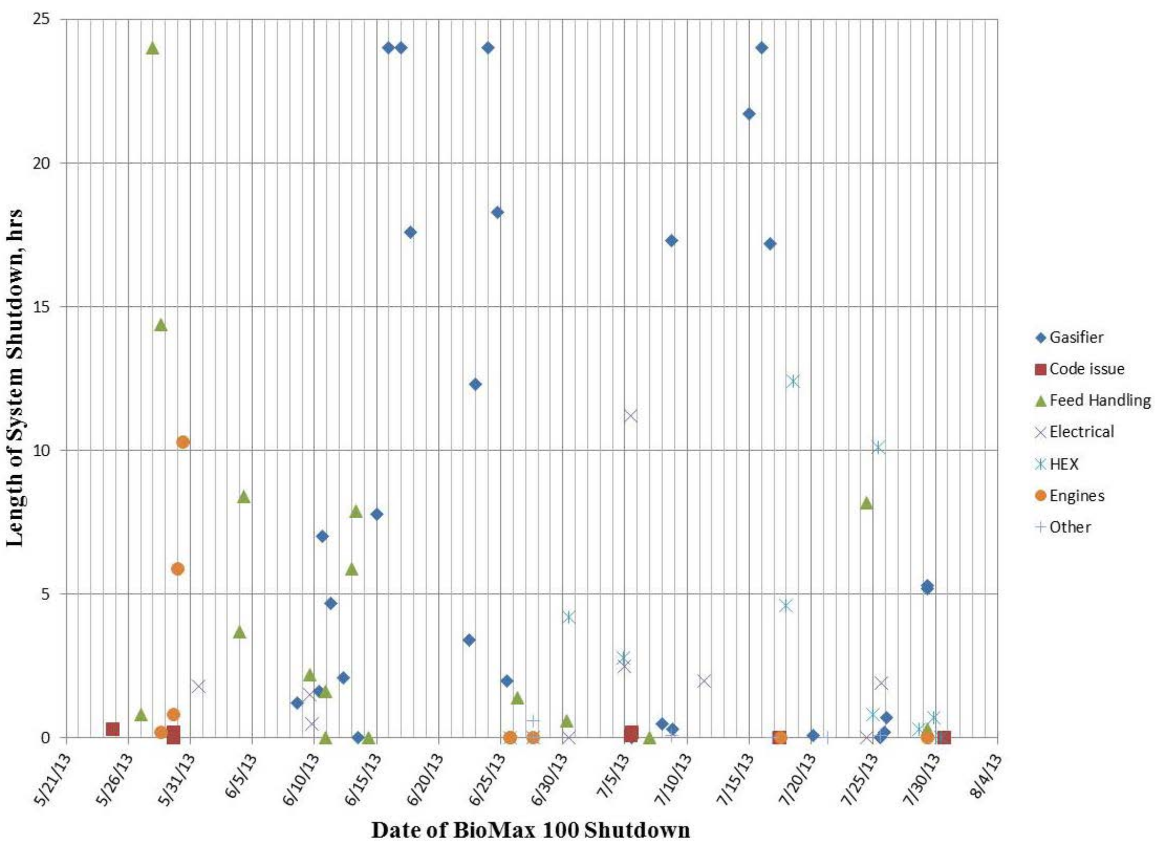

Figure 10. Date, cause, and severity of system shutdowns.

Gross Power and Heat Production: The net electrical power exported from the BioMax® 100 to the grid was recorded with a power meter and reported as kW_eh. The net recovered waste heat delivered was calculated by the commercial Onicon Btu meter from the measured flow rate of the heat-transport fluid and its temperature as it entered and left the Power Generation Module (PGM). The extent of heat losses in delivering the recovered waste heat from the BioMax® 100 to the client's building will be site specific and were not deducted from the recovered energy values. The criteria for success were to consistently deliver in excess of 100 kW_e and 150 kW_{th} (500,000 Btu/hr) and meet the operational availability goals.

The BioMax®100 system was able to deliver 83 kW_e at the high elevation of Fort Carson of 5830 feet above sea level. This net electrical power output is in excess of the contractual goal of 75 kW_e at an unspecified altitude by a comfortable 11%. The lower performance at high elevation (80% of that at sea level) is well predicted by the ratio of the local atmospheric pressures (~11.9 psia at Fort Carson divided by ~14.7 psia at 131 ft elevation or ~0.81). This factor was divided into the waste heat recovered at Fort Carson to extrapolate the expected waste heat recovery, when operating at sea level.

Even at the reduced electrical power generated at Fort Carson's high elevation, 180 kW_{th} of waste heat were recovered from the engines' exhaust gases and coolant, exceeding the contractual goal of 150 kW_{th} by 20%. This value of recovered heat does **not** include the heat remaining in the flue gases as they left the stack nor the radiant heat lost from the engine block and exhaust manifold that was exhausted to the atmosphere as warm air. At sea level, the recovered waste heat is extrapolated by the atmospheric pressure ratio to increase further to 222 kW_{th}, based on the increased gross electrical power output at the lower elevation.

Emissions Quality: It is desired to have very low emissions of CO, NO_x, and hydrocarbons. Because the siting of the BioMax® 100 could be in locations with very stringent emission requirements, it is paramount to the ease of obtaining environmental permitting that the engine exhaust emissions be very low.

During the baseline testing at CPC period, the services of an environmental testing contractor were retained to measure on August 7, 2012, the concentration of the pollutants and the flow rate of the exhaust gases from the 8.1-L Vortex engines, using the test protocols specified in 40 CFR Part 60 for spark-ignited engines. The gaseous emissions from the 8.1-L GM Vortec engines were considerably below the upper limits allowed by 40 CFR Part 60 "Standards of Performance for stationary spark Ignition Internal Combustion Engines," when fueled with either gasoline or with producer gas. No further exhaust-emission testing was required to obtain the Colorado operating permit.

The particulates in the exhaust gases from the 8.1-L Vortec engines were also measured on August 7, 2012, while burning only producer gas at CPC and found to average only 0.000313 grain/dscf. This low level of particulates is a result of the removal of the char fines from the producer gas by the filters and the low level of residual tar vapors that could react to form particulates in the engine. There is no visible opacity in the exhaust gases.

Bio-Char Quality and Usage: Samples of char recovered from the filter and from just after the gasifier were tested to verify that they are non-hazardous materials for disposal and could be used as a soil amendment. This included testing for heavy metals (RCRA) and for toxic materials that could easily leach out of the char in a landfill (TCLP), as well as, for ten elements known to be plant nutrients such as nitrogen, potassium, phosphorus, etc. The criterion for success was that the bio-char retain its current non-hazardous designation. The mixed chars made from walnuts in a similar, but smaller BioMax® 50 at Winters, CA, have been more intensely studied and found to be non-hazardous in the State of California.

Although the filter char had benzene levels that exceeded the very low TCLP limits, it has been previously demonstrated[5] that when the two chars are mixed together that the gasifier char acts as an activated carbon to immobilize benzene released by the filter char. It is concluded that the mixed chars will be non-hazardous for disposal purposes, if there is no local market for them.

However, the chars have considerable economic value in them, both as fertilizer and as soil amendment. Due to the novelty of using char as fertilizer, no credit was taken for the small amount of char produced as a by-product.

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7.0 COST ASSESSMENT

7.1 COST MODEL

In order to maintain the factory-built, modularity, and mobility of the BioMax® systems, CPC does not now contemplate further scale up of the BioMax® from its current gasifier size, although small incremental power increases may be attained as the system matures and bottlenecks are eliminated. Consequently, where more feedstock is available and more power is desired, CPC will propose using multiple BioMax® 100 systems operating in parallel. This approach provides a superior ability to load follow for maximum efficiencies. Thus, the cost model chosen does not evaluate the beneficial effect of scaling up the relatively small scale of the BioMax® 100 system.

Table 6 shows cost elements and necessary data needed for the development of the cost model. Explanations of each cost element follow the table. The cost assessment is based on making several modifications to the BioMax® 100 design that were tested in the last several months of this demonstration at Fort Carson.

Table 6. Cost model for the BioMax® 100 system at sea level.

Cost Element	Details	
Capital cost	Including shipping, training, & commissioning	\$1,121,000
Consumables	Estimates of the cost of charcoal, filters, engine oil, engine rebuild parts, etc.	\$18,326/yr
Facility O&M costs	• Operational labor • Frequency of required maintenance • Maintenance labor • Total labor cost	Daily, Weekly, Annually, Bi-Annually \$25,480/yr
Hardware lifetime	Estimate based on component degradation during demonstration	15 years
Feedstock cost	Dry basis	\$40/ton
Feedstock rate	Dry basis	2 lb/kW_eh gross
Feedstock cost/yr	Using the values from this table	\$38,894
Electricity produced	At about sea level (100% useful to client)	100 kW_e
Recovered waste heat	At about sea level, extrapolated from Fort Carson data (100% useful to client)	222 kW_{th}
System availability		80%

7.2 COST DRIVERS

Hardware Capital Costs: An accurate bill of materials and costs were maintained during the build of the BioMax® 100 system used in this demonstration. However, these costs were based on buying many of the items one at time or in low volume and we did not have the advantage of lower costs possible when buying in larger quantities, as an original equipment manufacturer would do.

Assembly Costs: The labor required to assemble this first prototype unit was tracked by the CPC accounting department. We expect the succeeding assemblies to go much faster and predictably with lower resulting costs. CPC has now assembled four other BioMax® 100 systems for other clients and one new BioMax® 100 GEN2 prototype.

Installation Costs: The labor required to first re-assemble the modules and the controlled testing at Fort Carson were recorded. The labor to re-assemble succeeding systems was then estimated, taking into account an experience factor. The installation costs are included in the total capital cost.

Consumables: The BioMax® 100 uses very few consumables, but they are significant in cost, as Table 6 shows. This cost includes standard consumables for the engine/gensets such as oil, grease, filters, gaskets and seals as well as BioMax® system specific items such as char/ash disposal bags, charcoal (startup feedstock), gasifier air injection fingers, replacement blowers, and bi-annual engine overhauls. A log and cost of these consumables was maintained during the field demonstration and used to project the life-cycle costs.

Facility Operational Costs: A detailed timesheet was used to break down the time charged to various facets of operating the BioMax® 100 in the field, e.g., data review, remote operating, on-site operating, scheduled maintenance and repair, breakdown maintenance and repair, number of site trips, etc. These costs were used to project facility operational costs for the life-cycle evaluations.

Maintenance: Using the maintenance logs from the operational testing phase, the labor and parts to keep the system running were used to project these costs for the economic evaluations. In addition, the summary of the maintenance required was used to identify subsystems in need of improvement. Based on good experience at another BioMax® system operating site, it was assumed that the engines would need to be rebuilt only every other year.

Hardware Lifetime: At the end of the operational testing, the system was examined for signs of wear, which could be used to estimate the expected lifetime of the equipment and alter the expected operating expenses during long pay-back periods. Other than the bulge in the gasifier there was nothing observed that indicated incipient failure or excessive wear. It is assumed that the excessive-temperature-control issue with the gasifier will be resolved and that the hardware will have a 15-year life, with engine rebuilds every 2 years.

Operating Training: Due to the high degree of system automation, it is expected that operating training requirements will be fairly low and not be a major part of the operating costs. However, this cost was estimated for the life-cycle analysis and is included in the total capital costs.

Energy Cost Avoidance: The system was credited with the energy costs avoided by virtue of the electrical and thermal energy delivered by the system, assuming that the facility can beneficially utilize all or an assumed fraction of the delivered thermal energy. It will be assumed that all net electrical energy generated and all recovered thermal energy will be consumed by the host site. More complex situations can be estimated from these data, as discussed below in Section 7.3.

7.3 COST ANALYSIS AND COMPARISON

7.3.1 Simple Payback Perspectives

Figure 11 shows the relationship between the value of the electricity produced and the value of the recovered thermal energy required for a 7-year simple payback, with the assumptions that:

1. The recovered thermal power is linearly proportional to the gross electrical power output;
2. All recovered net thermal and net electrical energy is used by the client to offset conventional fossil energy sources;
3. Higher gross electrical outputs require proportionately more feedstock;
4. $40/dry ton of biomass feedstock;
5. 2 lbs dry feedstock/gross kW_eh;
6. $1,121,000 capital investment including installation and commissioning costs;
7. $25,480 / year O&M costs;
8. $18,326 / year operating materials costs, including charcoal, motor oil, etc.;
9. 111 kW_e gross electrical output;
10. 100 kW_e net electrical output;
11. 222 kW_{th} available in hot water;
12. 80% efficient fossil fuel boilers/air heaters for comparison to fossil fuel costs; and
13. 80% BioMax® system availability.

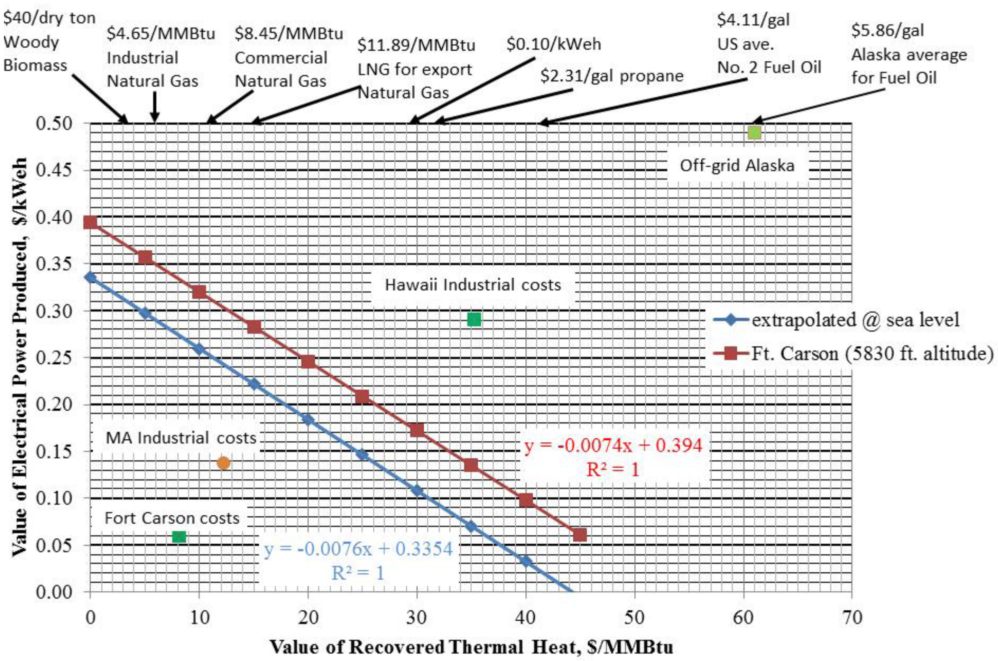

Figure 11. Coinciding energy costs required for a 7-year simple payback.

An important economic parameter is the local value of the usable electrical and thermal energy, each of which is the product of:

1. The availability of the BioMax® system;
2. The value per unit of the energy displaced; and
3. The client's energy load profile; or the energy output levels.

Because the power output of the engines is degraded by the lower atmospheric pressure present at higher elevations, two curves are shown in Figure 11 based on the performance of the BioMax® 100 at:

1. Fort Carson at 5830 ft. elevation with 90 kW_e gross (83 kW_e net) and 180 kW_{th} net; and
2. Sea level, with performance corrected by the ratio of the atmospheric pressure at sea level divided by that at Fort Carson, to result in 111 kW_e gross (100 kW_e net) and 222 kW_{th} net. (This correction was validated when a "sister" BioMax® 100 system in CA at 131 ft elevation fed with walnut shells produced 113 kW_e gross (104 kW_e net) and could produce an extrapolated 226 kW_{th} net.)

In Figure 11, any combination of thermal and electrical values that are above the curve of interest will result in a simple pay-back period of less than 7 years. Some sites will have only seasonal use for the recovered waste heat, which has a negative impact on the economics. For example, to use Figure 11, if the thermal energy can only be used 40% of the time, then the correct equivalent value of the cost of thermal energy to use in Figure 11 is 40% of the displaced heating fuel's local energy cost per MMBtu.

The value of the recovered waste heat depends upon the fossil fuel it displaces and upon the local distribution and delivery costs to the client. Typical recent average costs in the U.S. during 2013 of recovered heat from various fossil fuels[10] are shown across the top of Figure 11, when burned in a boiler having an assumed efficiency of 80%.

For example, the average contiguous U.S. price of recovered heat from No. 2 Fuel Oil at \$4.11/gallon was \$41.62 MMBtu, assuming a specific gravity of 0.80, an 80% efficient fossil-fuel boiler, a heating value of 18,500 Btu/lb (0.123 MMBtu/gal of fuel). The effect of operating at the lower power level at the higher elevation is to increase the cost of electricity by about \$0.061/kW_eh. The effect of a cheaper feedstock costing \$10/dry ton less is to shift the curves downward by about \$0.011/kW_eh. The effect of increasing the net electrical power by 10 kWe is to shift the curves downward by \$0.028/kW_eh. The effect of reducing the installed capital cost by \$100,000 is to shift the curves downward by about \$0.030/kW_eh. If these reductions in cost were all met for a \$0.07/kWh reduction in electrical cost, then the Massachusetts Industrial case near sea level would have still have over a 7-year simple payback period.

The low electrical and heating costs are shown for Fort Carson where a BioMax® 100 system would not meet the assumed 7-year payback. Industrial-sized users of natural gas and electricity in Massachusetts have higher energy costs than at Fort Carson in Colorado, but the payback period would still be longer than 7 years. However, in an island environment, such as Hawaii where all fossil fuels are imported a long distance, the high cost of both electricity and natural gas to industrial users combine for a payback period of less than 7 years.

Figure 12 shows the results for several different simple payback periods, using the sea-level performance of the BioMax® 100, and the same cost parameters as in Figure 11. The Hawaiian Industrial example would have a simple payback period of between 3 and 4 years.

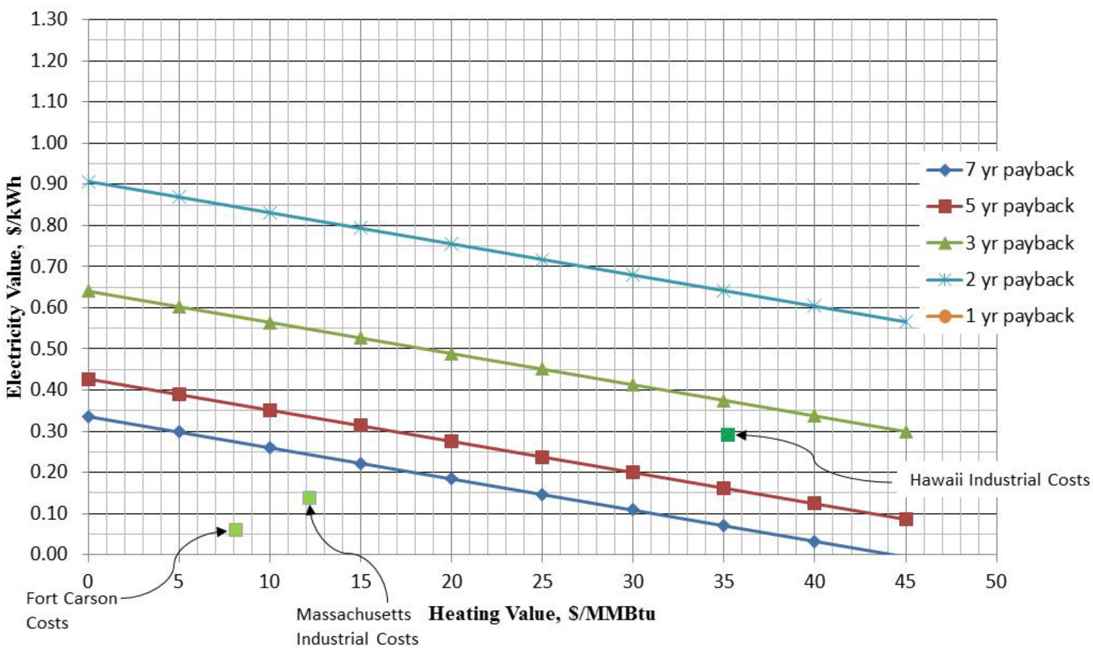

Figure 12. Effect of energy costs on various simple payback periods at sea level.

Life-Cycle Cost CPC performed a life-cycle cost evaluation using the experimental results of the 6-month field demonstration and the system's projected cost and performance for the BioMax®100 at sea level. Table 7 summarizes the life-cycle cost (MILCON Energy) analysis made by the NIST computer program based on the NIST Handbook 135 for building life cycle costing. A site in Massachusetts was selected because of the high local energy costs there. Values were used for the industrial costs of electricity of \$0.1378/kW$_e$h and recovered heat from natural gas of \$12.175/MMBtu (in an 80% efficient boiler), which are listed for industrial users in Massachusetts in 2013 according to the U.S. Energy Information Administration. A 15-year life of the BioMax® 100 was assumed, with engine rebuilds every 2 years and no salvage value for the system. An availability of 80% was assumed, as was the ability to utilize all of the electricity produced and all of the recovered waste heat from the engines' coolant and exhaust gases. The MILCON Analysis, Energy Project option was selected from the NIST BLCC 5.3-13 software, which used a 3% discount rate. It was assumed that the client already had a boiler in place and that the BioMax® 100 would be supplementing the existing boiler's output and displacing part of the fossil fuel used by the existing boiler, as well as, the BioMax® 100 supplementing the existing use of electricity from the local electrical grid.

Table 7. NIST BLCC 5.3-13: Summary LCC (Massachusetts fuel costs).

Present Values	Two 60 kW TQG's	Without CHP BioMax® 100	With CHP BioMax®100
Initial Cost	- $97,226	-$1,113,000	-$1,121,000
Fuel Cost	-$3,982,527	-$469,816	-$531,404
Routine OM&R Cost	- $699,953	-$661,421	-$661,421
Electricity Exported Value	+$1,471,147	+$1,484,603	+ $1,484,603
Recovered Heat Value	0	0	+ $1,153,126
Total	**-$3,308,559**	**-$759,634**	**+$323,904**

TQG = tactical quiet generator

A possible alternative to a BioMax®100 system would be military engine/gensets powered by diesel engines, i.e., two 60-kW military TQGs. The cost of each TQG is $48,613[11], or $97,226 for the two TQGs required generating 100 kW_e. These TQGs do not recover any waste heat. The two TQGs would consume a total of 8.14 gallons of diesel fuel per hour of operation at the combined net load of 100 kW_e (based on measurements previously made at CPC with a 60-kW TQG). The operating manual requires an oil change every 300 hours of operation that uses 20 quarts of motor oil per engine. An average cost of $3.00 per quart of motor oil was assumed. JP-8 was assumed to have the same average price as No. 2 Fuel Oil at $4.11 per gallon. This results in a variable cost of $0.335/kWh, just for the JP-8. An average availability of 80% was assumed, as were operational and maintenance costs of $2.94/hr.[12]

The NIST software was designed for comparing modifications to buildings, so it appeared to only allow the consumption of electricity and of fossil fuels for heating, not the generation of electricity and heated water. To remedy this dilemma, the present values of the investment costs and operating costs (operating, maintenance, repair, and feedstock) from the NIST LCC were subtracted from the present values of the electricity generated and the heat recovered by the BioMax® 100.

The results of these extra calculations are shown in Table 7, where the operation of two 60 kW TQGs results in the negative present value of -$3,308,559, whereas, the operation of a BioMax® 100 results in a positive present value of +$323,904 (with CHP). Even without recovery of waste heat, the BioMax® 100 system still has a much higher, more positive present value than the operation of the TQGs. Thus, the BioMax® 100 present value is worth $3,632,463 more than operating the two 60 kW TQGs over a 15-year period, when the electrical and heating (JP-8) energy costs are those found in Massachusetts.

With the assumptions used in this study, it is concluded that where long term generation of combined electrical and heating power are required, that the deployment of a BioMax® 100 rather than two 60 kW TQGs would result in a significant cost savings over a 15-year period. In fact, the production of only electricity (without CHP) with the BioMax® 100 fed biomass has a better present value (less negative) than the alternative case of operating two 60-kW TQGs fueled with JP-8. The BioMax® 100 will look even better with higher electricity and heating costs.

7.3.2 Transition Plan from Product Development to Production

CPC used this information to develop a transition plan. Testing continues on Alpha BioMax® 100 Systems similar to one utilized on this project. Lessons learned from these systems will be worked into the Beta GEN2 BioMax® Systems with the goals of improving reliability and output, while reducing cost.

Other changes made to achieve economies of scale include the relocation of CPC's operation to a new facility in the Denver Metro area, near Centennial Airport at 14800 Grasslands Drive, Englewood, CO 80112. The new 50,400 square foot facility houses both administrative and engineering offices as well as an expanded warehouse and manufacturing area. The new facility was designed to produce up to 72 BioMax® 100 GEN2 units per year.

Sales representatives are working to development markets for BioMax® System. Efforts have been concentrated in the West Coast, Northeast, and Hawaii, where energy costs are higher. Options being explored with potential clients include direct sales, leasing, and owning-and-operating.

Assisting in the sales efforts are government incentives. Federal income tax investment tax credits (ITCs) are available for CHP systems. Thirty percent (30%) credits are available for CHP systems as long as construction begins prior to December 31, 2013. Subsequent to that date, a ten percent (10%) credit is available for systems placed in service before December 31, 2016. These ITCs are critical in making the economics for early system installations work for both CPC and its customers, but are subject to change by acts of Congress.

At this time, CPC does not envision scaling up the BioMax® 100 to a larger size, although it is anticipated that minor system changes will increase the magnitude of the exported electric and thermal power. This will keep the systems small enough to be factory built and transported to the site in rugged ISO containers that then serve as equipment shelters. For those sites that could supply the required feedstock and consume the power generated, CPC will propose using multiple BioMax® 100 systems operating in parallel. This paralleling of systems will greatly increase the availability of the overall system, with planned maintenance occurring on only one of the BioMax®100 systems at a time.

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8.0 IMPLEMENTATION ISSUES

8.1 ENVIRONMENTAL REGULATIONS

Military installations are required to meet local rules and regulations for air, water, and soil pollution. Early discussions with personnel representing the local air quality district are highly recommended to avoid program delays due to a slow permitting process. The BioMax® system represents a potentially new and different source of pollution to most of the air permitting personnel. Unfortunately in the past, there have been environmental problems with some biomass gasification systems by others that were not well engineered.

This requires an effort to educate both the military and local civilian environmental groups involved on this new technology of CPC that produces:

1. No liquid wastes for disposal;
2. A minimum of solid char as a non-hazardous byproduct for disposal or a soil amendment (Note: the feedstock must not be an uncontrolled waste to avoid possible contamination with hazardous materials); and
3. A very clean producer gas used to fuel a spark-ignited internal combustion engine resulting in low exhaust-gas emissions.

8.2 GRID-TIE ISSUES

The most efficient mode of operation of the BioMax® 100 is to provide a base load, rather than one that provides a variable peak load. Operation with low electrical loads will decrease the potential income from electricity and recovered waste heat, as well as, tend to lead to char deposits in the producer-gas heat exchanger and more frequent maintenance. Consequently, it is imperative to connect to the local grid, so that the commercial grid or local engine/gensets fueled with fossil fuels provide peak power demands above the base load.

To connect to a grid requires that the BioMax® is generating power that is at the correct voltage and frequency. The BioMax®100 system includes all of the electrical equipment necessary to synchronize with and connect to an existing power grid and will shut down the system if the grid power is interrupted. This last feature is necessary to protect the linemen who may be sent out to repair a faulty grid. To convert the BioMax® 100 to be also automatically a back-up system, would require the addition of about $1,700 worth of electrical equipment, which is currently being added to the new GEN2 version of the BioMax® 100 systems. This extra equipment is exemplified by the Beckwith Electrical system that disconnects the grid in the event of a grid failure, which reduces the power generated by the BioMax® 100 to only that consumed locally.

A permit to connect to a grid is normally required by the power company. The length of time required, the difficulty, and the cost of attaining this permit varies considerably within the U.S. power industry, reflecting each of the individual power company's requirements and attitudes toward accepting distributed power generation (as well as, legislative or command mandates to use more alternative energy).

8.3 FEEDSTOCK ISSUES

Although this test program only tested softwood chips made from beetle-killed pine, a large number of other feedstocks, including hardwood chips and walnut shells, have been successfully gasified in BioMax® systems. The composition of the resulting producer gas from the various feedstocks is relatively constant, reflecting the close approach to thermodynamic equilibrium in the gasifier. However, there have been some problematic feedstocks.

It is recommended that CPC be consulted concerning the suitability of a particular feedstock for gasification in the BioMax® system. It may be necessary to complete gasification tests at CPC to determine the feedstock's suitability.

8.4 GASIFIER SHELL INTEGRITY

Upon removal of the insulation from the BioMax® 100 gasifier, evidence of high-temperature metal creep was found in the SS304 gasifier shell. This creep resulted in a bulging of the gasifier shell, between the first and second char-air injection nozzle planes. Normal operating temperatures are typically higher below the second char-air injection level than above it, suggesting that the conditions of high temperature that caused this creep were not part of the normal operating regimes.

It is hypothesized that this gasifier-wall deformation occurred during one or more abnormally high temperature excursions that could have been caused when:

1. The control system failed to recognize the need to add more fresh feedstock, or
2. A "controlled shutdown" of the gasifier failed to shut down the system before excessively high temperatures occurred in the upper levels of the char bed.

8.5 END-USERS' CONCERNS, RESERVATIONS AND DECISION-MAKING FACTORS

The visual appearance of the BioMax® 100 system is a small grouping of 20 ft ISO shipping containers and a semi-truck trailer delivering the feedstock, which can be all painted to the military's specifications to blend in with other military equipment.

For the base commander to be enthusiastic about accepting the BioMax® 100, it would be advantageous for there to be:

1. Incentives in place for the command to reduce dependency on off-base power and fuel supplies;
2. Potentially unreliable sources of electricity and fossil fuels;
3. Relatively high variable electrical and fossil costs;
4. An openness to alternative energy sources;
5. An abundant supply of feedstock nearby or within the installation's boundaries that is being harvested or culled;

6. Evidence presented of the low polluting nature of the BioMax® 100 compared to diesel engine/gensets;
7. An increased availability level for the BioMax® 100 system;
8. Low manpower requirements for operation; and
9. Demonstrated operation by military or contracted personnel.

Items 1 through 5 are site specific issues that vary from one installation to another. CPC has consistently developed the BioMax® systems to have low pollution characteristics and low manpower requirements featuring a fully automatic system that provides reliable operation without an operator being physically present.

8.6 PROCUREMENT ISSUES

The BioMax® 100 is in the early stages of commercialization. The prototype BioMax® 100 used in this demonstration was the first of its kind and was considerably modified during the early part of the demonstration. To date, three other BioMax® 100's have been built based on the final version of this first system, which are now in the field.

CPC has just recently moved to a new location that will facilitate producing the BioMax® 100 at a rate of up to 72 systems per year. CPC is now in the process of establishing efficient assembly methods with ongoing quality assurance, which will have the desired effect of producing reliable systems on a regular basis at lower cost.

However, the BioMax® 100 was inherently more expensive than desired. A GEN2 version of the BioMax® 100 has been designed and is currently being fabricated and assembled that significantly lowers the parts count and cost. It is expected that the first GEN2 unit will need a lengthy commissioning period before reliable 24/7 operation is attained. The first prototype of the upgraded BioMax® 100 GEN2 is in early evaluation testing.

In summary, the BioMax® 100 is currently available in relatively small numbers. The first prototype of a less expensive BioMax® 100 GEN2 is being tested, which will significantly lower the capital investment in the near future and have a higher CHP energy output.

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APPENDIX A

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