Arnold Schwarzenegger
Governor

THE DEVELOPMENT OF A 100 KILOWATT PREMIUM POWER COMBINED HEAT AND POWER MODULE

PIER FINAL PROJECT REPORT

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

The Development of a 100 kW Premium Power CHP Module is the final report for the Premium Power for Small CHP Systems project, Contract #500-03-039, conducted by Tecogen, Inc. and Key Subcontractors The Switch, Inc. (formerly Youtility, Inc.) and DE Solutions, Inc. The information from this project contributes to PIER's Environmentally Preferred Advanced Generation Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

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Abstract

This project with Tecogen, Inc., an established manufacturer of engine-driven combined heat and power for more than 25 years, successfully developed a 100 kilowatt (kW) premium power combined heat and power. The design brought inverter-based technology to small combined heat and power systems. Inverters convert the direct current produced by distributed generation technologies into 60 hertz alternating current before connecting to the grid. Features of this technology include the capability to start in isolation or without the supplemental power from the grid (black-start capability), simplified interconnection, premium power quality, and the ability to improve system efficiency when operated with loads below the rated capacity (part-load efficiency).

The primary technical innovation was the power module, which included the inverter power electronics power conditioning system integrated with a variable-speed permanent magnet generator. The Switch, Inc (formerly Youtility), a key subcontractor, designed and manufactured the PCS. The technical challenges included compatibility with the generator, communications with the master combined heat and power control system, and reliability for long term operation. After four years of development and field testing, The Switch, Inc., produced a commercially viable and robust system that met the interconnection and safety criteria required for UL 1741 certification. UL 1741 is the interconnection standard that applies specifically to the functionality of the PCS as it relates to being grid-connected (protection features, power quality, etc.), as well as the safe construction of the PCS.

The design of the combined heat and power package also included the engine subsystems, driveline, exhaust heat recovery heat exchanger/catalyst, and control system. A performance baseline was established with laboratory testing of a first generation design unit, which subsequently completed a 4000-hour field test demonstration in California. With the data and experience gathered from the field testing, second generation design emerged, meeting performance and reliability goals. This success in system development was followed by extensive technology transfer activities and comprehensive production readiness plan.

Tecogen, Inc. commercially launched this product in 2008 and is becoming a significant contributor to product sales. Carbon reduction, fuel reduction, electricity savings, grid peak power reduction, delayed and avoided costs associated with central power station and transmission brought about by availability of distributed generation, and energy security are among the potential benefits to California ratepayers that can be realized with a widespread deployment of these units.

Keywords: COP, premium power, simplified interconnection, inverter, PMG, black-start, UL 1741, engine-driven, carbon-reduction, electricity savings

Executive Summary

Introduction

The application of cogeneration or combined heat and power is generally recognized as one of the most important technologies available to improve energy efficiency in many businesses and institutional facilities. Properly applied, net energy consumption is reduced by 50 percent or more with a moderate investment in capital equipment, and ongoing maintenance. The energy savings benefit translates proportionally to reduced greenhouse gas emissions, which has resulted in widespread national support for combined heat and power implementation.

One of the most significant barriers to combined heat and power in the United States is the contentious relationship between the utility and combined heat and power host. Utility interconnection is necessary to the combined heat and power concept – the byproduct electricity needs an invariant load – but the basic structure of the relationship is problematic; the utility will permanently lose a significant portion of its market share to another party upon successful interconnection. As such, utilities regard the combined heat and power systems as intrusive, potentially hazardous competitors on their power networks. Wherever a determined utility opposition exists, small-scale combined heat and power has generally failed to develop except with significant economic drivers. In this market segment, the costs associated with electrical interconnection – the permitting process, elaborate safety devices, and so forth – are not tolerable. Thus, and despite the societal benefits of combined heat and power, the largest opportunity for implementation, the sub-megawatt market, has been largely undeveloped.

The interconnection issue has been widely recognized by combined heat and power proponents as a technical barrier that could be overcome with a universal process developed jointly among the electric power industry, state regulators, and combined heat and power developers. While the need for such a process was well appreciated in the early years of combined heat and power, the concept languished for several decades until combined heat and power was joined by other technologies in the wider category of distributed generation. More specifically, as wind, fuel cells, and solar photovoltaic systems became increasingly popular, their interconnection issues aligned with those of combined heat and power, and the necessary, collective will became sufficient to move forward with standardized interconnection. Approximately seven years ago, California completed the initial version of the first standardized interconnection process, Rule 21, and regulation committed the major investor-owned utilities to abide by its stepwise process. Most significantly, small, standardized distributed generation products could follow a "simplified interconnection" process if they were "type-tested" or certified by a national laboratory (such as UL) and if the host facility met certain guidelines. The breakthrough needed to move combined heat and power into a new era appeared at hand. The reality, however, was to prove quite the opposite; most small-scale combined heat and power suppliers would not qualify for the Rule 21 "simplified" process, and interconnection would remain a battleground.

Problem to Be Solved

Under the California Rule 21, standardized products may undergo a one-time rigorous process and, upon successful completion, be certified as utility-safe. The key testing in the process involves proving that the product's onboard safeties work properly; that is, the product must demonstrate that it will safely cease operating whenever conditions on the grid become abnormal. Once certified, the aforementioned utility interconnect difficulties are eliminated in most cases and projects can move forward with only modest interaction with the electric utility.

Despite high expectations that the certification rule would be technology neutral, the process in fact became polarized: Inverter-based systems[1] that completed the process were granted full certification status, while conventional machine-based products[2] were prohibited from being certified even if meeting the requirements.

This outcome was a significant setback to combined heat and power. Small-scale projects were not viable under the difficult interconnection process given to an uncertified product. While some microturbines and fuel cell CHP modules were certified, these technologies were not generally accepted commercially and would have limited market impact. The viable commercial combined heat and power option – natural gas engine-driven combined heat and power modules – were not certifiable, as they universally employ the disqualified generation technology.

This Commission-sponsored project was proposed and carried out to eliminate the certification disparity that resulted when Rule 21 was implemented. The project goal was to develop an engine-driven combined heat and power product, or premium power module, that would meet the certification requirements of the rule and be accepted by the utilities as equally qualified for full certification status. The product would therefore qualify without caveat for "simplified interconnection" throughout applicable regions of California.

Developed Technology

The developed technology is an engine-based combined heat and power module that utilizes an entirely new power generation system. Specifically, the engine drives a water-cooled "permanent magnet" generator that produces three-phase electricity at significantly higher efficiency than conventional generators, but without voltage and frequency regulation. Rather, both variables are in proportion to engine rpm. This power source is corrected to conventional utility values (i.e., 60 hertz and 480 volts) through a power inverter in two steps. First, it is

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[1] Inverters are power conversion devices that convert electric power from one form to another. Distributed Generation (DG) technologies that produce direct current (DC) must of course convert this power to 60 hertz AC before interconnecting to the grid. Inverters are used universally to accomplish this conversion.

[2] Electrical engineering terminology for conventional electric generators (alternators) is to refer to them as "machines" as opposed other sources of electrical power (batteries, and so forth).

rectified to direct current then, through the use of an inverter, converted to the standard alternating current value.

The power electronics is a microprocessor that is controlled to remain synchronized to the utility grid while producing high quality power. The microprocessor monitors the grid for disturbances and will immediately cease power export in the event of a fault, per the requirements of Rule 21. The engine is not restricted to a single rotational speed or revolution per minute, as in conventional power generation, but is able to optimize its rotational speed to minimize fuel consumption. If more power is required, the engine simply speeds up and vice-versa when the output requirements decrease. Because the engine speed can vary, part-load operation does not compromise the system efficiency. The unit is able to "sprint" (overspeed) for short periods when advantageous (such as peak demand periods, and so forth). The power electronics are fully certified to UL 1741, thus meeting the certification requirements for Rule 21[3].

The product itself is mounted on a single skid with the required combined heat and power components. The engine is Tecogen's proprietary version of the General Motors 7.4L engine, adapted to run on natural gas and equipped with an industrial catalytic converter for emissions after-treatment. Heat is recovered from the engine oil cooler, block, and exhaust to an internal water system and is available for process use up to 230 degrees F. An extended oil sump of 18 gallons is located within the steel skid to extend the service interval to 1000 hours. The aforementioned microprocessor fully automates system operation and monitors all aspects of the operation for safe compliance to the operating limits of the module. A sound attenuating enclosure covers the mechanical components of the system.

A significant feature of the product is that it will operate in an alternative control mode to produce power in the event of a utility outage. Further, the authors have incorporated the technology from the Commission-sponsored Consortium for Electric Reliability Technology Solutions project that enables the unit to be configured as a "microgrid". As such, a single unit or multiple units can be installed to transition seamlessly during an outage to power an isolated group of loads.

Project Goal and Objectives

The project developed a new generation of engine-driven combined heat and power product that would utilize an inverter interface between the generator and utility. By combining the best attribute of the Tecogen product (a lost-cost, extremely well-supported prime mover) with today's state-of-the-art inverter/semiconductor technology, a modular combined heat and

[3] At present no Rule 21 committee exists to certify the product, as the California Energy Commission is no longer managing the Rule 21 working group. The California Public Utility Commission is now charged with this task, but it has not resumed active certification management.

power unit having the long sought after features listed below would be available in a single machine – a major innovation in the combined heat and power marketplace.

The product's attributes are listed as follows:

- Reliable, clean, and efficient low-cost prime mover, mass-produced for another application (such as vehicles) for which there is a near-certain, long-term demand.
- Unassailable certification for "simplified interconnection" to the utility (without lingering controversy and/or exception).
- Black-start capability (utility outage operation) in a power outage, including the ability to handle large (that is, near- full rated output) non-linear loads such as variable frequency devices, computers, etc.
- No reactive power draw (that is, uncompromised transmission and distribution benefit when grid paralleled)
- True modular design without complex, site-specific, interunit controls for either mode of operation (parallel or standby).
- Ability to operate the engine throughout its effective speed range to maximize efficiency at part-load, optimize emissions, and peak-shave at higher than normal outputs for short duration. Part-load refers to the condition when the engine capacity is under-utilized caused by low power demand while peak-shave refers to the practice of operating the engine-generator during period of the day when the demand and the peak price of grid-supplied electricity are highest.
- Ease of integration with direct current outputs from renewable energy sources such as photovoltaic systems. Variable voltage direct current can be delivered through the engine generator's inverter interface.
- Ability to produce, as required, a premium quality wave form, voltage and power factor for special applications (example, computer server farms or precision instruments).

These features dramatically enhance combined heat and power viability in the marketplace; utility interconnection controversy is eliminated, customers have access to a superior product that includes the essential feature of black-start. The product does not require significant design changes nor deration to operate at alternate frequency and voltage. As such, it is internationally adaptable, requiring only software changes.

Technical Approach and Project Steps

The technical approach to the product design and development was to engage two major subcontractors/suppliers for the power systems: Danotek Motion Technologies (permanent-magnet generator) and The Switch Inc.[4] (the inverter subassembly). Each was provided with

[4] Danotek was the second generator supplier, replacing "Light Engineering" which failed to deliver a

detailed specifications for their respective subsystems. Prototypes were tested in Tecogen's laboratory and the design refined as the program progressed. In parallel with this work, other aspects of the design were completed including the system controller, emissions reduction system, exhaust heat recovery heat exchanger, sound enclosure, and specialized engine accessories for black-start operation. The design details were incorporated into Tecogen's manufacturing system during the project.

Midway through the program, the Consortium for Electric Reliability Technology Solutions microgrid software was added, which became the standalone operating system and included the ability to cluster groups of units on a single circuit during outage without interunit or supervisory controls.

During the final stages of the program, a first generation design was completed for field testing. Because of strong interest in the product, 10 first generation units were constructed and provided to sites in California (1) and in New York (9). The latter were funded in part by the New York State Energy Research and Development Authority.

Results

The project was successful in all respects. All technical goals were met, and a successful premium power combined heat and power module is in production at Tecogen, Inc. under the trademark name *InVerdé*. The following summarizes the significant results:

- The specific product model is the INV-100, which produces 100 kW of electricity (continuous) and 125 kW in peaking or "sprint" mode (100 hours per year).
- Overall efficiency is 81.9 percent (higher heating value) and electrical efficiency is 27.3 percent (higher heating value).
- Specifications are very close to projected values in the authors' proposal. Continuous and peaking power (kW) matches the program goal. Fuel consumption is actually 5 percent better than anticipated for production units due to engine improvements (proprietary cam) and reduced power conversion losses (higher efficiency inductors). Heat recovery is slightly less than the authors' proposal estimate (1 percent). It is notable that the electrical efficiency of the product matches our conventional units; an important achievement given the power conversion steps in the process. The permanent magnet generator upgrade relative to conventional types (+5 percent) has offset the inverter losses (-5 percent).
- Full UL 1741 Certification was obtained for the product in December 2008 through Electrical Testing Laboratories/Intertek Laboratories.
- All units are capable of operating without the grid during power outages. The microgrid software from the Consortium for Electric Reliability Technology Solutions program used in

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successful prototype. TSI was the project's inverter supplier from the start, but their corporate name was formerly Youtility Inc.

this operating mode has worked flawlessly in maintaining stable load control in single and multiple unit operation. The authors' demonstration has included a six (6) unit beta site in New York state.

- Variable speed operation has been successfully incorporated into the design with its inherent advantage of higher part load efficiency. Algorithms used in this mode were successfully patented[5].
- A 50-hertz version of the product was tested and shipped to a customer in Eastern Europe. As anticipated, no significant changes to the product were required, except software, and the specifications were otherwise unchanged.

Conclusions

The project met its objectives and, in particular, was successful in developing a commercial product. In addition, the authors have formed the following conclusions:

- Utility reaction to the inverter design approach has been highly favorable. This is true for East Coast utilities as well as those in California. The authors have successfully interconnected to the Consolidated Edison Company (New York City), Niagara Mohawk (upstate New York), NSTAR Electric and Gas Corporation (Massachusetts), and Connecticut Light and Power Company (Connecticut), and Southern California Edison (California). No units have been permitted as "certified" product at this time (certification was just obtained). The authors are hopeful that certified units, which have just begun to ship from our factory, will qualify for simplified interconnection processes in California and other states, which have copied the Rule 21 process.
- The black-start operation feature has been incorporated into all installations thus far. Tecogen's pre-existing products (CM-60 and CM-75 modules) were without this feature, so the authors were uncertain as to how widely it would be used. It would appear to be a major sales driver for the product. Notably, black-start operation is a necessary requirement for qualification for New York State Energy Research and Development Authority combined heat and power grants.
- The InVerdé product has quickly overtaken our pre-existing products in sales by about 2 to 1. While the authors do not anticipate the obsolescence of these older models, they do anticipate the inverter product will dominate.
- The California combined heat and power market has been highly depressed due to largely unfavorable economics; electric rates, while quite expensive, are poorly structured for combined heat and power and the expiration of the Self-Generation Incentive Program has been particularly negative. The InVerdé product is generating renewed interest, and the authors are hopeful of a mild sales resurgence. However, if the Self-Generation Incentive

[5] United States Patent 7239034. Inventor Joseph P. Gehret, assignee Tecogen, Inc.

Program were reinstated and other economic drivers were to improve (carbon credits, improved tariff structure, expiration of legacy costs, and so forth) then the authors would anticipate very strong sales of the product.

- The disbanding of the Rule 21 Working Group is unfortunate relative to obtaining Rule 21 certification. The authors expect that it will return under the California Public Utilities Commission management at some point. In the meantime, the authors are hopeful that the California utilities will regard the product as certified since the criteria for certification – UL 1741 certification – has been met. Approval by the working group is essentially a formality.
- Selling price of the product is currently $1300-1400/kW about 30 percent greater than the authors' conventional combined heat and power modules and their program goal. Reaching this goal will require better pricing from the authors' key suppliers, Danotek and The Switch, Inc. Higher volumes and secondary sources will help significantly.

Recommendations

The InVerdé successfully addresses the significant shortcomings of pre-existing combined heat and power technology – most notably, utility safety and power quality concerns, utility outage ineffectiveness, and poor part-load performance. Under favorable market conditions (such as in the Northeast), it will have very rapid and significant market penetration. For its benefits to be effective in California, however, combined heat and power needs to be better integrated across applicable state regulations and legislation to maximize its cost, environmental, reliability, and grid benefits. In particular,

- The Self-Generation Incentive Program for combined heat and power needs to be restored. Its current status, whereby certain technologies are favored, has been particularly negative.
- Utility tariff barriers need to be removed. These would include legacy costs (standby rates, departing load charges, and so forth) and tariff structures that are strongly biased toward fixed and demand charges and are, therefore, anti-efficiency in nature.
- Utility interconnection requirements need to be simplified to enable inadvertent export and simple means for utility sell back of excess power. Power export control should never be required for the InVerdé product as it is fully certified with anti-islanding protection. To do so for the simple reason that the utility will not participate in a sellback program is highly objectionable given the energy and societal benefits of combined heat and power.

The microgrid aspect of the InVerdé product is a highly significant feature that should be further evolved. The authors would recommend program(s) that continue to develop the solid-state switching device needed to connect/reconnect to the utility seamlessly in outage conditions.

Public Benefits

The public benefits for the project will be realized with the deployment of the INV-100 module that began in 2009 with a few initial units, followed by a ramp-up of sales in California and

elsewhere. California's investor-owned utility ratepayers will realize significant near-term benefits from this project, which can be summarized as follows for Year 6 (2015):

- Annual carbon reduction of approximately 200,000 tons (as CO_2).
- Annual fuel reduction of approximately 3.5 million British thermal units (3.4 billion cubic feet, bcf).
- Annual electricity savings of approximately $70 million (6000 hours/module x 10 cents/kWh x 100 kW x 1170 modules operating).
- Grid peak reduction of approximately 93 megawatts (80 percent of 1170 units operating x 100 kW each).
- Commensurate reduction in deferred central station plant and transmission costs.
- A strengthening of California's economy and energy security.

1.0 Introduction

1.1. Background and Overview

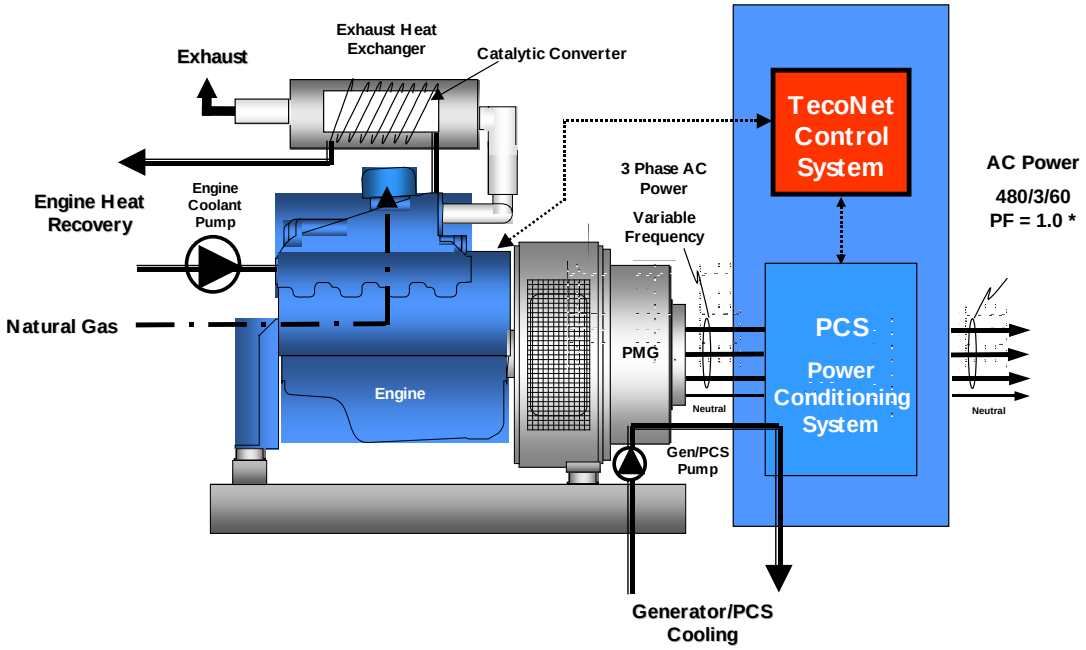
Tecogen, Inc. (Tecogen) is a leading manufacturer and marketer of gas-engine driven, air-conditioning, refrigeration, and cogeneration equipment for commercial and industrial markets. The cornerstone of Tecogen's business offering has been a 75 kilowatt (kW) combined heat and power (CHP) module, a product introduced in 1983, that subsequently was refined and upgraded over the past 25 years in the areas of engine durability, engine emissions, and sophisticated control algorithms for energy management and building interface systems. Tecogen's core engine technology has also provided the foundation for a number of mechanical drive CHP packages including engine driven chillers and refrigeration systems. To date, Tecogen has over 100 CHP units operational in California and more than 1,500 units throughout the United States along with a seasoned service organization with 10 locations throughout the United States. Overall, Tecogen equipment has amassed over 50 million hours of commercial operating experience.

In 2003, the design limitations of the 75 kW unit were fast becoming market barriers in California. This existing technology incorporated an induction generator set, as did most other CHP packages less than 300 kW in size. It was not considered utility-friendly by the newly formed Rule 21 Committee, and was, thus, unable to follow the simple interconnection path. Also, induction generators depend upon the utility grid for their excitation energy, so they are not available during a power outage. The need for black-start capability was becoming a requirement because of the increasing occurrences of power outages, as those experienced in August 2003, raising concerns about grid reliability.

With the need for a new generation of CHP unmistakably evident, Tecogen proposed to the Public Interest Energy Research (PIER) program of the California Energy Commission (Energy Commission) a CHP product that included an innovative power generation system to ensure a utility-approved interconnect, black-start capability, and premium power quality. Consequently, this inverter-based technology was also more efficient since it permitted variable-speed operation, an optimum methodology for internal combustion engines. In June 2004, Tecogen was granted the PIER funding award (53.3% of total program costs), along with match funds from Sempra Energy (9.6%), DE Solutions (4.5%) and the authors' own significant investment, composed of both cash and in-kind support of 32.5% of the total program cost.

A conceptual design of the Premium Power CHP unit is presented in Figure 1. It evolved from the Tecogen 75 kW CHP module, utilizing the same prime mover with its subsystems, as well as the same basic master control system. The primary scope of the funded development program was to replace the induction generator with a permanent magnet generator (PMG) and a power conditioning system (PCS) – an inverter-based power electronics. Additionally, it was necessary to implement and refine the communications link between the PCS and the Tecogen master control system. Lastly, an innovative exhaust heat exchanger was designed that

incorporated the exhaust catalyst, providing a more integrated packaging concept for a system



now equipped with emission controls as a standard feature.

Figure 1. Premium Power Unit Conceptual Design

Source: Tecogen, Inc.

1.2. Project Objectives

The objectives of the project were as follows:

- Develop a small-scale, inverter–based CHP module that provides premium power quality and streamlined grid interconnect acceptance.
- Provide low-cost, grid-isolated (standalone) operating capability for small CHP, a feature desired by the marketplace but historically impractical.
- Provide peaking capacity equal to 25% of baseload power rating as added insurance on high demand days and for participation in demand-side response (DSR) programs.
- Decrease the installed capital cost of small engine-powered CHP systems by 20%.
- Increase the adoption rate of CHP in the commercial and light industrial markets by 500%.

1.3. Report Organization

Section 2 outlines the project approach. Sections 3 through 9 detail the project outcomes including the power generation module development, product design, factory testing, field test

report, UL certification, technology transfer, and commercialization. Finally, Section 10 presents the conclusions and recommendations, including the benefits to California.

2.0 Project Approach

The goal of this project was to increase the acceptance of small scale CHP in California by providing value-added features, in a cost-effective manner, thereby accelerating the implementation into commercial and small industrial markets.

The technical development work to achieve this goal consisted of the following:

- Power Module Development – This work included developing the inverter and integrating a variable speed generator.
- CHP Module Design – This work included the driveline, controls, heat recovery system, gas and exhaust system, ventilation, and packaging.
- Factory Testing - This work involved performance testing the power module (inverter and generator), as well as the full CHP Module.
- 4000 Hour Field Test – This work included the installation and monitoring of a premium power CHP module at the Claremont Tennis Club in Claremont, California.
- UL Certification – This work included obtaining UL1741 certification, a requirement of California's Rule 21 for streamlined grid interconnection of Distributed Energy Resources (DER).
- Technology Transfer Plan – This work included development and implementation of a plan for market outreach and education, delivering presentations, developing literature, training and mobilizing sales and distribution and support network, and providing support and education to developers, engineers, and utilities.
- Production Readiness Plan – This work included the development and implementation of a plan for the commercialization of the product that consisted of key supplier agreements, as well as establishing a manufacturing infrastructure at the Tecogen factory to support a full product launch.

3.0 Power Generation Module Development

The authors refer to the PCS (inverter-based power electronics) and the variable speed permanent magnet generator as the power generation module. These are the components that differentiate the Premium Power module from Tecogen's induction-based CHP module. The engine and its subsystems, as well as the CHP control system, is mature technology that can be readily adapted to accommodate the new components. Although design and development work was necessary for package integration and control interface, the highest priority at the outset of this project was to design a well performing, cost-effective, and reliable power generation module.

3.1. Power Electronics

Inverter power electronics enable various types of power sources to interface with the standard utility voltage waveform (alternating current (AC)/60 Hz). Photovoltaics (PV), fuel cells, and microturbines all require inverter technology since these sources produce either low-voltage, direct current (DC) power, or a waveform that is grossly mismatched from that of the utility. The inverter conditions and converts this power through the use of semiconductor technology and microprocessor–based controls.

Historically, engine-generator technology did not require inverters because conventional generators were designed to match the voltage and frequency of the grid. However, this limited the engine to a constant speed. With the maturation of inverter technology, as well as the introduction of variable speed generators into the market, the application of power electronics to the engine-generator had now become a viable alternative. Many benefits can be realized, namely: 1) improved part-load efficiency, 2) ability to operate at higher engine speeds for increased peak output 3) simplified controls for paralleling multiple units, 4) reduced noise levels at part load, and 5) the ability to be coupled to higher non-linear loads and to start larger motors than a simple synchronous generator while running in standby.

Although the application of inverters was becoming more widespread, it was a new technology to the engine CHP market. It did not exist as an off-the-shelf technology for this application, therefore requiring significant resources for its development.

3.1.1. Inverter Developer Selection

With the inverter being the cornerstone of this development program, it was necessary to identify an inverter developer that was interested in partnering with Tecogen prior to entering the PIER solicitation process. Tecogen selected Youtility, Inc. (now known as The Switch, Inc. or The Switch), in Hudson, New Hampshire, as a Key Subcontractor.

The first consideration in this selection process was the inverter developer's capability to cost-effectively design and manufacture an inverter in this size range (100 kW/125 kVA), with the required features for both grid-tie and standalone operation. They had to demonstrate a willingness to work with the generator manufacturer to ensure a functional and well-

performing interface between the two components. The inverter needed to be designed in accordance to UL1741, the industry standard for grid interconnection, and the developer had to be prepared to pursue the type testing and certification, typically a long and arduous process. Lastly, the developer's business plan needed to have the resources and flexibility required for a product launch.

The authors investigated a total of four inverter manufacturers and concluded that Youtility, Inc. (The Switch) was the best fit for our requirements. In addition to the mandatory considerations, they offered other benefits. The Switch was a subsidiary of Semikron International, one of the top four manufacturers of power semiconductors in the world. It was formed to develop power electronics, specifically for the distributed generation market. The Switch also had an important distinction when compared to the more general inverter manufacturing community. It had a patented topology for handling highly unbalanced and non-linear loads, critical for standby operation. Most inverters available in the market had been developed for paralleling to the grid for solar, wind, and fuel cell applications. The Switch had already developed inverter products for engine/generator systems in smaller sizes, as well as larger inverters for other DG customers (fuel cells, etc).

The Switch's inverter was configured for generators to power an emergency load. It learned how to leverage the large maximum to minimum speed ratio available with an engine, allowing their inverter system to operate in an extremely efficient manner while providing excellent transient response. The Switch had already fully implemented this system on inverters developed for the standby market.

The Switch also had experience with direct control of the engine throttle for load modulation in grid tie, as well as for fast response to step load changes in standalone operation. Tecogen viewed that as a significant advantage in accelerating the design process. However, the authors later found these throttle control algorithms to be somewhat primitive and unreliable, and reclaimed control of the engine speed on board the CHP master control system (see Section 3.1.2).

Tecogen investigated three other manufacturers. Two, Mecc Alte Spa and Marathon Electric, projected prices considerably higher than The Switch and were not sufficiently aware of the peculiarities of the authors' proposed system. Newage in Stamford, England was actually on par technically with The Switch and had a variable speed generator product as well. However, the authors' decision to go with The Switch over Newage was based on the following factors.

- The Switch had better pricing.
- The Switch's inverter was more efficient.
- The Switch was already familiar with the requirements of UL1741, specifically the anti-islanding requirements, and had already developed concepts on how to deal with it.
- Coordination of the overall development effort would be facilitated with a partner close to our facility.

- Newage would supply only the inverter when packaged with its generator, and at the time it seemed that more efficient generators were available.
- The Switch inverter offered the capability of being water-cooled, allowing recovery of additional heat and easing thermal management problems.
- The authors believed there was a marketing advantage to having our unit entirely US made, plus the exchange rate issue would be worrisome with a UK supplier.

Considering all of these issues, the authors felt confident that The Switch was their optimum partner for the development of inverter-based CHP system.

3.1.2. Power Conditioning System (PCS) Beta Design

The scope of The Switch's design effort involved increasing the capacity of their current system with hardware modifications, as well as developing customized control algorithms and software modifications. The customizations of the hardware were done to the power transmission section housing the semiconductors. All of the size-independent components were directly transferable and required only minor modifications; that is, the microprocessor, circuit boards, software, sensors, and wiring harnesses.

The Switch's design objectives can be summarized as follows:

- Match the requirements of the selected generator to ensure the highest efficiency possible.
- Implement a control system to allow the inverter to run both grid-connected and in standby modes.
- Refine the control area network (CAN) Bus communications system , to interface with the Tecogen master control system.
- Upgrade to a water-cooled design.
- Meet the requirements of UL 1741 that includes, but is not limited to, construction, harmonics, and anti-islanding.
- Properly control the engine throttle.

The PCS developed by The Switch for this project is a 125 kVA, 3 phase-4 wire system. It is based on a transformerless topology, meaning that an output transformer is not required to acquire a neutral wire. In grid-tie mode, the PCS synchronizes to the utility grid (AC line) frequency and voltage with a phase lock loop (PLL), and then acts as a fundamental frequency current source. It operates at a power factor of unity (1.0). In standalone, the PCS operates as a voltage source with an overload current limit scheme. Three independent PI voltage loops provide good transient stability and a high quality output voltage waveform. It can withstand a 100% unbalanced load condition and high non-linear load content (ie. fluorescent lighting, AC and DC motor drives, computer power supplies and uninterruptible power supplies (UPS) systems). Components within the PCS are water-cooled. These are the rectifier, top boost, bottom boost, and inverter. An air ventilation system with fans is also required for cooling the

remaining components such as control boards, inductors, capacitors and other miscellaneous electrical components.

A block diagram depicting the topology is presented in Figure 2. A basic description on the flow of electricity through the PCS is as follows:

1. The variable frequency AC power output from the generator enters the PCS.
2. The variable frequency AC power is converted to DC power with a rectifier.

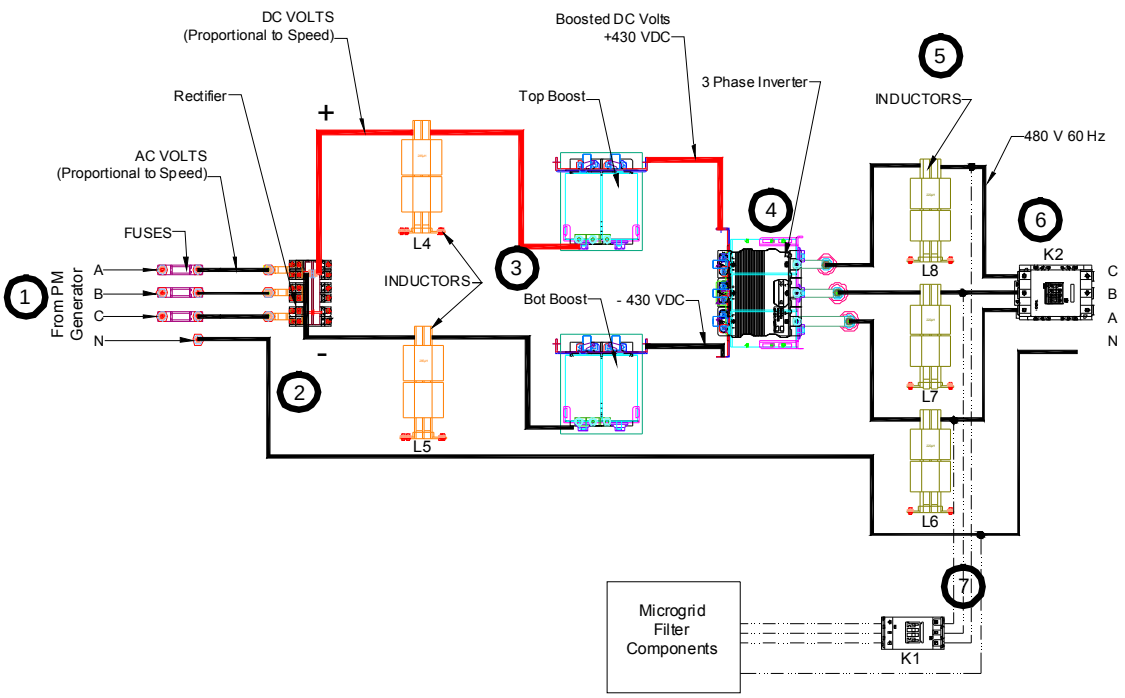


Figure 2. Simplified PCS Block Diagram

Source: Tecogen, Inc.

3. The DC power enters a boost stage, which includes two inductors and two DC boost modules, one positive and one negative. The boost stage increases the voltage level of this DC power to 860 V prior to entering the inverter.
4. The inverter then converts this elevated voltage DC power back to AC 60 HZ power. It does this with insulated gate bipolar transistors (IGBT) technology which is a power semiconductor switching device. Referring to the Figure 3 below, it is analogous to a transformer where the direction of flow of DC current gets rapidly switched on the primary winding producing alternating current in the secondary circuit.

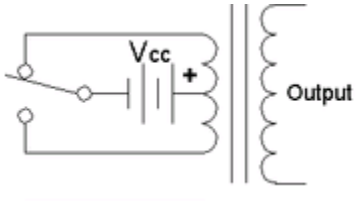


Figure 3. IGBT Analogous Circuit

Source: Tecogen, Inc.

5. Each phase has an output inductor to provide filtering to produce a high quality sinusoidal waveform. Other secondary filtering is provided by various capacitors and resistors in the circuitry that are not shown in this diagram for simplicity.
6. A contactor (K2) provides connection of the PCS to the grid.
7. A second contactor (K1) is enabled for standalone operation only that engages additional required capacitors and resistors into the circuit.

A photograph of the first beta design of the PCS is presented in Figure 4.

Figure 4. PCS Beta Design

Photo Credit: Tecogen Inc.

The objectives achieved with the beta unit were as followed:

- Demonstrated grid tie and standalone operation.
- Demonstrated premium power quality.
- Demonstrated ability to manage step loads in both grid tie and standalone operation.
- Demonstrated conformance to draft UL 1741 standard.
- Providing a platform for testing and qualifying the variable speed generator.

Extensive testing was done at The Switch to verify proper operation of the PCS. A breadboard engine/generator driveline was furnished by Tecogen to provide the variable frequency/voltage input, rather than using a simulated power source. Various power levels were tested in both grid-tie (GT) and standalone (SA) modes. The quality of the waveforms was monitored, including total harmonic distortion (THD) (Harmonic distortion is the change in the waveform of the supply voltage from the ideal sinusoidal waveform). The DC bus stability was monitored and the soft-start waveforms were verified to ensure the correct ramp up and ramp down rates. The transition from SA mode and back to GT mode was completed and proper operation of the GT contactors was verified. Lastly, the overload current for SA mode was verified to ensure proper regulation of current during the overload; one second for the 400 percent overload and 10 seconds for the 200 percent overload.

A sample of the data collected to validate the beta design of the PCS is depicted in Figure 5. It is an oscilloscope output showing the sinusoidal voltage and current waveforms overlaying each other. The timescale on the x-axis is 5 millisecond (mS) per division. As shown, the waveform spans one cycle across 3.3 divisions or 60 Hz (16.7 mS). The voltage measurement is shown to the right of the graph as C1 288.7 RMS or 480 VAC. The current output is also shown on the right as C2 1.206 Volts, where 1.0 Volts is equivalent to 100 A. Therefore, the current output is 120.6 Amps.

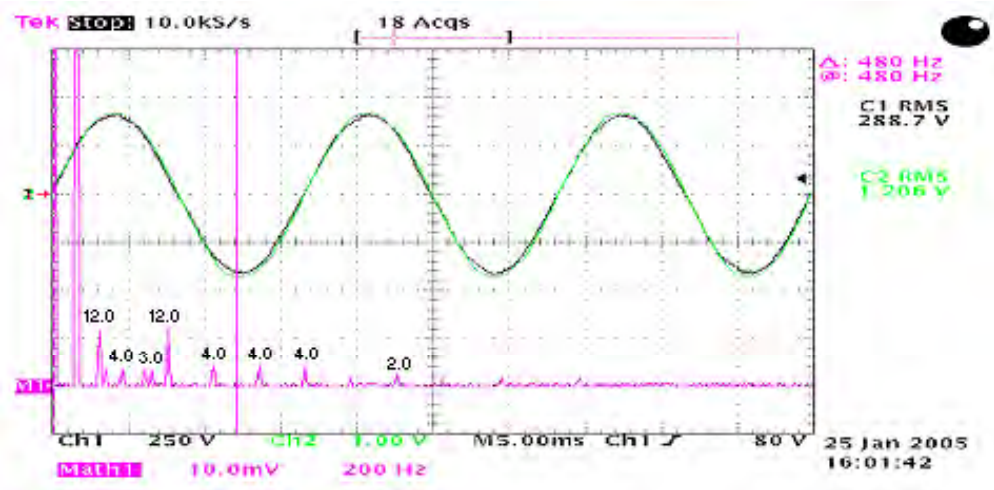


Figure 5. Voltage, Current and THD at 100 kW in Grid Tie

Source: Tecogen, Inc.

The bottom tracing of the graph shows the Fourier spectrum representation of the inverter voltage (Math1 pink trace) which indicates the harmonic distortion where 1.0 mV = 0.1 Amps. For clarification, this data is also presented in tabular form in Table 1 showing the current distortion measured in amps for each harmonic order up to the 15th order (higher orders not shown since near zero). The %THD is calculated at 1.69% using Equation 1, which is well within the requirements of the UL1741 standard for power quality of 5.0%.

$$\frac{\sqrt{\left(|2nd|^2 + |3rd|^2 + |4th|^2 + |5th|^2 .... + |13th|^2 + |14th|^2 + ...\right)}}{1st} \qquad \text{Eq 1.}$$

Table 1 Total Harmonic Distortion at 100 kW Output

Harmonics	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	%THD
Load 100KW	120.6 A	1.2	0.4	0.3	1.2	0.0	0.4	0.0	0.4	0.0	0.4	0.0	0.0	0.0	0.2	1.69

Source: Tecogen, Inc.

Another data sample is presented in Figure 6 to demonstrate the transient capabilities of the beta unit. This oscilloscope output presents the response of the PCS to a step load of 0 – 100 kW in standalone operation. Since the timescale is 2.5 sec per division, the sinusoidal waveform is compressed. However, the purpose of the graph is to show that the current output (bottom tracing) immediately picks up the load in less than 1 second and the voltage recovers within approximately 12 seconds.

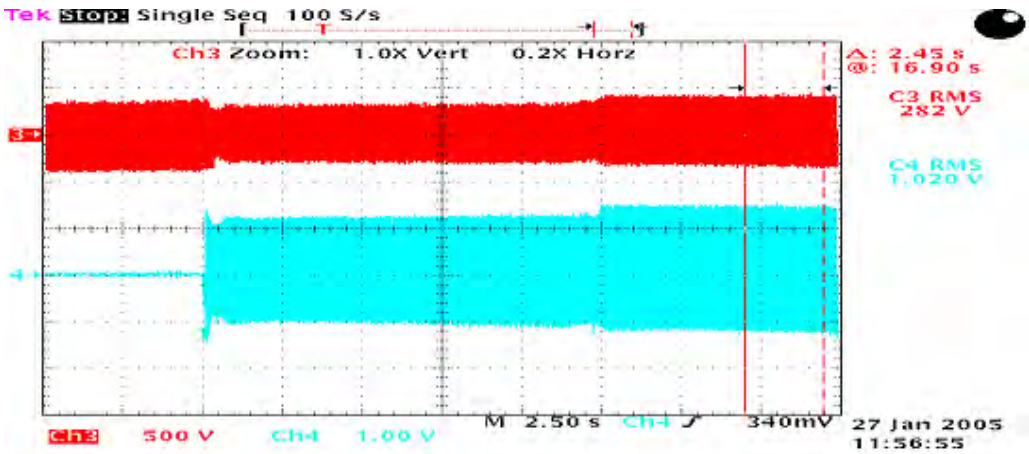


Figure 6. Inverter voltage and current during a 0kW to 100kW Step Load

Source: Tecogen, Inc.

The PCS beta unit did have design shortfalls, however. First, the packaging was too compact and impractical for manufacturability and maintenance. Second, the water-cooling system design was flawed, as discovered when a leak on the beta unit destroyed many components. Additionally, although much knowledge was gained on the UL1741 type testing, the standard changed shortly thereafter-incorporating IEEE 1547 requirements. In order to obtain Rule 21, retesting would have been required. It is important to emphasize, however, that the software for anti-islanding, harmonics, and response to abnormal voltage and frequency was developed during this phase and readily transferable to the later designs.

Lastly, development and testing was done with the engine throttle controlled by the PCS. This system was found to be primitive in its design, as well as unreliable. Moving forward, the authors could either put more resources into maturing this design, or alternatively decouple this control from the inverter, and have the CHP module master control system modulate the engine speed while having the inverter communicate the power demand and responding appropriately. The authors opted for the latter course of action in the next generator design, which proved to be a prudent decision.

3.1.3. First Generation Commercial Design

The primary objective of first generation commercial design for the PCS was to correct the shortfalls of the beta unit. Also, it now had to be fully integrated with the CHP module, both in packaging and controls. At this time, the authors had found a host site for the field test unit, the Claremont Tennis Club in Claremont, California. We also had agreements in place for nine units, at two different sites, in the state of New York. The New York State Energy Research and Development Authority (NYSERDA) offered funding incentives to facilities for the demonstration of DG-CHP systems. The DG units had to have the emergency power capability, among other requirements with regards to efficiency, emission, and grid interconnection. The Tecogen premium power unit fit the criteria, resulting in the accelerated introduction of additional field test units.

The first generation commercial design had the same design topography as the beta unit. But, given that a total of 10 units needed to be manufactured within a relatively condensed time period (less than one year), important objectives for modifications were established and met:

1. Rework the layout of the PCS to streamline manufacturability and improve serviceability.
2. Remove the engine throttle control feature.
3. Design a water cooling system that was sufficiently isolated from the electrical components in the event of a leak.
4. Source components with commercial objectives in mind, namely pricing and availability.
5. Develop a manufacturing model with The Switch that was cost-effective, and could meet the challenging schedule.

One objective that the authors did not try to accomplish in the first generation commercial design was the UL1741 certification. Since this was not a requirement for these field test demonstrations (that is, a utility-grade relay was used at the PCC for grid protection), and since the resources to complete the certification would have been substantial for both The Switch and Tecogen technical teams, it was decided to postpone this effort until the second generation commercial design.

A photograph of the first generation commercial design is presented in Figure 7.

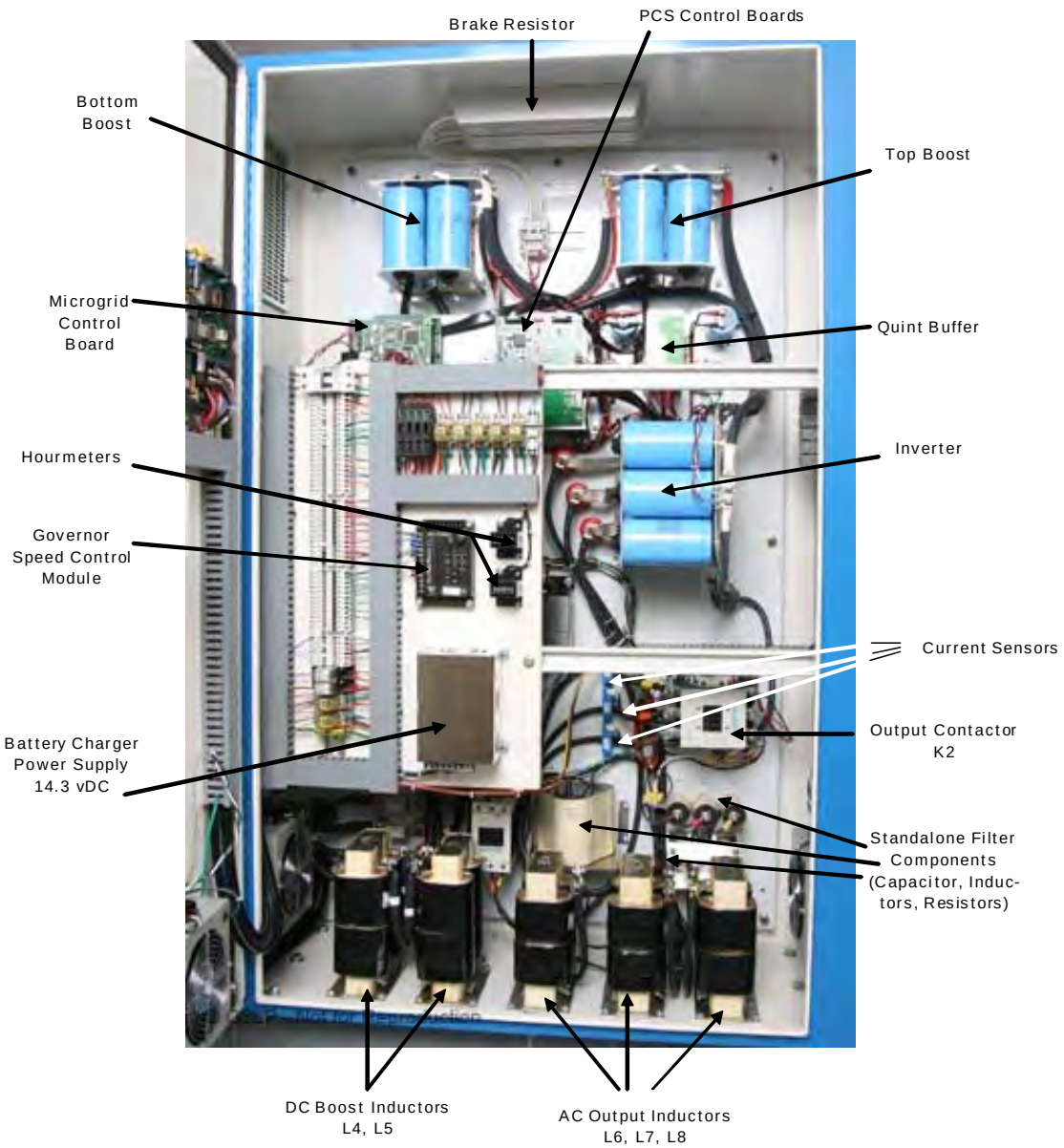


Figure 7. First Generation PCS Commercial Design
Source: Tecogen, Inc.

The authors experienced some technical problems with this first generation commercial design as follows:

1. All of the large inductors (two on the DC boost circuit and three on the 3-Phase output) operated at very high temperatures (close to the Class H insulation limit of 180 °C). This required that we limit the output of these units to the continuous rating of 100 kW rather than the peak 125 kW. It also diminished the efficiency of the PCS.

2. The filtering components (i.e. capacitors and inductors) at the generator input were found to have a detrimental effect on the system efficiency. These components were subsequently removed on all units.

3. The authors learned from a failure in the field that the rectifier rating was marginal.

4. The authors also learned from a field failure that the generator input required not just fused protection, but an actual current measurement on each phase for sooner detection of the fault.

All of these problems were addressed on the Second Generation design.

3.1.4. Second Generation Commercial Design

In the transition from the first production run of inverters to the second, Youtility came under new ownership and was renamed The Switch, Inc. Although it still had an affiliation with Semikron, Youtility became part of the parent company, The Switch (Finland), which was also within the Semikron family. The Switch (parent company) is a leading supplier of megawatt-class permanent magnet generators and full-power converter packages for wind power and other new energy applications. Their management team brought a different business perspective to Youtility, focusing on standardizing products and commercialization.

As such, the new management team for The Switch was not satisfied with the business model for the first generation PCS design, where Tecogen did approximately 50% of the final assembly work. It felt The Switch needed to have a more value-added role in the manufacturing.

It was also not entirely satisfied with the component layout and packaging design. Although, it was an improvement over the beta design, it wanted to take a more modular approach to the assembly. This would allow them to easily subcontract portions of the assembly work with more than one supplier. The Switch could then perform final assembly and specialized testing, and then supply Tecogen with a complete component. In addition, The Switch contended that the new design would improve serviceability.

This manufacturing approach also made sense with respect to the UL 1741 certification. With this second generation production run, it was now time to pursue certification, as the market was demanding it. In revamping the layout design, The Switch could be mindful of the standard's construction requirements. Also, certification requires certain tests to be implemented on every production line unit. With The Switch being accountable for the full scope of the PCS manufacturing, it simplified the compliance process.

The design topography, functionality, and most of the hardware and software remained the same between the first and second generation commercial design. There were some design upgrades based on experiences with the first generation PCS design (see Section 3.1.3). A photograph of the second-generation design is presented in Figure 8. As shown, it is constructed in a modular fashion with three subpanels and one swing-out panel. The modular panels allow for replacement of full panels in the field if necessary. Also, unlike the first generation design, there is full access to all components.

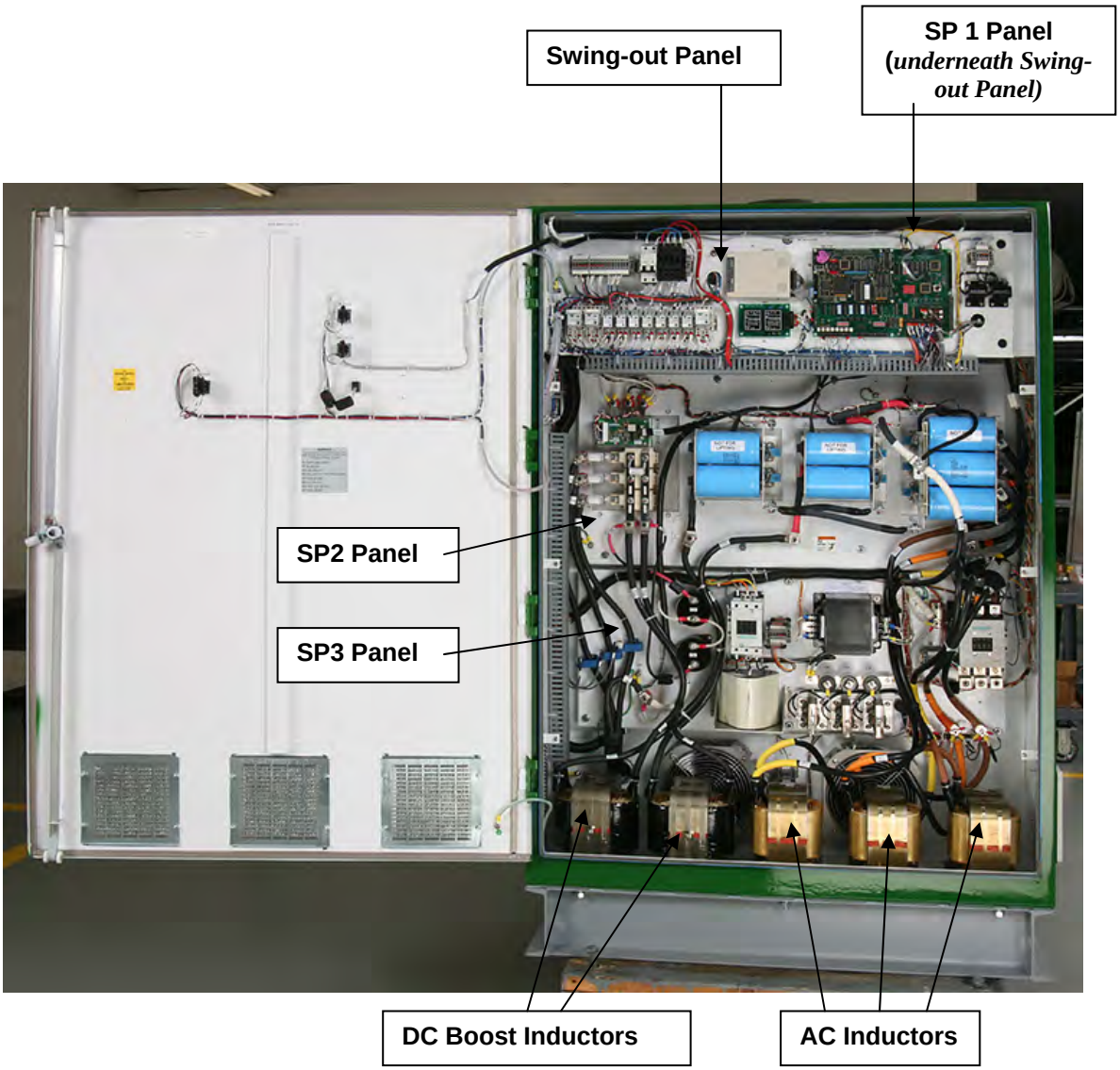


Figure 8. Second Generation PCS Commercial Design.
Photo Credit: Tecogen, Inc.

This revamped PCS design went through a full UL 1741 construction review and met the requirements of the certification. For more information on the UL 1741 certification, refer to Section 7.0.

3.2. Generator

The generator is a critical component for a successful application of an inverter to an engine drive. One of the primary benefits of this combination is the ability to operate the engine at

variable speed. This results in improved part-load efficiency since the engine is able to operate along its maximum torque curve vs. speed. This point is illustrated in Figure 9 for the Tecogen 7.4 liter engine. Also, the higher part load efficiency has the secondary benefit of reducing combustion chamber temperatures, and therefore lowering NOx concentrations into the catalyst system. Lastly, variable speed operation provides the ability to operate at higher engine speeds for increased peak output.

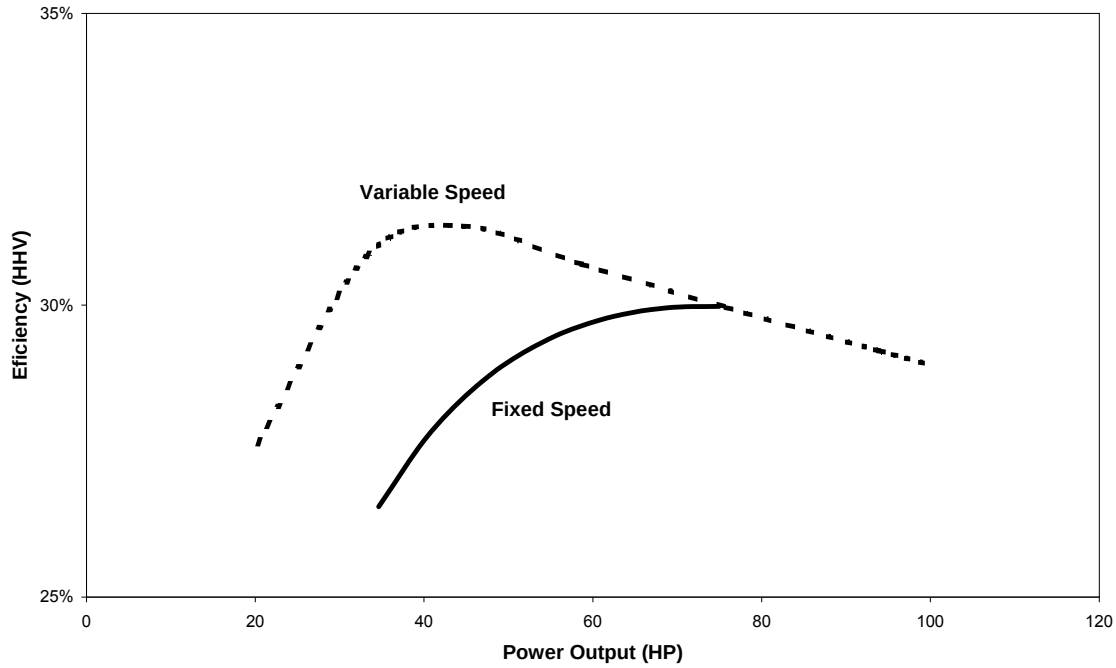


Figure 9. Engine Efficiency vs. Power Output for and Engine Operating at Fixed and Variable Speed (Tecogen 7400 Engine)

Source: Tecogen, Inc.

At the outset of this program, variable speed generators appeared to be readily available in the marketplace. However, Tecogen did discover that this technology was not well developed, specifically in this size range, and the generator proved to be a significant hurdle in the design. The authors' first choice, the Marathon/Light Engineering (LE), Inc. amorphous metal generator, never was able to produce 100 kW. Its performance degraded at higher outputs (> 80 kW), and it would overheat. Marathon pulled this model from their product line and, at the time, decided to remove it from its Business Plan.

The authors then partnered with Danotek, which did in the end provide them with a commercially viable generator. However, this path required significant development funds from Tecogen (Tecogen provided cash contributions as match funding). The authors also experienced a major design failure on the field tests units, requiring an extensive field replacement program. Later, there was another design upgrade in the field of lesser magnitude. Although Danotek was very supportive and engaged and the technical design issues were

resolved, Tecogen had to endure a financial burden as well as damage to our reputation with the host sites. However, in the end, the Danotek generator proved to be well-performing and commercially viable. Consequently, Tecogen entered into a long-term supplier agreement with them (see Section 9.1.4)

The following sections provide the background, experiences, and results with both generators.

3.2.1. Marathon/LE Amorphous Metal Generator

During the proposal phase and early in the PIER program, Tecogen evaluated available generator technologies, examining the effects on system efficiency as well as first cost. The generator had to be synchronous for the black-start capability. However, the distinctive feature that really limited the choices was the variable speed operation, with the maximum speed reaching as high as 3000 rpm. Most manufacturers do not allow operation above 1800 rpm. Marathon had an off-the shelf generator that could operate up to 2200 rpm, and Mec Alte Spa proposed to build a custom generator for 3000 rpm operation. The efficiency and cost of these generators did not make them feasible options. The authors also reviewed a variable speed permanent magnet generator (PMG) made by Newage AVK-SEG. While the efficiency of permanent magnet technology was improved, it still fell short of the amorphous metal generator that was ultimately selected.

The amorphous metal generator, made by Light Engineering, Inc., was a technologically-advanced design that was smaller, lighter, and more efficient than conventional generators (see Figure 10). Amorphous metal is made by cooling molten iron through a rapid spinning process. The material is cooled so quickly that it prevents a crystalline structure from forming, creating a more stable material that can operate at higher frequencies efficiently. It is wound into a coil and used in the stator core instead of the silicon iron used in most conventional generators. Additionally, less of it is required for a given power output, which results in a reduction in weight and size. These features have made amorphous metal generators an ideal fit for hybrid vehicles and likewise, variable speed/frequency power generation technologies. Another benefit LE's generators offered was that they were water-cooled, a valuable attribute for CHP applications.

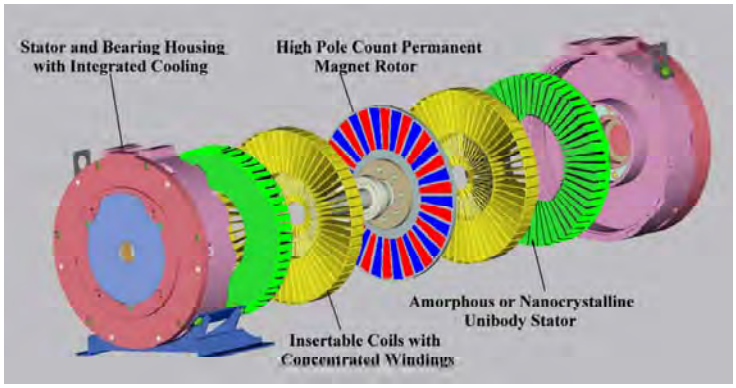


Figure 10. LE Amorphous Metal Generator

Source: Tecogen, Inc.

LE, Inc., a manufacturer of high-performance, high power density variable speed electric motors, had been in product development with this generator for five years. They had a licensing agreement with the generator manufacturer, Marathon, in order to gain a more widespread marketing effort. Because this generator was a recently introduced product for LE, a customized design was required for the Tecogen CHP. From Tecogen's standpoint, the advantages this generator offered in terms of efficiency and size outweighed the uncertainties inherent with new product development.

This generator was sent to The Switch for breadboard testing with the engine and the PCS. However, it was unable to operate above 80 kW. The poor performance of the generator was caused by overheating. Irregular heating of one stator created increased voltage loss and reduced the overall output power capability. The PCS was forced to use more boost current to compensate, producing more power, but increasing generator heating. This exacerbated the problem, resulting in an over-temperature failure.

Computational analysis was done by LE and several tests were run at The Switch to determine the root cause for the irregular heating. Three iterations of the generator design were tested, each with different back EMF characteristics and output impedance characteristics. In the end, LE determined that overheating was attributed to Ohmic losses in the wire due to circulating currents, resulting from manufacturing deficiencies related to the coils (i.e. positioning in the air gap, positioning in the stator, different lead lengths or number of turns). As a result of these findings, LE recommended a complete electromagnetic re-design to address marginal power output capability. In January 2005, they proposed a more robust design that would have significant margin capability over the previous design. Later however, in April 2005, LE revised their Business Plan and decided not to produce this model in the near future. As a result, Tecogen needed to find an alternative generator supplier.

3.2.2. Danotek Permanent Magnet Generator

As a result, Tecogen investigated alternative generator designs. There were basically two options; synchronous generators or PMG. A synchronous generator is conventional technology that uses electromagnets and requires a field exciter to control the current output. The reason why it is called synchronous is that, the electro-magnets in the center will rotate at a constant speed that is synchronous, or running at the exact cycle of the electrical frequency of the grid (60 Hz).

Alternatively, the rotor construction of a permanent magnet generator consists of a ring of magnetic iron with magnets mounted on its surface. Each magnet is custom machined, then charged. The magnets are made of rare earth metals, such as neodymium-boron-iron or samarium-cobalt, which increases the cost of the generator when compared to conventional synchronous generators. Since there is no field excitation, power modulation is achieved by varying the rotation speed, requiring an interface with power electronics.

A general comparison of the benefits and drawbacks of these two types of generators is presented in Table 2.

Table 2. Comparison of Generator Technologies

Type	Benefits	Drawbacks
Synchronous	Proven technology Easily compatible with inverter Low cost Readily available	Maximum speed 2250 rpm (95 kW), so no peaking capability Efficiency optimized at standard operating point of 1800 rpm – efficiency at other speeds unknown Air-cooled Difficult packaging
PMG	High efficiency Water-cooled (Eliminates cumbersome ventilation system and in some cases, can contribute to the heat recovery) Small size Compact Packaging	Higher cost New technology – higher risk

Source: Tecogen, Inc.

The investigation into synchronous generator technologies discovered many standard models that fit the authors' engine profile. However, as indicated in the "Drawbacks" column of Table 2, these generators have a speed limitation. Most manufacturers (Mecc Alte, Heimer, Weg) will not allow operation above 1800 rpm, the standard operating speed for a 60 Hz application.

Marathon (and Leroy Somer) approved operating up to 2250 rpm. However, this would only achieve a power output of 90 - 95 kW, depending on the efficiency. Also, these manufacturers had no models to predict efficiency at the higher rpm but did conclude that it would drop off from the optimum design point of 1800 rpm due to fan and resistance losses.

There were no standard designs of permanent magnet generators that fit the authors's power requirement and engine torque profile. In all cases, product development of a custom size was required by the manufacturer. The authors spoke to Newage and Rotatek, both European companies, and Danotek, a company in Ann Arbor, Michigan. Danotek quoted the best efficiency and the most reasonable development costs. Another advantage for Danotek was that they had worked with The Switch on an inverter design for one of Danotek's smaller size generators. The Switch had tested this smaller generator at its facility with favorable efficiency results.

The authors concluded that Danotek was the best choice for the generator. The fact that a PMG could operate over a broader speed range than a synchronous generator was a significant factor. Also, PMG's are more compact and can be water-cooled. Danotek was the most favored over the other PMG options because of the high efficiencies, history with The Switch inverters, and product development located in the United States. The costs of PMG generators are significantly more than the synchronous. Some of these are the material cost of the magnets. The remaining manufacturing costs can be significantly reduced with production of higher quantities.

The critical disadvantage of the Danotek was that it was an unproven, custom design that had to be validated, both in terms of performance and long-term reliability. The authors were able to do performance test of the prototype at their facility, but unfortunately the integrity of the design with field operating experience did not become apparent until the authors had a population of generators on the field test units.

The Danotek generator was performance tested at Tecogen's facility in Waltham (see Figure 11). It was coupled to the engine, but the electrical output went directly to a resistive load bank rather than to the PCS. The reason for this was to measure the performance of the generator alone by removing the effect of the PCS (i.e. THD).

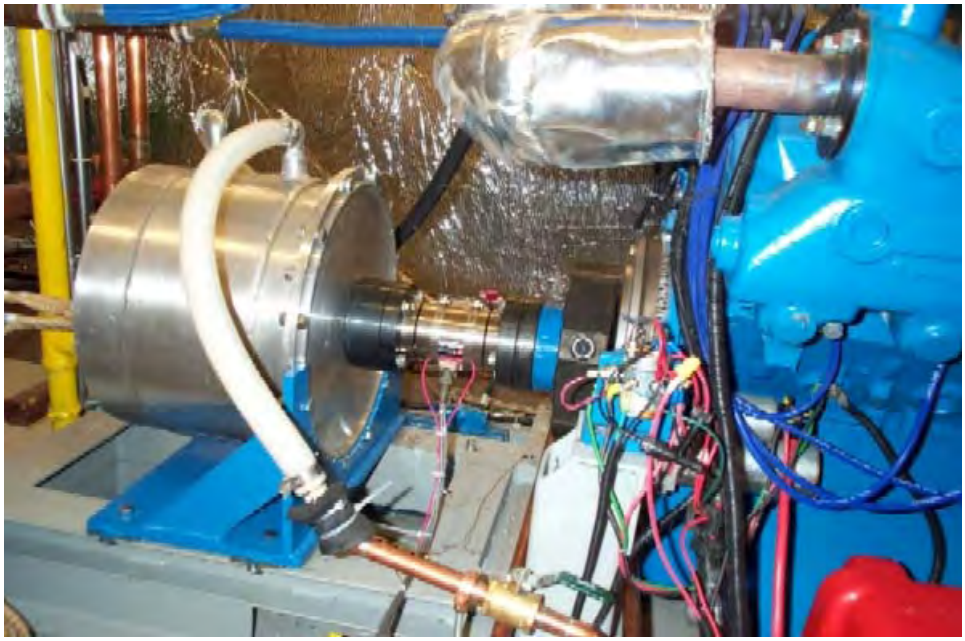


Figure 11. Danotek Generator Test Set-up.

Photo Credit: Tecogen, Inc.

The instrumentation used for this testing is presented in Table 3. A torquemeter measured the horsepower out of the engine, and an oscilloscope measured the power output of the generator. This power measurement could not be done with a conventional power meter (i.e. Dranetz meter) because the output of the generator was at variable frequency and voltage due to the variable speed operation. A Dranetz meter was used however to verify a few points that were in its range of frequency measurement.

Table 3. Danotek Generator Performance Test Instrumentation

Measurement	Instrument	Model
Engine Horsepower	Torquemeter	SensorData T251-STD w/Daytronic 5D78 Signal Conditioner
Generator Output Power 1	Oscilloscope	Tektronix TDS3014 (4 channel)
Generator Output Power 2	Dranetz Meter	DRA/4300;C Power Analyzer 2MB/H

Source: Danotek.

The test results were very encouraging (see Table 4 and Figure 12). The generator was able to meet the power requirement at both the continuous rating point and the peaking rating point.

The continuous power rating point for the premium power module is 100 kW at approximately 2400 – 2500 rpm. This is the power out of the inverter, so with a PCS efficiency of 95%, the

generator must produce at least 105 kW. The test results measured 107.9 kW at 2500 rpm. The design specification for the peaking rating point is 125 kW (output from the inverter @ 1.0 PF) at 3000 rpm. The test results measured 129.7 kW from the generator. Again with a PCS efficiency of 95%, the power output of the unit would be 123 kW. Although this is 1.6% less than the design specification, it is within the accepted +/- 5% allowable deviation from the rating point Also, efficiency at the peaking rating point is not as critical since the system will only operate there under exceptional circumstances such as demand side response or standby operation (blackout). However, the authors later found that we could achieve the 125 kW at 2900 rpm (see Section 5.2) because the PCS efficiency at that power level was better than expected.

Table 4. Danotek Generator Test Results

RPM	KW	Gen Eff	Projected Premium Power CHP Unit Output
1000	38.8	96.4%	36.9
1800	77.6	95.8%	73.7
2000	88.9	96.1%	84.5
2200	93.0	97.1%	88.4
2500	107.9	97.1%	102.5
2600	112.5	96.4%	106.9
2900	129.1	97.0%	122.6
3000	129.7	96.0%	123.2

Source: Danotek.

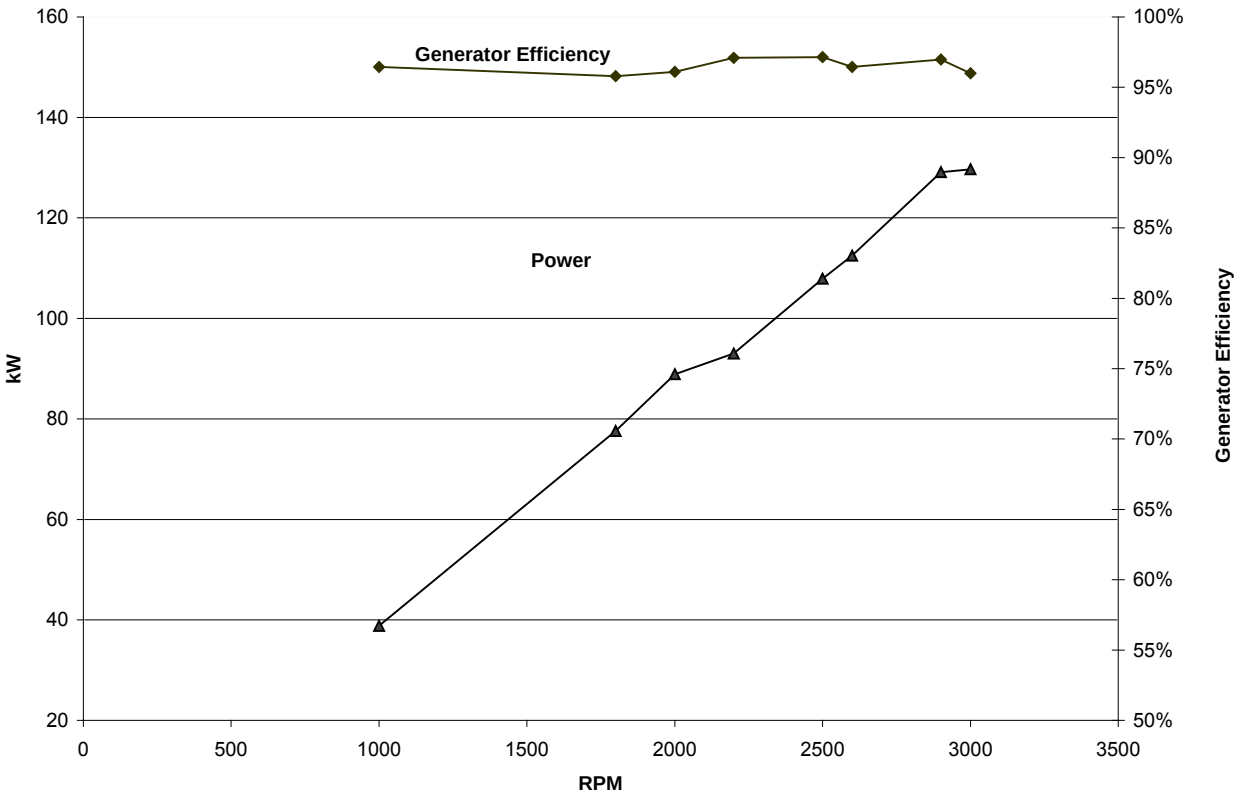


Figure 12. Generator Efficiency vs. RPM

Source: Tecogen, Inc.

Danotek fulfilled the authors' performance expectations. However, once the authors got into production with these generators, we began to experience failures, some in the initial hours of operation at the factory, and some in the field after several hundred hours of operation. The resolution required a major redesign of the rotor by Danotek, along with an extensive field replacement program of generators. Later, a limited amount of generators experienced a secondary failure mode that required just a generator component upgrade in the field. These events are summarized below:

1. The primary failure mode for the generator was a detachment of the magnets from the rotor. The rotating part of the generator, or rotor, is constructed of magnets. The magnets are configured as thin plates glued to the circumference of a steel drum. In addition to the glue or adhesive, the magnets have a secondary retention system of a glass tape wrap. The stator, or stationary part of the generator, contains the copper windings.

   The failure mode that occurred was the magnets became detached from the rotor by a combination of shear forces and centrifugal forces. To address this problem, the following upgrades were made:

   - The adhesive used to secure the magnets to the rotor was changed to one with better shear strength and tensile strength. The process of applying the adhesive also became more controlled.

- The glass tape wrap thickness was increased. It went from 3 wrap revolutions to 5 wraps.
- A system of mechanical retention, or rotational stops, for the magnets was added. This is essentially 2 sets of three pins protruding along the axis of the rotor to prevent any magnets from creeping in the rotational direction.

With these design changes, Danotek felt that they significantly improved their safety factors against both shear and centrifugal forces.

2. A secondary failure mode was related to the bearing. When the rotor/magnet problem had been identified, Danotek had inspected several generators, and felt that the bearing design could be improved. The bearing housing was aluminum, and it was seeing excessive wear. As a remedy, it designed a hardened steel insert ring for the bearing housing that required machining of all of the end bells on the replacement generators. This sleeve had an interference fit with the housing.

   Two field units (including the field test unit at Claremont Club) experienced failures where a sleeve dislodged from the housing. Danotek determined that one of their two machining vendors did not have sufficient quality control on their machining tolerances. Although this was a quality issue, Danotek had decided to modify the design to mechanically retain the insert ring to the housing, with a pin, for added security. This change was made on all production generators going forward, and generator end bells were upgraded on the units already in field operation.

Although the early production generator design had some significant design flaws, the exceptional efficiency, and Danotek's accountability and commitment to resolving the problems, solidified the use of this permanent magnet generator on the Premium Power product. As a result, Tecogen entered into a multi-year supplier agreement with Danotek to provide cost certainty and ensure availability in the upcoming future (see Section 9.1.4).

3.3. Power Generation Module Cooling System

Both the generator and PCS require water-cooling. Permanent magnet generators are very sensitive to dust and debris, so air-cooling systems is not recommended. The generator is designed with a water cooling chamber around the circumference of the generator housing, and the water connections on the top (see Figure 13).

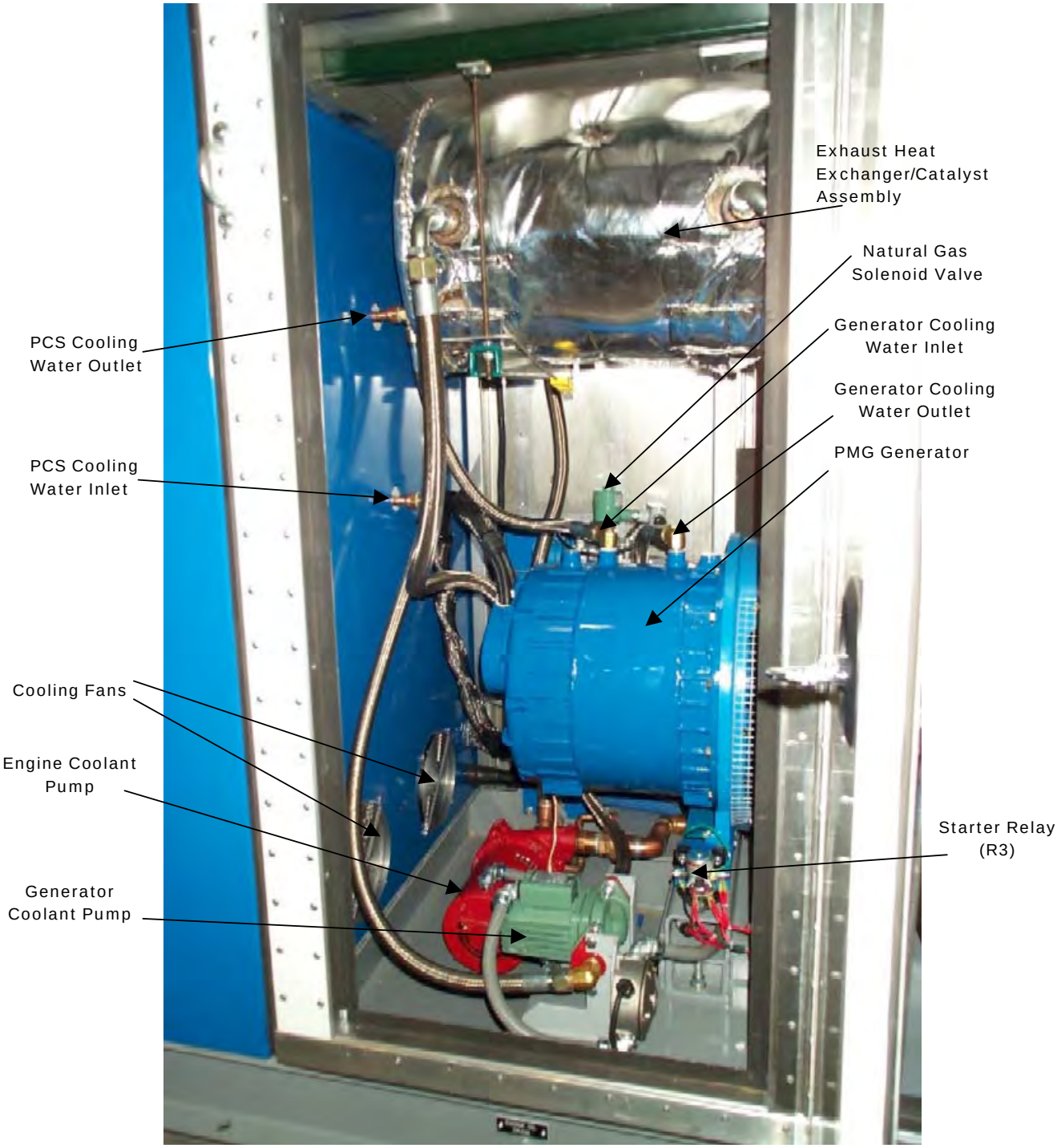


Figure 13. Generator /PCS Water Cooling.
Photo Credit: Tecogen, Inc.

Components within the PCS are also water-cooled. These are the components on the SP2 panel (see Figure 8): the rectifier, top boost, bottom boost, and inverter. The PCS enclosure was designed to separate the water circuit from the electrical components. Referring to Figure 8, each of the four major components on the SP2 panel are mounted on a small heat exchanger or "cold plate." This panel actually has cutouts the size of the cold plates so that once the component is secured to the cold plate, the panel provides a barrier for the electrical system and the water system in the event of a leak.

The cooling system for these PCS components is combined with the generator cooling system. Since these devices must run cooler than the engine loop, they are on a separate water circuit that includes a factory-supplied pump. A customer can recover this lower grade heat or must supply an external fluid cooler. The specifications of the generator/PCS cooling system are presented in Table 5.

Table 5 Generator/PCS Cooling System Specification

	Continuous	Peaking
Thermal Output (Btu/hr)	30,750	38,400
Water/Glycol Flow	8 gpm	
Maximum Leaving Water Temperature	129 °F	
Minimum Supply Temperature	40 °F	

Source: Tecogen, Inc.

The PCS also has an air ventilation system for the balance of components that are not equipped with cold plates. Referring again to Figure 13, two 600 cfm ventilation fans are mounted at the bottom of the PCS enclosure. They draw air in through several vents in the PCS enclosure and discharge it first into the engine compartment, and eventually out the enclosure exhaust hood. These ventilation fans also provide combustion air for the engine.

4.0 Product Design

As described in Section 3.0, the innovative technology introduced in the premium power module was the power conversion system, namely the inverter (or PCS) and the permanent magnet generator. However, a substantial effort was required to integrate these components together with the existing CHP module design. The engine needed a speed control system to effectively operate at variable speed, as well as accept step load changes for standalone operation. Also, all of the engine's subsystems (heat recovery, oil lubrication, emission controls, exhaust, air intake) had to be upgraded to manage the increase in power output from 75 kW to 100 kW (continuous) and 125 kVA (peaking).

The control system required significant rework to interface with the PCS via the control area network (CAN) bus communications system. Also, it needed to have the capability to manage as the master controls system for both grid-tie operation and standalone operation. This involved additional inputs and outputs, as well as new control algorithms.

Lastly, a thoughtful approach was needed for the structural base, driveline, packaging, and enclosure. Service access, manufacturability, footprint, noise, and appearance were all considerations in addition to cost.

4.1. Engine and Subsystems

4.1.1. Engine Speed Control

A design feature that could not be readily transferred from Tecogen's induction-based 75 kW products was the engine speed control. The premium power unit had to operate at variable speed rather than at the fixed speed of 1800 rpm. Even more significant was that the premium power unit needed to handle step load changes, as high as 0-100 kW, in standalone operation. This degree of transient response was beyond the torque limits of the stepper motor driven throttle linkage used on Tecogen's existing product.

As discussed in Section 3.1.2, the authors' initial approach to engine speed control was to utilize the system on board the PCS, devised by The Switch. They had a separate control board with an algorithm that considered speed, power, and control mode (grid connected or standalone) and accordingly output an analog signal to drive a heavy-duty actuator on the throttle plate.

The authors found that The Switch speed control system worked pretty well in a controlled environment. However, the flaws in the design became very apparent during the CERTS field demonstration at the American Electric Power (AEP) Test Bed[6]. This test program required the

[6] Tecogen participated in the CEC funded CERTS Microgrid Demonstration program at AEP in Columbus, Ohio. Tecogen furnished three 60 kW, inverter-based, engine-driven power generation units of an alpha design. These had air-cooled inverters, synchronous generators, no heat recovery systems, and a reduced output of 60 kW. They also had minimal variable speed capability.

generators to operate under a variety of scenarios that more accurately simulated standalone power generation requirements. The control system proved to be inconsistent, needing constant adjustment.

It was determined that significantly more development work was required to refine The Switch's speed control algorithm. Also, consideration was given to the merit of regaining the engine control functionality back on to the Tecogen master control system. This would leave the authors less dependent on the inverter manufacturer, reducing their vulnerability to their design and reliability issues later. Consequently, the authors decided to remove the inverter interface to the engine speed control, and implement a variable speed governor controller that interconnected to the Tecogen control system.

The system the authors selected was comprised of off-the-shelf components that included a control module, and a throttle body equipped with an actuator. The Tecogen control system sends the governor controller a speed setpoint based on the load demand. The controller uses closed-loop PID control to modulate the actuator. It has an rpm input from a magnetic pick-up on the engine flywheel. The controller will also sense an overspeed and will immediately close the throttle, causing the engine to stall, providing a redundant safety to the master control system.

The governor speed control has proven to be reliable and consistent. In most cases, it steadily maintains engine speed and can handle a step load in standalone mode very effectively. However, the authors still need to refine its operation at part load, which is where they see some instability unless they operate the throttle in a partially open position, rather than a wide-open position. Operation with a partially open throttle results in throttle losses, thus compromising efficiency. The authors plan to work with the throttle manufacturer, to perhaps adjust their software code, so they can achieve control stability over a wider speed operating range. This should improve their current part load efficiencies to the levels expected at the outset of the design (see Section 5.2).

4.1.2. Lubrication System

The engine lubrication system required an upgrade to increase the sump capacity from that of that 75 kW module. The 75 kW machine has an enlarged 34 quart (8.5 gallons) oil pan, which extends the oil change interval to 750 run hours. Since in the premium power application, the engine operates at both higher speed and load, the sump capacity needed to increase. Enlarging the engine's oil pan any further was not practical for space considerations, as well as structural integrity. Alternatively, an enlarged oil sump was built into the structural base of the unit.

This design provided several advantages. First, with the oil reservoir directly under the engine, the engine's internal oil pump could be used to draw oil up, and gravity would provide for draining. This eliminates the need for an external circulating pump. Also, having the tank built into the frame is a packaging benefit, without the clutter of a surface-mounted tank.

The 18 gallon sump, located underneath the engine, extends the maintenance interval for the oil

to 1000 run hours or 750 EFLH (equivalent full load hours). Figure 14 presents a schematic of the engine lubrication system. The engine's internal pump is a gear-type oil pump that is driven from the distributor shaft, which is gear-driven from the camshaft. Oil is drawn into the oil pump through a very long pick-up tube that feeds through the oil pan, down a connecting tube, and into the tank. At the end of the pick-up tube is a check valve to ensure the engine does not lose its prime during downtime. There is also a screen to filter out any debris.

Pressurized oil leaving the pump is first filtered with an external block-mounted oil filter. It is then routed via external plumbing to the oil cooler. Once it leaves the oil cooler, it is plumbed to the external pressure regulator mounted on the oil tank. Some of the oil is relieved to the sump by the external pressure regulator (relief), and the remainder returns to the engine through port B.

Oil returning from the oil cooler ("B" in Figure 14) flows into the main gallery, and then to the camshaft and crankshaft bearings. The valve lifter oil gallery supplies oil to the valve lifters. Oil flows from the hydraulic lifters through the hollow push rods to the rocker arms. Oil from the overhead valve train drains back to the crankcase through oil drain holes in the cylinder head and block. The timing chain is drip-fed from the front camshaft bearing. The pistons and piston pin are lubricated by oil splash. Oil that collects in the oil pan drains down into the oil tank via the connection tube.

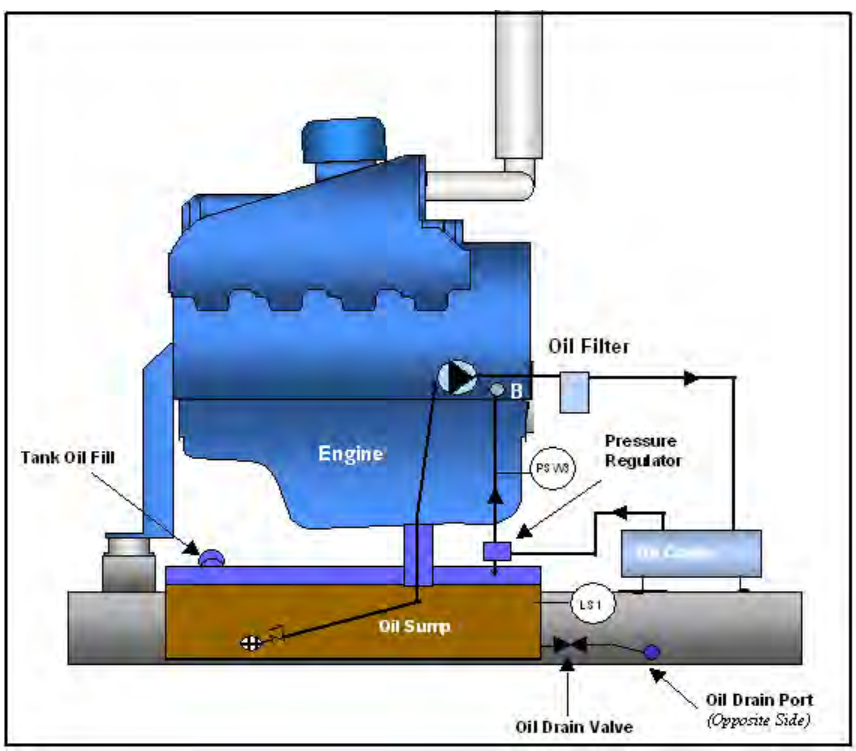


Figure 14 Engine Lubrication System Schematic

Source: Tecogen, Inc.

4.1.3. Engine Heat Recovery System

The major innovation required for the engine heat recovery system was to upgrade the design of the exhaust heat exchanger. The 75 kW Tecogen cogeneration module used two separate heat exchangers, one on each engine exhaust manifold, for units without emission controls. For units with emissions controls, the catalytic converter needed to be upstream of the exhaust heat exchanger in order to operate at the high exhaust temperature. This warranted using a single off-the-shelf heat exchanger and installing it in the customers piping along with the catalytic converter.

The premium power unit was designed on the premise that emission controls was a standard feature of the design. This meant that in order to have a compact and inclusive package, it was necessary to integrate the catalyst and exhaust heat exchanger on board the skid. This presented a challenge of managing the heat from the catalyst within an enclosed space. It was decided to design a custom exhaust heat exchanger that embedded the catalyst within the center of the heat exchanger.[7] This resolved the problem of the extreme surface temperature of the catalyst (~1200 °F) by isolating it from the ambient space. As a bonus, this exothermic heat from the catalyst was recovered, rather than lost to ambient.

A piping and instrumentation diagram is presented in Figure 15. The heat recovery system is a pressurized, closed-loop hydronic system requiring a city-water make-up line, regulated to 12–15 psig, with a pre-charged bladder-type expansion tank to maintain coolant system pressure. Two connections are provided on the unit for hook-up to the customer's system. Heat is recovered from the oil cooler, engine jacket, exhaust manifolds and exhaust heat exchanger. The system includes a 30 gpm pump and a thermostatic control valve to maintain a minimum engine temperature of 170 °F. Table 6 presents the heat recovery system specifications.

Table 6. Heat Recovery System Specifications

	Continuous	Peaking
Thermal Output (Btu/hr)	700,000	920,000
Hot Water Flow	30 gpm	
Maximum Leaving Water Temperature	230 °F	
Maximum Entering Water Temperature	180 °F	

Source: Tecogen, Inc.

It is important to note that the PCS cooling and generator cooling were not included as part of the primary heat recovery circuit. The operating temperatures of the engine loop exceeded the limits of these components. As presented in Section 3.3, the power module cooling has a

[7] Design is based upon Tecogen Patent 5033264 (7/23/1991).

separate cooling system, where the low grade heat can either be recovered or rejected to an external fluid cooler.

4.1.4. Emission Control System

The emission control system technology was directly transferred from Tecogen's existing CHP product. It is a system based upon a method of controlled combustion with exhaust gas treatment. A microprocessor-based, closed-loop, feedback control system maintains the air/fuel (A/F) ratio within a tight window, slightly rich of stochiometric. This allows complete combustion of the fuel. The exhaust is then treated with a catalytic converter that achieves optimum efficiency with complete combustion of the fuel, ultimately reducing emissions to very low levels.

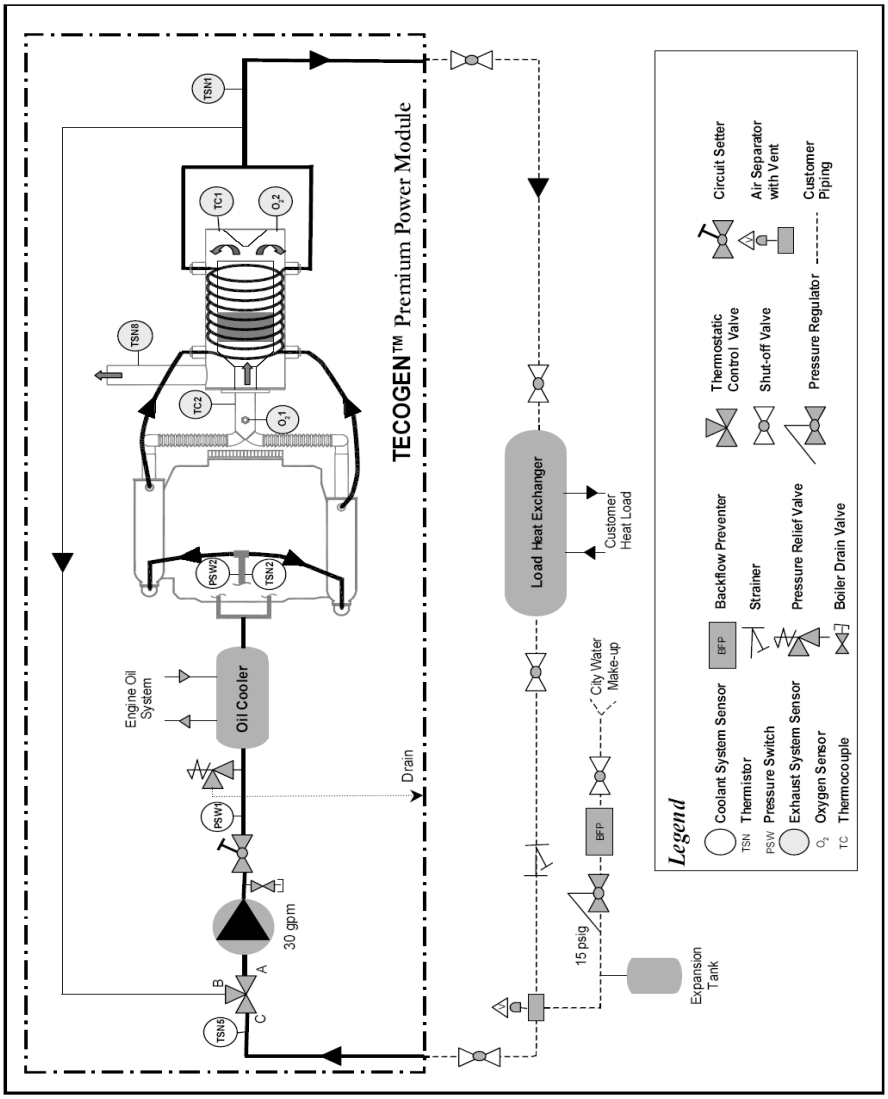


Figure 15 Engine Heat Recovery System

Source: Tecogen, Inc.

The A/F ratio control is done by precision control of a stepper motor-controlled fuel control valve that modulates the fuel flow. This is a closed-loop control system with the feedback signals coming from two oxygen (O_2) sensors in the exhaust system (see Figure 16). A measurement of O_2 in the exhaust is indicative of the A/F ratio. One O_2 sensor measures the A/F ratio at the inlet of the catalyst and the other measures the A/F ratio leaving the catalyst. Other monitored parameters that contribute to the control algorithm of the fuel control valve are load (kW) and engine intake manifold pressure (MAP).

As presented in Section 4.1.3, the catalytic converter element is embedded within the exhaust heat exchanger. The exhaust entering the catalyst at 100 kW is greater than 1100 °F. There is actually a temperature rise of 50 –100 °F across the catalyst, due to the heat generated by the chemical reactions occurring within it. Having the catalyst inside the exhaust heat exchanger allows this additional heat to be recovered, while preventing exposure of these excessive surface temperatures to the enclosed environment.

The primary safety of the emission control system is an exhaust system thermocouple that will initiate an engine shutdown when a catalyst outlet over-temperature is detected. This protects against a fault when the A/F ratio is maintained too rich. There is also a thermocouple on the inlet of the catalyst for diagnostics.

A schematic of the Emission Control System is presented in Figure 16.

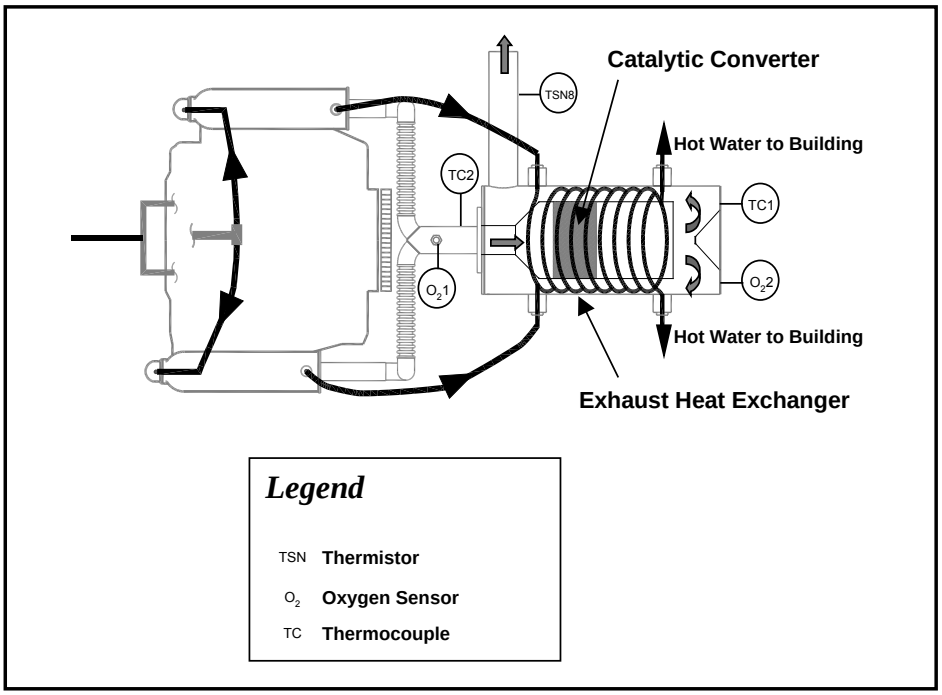


Figure 16. Emission Control System Schematic

Source: Tecogen, Inc.

4.1.5. Sound Attenuation and Ventilation

The engine/generator assembly is housed in an aluminum enclosure to provide an attractive, protective shelter for the module, as well as sound attenuation. The interior of this enclosure must be kept cool to prevent premature failure of the various components within it. Both the engine and generator are water-cooled, but other accessories such as the drive coupling, distributor, solenoid valves, and pump motors, require ventilation. The PCS enclosure also requires air ventilation, even though some of the components are water-cooled.

The ventilation system contains two 600 cubic feet per minute (cfm) ventilation fans for a total flow of 1200 cfm. These fans are located at the bottom rear of the enclosure (see Figure 13). They draw air through the enclosure via seven (7) grill openings and exhaust the air into the engine enclosure (see Figure 17). This air then cools the engine compartment before being exhausted out the rear hood. This ventilation air also provides combustion air for the engine.

Both ventilation fans are activated whenever the module is operating and they will continue to operate even after shutdown. A wall-mounted thermostat, within the engine enclosure, ensures that the space is cooled to below 115ºF before deactivating the fans.

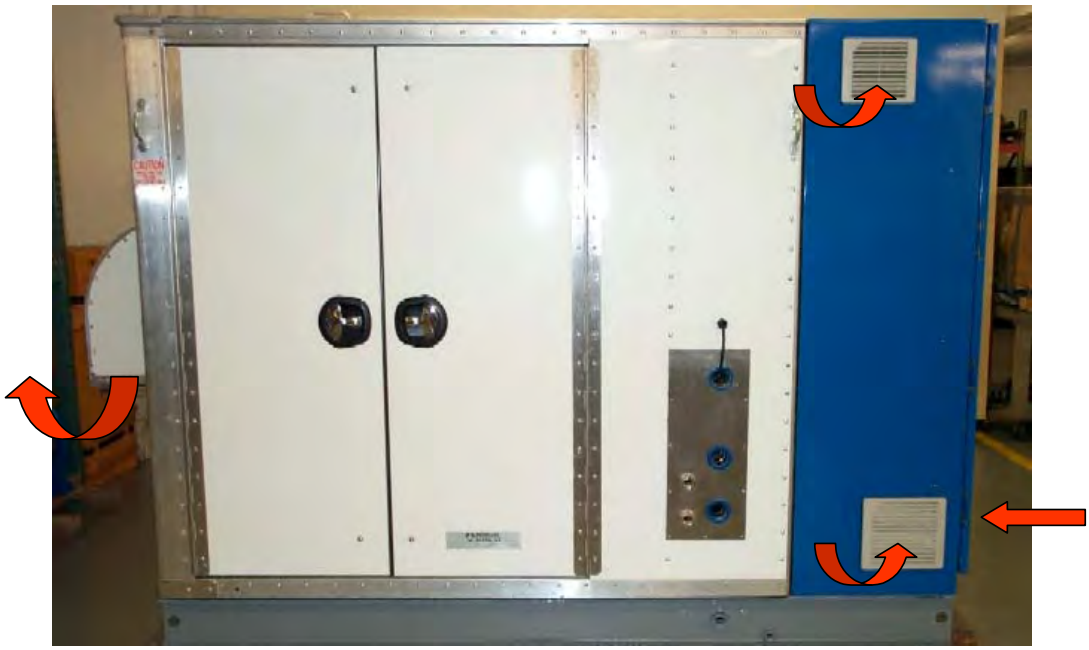


Figure 17. Engine Sound Attenuation Enclosure and Ventilation Flow.

Photo Credit: Tecogen, Inc.

4.2. Control System

The premium power module has a fully integrated microprocessor control system (*TecoNet*™) that provides master control over both the engine and the PCS. This system was directly derived from the Tecogen 75 kW cogeneration module. It is a customized microprocessor-

based control system with two primary printed circuit boards (PCB). The heart of the system, the microprocessor PCB, is identical to Tecogen's existing product. The interface board, which provides the input/output (I/O) link to the rest of the system, required modifications for application to the Premium Power unit.

The most significant adaptation for the control system was the interface with the PCS. This is done via a CAN bus communications link, which utilizes a standard industry protocol. The connection point for the CAN Bus was added to the interface board. A significant software development effort was required to integrate this communications protocol. It also took hundreds of hours of field operation to refine the intricacies of this interface, such as the timing of software handshakes and eliminating noise on the line. CAN bus communications issues proved to be one of the most problematic nuisance faults in the initial months of field operation. A highly methodical approach to diagnostics and troubleshooting, including trap software routines and laboratory simulations, was necessary to address these problems.

During normal CHP operation, the control system modulates the output of the Premium Power unit by regulating the flow of current to meet the power (or heat) setpoint, while continuously adjusting the engine speed to optimize efficiency. The PCS has its own control boards that regulate the power, the DC Boost, and microgrid operation (required for multiple units in standalone). The *TecoNet™* enables/disables the PCS and provides it a power setpoint when the system is grid-connected. The PCS relays all of the AC power related information back to the *TecoNet™* including the voltage, current, frequency, and power factor.

In addition to controlling the engine output and providing the setpoint for the PCS, the *TecoNet™* monitors safeties via various input switches, monitors temperatures, and controls devices such as fans, pumps, and solenoid valves. It can interface with a customer's building control system via various analog and digital inputs and outputs, Modbus communications (standard communications protocol) or remote monitoring and control system (RMCS).

The *TecoNet™* control system is housed within the electrical cabinet that also contains the PCS and its control boards. The customer interface with the control system is the operator terminal interface, a handheld terminal that is located on the outside of the PCS enclosure. The terminal allows the operator to move the terminal to an area more suitable for troubleshooting, service, etc.

Figure 18 depicts the system schematically in a block diagram format, segregating devices by their location.

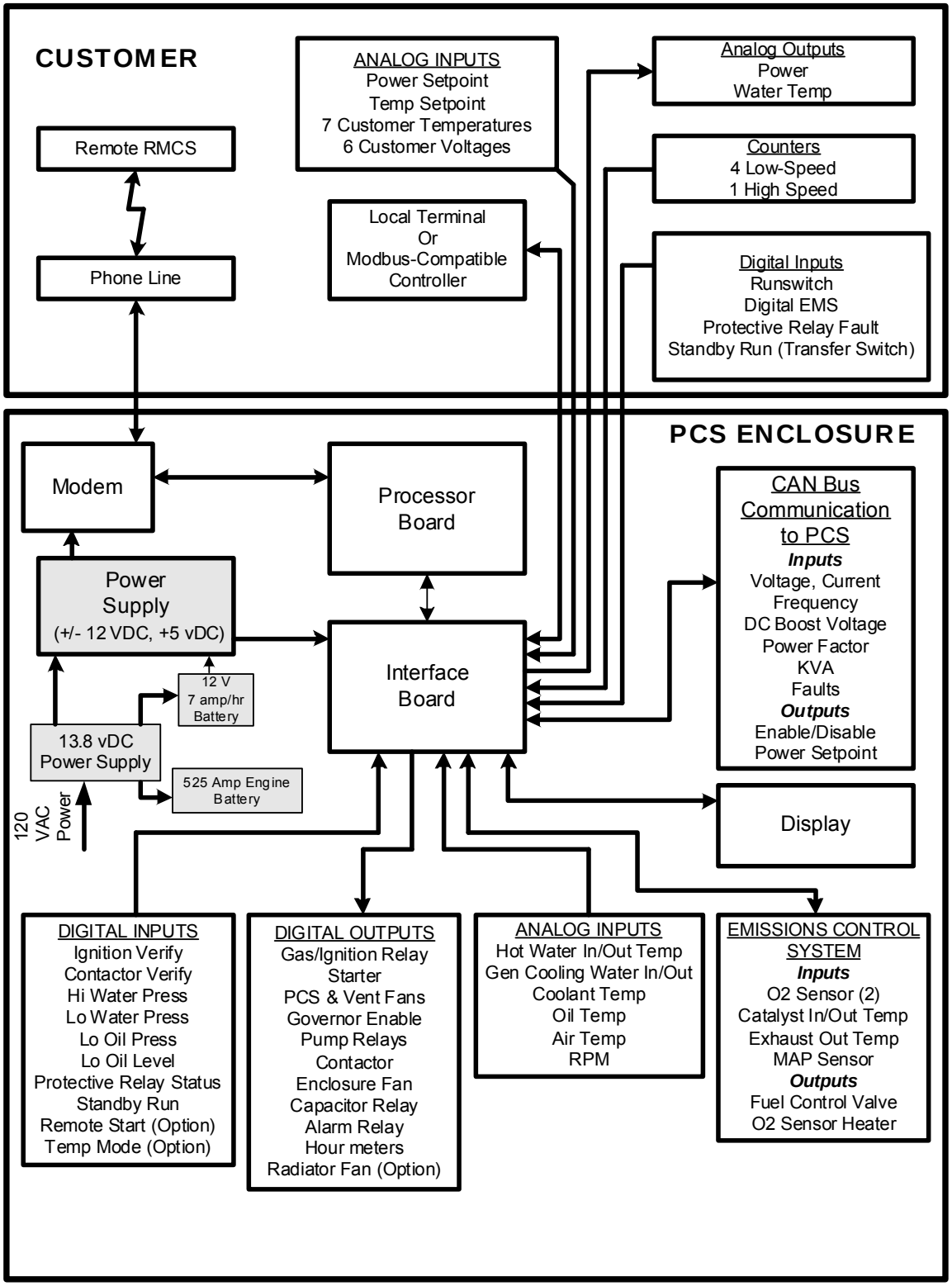


Figure 18 Control System Block Diagram

Source: Tecogen, Inc.

4.2.1. Modes of Operation

The control system has two distinct operating methodologies; grid-tie mode (GT) and standalone mode (SA).

Grid-Tie Operation

In GT, the output can be controlled either based upon a power setpoint, or heat load requirement. When controlling heat, a water return temperature setpoint provides the control limit. For example, if the heating load is only at 70% and the hot water returning to the unit exceeds 180°F, the CHP unit reduces its power output to where the heating load is satisfied. This avoids rejecting excess heat to a radiator, which can in some case defeat the favorable economics of cogeneration. These choices are site specific and based upon the economic optimization of the CHP unit. *TecoNet™* also has a scheduling feature for setting up a seven-day clock with 32 independent scheduling points per week.

Independent of the method chosen, the control system will determine a power output and a corresponding current requirement. It will communicate the current command to the inverter via the CAN bus interface. The PCS will operate as a current source with the voltage fixed by the grid. It will adjust the engine speed to increase or reduce current output as necessary to meet the power requirement.

The control system also offers various control schemes and functions that can be activated by the position of DIP switches. It also has a complete safety monitoring and shutdown system, including a redundant engine overspeed safety device as well as an emergency stop pushbutton on the outside of the control enclosure door. *TecoNet™* has a diagnostic mode (CALIBRATE Mode) that allows all output devices (i.e. pumps, solenoids, heaters, etc.) to be energized individually when the system is shutdown for the purpose of trouble-shooting.

Standalone Operation

In SA mode, when the utility power goes out, the *TecoNet™* control system becomes passive with respect to controlling power. It directs the engine to operate at a fixed speed of 3000 rpm. The PCS operates as a voltage source and supplies current to the building load as required. The control system reports the output on the display and continues to monitor safeties. The heat recovery may or may not be utilized. This will be site specific. However, all sites will have to have the radiator and radiator pump on the emergency power bus to ensure the engine heat is rejected.

4.2.2. CERTS Control Algorithm

As previously mentioned in Section 4.1.1, during the earlier stages of the program, Tecogen became involved with the CERTS Microgrid Test Bed program, also funded by the Energy Commission. CERTS, the Consortium for Electric Reliability Technology Solutions, was formed in 1999 to research, develop, and disseminate new methods, tools, and technologies to protect and enhance the reliability of the U.S. electric power system and efficiency of competitive

electricity markets.[8] The purpose of the CERTS microgrid laboratory test bed demonstration program, led by Lawrence Berkeley National Laboratories (LBNL), was to enhance the ease of integrating small generating sources into a microgrid. This included implementing a method of microgrid control that achieved voltage and frequency stability under islanded conditions without requiring high-speed communications or hierarchical control among power sources.[9]

Tecogen was commissioned as subcontractors to LBNL to provide the three distributed generation (DG) units required for the microgrid network. The criteria were that they had to be 60 kW, inverter-based, and had to have the capability to incorporate software algorithms developed by the University of Wisconsin. These control algorithms provided an effective solution to the issue of power control and load sharing of multiple CHP units in standalone operation. Up until this point, conventional technology required extensive external control components interconnecting the units and supervising the power distribution and synchronization. Using a method of frequency droop, these innovative algorithms ensured that each inverter could respond effectively to load changes without requiring data from other sources, while voltage sag and system imbalances could be corrected.[10] This proprietary control software is now incorporated to Tecogen under exclusive license from the Wisconsin Alumni Research Foundation (WARF).

The CERTS software ultimately propelled the Premium Power units into the large CHP market earlier than anticipated, by providing a cost effective approach to multiple unit power sharing in standalone operation. An alternative approach would have been the traditional external controls, which would have been costly and unreliable, posing a significant hurdle for the Premium Power unit in these applications. Field implementation of the CERTS software has been successful, not only at the AEP Test Bed, but it has also been successfully demonstrated at the NYSERDA field test sites, Madison Oneida Boces school and Jewish Home and Hospital (see Section 9.4).

4.3. PV Integration

Inverter technology is particularly amenable to integration with DC sources from renewables, such as photovoltaics (PV) and fuel cells. This is because the topography of power electronics includes the flow of DC power. In the Premium Power unit's PCS, this DC bus is after the rectifier (see #3 of Figure 2). This would be the interface point for variable voltage DC from an external source.

The Switch performed some initial development work in this PIER program on a breadboard control module to provide this interface. However, this system was later refined and packaged

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[8] CERTS website "www.certs.lbl.gov"

[9] CEC Final Report, Commission Contract No. 500-02-004. "CERTS Microgrid Laboratory Test Bed"

[10] Patent No. 7116010, "Control of Small Distributed Energy Resources", Robert H. Lasseter, Paolo Piagi, October 3, 2006

for the CERTS microgrid test bed demonstration. The CERTS program required external DC sources as a means to supplement the engine's output in the event of a step load in standalone operation. Although engines are well-suited to handle step-loads, the concern was that the transient response time would be excessive so as to impact the waveform quality. Consequently, a DC source or "surge module" was designed that consisted of batteries, power electronics, and controls, to provide the instantaneous power needed for a smooth transition.

In a PV integration application, external power is input on a continuous basis to offset the engine load. Although the purpose of the surge module was not quite analogous to PV integration, this development work and testing provided a solid foundation for interfacing the Premium Power PCS with DC sources.

Figure 19 illustrates an oscilloscope trace obtained during factory testing of the surge module at Tecogen.[11] This is a 30 - 55 kW step load. The oscilloscope data is formatted as follows:

<u>Channel 1 = Engine RPM (black)</u>;
120 Hz (3600 rpm) per 3.3 volts
1 volt per division
Zero point is at black "1" marker on left-hand side of Figure
Nominal Minimum Speed = 50 Hz (1500 rpm)

<u>Channel 2 = Bus Voltage (red)</u>
250 volts per division
Nominal Voltage; 860 volts

<u>Channel 3 = AC Current (green) ; 1 V = 100 amps</u>

<u>Channel 4 = Surge Module Current (blue)</u>
10 mV = 20 amps
10 mV per division
Nominal Current; 26 amps

<u>Timescale: 400 ms per division</u>

As shown, the introduction of current from the DC source (Channel 4-blue), with the engine operating (Channel 1-black), did not impact the quality of the output waveform (Channel 3-green). Although there was some adjustment being made on the DC bus (Channel 2-red) during the few seconds that this data is being captured, it did not affect the output voltage waveform. Therefore, not only could the DC input work harmoniously in parallel with the generator input power, any disturbances on the DC side of the inverter were effectively decoupled from the output waveform.

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[11] Energy Commission Final Report, Commission Contract No. 500-02-004. "CERTS Microgrid Laboratory Test Bed", Appendix D

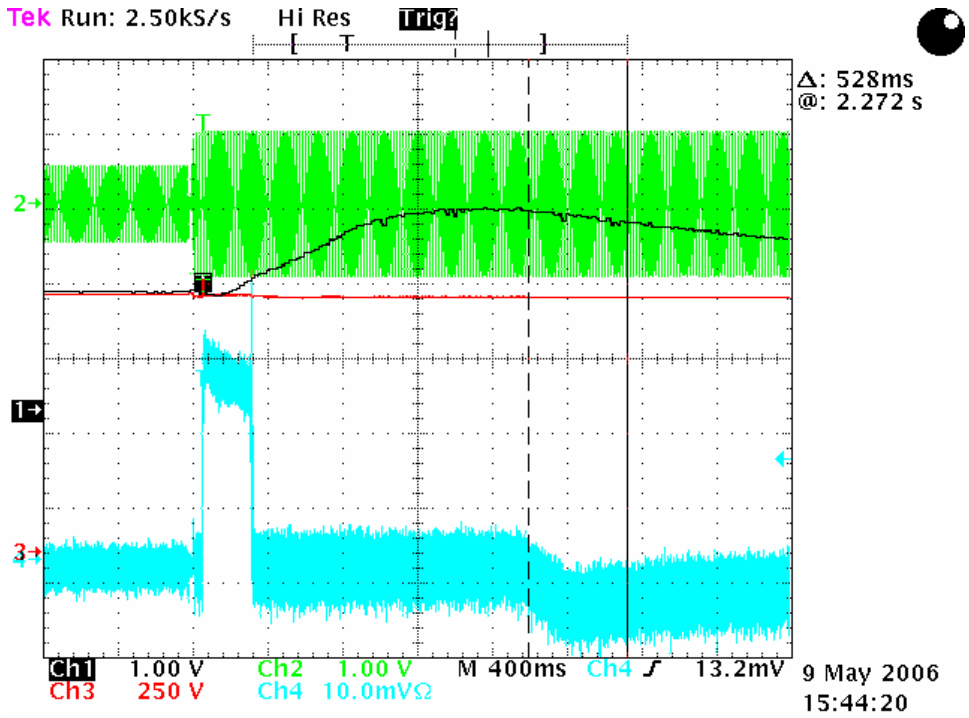


Figure 19. DC Source (Surge Module) Test Data

Source: Tecogen, Inc.

To summarize, the authors demonstrated that PV integration is technically viable with the premium power module. Further work is needed to investigate the specifications of actual PV technologies available in the market in order to narrow the requirements of the premium power module's interface hardware and software. Also, further study is required on the cost effectiveness of integration, and the market demand.

5.0 Laboratory Testing

The objectives of laboratory testing are listed below;

- Confirm the functionality of the unit in both grid connected and standalone operation.
- Confirm its power output.
- Confirm the thermal output.
- Measure efficiency.
- Measure emissions.
- Verify power quality.
- Measure sound.

Figure 20 is a schematic of the authors' test facility. There are four subsystem connections; natural gas supply, exhaust, hot water, and electrical. On the electrical output, the unit must operate both grid connected and standalone. A load bank is connected in parallel with the grid for the standalone testing. The thermal loads, both engine and PCS/generator, are rejected to radiators.

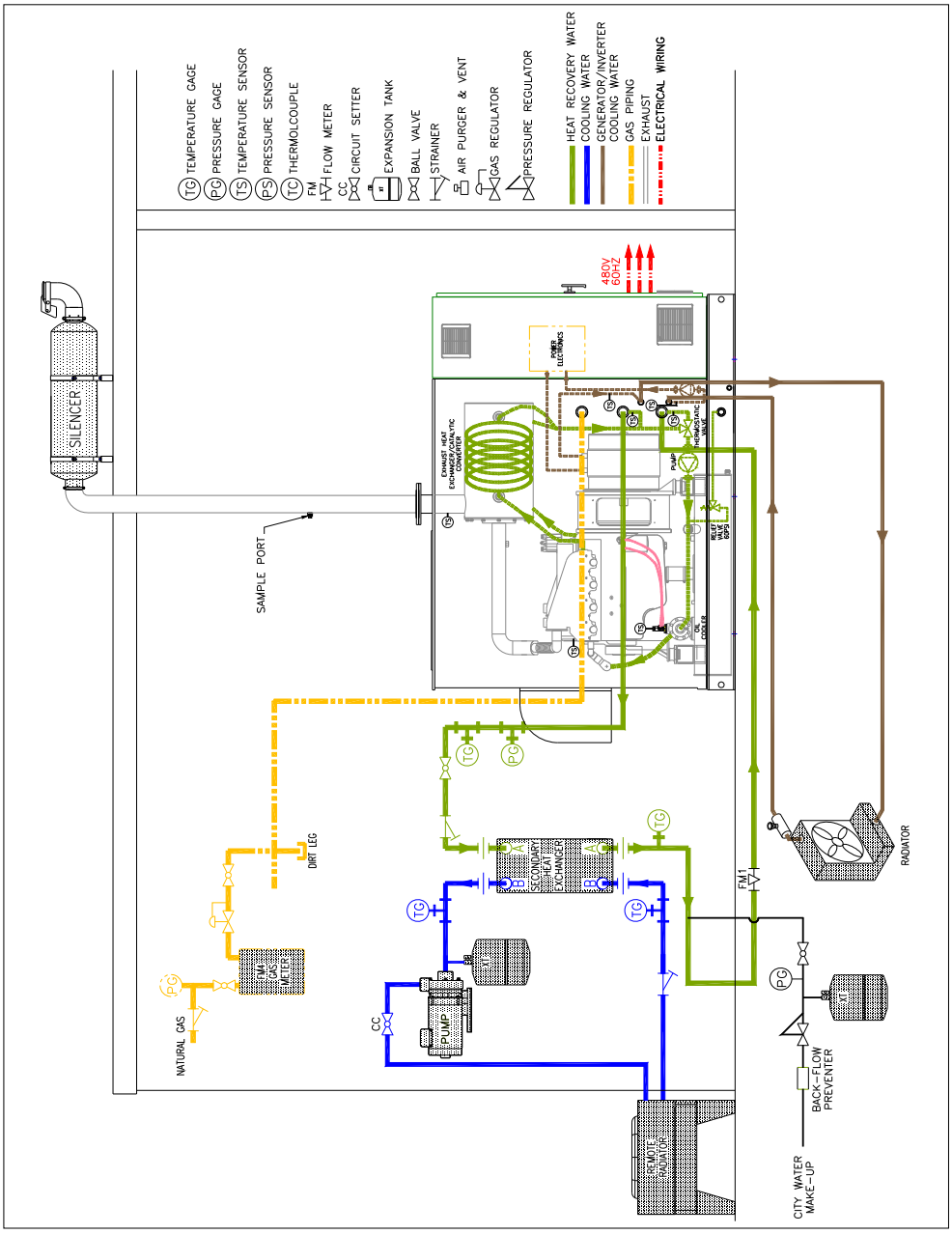


Figure 20. Test Facility Schematic

Source: Tecogen, Inc.

5.1. Functional Testing

The premium power unit was subject to a variety of functional tests to verify the sequence of operation, various control modes, and alarm safeties. It was also necessary to tune and verify

control subsystems such as the engine governor speed control and the emission's system air/fuel ratio control.

The sequence of operation is composed of seven control steps that are listed in Table 7. The same seven steps are present in both grid connected and standalone operation, but the timing and actual activity within the operating step differs.

Table 7 Operating Sequence

Number	Name
1	ENABLED or READY TO START
2	PREPARE TO CRANK
3	CRANK
4	WARMUP
5	RUN
6	SHUTDOWN
7	STOP

Source: Tecogen, Inc.

Also, the control methodology between grid-connected and standalone is not the same. Within grid-connected mode, the inverter controls the output based on a power setpoint or a water temperature setpoint. These setpoints can be input via the operator interface terminal or via an external signal. All of these functions were checked.

The transitions from grid-connected to standalone operation and back, as well as black-start, are all critical functions that were simulated in the laboratory. The unit automatically disconnects (contactor opens) when it detects the loss of grid power (i.e. IEEE 1547 compliance). An external signal is required (i.e. from a transfer switch or other device) to command the unit to go into standalone. Depending upon the timing of this signal, the engine may stay running and the unit can reconnect to the emergency loads very quickly, otherwise a full restart is required. The unit will transition back to grid-connected operation upon loss of the external standalone signal. In a black-start situation, the engine must run without a coolant pump for a short period. This timing was determined with these laboratory simulations.

In standalone operation, transient loads were tested using the load bank. Large step loads are typical on an emergency bus. It is important to ensure the engine can respond quickly enough to handle the change, since unlike grid connected operation; there is no supplemental power source. This testing involved proper tuning of the governor speed control module, as well as the fuel control system. Table 8 outlines the test matrix that was used and has since been incorporated into our factory test procedure.

Table 8. Step Load Test Matrix

Start Power (kW)	End Power (kW)
0	50
50	0
0	75
75	0
0	85
85	0
85	100
100	0
100	25
100	50
100	75

Source: Tecogen, Inc.

Alarm safeties were checked, both the limits and the trip time, under different types of conditions.

5.2. Performance

First and foremost, the premium power unit achieved the power output targets. The continuous power of 100 kW, and peaking power of 125 kW, matched the program goal. This validated the authors' modeling and selection of the engine, generator, and power electronics.

Electrical efficiency and system efficiency are the primary performance indicators. Electrical efficiency is the power output as a percentage of the gas power input. System efficiency takes credit for the thermal output, in addition to the power output. These calculations are as follows:

$$\text{CHP Electrical Efficiency} = \frac{\text{kW [PCS Out] x 3410}}{\text{Gas Input [Btu/hr]}}$$

$$\text{CHP System Efficiency} = \frac{[\text{ kW [PCS Out] x 3410] + Heat Output [Btu/hr]}}{\text{Gas Input [Btu/hr]}}$$

where,

kW [PCS Out] = Premium Power unit's electrical output

Gas Input = Natural gas flow to engine (Btu/hr @ higher heating value (HHV))

Heat Output = Heat Recovered from Engine Coolant System (Btu/hr @ HHV)

Figure 21 presents a graph of electrical efficiency vs. power output. The dashed curve represents the target performance from the authors' PIER proposal (12/12/2003). One line is the data from the first generation units while the other line presents the data for the second generation or commercial version of the unit.

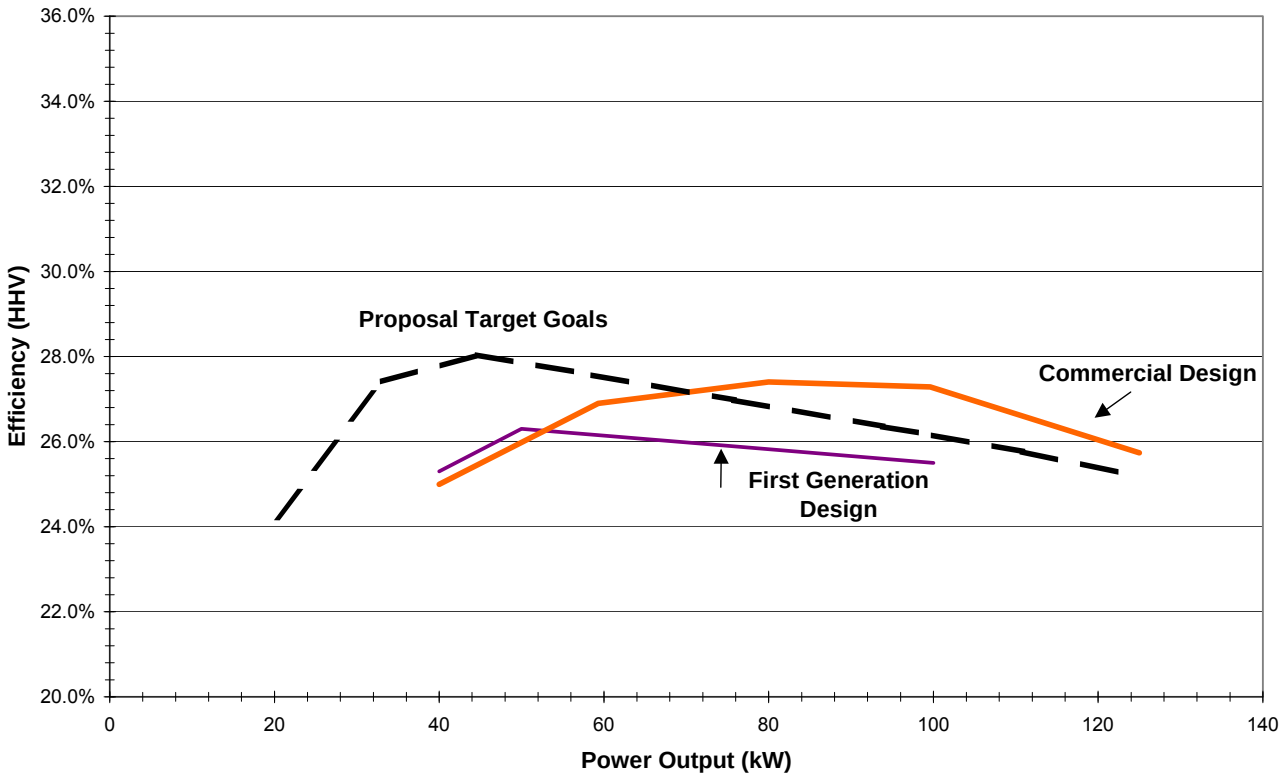


Figure 21 Electrical Efficiency vs. Power Output

Source: Tecogen, Inc.

The electrical efficiency of the Premium Power unit with the first generation PCS was close to matching the authors' projected efficiency at full load; however it fell short as the power output decreased. However, when the authors incorporated the second generation PCS design on the commercial units, there was significant improvement to the electrical efficiency. This is due to two factors. First, as mentioned in Section 3.1.3, the main power inductors and the boost inductors were upgraded to a more efficient design. This reduced the losses within the PCS. Secondly, the authors upgraded the cam on the engine to the model that is used on their CM-75 product. At the outset of the design, they decided to use the General Motors stock cam since it had sufficient power characteristics for the Premium Power product. However, the authors were not aware that their custom CM-75 cam would actually provide an efficiency benefit at 2500 rpm, since all of their operating experience with it was at the induction-machine based

speed of 1800 rpm. When the authors decided to test the custom cam on the second generation design, it proved to be a very beneficial upgrade.

Table 9 presents a summary of the efficiency data of the final commercial design of the premium power unit as compared to the targets the authors had outlined in their PIER proposal. Both electrical efficiency and system efficiency are calculated and compared to the proposal target goals. At the nominal rating of 100 kW, they have exceeded their target goal for electrical efficiency by 4.5% and have matched their system efficiency target.

Table 9. Premium Power Unit Performance Data

				Electrical Efficiency [%] @ HHV			System Efficiency [%] @HHV		
Power (kW)	Gas Flow [scfh]	Engine RPM	Heat Output [Btu/hr]	Actual	Proposal Target	% Deviation	Actual	Proposal Target	% Deviation
125	1625	2917	867,890	25.7%	N/A	N/A	78.1%	N/A	N/A
100	1221	2313	680,000	27.3%	26.1%	4.5%	81.9%	81.9%	0.0%
80	972	1903	557,800	27.5%	26.9%	2.2%	83.7%	79.0%	6.0%
59	737	1466	422,100	26.9%	27.6%	-2.5%	83.1%	76.6%	8.5%
40	531	1419	330,720	25.2%	27.8%	-9.2%	86.3%	71.2%	21.2%

Source: Tecogen, Inc.

The authors have not yet achieved their electrical efficiency goal at low-load operation, with performance well below their target (9.2%). The primary reason for this is the governor speed control algorithms. The authors have found that with the governor speed control tuned for optimization at full load, it becomes unstable at partial load near the wide open throttle position, which is the most efficient operating point. The authors plan to work with the governor manufacturer to determine it the controller can be custom-tuned to our application.

Nevertheless, the part load system efficiency actually exceeds the proposal targets. Since the engine is operating less efficiently than expected, the recoverable heat value has increased. Figure 22 is a graph of the heat recovery output versus load. It illustrates that the actual heat recovery at full load is less than proposed because the engine efficiency exceeds the predicted performance. Likewise, the opposite is true at the lower loads. Trading off efficiency for heat is not considered a beneficial swap since electrical kW, per unit of gas input, is more valuable than the hot water. Fortunately, most cogeneration applications typically do not operate at less than 60% load very often, but the authors will continue to take the necessary steps to improve this low load efficiency.

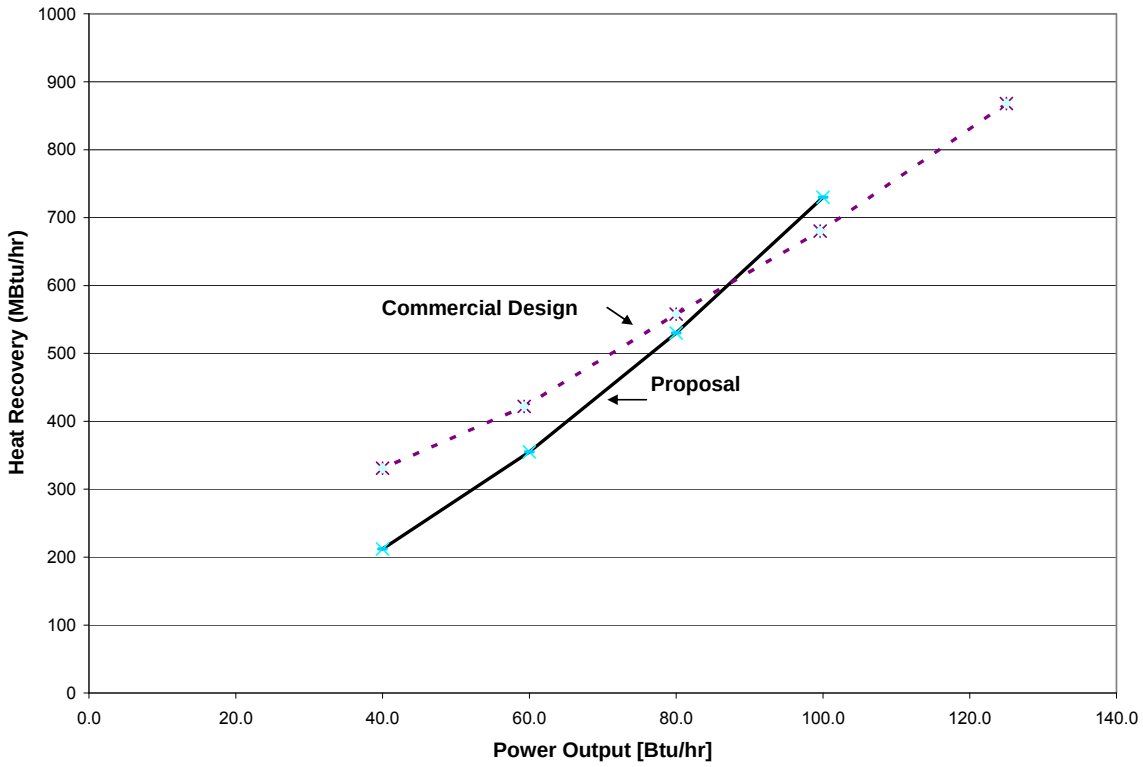


Figure 22. Heat Recovery Ouput Versus Load

Source: Tecogen, Inc.

5.3. Emissions

The program objective for emission compliance was to meet the requirements of the interim 2005 ARB standard, with a stretch goal of meeting the ARB 2007 standard. As presented in Section 4.1.4, the emission control system design includes the authors' custom air/fuel ratio control hardware, as well as proprietary software algorithms. The authors have incorporated a double O_2 sensor design, which has provided a higher level of feedback control for maintaining compliance over longer periods of service hours. Along with precision air/fuel ratio control, the authors have an after-treatment system of a catalytic converter embedded in the center of the exhaust heat recovery heat exchanger. With this system, the authors have been able to meet the target emission standards on the premium power unit. Moreover, the authors are currently involved in the Energy Commission-funded program to further develop their technology so that they may attain the stretch goal of compliance with ARB 2007.[12]

For their commercial production, the authors have instituted two levels of after-treatment; one that meets East Coast emissions standards (NY, NJ) or Level 1, and the other that meets the

[12] Engine CHP Emission Control Technology, DE Solutions, PNG-06-002.

more stringent California emissions or Level 2. The Level 1 system contains one catalyst element while the Level 2 system contains two catalyst elements. The Claremont Club field test unit was equipped with two elements. The results of the factory testing are presented in Table 10.

With clean catalytic converters and a new engine, the system easily met the permitting requirement. In fact, the factory test exhibited compliance with ARB 2007. However, this level of emission control is difficult to sustain in the field. In Section 6, the emissions test results of this unit, after thousands of hours of operation, will be presented. While the field test unit continues to meet the permitting requirements, as well as the ARB 2007 regulation for NOx, the system did not sustain the ARB 2007 emission level for CO. The authors expect their continued work on the Energy Commission emissions program will help attain their goal of sustainable compliance with ARB 2007.

Table 10 Field Test Unit Laboratory Emissions Measurement

	NOx		CO	
	ppmvd@ 15% O2	lb/Mw-hr (100% HR)	ppmvd@ 15% O2	lb/Mw-hr (100% HR)
Measured	**1**	**0.013**	**11.5**	**0.093**
CA Field Test Permit Limits	12	0.17	76	0.64
CARB 2007 (w/100% Heat Recovery)	5	0.07	12	0.1

Source: Tecogen, Inc.

5.4. Power Quality

The power quality of inverter-based equipment is inherently superior to machine-based equipment. This is because power electronics are microprocessor-controlled, so the switching frequency of the inverter can be optimized. Also, the inductive/capacitive (L/C) filtering circuit conditions the inverter output waveform to a nearly perfect sine wave shape. Consequently, the premium power unit controls to a power factor of 1.0 when grid connected, and the DC injection and total harmonic distortion meet the requirements of IEEE 1547[13].

The power quality testing for IEEE 1547, a subsection of UL 1741[14], requires the output harmonics and DC injection be measured on each phase individually at 100% load, 66% load and 33% load. Table 11 presents a sample of the data collected using a high precision power analyzer[15]. This data is for one of the three output phases, at the 100% load condition. The table

[13] IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems.

[14] UL 1741, Inverters, Converters, Controllers, and Interconnection System Equipment for Use with Distributed Energy Resources.

[15] Yokogawa WT-3000 Precision Power analyzer.

is divided in half, with the odd harmonic orders listed on the left hand side and the even harmonic orders listed on the right hand side. The rated power of the unit is listed in the first row as 150 amps. The column titled I(A) is the actual current measured for a given harmonic order. So, for example, the third order harmonic is 1.109 amps, which corresponds to a harmonic distortion frequency percentage (%hdf) of 0.739 %. Since this is below the maximum limit of 4.0%, this harmonic order "passes" the criteria of the standard.

This %hdf is calculated as follows:

$$\%hdf = \frac{\text{current harmonic}}{\text{Rated current}} = \frac{1.109}{150} = 0.739\%$$

As indicated in the P/F (Pass/Fail) column, the harmonic content was acceptable for each of the harmonic orders (2-40).

Also the DC current injection content is presented in the right hand side of the first row. The %hdf was measured at 0.251%, which was less than the 0.5 limit required by the standard.

This harmonic testing was performed in our laboratory, and was later witnessed by Intertek Testing Services[16] for the UL1741 certification (refer to Section 7.1)

[16] Intertek Testing services is the Nationally Recognized Testing Laboratory (NRTL) that performed the UL1741 certification on the Premium Power unit.

Table 11. Total Harmonic Distortion, 100% Load

Or.	I (A)	hdf(%)	Max. Limit	P/F	Or.	I (A)	hdf(%)	Max. Limit	P/F
	150.000				dc	0.377	0.251	0.5	PASS
1	145.117	96.745			2	1.010	0.673	1	PASS
3	1.109	0.739	4.00	PASS	4	0.175	0.117	1	PASS
5	0.976	0.651	4.00	PASS	6	0.683	0.455	1	PASS
7	0.932	0.621	4.00	PASS	8	0.339	0.226	1	PASS
9	0.282	0.188	4.00	PASS	10	0.150	0.100	1	PASS
11	0.294	0.196	2.00	PASS	12	0.508	0.339	0.5	PASS
13	0.584	0.389	2.00	PASS	14	0.238	0.159	0.5	PASS
15	1.050	0.700	2.00	PASS	16	0.186	0.402	0.5	PASS
17	0.352	0.235	1.50	PASS	18	0.144	0.096	0.375	PASS
19	0.280	0.187	1.50	PASS	20	0.179	0.119	0.375	PASS
21	0.404	0.269	1.50	PASS	22	0.102	0.068	0.375	PASS
23	0.130	0.087	0.60	PASS	24	0.089	0.059	0.15	PASS
25	0.080	0.053	0.60	PASS	26	0.052	0.035	0.15	PASS
27	0.208	0.139	0.60	PASS	28	0.069	0.046	0.15	PASS
29	0.228	0.152	0.60	PASS	30	0.099	0.066	0.15	PASS
31	0.154	0.103	0.60	PASS	32	0.053	0.035	0.15	PASS
33	0.151	0.101	0.60	PASS	34	0.041	0.027	0.15	PASS
35	0.090	0.060	0.30	PASS	36	0.045	0.030	0.075	PASS
37	0.046	0.031	0.30	PASS	38	0.043	0.029	0.075	PASS
39	0.041	0.027	0.30	PASS	40	0.039	0.026	0.075	PASS

Source: Tecogen, Inc.

5.5. Sound Measurements

Acoustical sound levels were an important design consideration because of the higher engine speed of the Premium Power unit. Our existing CHP unit, the CM-75, has a sound level rating of 70 dBa at 20 feet. However, the engine operates only at a maximum speed of 1820 rpm. Contrasting Tecogen's engine-driven chiller product, it has a maximum sound level emission of 88 dBa at 1 meter because of the 3600 rpm operation. Since the premium power unit operates at 2500 rpm at 100 kW, the goal was to achieve a sound level as close as possible to the existing CHP product.

The primary course of noise remediation involved designing an engine sound enclosure with adequate attenuation characteristics, including minimal penetations. Also, we learned that the power electronics emit higher frequency noise as well, but since they were already within a NEMA enclosure, no specific steps were taken to address this source of noise.

The measurements the authors obtained in their laboratory are presented in Table 12 at the continuous full load output of 100 kW and at 75 kW as well. Figure 23 illustrates each of the measurement points in a plan view. This data is raw and has not been corrected for adjacent walls.

The sound level reached a maximum of 77 dBa at 1 meter in front of the unit. From the authors' experience with various types of applications, as well as their firsthand knowledge with this product thus far, these sound emissions are acceptable. There is always the possibility that there can be site specific issues, such as mechanical room location or application sensitivity, that may require reduced sound levels. If that is the case, the authors can enhance the sound enclosure or make special provisions within the mechanical room to address the issue.

Table 12. Premium Power Unit Sound Levels

Measurement Point*	100 kW [dBa Range]	75 kW [dBa Range]
A	75.5 – 76.5	71.5 – 72.5
B	75.9 – 77	73.5 – 74.5
C	80 –82	75.7 – 76.8
D	77.4 – 78.2	75.4 - 76
E	79.5 – 80	78.2 – 79.6
F	73 –74	72.6 - 73.6

**Data has not been corrected for adjacent walls*

Source: Tecogen, Inc.

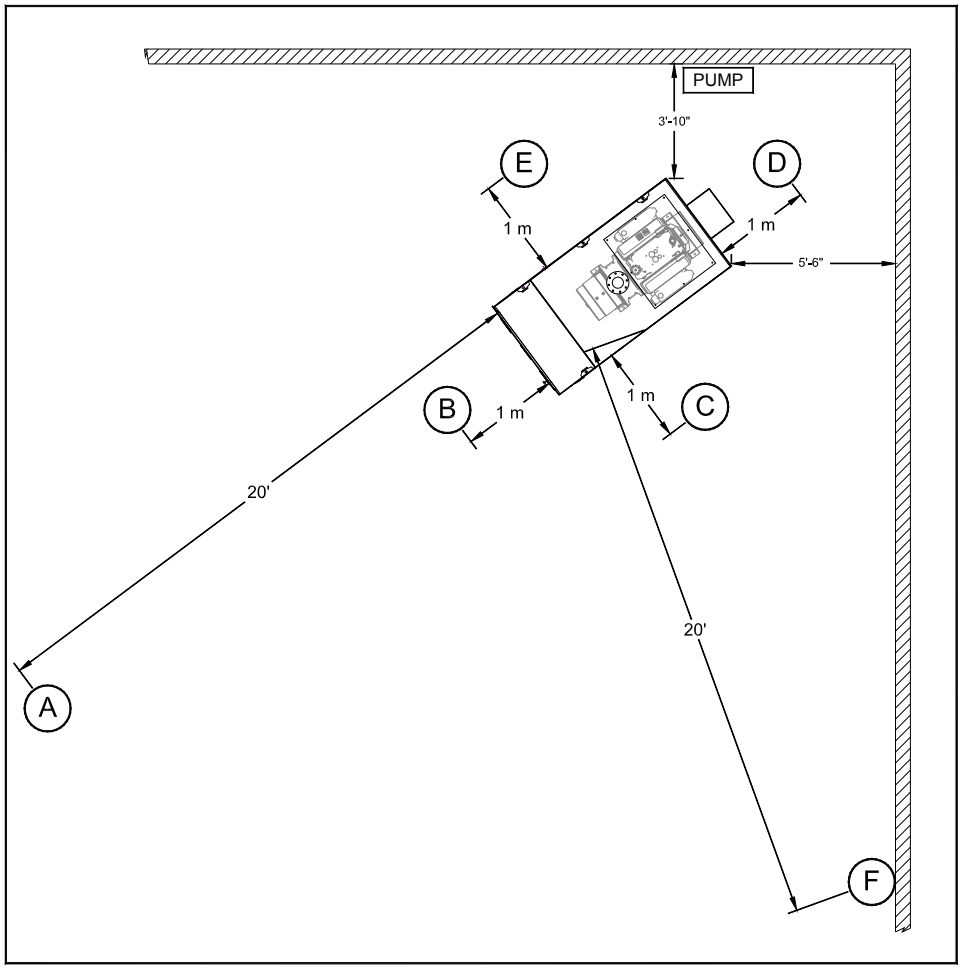


Figure 23. Sound Level Testing Measurement Points

Source: Tecogen, Inc.

6.0 Field Test Report

The California site selected for the premium power unit's 4000-hour field demonstration was the Claremont Club. It is one of Southern California's premier health, tennis, fitness, and aquatic facilities. Located on 19 acres, with two heated swimming pools, showers, and a spa, the club has a large demand for thermal energy making it an excellent prospect for CHP. Prior to the premium power unit, the site housed three Tecogen 60 kW units (CM-60). The three CM-60s did not have a dump radiator so the system operated in a thermal load following mode. Along with the addition of the premium power unit, the club added a dump radiator to enable operation of the units to economically dispatch during high-priced summer Electric Peak periods, when dumping some of the heat makes economic sense.

6.1. Site Description

The existing three 75 kW CHP units (CM-75s) were located in the facility heating equipment room. The heating fluid (water) flowed through the 3 engine jackets in parallel and then through respective exhaust heat recovery units (EHR) where they were joined together in a common header. The hot water from the engines then flowed through a heat exchanger (HX) linked to a 2,400 gallon thermal energy storage (TES) tank. The cooled engine water then returned to the 3 inlets to the engine blocks. The water in the TES tank was used for domestic hot water, pool heat and laundry. Water from the TES tank was distributed around the campus and connected to the various loads through ten heat exchangers. Supplemental heat was added, as required, via a distributed boiler network. There was no heat dump radiator so the system operated in a thermal load following mode, with engines throttled back to part-load or turned off to track the thermal demand.

The new 100 kW premium power unit, with integral EHR and a coolant pump, was co-located with the other CHP equipment and TES. The high temperature coolant loop (700,000 BTU/h at full load with a maximum water temperature of 230 °F) was connected to the TES loop through a dedicated heat exchanger in parallel with the original heat exchanger. All the engine coolant leaving the TES heat exchangers was joined together in a common return pipe. A three way valve was added between the TES heat exchanger and the engine return to divert some or all of the coolant return through a dump radiator to enable economic optimization during summer days when the heat load was lower, but the retail electricity price is highest. A secondary low temperature loop to cool the inverter and generator (30,000 BTU/h with a maximum return temperature of 129 °F) was connected directly to the pool heating equipment via a heat exchanger. The premium power unit was operated as the lead CHP unit and was dispatched first ahead of the older units.

A process flow diagram is shown in Figure 23 below. Pictures of system components at the Claremont Club follow in Figures 24 and 25.

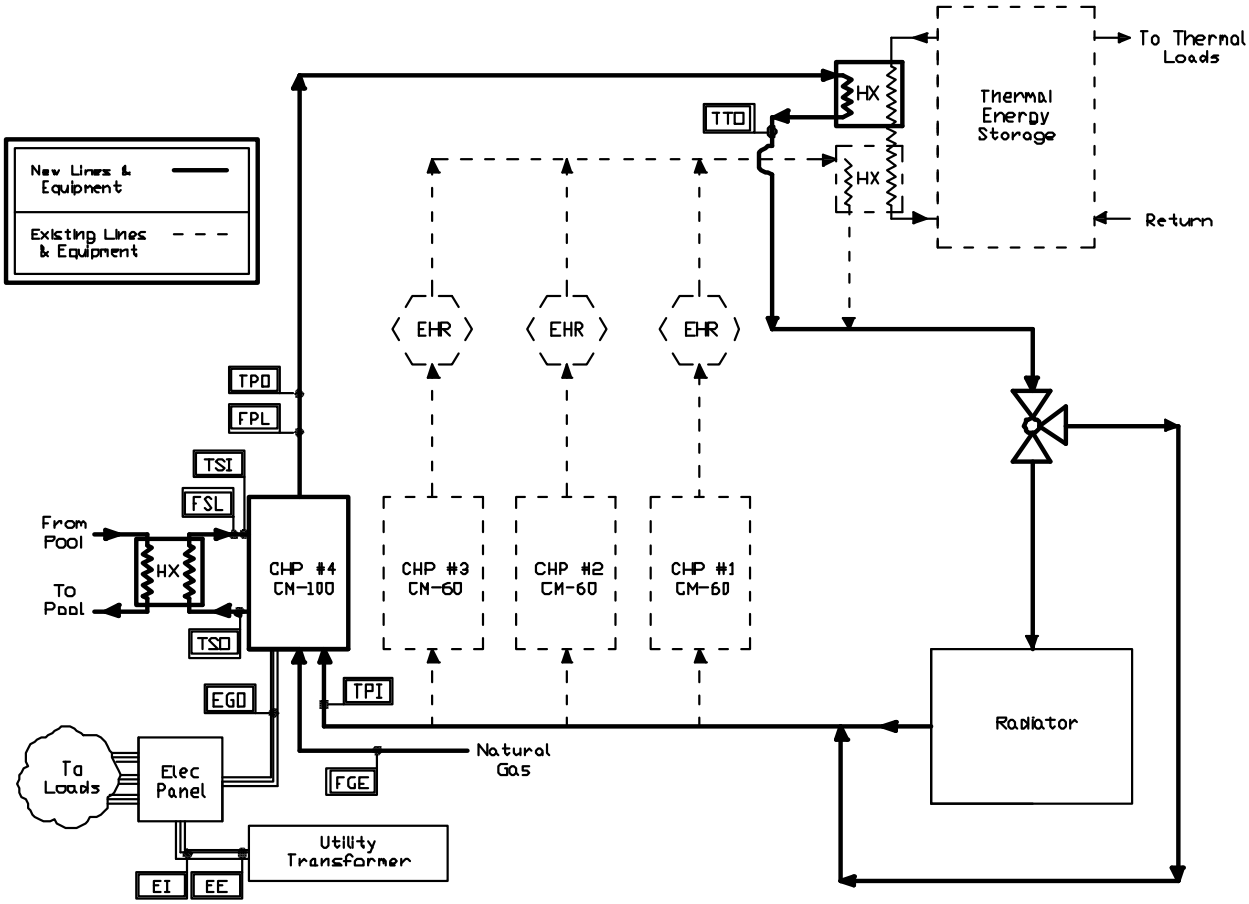
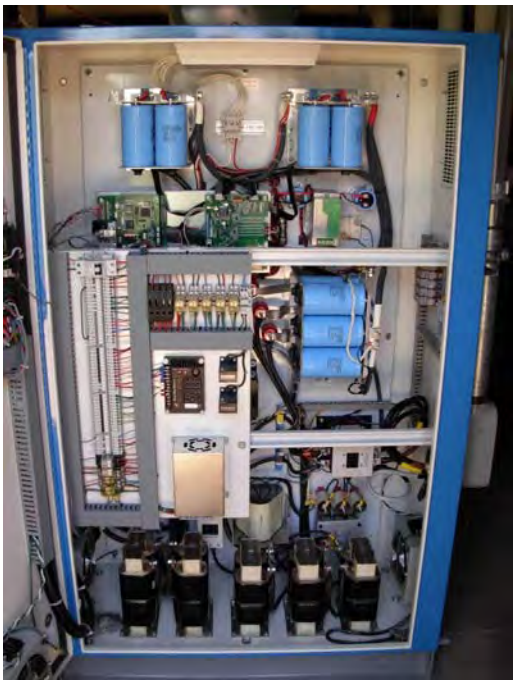


Figure 23. The Claremont Club Process Flow Diagram

Source: Tecogen, Inc.

CM-100 Unit at Claremont

Gas Meter on top of CM-100



Inverter, Controls, Breaker

Primary Loop Heat Exchanger

Figure 24. The Claremont Club Photographs (Part 1)

Photo Credit: Tecogen Inc.

Dump Radiator

Utility Interconnect and Meter

Primary Loop flow Meter

3-way Valve to Radiator

Figure 25. The Claremont Club Photographs (Part 2)

Source: Tecogen, Inc.

6.2. Monitoring System

Figure 23 also shows the location of monitored data points that were included to measure system performance. The data point name, or tag, corresponding to each sensor is shown as the text box on the schematic. The data points are described in Table 13. The type of sensor used to measure each point is also specified.

Table 13. Monitored Points for Claremont Club Field Test

Sensor Designation	Description	Eng Unit	Sensor type	Instrument
			Tecogen Microprocessor	Current-LEM HAC 400-S
EGO	CHP Unit Generator Output	kW, kWh	Current/Voltage Calculation	Voltage -Inverter Control Board
EI	Main UtilityMeter Import	kW, kWh	Pulse-output power transducer	
EE	Main UtilityMeter Export	kW, kWh	Pulse-output power transducer	
FGE	Engine Natural Gas Use	scf	Diaphragm Meter -Temperture Compensated	American Meter AL800-TC w/pulse transmitter output
FPL	Primary Loop Hot Water Flow	gpm	Turbine Flowmeter	Niagra MTX 421-1" w/ pulse transmitter output
FSL	Secondary Loop Hot Water Flow	gpm	Turbine Flowmeter	Niagra MTX 421-3/4" w/ pulse transmitter output
TPI	Primary Loop Inlet temperature	° F	Thermistor	Betatherm FSR 20910041
TPO	Primary Loop Outlet temperature	° F	Thermistor	Betatherm FSR 20910041
TSI	Secondary Loop Inlet temperature	° F	Thermistor	Betatherm FSR 20910041
TSO	Secondary Loop Outlet temperature	° F	Thermistor	Betatherm FSR 20910041
TTO	Primary Loop TES HX Outlet Temp.	° F	Thermistor	Betatherm 30K5D106
HO	Operating Hours	Hrs	Tecogen Microprocessor	Internal clock

Source: Tecogen, Inc.

The unit's RMCS scanned each point at 3 times per second intervals and recorded summed or averaged data for each 15-minute interval. Data was collected by modem once each day and uploaded into Tecogen's data base.

The electrical output of the Premium Power Unit (EGO sensor designation) was measured with the unit's own internal Current-Voltage calculation. The current was measured with current sensors and the voltage measurement was done by one of the PCS control boards.

The natural gas input to the engine (FGE sensor designation) was measured by a diaphragm gas meter (with temperature compensation) that provided pulse output proportional to the volume flow. The line pressure compensation was done manually. The heat content of the natural gas was obtained periodically from Southern California Gas Company. From these measurements the authors can calculated the engine efficiency and compared it to their expectations.

The thermal output from the Primary Loop used to heat the TES was determined from the flow and temperature difference (sensors designated as FPL, TPO, and TTO in Table 13). The authors also monitored the heat rejected to the dump radiator (sensors FPL, TPO, TTO and TPI) as well as the heat transferred from the secondary loop to the pool (sensors FSL, TSO and TSI). The total heat supplied to the campus thermal loads and dump radiator was summed and compared to the expected thermal output from the engine.

The electrical interconnection was set up for power export, however throughout the course of the field test demonstration, permission by Southern California Edison (SCE) to export power was never granted to the site.

A third-party emissions test was done at the time of commissioning (July 2008) for permitting purposes. Beginning in December, Tecogen employed the required South Coast Air Quality Management District (SCAQMD) Protocol for the Periodic monitoring of Nitrogen Oxides, Carbon Monoxide, and Oxygen From Stationary Engines Subject To SCAQMD District Rule

1110.2, which included weekly emissions measurements and strict instrument calibration requirements.

6.3. Test Results

The premium power unit successfully completed the 4000-hour field demonstration test in early February 2009. The unit accumulated 4342 hours from July 2008 through February 2009. During that time, it produced 375,800 kWh of electricity and approximately 1.3 million Btu of heat. Figures 26 and 27 illustrate the dispersion of daily run hours and kWh produced over the span of the test.

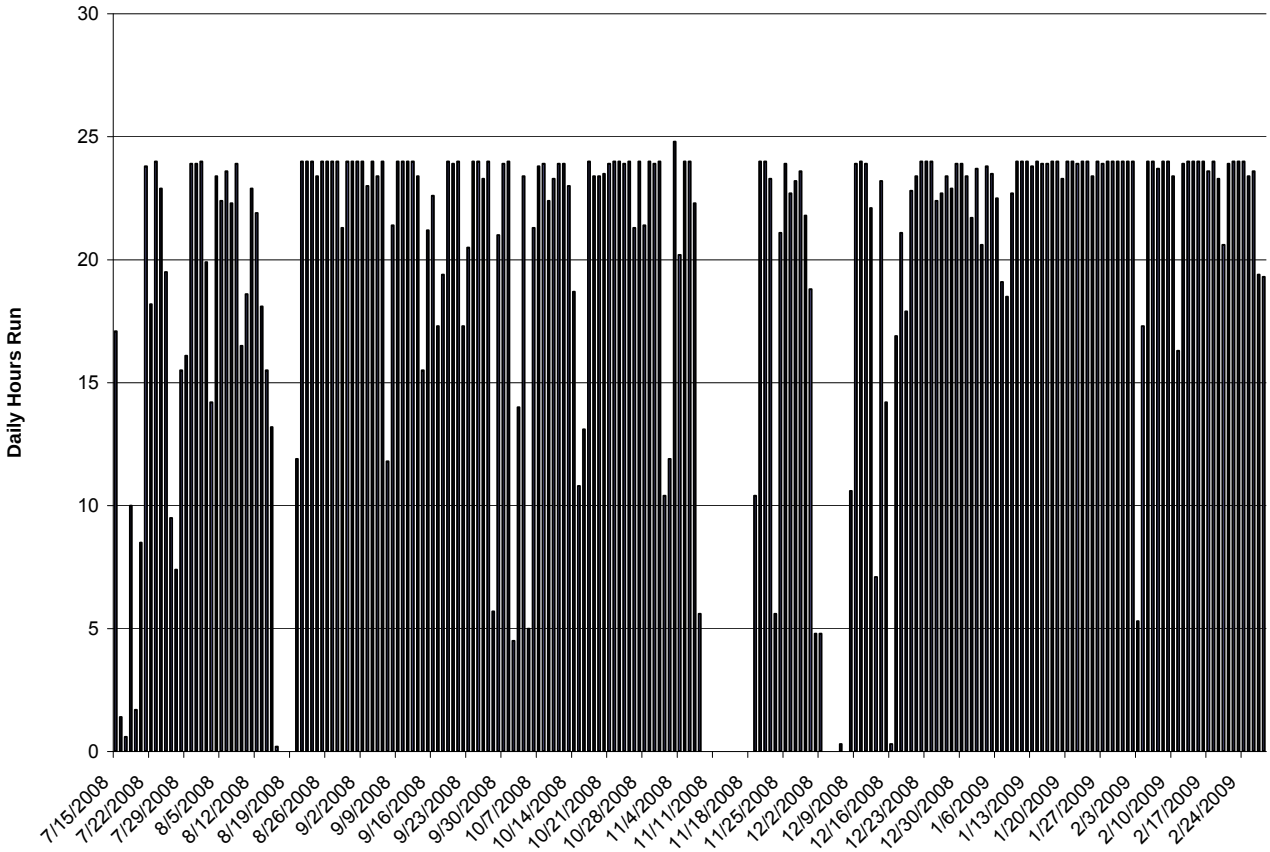


Figure 26. Field test unit daily run hours

Source: Tecogen, Inc.

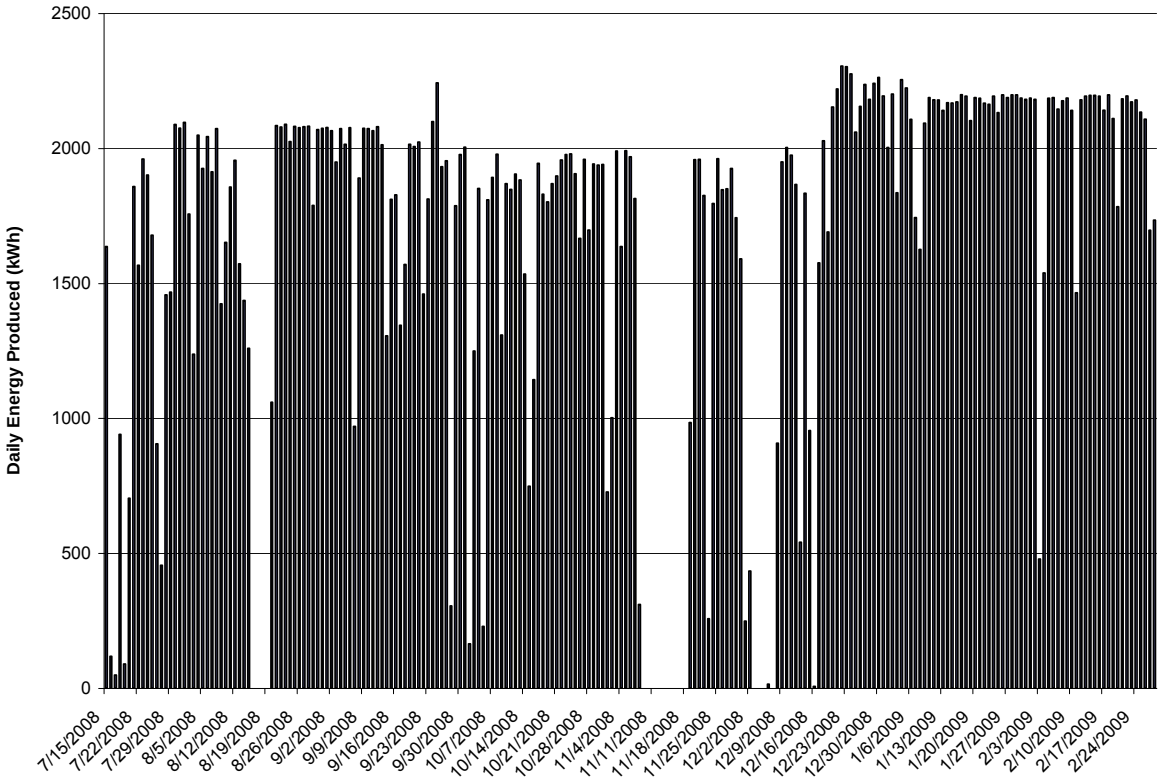


Figure 27. Field Test Unit Daily Electricity Produced

Source: Tecogen, Inc

The field test unit experienced nearly all of the reliability problems that were discovered in the first generation design (see Section 9.4.1); generator failures (both modes), power electronics module failure, boost capacitor failure, CAN bus faults, and board failures. For this reason, the availability of the unit was subpar at 76.4%, which is far below the average of the first generation fleet of 89% (see Section 9.1). Referring to Figure 28, there were a few particularly bad months that correlate to the two generator failures (July, November/December) and the Boost capacitor failure (July). In the months when the units ran well (August –October, January, February), the availability was still below the fleet average, mainly due to site heating loop problems.

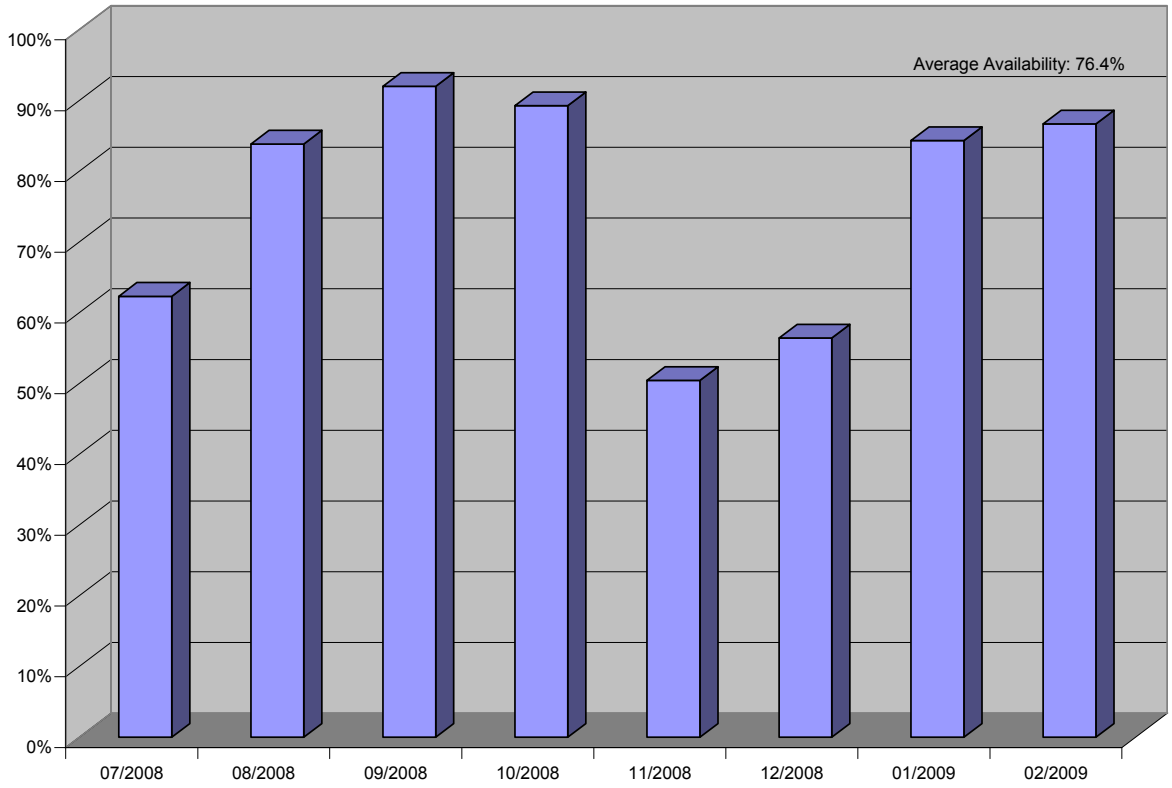


Figure 28 Field Test Unit Availability Per Month

Source: Tecogen, Inc.

The efficiency performance of the field test unit correlated well to the data the authors had taken in the laboratory for the first generation units. Figure 29 presents the electrical efficiency vs. power output. The top curve is the predicted efficiency in the proposal. The curve below it is the first generation design data, corrected for altitude[17]. The dots represent the more than 14,000 data points captured during the field test. The authors expected the performance to fall short of the proposal since the first generation design had some design limitations that were later corrected in the Second Generation design. As such, the data does correlate well with the first generation laboratory test data. The average error from the predicted value was –1.5%, with a standard deviation of 2.5%.

[17]The location of the Claremont Club is 1050 feet above sea level. Operating at a higher altitude requires the engine to run at a higher speed to produce the same kW due to the lower mass density of the air. This resulted in an efficiency penalty which we calculated to be approximately 2%.

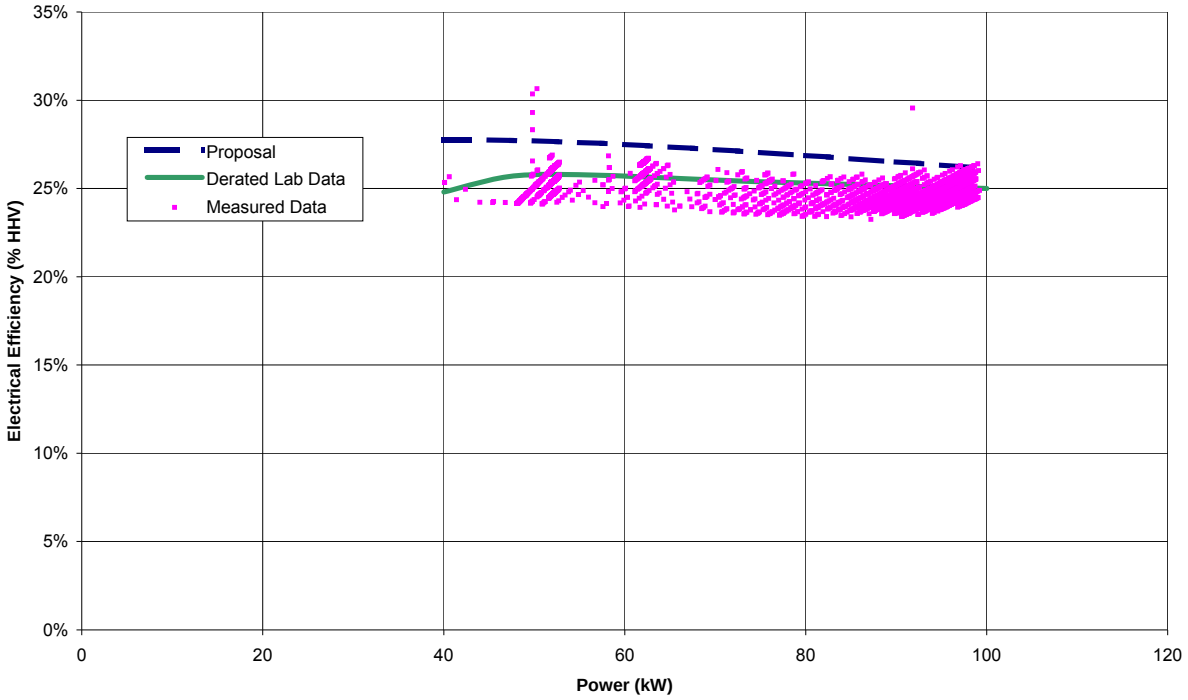


Figure 29. Field Test Unit Electrical Efficiency

Source: Tecogen, Inc.

The System Efficiency is presented in Figure 30. This includes only the heat recovered from the engine (see equation in Section 5.2). The data correlates well with the proposal with an average error of –2.7% and a standard deviation of –1.4%.

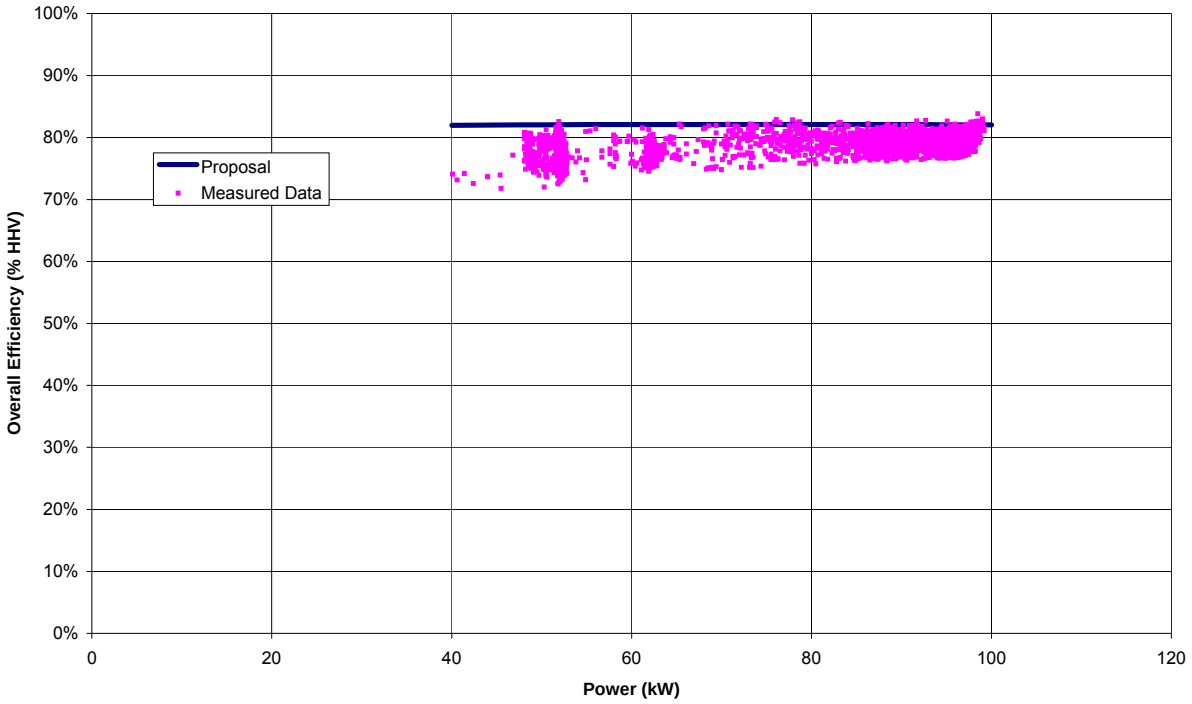


Figure 30. Field Test Unit System Efficiency

Source: Tecogen, Inc.

However, the Claremont Club also recovered the secondary heat from the power electronics and generator for heating the swimming pool. Although this was a lower grade heat (average temperature of 116 °F), it can contribute to the overall system efficiency for the unit. Figure 31 presents this data. This additional heat boosted the average overall efficiency at full load from 79.3% (@ Higher Heating Value) to 82.1%.

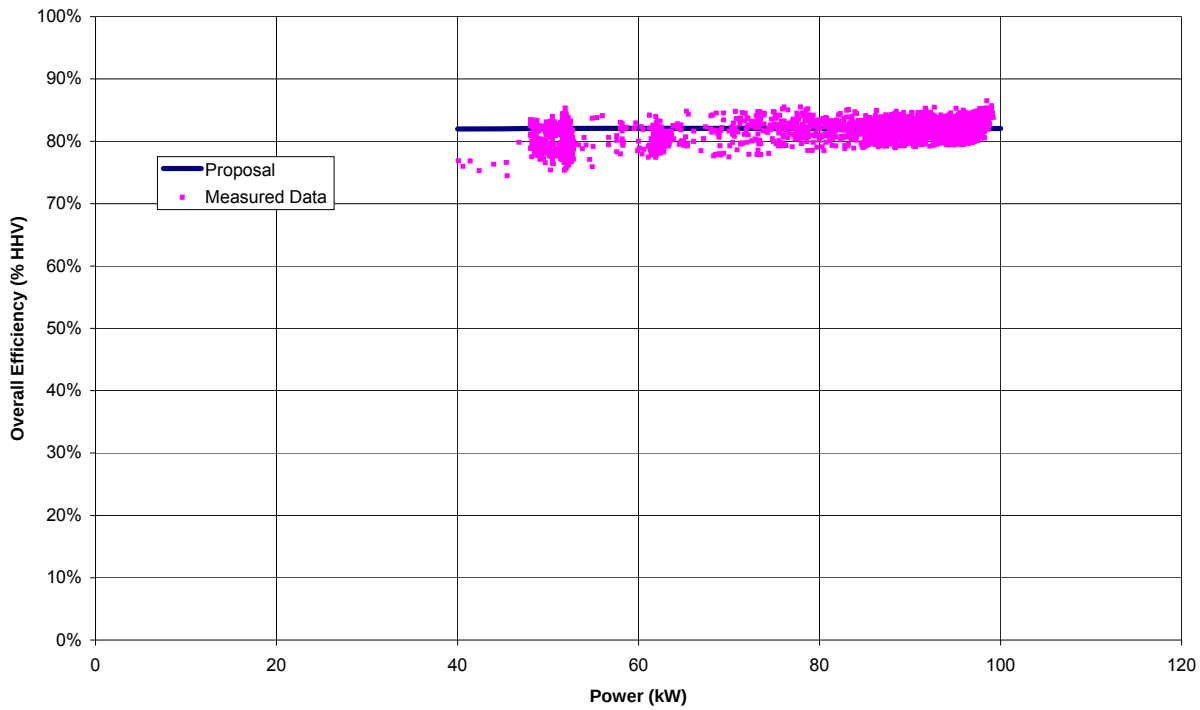


Figure 31. System Efficiency Including Secondary Heat.

Source: Tecogen, Inc.

The Claremont Club unit's energy management system followed the load, based upon electricity demand, rather than heat. As a result, the site rarely utilized all of the heat. Figure 32 presents the heat usage as a function of load, which illustrates that the heat from the main engine heat recovery system (not the pool) was often dumped to the radiator during this field test time period. Having the three other Tecogen CM-75 cogeneration units contributed to the excessive heat supply.

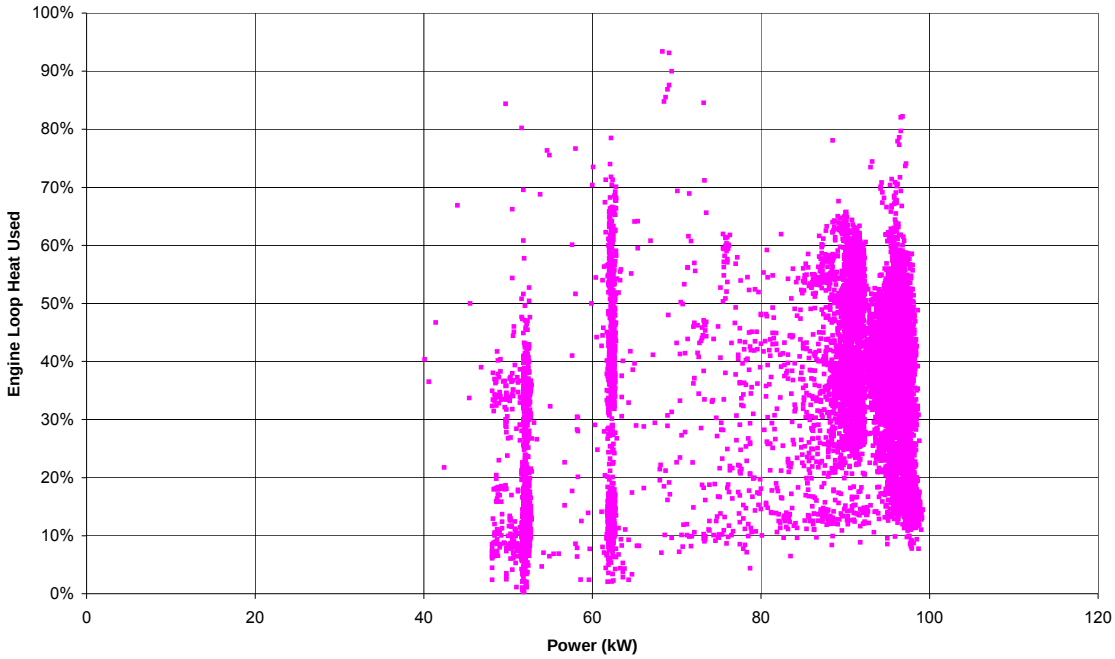


Figure 32. Utilization of Engine Heat Recovery

Source: Tecogen, Inc.

The engine emissions were measured by a third party when the unit was commissioned, in order to obtain the air permit. Later, Tecogen implemented its own self-monitoring program as required by the SCAQMD protocol (Rule 1110.2). The field test unit continued to meet the permitting requirements when checked regularly, as presented in Table 14

Table 14. Field Test Unit Engine Emission Checks

		NOx			CO		
Date	Load [kW]	Permit Limit ppm @ 15%	Measured [ppm]	Corrected ppm @ 15%	Permit Limit ppm @ 15%	Measured [ppm]	Corrected ppm @ 15%
12/17/2008	95.0	11	8.4	2.35	73	76.3	21.5
12/22/2008	96.1	11	3.6	0.99	73	20.4	5.71
1/5/2008	94.3	11	17.1	4.84	73	72.6	20.55
1/13/2008	90.0	11	14.5	4.06	73	124.02	35.12

Source: Tecogen, Inc.

Overall, the field test was a success, and the unit continues to operate today. This demonstration exposed the reliability issues, giving the authors the opportunity to resolve them prior to commercialization. The authors continue to monitor the unit, as it is under a maintenance contract. The authors plan to work with the site to better coordinate the energy management so that they may maximize the economic benefit.

7.0 UL Certification

One of the primary market barriers to CHP, specifically in California, but also in other parts of the country, was utility acceptance of the equipment for grid interconnection. One of the principal driving forces for developing an inverter-based unit was to simplify the interconnection process. Inverter technology is more widely accepted by utilities as being safe and friendlier to the grid because of superior power quality and the reduced fault current characteristics, as compared to machine-based (induction and synchronous) equipment. Therefore, obtaining agency approvals was critical to the commercialization process.

There are two national standards applicable to the premium power unit. First, UL 1741 is the interconnection standard titled Inverters, Converters, Controllers, and Interconnection System Equipment for Use with Distributed Energy Resources. This standard applies specifically to the functionality of the PCS as it relates to being grid connected (protection features, power quality, etc.), as well as the safe construction of the PCS. The second standard, UL 2200 Stationary Engine Generator Assemblies, is a product safety standard that certifies the construction and safe operation of the entire package, including the engine and generator, in addition to the PCS.

Individual states in the country have their own regulations for interconnection. However, most states have adopted UL 1741 as a minimum prerequisite for interconnection. This is the case in our two major markets of the New York and California, where both the NYSIR[18] and Rule 21 have this requirement. UL 1741 is also becoming mandatory in other states in the Northeast.

Since interconnection is the hurdle of highest priority, we determined that obtaining UL 1741 first, rather than UL 2200, was the appropriate strategy. Also, UL 1741 included a thorough review of the safe construction of the PCS, which is the entire electrical portion of the unit. Therefore, once UL 1741 was obtained, it would only be an incremental effort to gain UL 2200 certification on the entire package.

7.1. UL 1741

The UL 1741 interconnection standard also incorporates IEEE 1547, Standard for Interconnecting Distributed Resources with Electric Power Systems. It is within IEEE 1547 that the utility interactive testing and requirements reside. The remaining provisions of UL 1741 deal with abnormal conditions within the unit to ensure that it safely shuts down, or does not experience an explosion or fire.

In order to obtain certification, it is necessary to commission a third party NRTL or Nationally Recognized Testing Laboratories. An NRTL is an organization that has met the necessary qualifications, established by the Occupational Safety and Health Administration (OSHA), to

[18] NYSIR -New York Standard Interconnect Requirements

determine that products meet consensus-based standards of safety for use in the U.S. workplace.[19] Tecogen selected Intertek Testing Services, in Cortland NY, as the NRTL.

The certification process was divided into two major tasks. The first step was a thorough construction review. For this, a detailed bill of materials had to be prepared and submitted that included all of the safety-critical components and the specification of all of the electrical wire that was used. The list had to contain manufacturer specifications, electrical ratings, flammability ratings, and product certifications. Most components needed to already have a UL listing, otherwise the component required special review, additional testing, or replacement with an equivalent component that already had a UL File number. In addition to the materials list, a sample PCS had to be sent to Intertek's facility for a thorough review of the construction layout to ensure proper spacing, wire routing, etc. Type testing would not commence until the construction review was complete.

The second major task in the certification process was the type testing. The sample PCS unit from the construction review was tagged for the type testing. Table 15 presents the list of the type tests required. The list specifies whether the test is part of the IEEE 1547 subsection of the standard or in the main body of UL 1741.

The acid test for UL1741 certification is to be able to pass the critical test sequence mandated by IEEE 1547. This test sequence, as highlighted in Table 15, is as follows; response to abnormal voltage and frequency (RAVF), synchronization, protection from electromagnetic interference (EMI), surge withstand, and then a repeat of the first two sequences. This sequence is viewed as the most challenging of the type tests and if an equipment under test (EUT) cannot successfully complete it, there is no point in administering the remaining tests until the design can prevail.

[19] US Government website: www.osha.gov/dts/optca/nrtl.

Table 15. UL 1741 Type Testing Requirements

IEEE 1547 Standard *(Section 46 of UL 1741)*			
Required Test Sequence	**IEEE 1547**	**IEEE 1547.1 Test Procedures**	**Test Description**
1	5.1.1	5.2	Response to abnormal voltage
1	5.1.1	5.3	Response to abnormal frequency
2	5.1.2	5.4	Synchronization
3	5.1.3.1	5.5.1	Protection from EMI (IEEE C37.90.2)
3	5.1.3.2	5.5.2	Surge withstand (C62.45 and C62.41)
3	5.1.3.3	5.5.3	Paralleling Device
4		5.2	Response to abnormal voltage (Repeat)
4		5.3	Response to abnormal frequency (Repeat)
5		5.4	5.1.2 Synchronization (Repeat)
	5.1.4	5.7	Unintentional Islanding
	4.2.6	5.10	Reconnection to Area EPS
	5.1.5	5.6	Limitation of dc injection
	5.1.6	5.11	Harmonics
		5.9	Open Phase
		5.1.2.1	Operational Temperature
		5.1.2.2	Storage Temperature
UL1741 Standard			
	Section		**Test Description**
	43		Temperature
	44		Dielectric Voltage-Withstand Test
	45.2		Output Power Characteristics – Output
	47.3		Abnormal Tests – Short-circuit test
	47.5		Abnormal Tests – Ventilation Test
	47.6		Abnormal Tests – Component Short- and
	47.8		Utility Compatibility – Loss of Control Circuit
	48		Grounding Impedance Test
	57		Capacitor Voltage Determination Test

Source: Underwriters Laboratories.

The first test of the sequence, RAVF, is a test to demonstrate that the unit will cease to energize the grid, within the prescribed trip times, when the voltage and/or frequency are outside of acceptable limits. This ensures that the unit will not continue to run during an outage or disturbance, which could among other things, potentially injure a utility lineman.

In order to administer this test, it was necessary to obtain a very sophisticated instrument; a 3 phase power source with line disturbance simulation capability. With this instrument, these voltage and frequency disturbances could be precisely simulated and repeated easily. With nearly 200 test points required, this instrument proved to be invaluable. Also, the instrument is now utilized for production line testing for RAVF, a requirement of maintaining certification (see Section 9.1.1).

The PCS successfully fulfilled the provisions of the standard for RAVF. Table 16 presents the details of the test requirements as well as allowable adjustable set point ranges. It was also necessary to demonstrate that the operator interface could accommodate field adjustable setpoints to provide local utilities with flexibility.

Table 16. Abnormal Voltage/Frequency Trip Points and Adjustment

	Default Factory Settings (per IEEE 1547)				Adjustment Range			
	Criteria	Voltage Trip (AC L-N)	Frequency Trip (Hz)	Trip Time (seconds)	Setpoint		Trip Time (seconds)	
Nominal Voltage		L-N)			Minimum	Maximum	Minimum	Maximum
Fast Undervoltage Trip	V < 50%	139 V		0.16	124	206	0.1	0.5
Slow Undervoltage Trip	50% ≤ V < 88%	244 V		2	206	259	1	4.0
Fast Overvoltage Trip	V ≥ 120%	332 V		0.16	317	375	0.1	0.5
Slow Overvoltage Trip	110% < V <120%	305 V		1	290	347	0.5	4.0
Underfrequency	< 59.3 Hz		59.3	0.16	59.0	59.7	0.1	0.5
Underfrequency (adj. Setpoint)	< {59.8 - 57.0}		57.0	0.16	57.0	59.7	0.1	0.5
Overfrequency	> 60.5 Hz		60.5	0.16	60.3	61.0	0.1	0.5

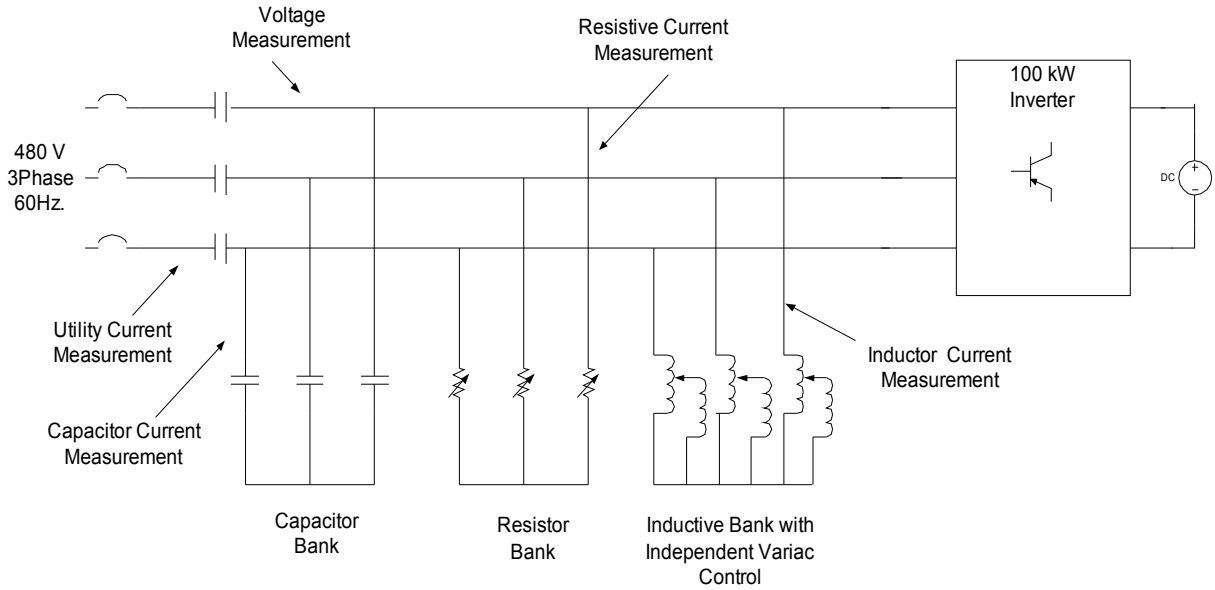
Source: Underwriters Laboratories.

The other taxing tests included in this sequence were the interconnect integrity tests, or protection from EMI and surge withstand. Protection from EMI is to ensure that the influence of EMI in the environment shall not result in a change of state or misoperation of the unit. This test had to be administered in a special chamber, so it was necessary to send the PCS to an Intertek facility equipped for EMI and surge testing. The PCS eventually passed this test after a few miscues. The authors needed to add some ferrite beads to some of the internal wiring to reduce the interference, and these were later incorporated into the standard BOM for the PCS.

After EMI, the most difficult test was the surge withstand. For this test, the input power circuit was subjected to a series of potentially damaging high voltage/high frequency oscillatory waves, simulating transient surges that are sometimes present on the grid. The PCS prevailed through this round of testing. Upon completion of the EMI and surge tests, the test for RAVF was repeated to ensure that the integrity of the firmware, as well as the hardware, was not compromised.

Once through the sequence, the next major hurdle was the anti-islanding test. This test is to ensure that the PCS does not form an "island" by unintentionally energizing a portion of the area EPS (Electric Power System) while that area is disconnected from the grid. The PCS must cease to energize within 2 seconds.

In order to administer this test, a very elaborate test circuit was constructed. Referring to Figure 33, this included a bank of resistance (R), a bank of capacitance (C), and a bank of varying inductance (L). This RLC circuit had to be tuned to the values indicated on the Figure 33 table for three separate power levels (100%, 66%, and 33%). The objective was to create an ideal load circuit, at each of these operating points, to prove that the PCS could, in fact, island. Then the anti-islanding algorithms were enabled to prove that the PCS would then cease to energize. These algorithms use deliberate perturbations of the voltage and frequency by the PCS software. If the utility grid is not present, then these perturbations will cause these parameters to exceed the abnormal voltage/frequency limits, and the PCS will cease to energize.



Power Level (kW)	"Q" Factor	Rnominal (Ohms)	Cnominal (ufarads)	Lnominal (mhenry's)	Line Voltage (Volts+/-1%)
33	1	6.98	380	18.52	480
66	1	3.49	760	9.26	480
100	1	2.30	1151	6.11	480

Note: Each power level requires eleven tests, one at nominal and then +/-1% variations to +/-5%
Note strict requirements on utility line voltage
Lnominal can be satisfied with single inductor and variac.
Resistors need to switched or reconnected
Capacitors need to be switched or reconnected

Figure 33. Anti-Islanding Test Circuit

Source: Tecogen, Inc.

Remaining tests included the harmonics and DC injection tests, which provide a measure of the power quality. Refer to Section 5.4 for further information on these tests.

Operational and storage temperature testing required that the PCS control boards be placed in an environmental chamber, at both the low and high temperature ratings, while still functioning to control the unit. The objective was to ensure that the control boards could safely cease to energize the PCS under various situations.

A temperature test was done where the unit ran at full power for several hours with several components outfitted with thermocouples. This was to confirm that these components did not exceed their listed temperature rating, and also to ensure there was no risk of fire or damage to safety-critical components. Immediately following the temperature test, a dielectric voltage-withstand test was done to check that there was no breakdown of wire insulation.

Abnormal testing required applying short-circuits and open-circuits to various safety-critical components, including those on the PCS's printed circuit boards. This was to ensure that even if the component failed, there was no risk of fire, electric shock, or injury to personnel.

This UL 1741 certification process covering the construction review, type testing, and listing report took nearly 10 months. The listing report was issued, and authorization to mark was granted in late December 2008. At that time, the authors were able to ship equipment that was officially labeled as UL 1741 compliant. An excerpt of the listing report can be found in Appendix A.

7.2. UL 2200 Compliance

UL 2200 - Stationary Engine Generator Assemblies is a product safety standard that certifies the construction and safe operation of the entire package, including the engine and generator, in addition to the PCS. Now that the UL 1741 certification is complete, the authors are proceeding with obtaining UL 2200. A significant portion of the UL 1741 work, such as the PCS construction review and some of the type testing, is directly transferable to UL 2200. The effort to complete UL 2200 will include a construction review of the engine, generator, exhaust system, natural gas system, combustion air system and enclosure. Also, a series of type tests will be required which are described in Table 17. The ones listed as "Not Required" are the tests that are transferable from UL 1741. The authors expect to complete this effort by the June of 2009.

7.3. Rule 21 and NYSIR

Once the authors obtained certification to UL 1741, they consulted the Energy Commission website for the latest procedure for inclusion on the list of "Equipment Certified to Meet California Rule 21 Testing Requirements" [20]. However, the authors found out that Rule 21

[20] http://www.energy.ca.gov/distgen/interconnection/certification.html

activities are transitioning over to the CPUC and there is not yet an application procedure for Rule 21 certification for conventional DG equipment. There is an established process for solar equipment with a new website (www.gosolarcalifornia.ca.gov/equipment/index.html), where about 400 certified solar inverters up to 330 kW in size are listed, but the authors are not aware of an analogous process, appropriate for their equipment. The authors will continue to pursue the availability of a Rule 21 Certification procedure with the CPUC.

Table 17. UL 2200 Type Test Requirement

Section	Test Name	Test Type			Description	Comment
		Operating Unit	Unit Deenergized	Coupon Sample		
38	Temperature Test	X			At full load, temperature measurements will be taken of contact surfaces, handles, electrical components, generator insulation, transformer insulation, inductor	
39	Dielectric Voltage-Withstand Test		X		A sinusoidal potential of 1000 plus twice rated voltage (1960 volts) will be applied to ac and dc power circuits for 1 minute between output current carrying parts and dead metal parts. Circuit boards and low voltage circuits are excluded.	
40	Harmonic Distortion Test	Not Required			Total rms of harmonic voltages shall not exceed 5% fo the fundamental rms output voltage rating.	Superceded by UL 1741-45.4
41	Output Voltage and Frequency Fluctuation Test	Not Required			Connected to a linear load with adjustable impedance, output voltage shall be within 90% to 110% of the nominal output voltage. Frequency shall be within 91 to 108%	Superceded by UL 1741-46.2
42	Blocked-Inlet Test	X			Air inlet is blocked at full load. Unit must shut down and show no evidence of fire risk.	
43	Backfire-Deflector Test	X			Backfire condition is induced in the engine, 10 - 20 times. No visible flame should be seen and the air filter/duct work shuld not continue to burn or smolder.	
44	Neutral to Ground Potential Measurement Test	X			Potential to ground is measured at 0 output current and full output current.	
45	10-Day Moist Ammonia - Air Stress Cracking Test			X	For brass parts exposed to fuel - FCV only	
48	Abnormal Tests				These tests should show no evidene of fire or risk of personal injury.	
48.2	Overspeed Test	X			Run engine at no load, WOT, overspeed safety disabled including governor, for 1 minute	
48.3	Output overload test	X			Operating at full power with load bank, increase AC load by 10% increments for 1/2 hour until unit shuts down. Measure generator temperature to ensure they do not exceed limits.	
48.4	AC output short circuit test	Not Required			Short circuit AC output L-L and L-N	Superceded by UL 1741-47.3
48.5	Component short- and open-circuit test	X			Components (Capacitors, diodes, etc) in input and output AC and DC power circuits are to be short or open-circuited during startup or operation.	
49	Overtemperature Protection	X			Protective device (SKIPPs?) subject to a current of 150%	
50	Grounding Impedance Test		X		Measure impedance of equipment ground (Not sure if this applies - for bonding conductors (i.e. rubber)	
51	Overcurrent Protection Caibration Test		X		Test fuses	
52	Strength of Terminal Insulating Base and Support Test		X		Test strength of output connection block or terminals+G18	
53	Mechanical Strength Tests for Mechanical Enclosures		X		Test strength of enclosure by applying forces with steel spheres	
54	Evaluation of Reduced spacings on Printed-Wiring Boards			X	Dielectric test and short-circuit test on printed-wiring boards	
55	Bonding Conductor Test			X	Short circuit test of bonding conductors	
56	Impact Tests			X	Impact test for guards over moving parts	
57	Heat Sink Temperature Cycling Test			X	Current carrying aluminum heat sink subject to temperature cycling test	
59	Bus Bar Tests			X	Samples of metallic materials are tested for corrosion resistance	

Source: Underwriters Laboratories, Inc.

8.0 Technology Transfer

8.1. Background

Tecogen has pioneered the development of reliable, clean, and efficient on-site cogeneration systems with integral heat recovery. Drawing upon two decades of real-world experience, comprising over 35 million hours of customer service, the company has made distributed DG an attractive option for reducing energy costs throughout the commercial, institutional and light industrial sectors.

Since first introduced in 1984, over 1800 of the company's Tecogen® and TECOCHILL® CHP units have been sold for applications that include hospitals, nursing care facilities, schools, hotels, health spas, food processing operations and light manufacturing industries. Tecogen natural gas engine powered systems yield overall energy efficiencies of 80 percent (HHV), and currently can be permitted in all California air districts except SCAQMD. Tecogen expects to offer SCAQMD capable products in 2010. In addition to packaged CHP equipment, the company also provides complete turnkey installations and long-term maintenance contracts through ten regional service centers.

For customers seeking to gain the economic benefits of CHP, without the need for a capital outlay, Tecogen's sister company, AmericanDG Inc., offers an on-site utility services option. Under this plan, the company installs, owns and operates the CHP equipment and sells electricity, heating and/or cooling services to end-users at a discount below prevailing utility rates.

CHP is expected to grow exponentially in response to increasing cost pressures experienced by energy users, and to escalating regulatory and policy initiatives at the federal, state, and local levels directed at efficiency and greenhouse gas mitigation. In order to capitalize on these swelling market drivers, Tecogen is forging closer relationship with electric utilities and has completed a technology path that transitioned us to inverter-based systems. This technology will reduce interconnection costs, provide backup power capability for the end users, and offer peaking capacity end-users as well as for utility demand-side response programs. The premium power unit, developed with support from the Energy Commission, is a key element of Tecogen's business strategy.

The system technology incorporates inverter and hybrid vehicle generator technology in a small (100 kW) package that provides grid independent operation, simpler grid interconnection, and peaking capability for utility demand side response programs.

8.2. Benefits

The premium power technology provides numerous benefits to the end user, the utility grid, and to society:

End User

- Energy cost savings will continue to be the primary motivator for CHP.
- Electric and thermal savings.
- Better part-load efficiency enables better thermal load following and higher overall efficiencies.
- Increased power availability becoming increasingly important.
- Shrinking reserve margins.
- Growing percentage of power quality sensitive loads.

Societal

- Air quality benefits relative to marginal dispatch capacity.
- Climate change mitigation.
- Fossil fuel conservation.
- Reduced need for transmission and distribution (T&D) expansion.

Grid

- Help shore up constrained T&D areas.
- Demand-side response capability.
- Interconnect friendly.

8.3. Target Markets

The market categories include traditional Tecogen markets and selected new market opportunities. The traditional CHP markets are those with long hours of operation, coincident electric and thermal loads, and in Tecogen's size reach (< 500 kW). Table 18 presents the primary traditional application sectors.

Table 18. Tecogen Markets

Commercial		Institutional	Industrial
Health Clubs	Ice Rinks	Colleges	Food Processing
Retail	Multi-Unit residential	Schools	Manufacturing
Hospitals	Nursing Homes	Military	
Hotels	Office	Municipal	

Source: Tecogen, Inc.

The cost attributes and enhanced functionality of the advanced CHP product would accelerate implementation in all the traditional markets. Those market segments valuing premium power would particularly welcome the new Tecogen product. These premium power segments include military, hospitals, nursing homes, and hotels.

It is expected that the premium power features will open new market segments up to small CHP. Included on this list are municipal waste, supermarkets, small data centers, and biotechnology laboratories.

The regional markets for the premium power technology will start in California, as well as in the Northeast states. High electric power prices and government support is key for good CHP economics.

The approximate total California market size for the proposed Tecogen product is 3,000 MW or 30,000 units, predominantly in commercial and institutional applications[21]. The magnitude of the Northeast opportunity is roughly the same size as the California market. Other states should ripen for CHP in the coming years including Illinois, Michigan and Ohio.

8.4. Commercial Deployment Challenges and Solutions

Although the benefits appear compelling and the potential market size is very large, the premium power product need to overcome barriers that plagued conventional CHP including utility resistance, marginal economics, and sluggish customer acceptance. Table 19 presents the important hurdles that had to be cleared with the new technology and the status of those efforts today.

[21] *Assessment of California CHP Market and Policy Options for Increased Penetration*, EPRI, Palo Alto, CA, California Energy Commission, Sacramento, CA: 2005.

Table 19. Technology Hurdles

Hurdle	Solution	Status
Utility resistance to Interconnection	UL 1741 Certification	Completed
Difficulty obtaining air quality permits	Attainable Emission Regulations Optional CARB Certification	Permit able everywhere in CA except SCAQMD. SCAQMD capable in 2010
Ability to operate in an outage	Demonstration of black-start feature in the field; utility acceptance and outreach to key markets	Demonstrated at multiple field locations with multiple units operating in parallel.
Improved part load performance	Demonstration of variable speed operation and controls in the field	Demonstrated operation in laboratory and on field test units. Governor control refinements are still require in order to meet goals.
Recognition of Demand Side Response value	Demonstration of Peaking capability and utility acceptance as DSR method	Demonstrated peaking capability in laboratory. Utility programs do not include generators at this time. They are mainly focused on load shedding.
Overall acceptance as customer and grid friendly	Utility support and market alliances	Microgrid project planned for 2009 at SMUD central plant

Source: Tecogen, Inc.

CHP in California is beginning to experience good momentum, and that momentum is expected to continue for CHP technologies that can keep pace with California's requirements for emissions. The benefits gained with the premium power technology will enable small CHP systems to see increased market activity and to participate in the improving climate for CHP in California.

8.5. Technology Transfer Activities

1. Technology Development - Technology development, system integration, and performance testing successfully validated the functionality and performance characteristics of the Premium Power unit.

2. UL Certification - The UL safety certification has been obtained through extensive testing by the Electrical Testing Laboratory (ETL) to the UL 1741 standard, "Standard for Inverters, Converters, and Controllers for Use in Independent Power Systems." The authors are in the process of obtaining compliance to the safety standard UL 2200, "Standard for Stationary Engine Generator Assemblies."

3. Rule 21 Certification and Utility Acceptance – The process for Rule 21 certification for non-solar DG equipment is currently undefined by the CPUC. However, in California thus far, SCE has accepted the certification merits and it has not been an impediment to

interconnection (Note: The authors have obtained interconnection approval at both the Claremont Club in Claremont, California and the Rancho San Antonio Boys Home in Chatsworth, California). Similar reactions are anticipated by the other investor owned utilities (IOU) and municipal utilities.

4. Field Test – The Claremont Club field test site, augmented with demonstration sites in New York, has confirmed the functionality range of the design in target applications in conjunction with motivated customers and cooperative utilities.

5. Emission Performance - The product can currently be sited in all 28 California air districts except SCAQMD. The Premium Power product qualified for SGIP in 2006 by achieving 0.14 lb/MW-hr NOx and in 2007 by achieving 0.07 lb/MWh with heat recovery credit. Tecogen expects to meet SCAQMD and ARB 2007 requirements in 2010, the culmination of a technology development program

6. Demand Side Response Value - The peak-shaving feature has been demonstrated in our test laboratory. Utility recognition of the demand response capability of the unit has yet to be sanctioned in a demand response program.

7. Utility Alliances – Tecogen is seeking to forge alliances with California utilities around the Premium Power unit, a very utility friendly CHP technology. The nature of the alliances will vary by utility but can include simplified interconnection, joint marketing, ownership, availability of DSR payments, customer services, etc. A microgrid demonstration project is planned at SMUD Headquarters central utility plant.

8. Market Outreach – The end use market sectors identified previously, have been targeted for education on Tecogen's Premium Power unit. This is being accomplished through presentations and exhibits at sector specific meetings, customer-oriented energy conferences, and select mailings. There have also been several articles written in trade publications. Also, Tecogen's sister company, American DG, is making a utility services offering for customers not wanting to invest their own capital.

   Table 20 presents a summary of Tecogen's market outreach activities within the past year. Appendix B includes a sample presentation.

Table 20. Tecogen Market Outreach

Date	Group/Organization	Organization Type	Outreach Type
Nov-06	IEEE Conference, Orlando FL	Technical Professional Association	Technical Paper: "Design and Testing of an Inverter-Based Combined Heat and Power Module for Special Application in a Microgrid", Robert A. Panora, Joseph B. Gehret, Dr. Paolo Piagi
Nov-07	Distributed Energy Magazine	Trade Publication	Article: "Dream Machine"
Dec-07	Power Gen	Trade Show	Presentation
Jan-08	ASHRAE Show, NYC	Trade Show	Booth
Jan-08	ConEd, New York	Electric Utility	Visit/Presentation
Jan-08	Keyspan	Gas Utility	Visit/Presentation
Feb-08	Energy Solutions Center	Energy technology development organization	Visit/Presentation
May-08	Distributed Energy Magazine	Trade Publication	Article: "Microgrids Up and Running"
Jun-08	Hydrochem, Poland	Manufacturer Representative	Presentation
Jun-08	Energy Concepts, NYC	Specifying Engineering Community	Presentation
Jul-08	Madison Oneida/NYSERDA Ribbon Cutting Ceremony	End User/State Energy Authority	Presentation of Equipment
Sep-08	New England Hotel Magazine	Trade Publication	Article: "Combined Heat and Power Equal Big Savings"
Sep-08	Norian Siani	Specifying Engineering Community	Presentation
Oct-08	Distributed Energy Magazine	Trade Publication	Article: "A "Mature" Market"
Dec-08	National Grid	Electric Utility	Presentation/Training

Source: Tecogen, Inc.

9. Sales and Marketing –Sales and marketing literature has been prepared and a product name "InVerde" and logo has been created. Tecogen has trained and mobilized its existing sales, distribution and support network to launch this product into the California market. Also, an innovative trade show booth display design is currently being created with the assistance of a marketing consulting firm.

   Appendix C presents two pieces of sales literature; the InVerde 100 Specification Sheet and the InVerde 100 Product Overview.

10. Installation and Operations Manual - An installation manual has been prepared which details all the information an engineer needs to design the CHP unit into both the building's electrical and thermal systems. An operating manual on the InVerde unit, including general theory of operation, detailed customer interface specifications, service information, and troubleshooting information has also been created. This manual provides all the information the end user will need to operate the unit. These manuals and other product information are being disseminated to key players in the CHP market to ensure that they are informed of the capabilities of the new machine.

11. Product Launch – The initial product launch has taken place in familiar Tecogen market segments, California and the Northeast, with seasoned service teams.

12. PV Integration - Tecogen plans to initiate a dialogue with PV system developers to increase the awareness of technical and economic synergies between CHP and PV technology.

9.0 Commercialization

9.1. Production Readiness Plan

As discussed in preceding sections of this report, the premium power unit has successfully made the transition from R&D to commercialization, with a brand name of "Inverde` INV-100". The compelling nature of the product caused Tecogen management to accelerate production implementation in parallel with the field test design effort. As such, the authors will present the plan below in conjunction with relevant updates as to their progress in that area. The authors current production rate is approximately one unit per week that could be accelerated 4-5 fold in their current facility if required.

9.1.1. Standard Production Model

The INV-100, 100 kW module will follow Tecogen's standard production approach that has evolved from the authors' approximately twenty five-year experience in small-prepackaged CHP module manufacturing. The basic elements of Tecogen's manufacturing capability and approach are outlined below:

1. Production Facility - The authors' current 25,000-ft^2 facility will be used for manufacturing the module. As configured for the researchers' standard production, it has separate areas for welding, testing, general assembly, and panel wiring. Approximately 30% of the area is under a moveable crane with a 20,000 pound capacity. This area includes the test area. The facility includes all other Tecogen departments, notably engineering/quality control, sales, accounting, shipping/receiving, and management.

2. Engineering Design -Tecogen design drawings are prepared with AutoCAD software and numbered using a company-specific system. Drawings are generally two-dimensional and may be specific to a single part, group of parts, or manufacturing process. In general drawing numbers match part numbers if the drawing is of a single part. Drawing revisions are made under a company-specific engineering change order (ECO) system, which requires serial approvals.

3. Engineering Bill of Materials - Highly detailed parts lists are developed for each product that utilizes a company master parts list system. Each product has an individual part number that is a subset of the master list. The product parts list or bill of material (BOM) will generally include subassemblies that are further subsets of the product BOM. New products typically have BOM's that are broken down according to function (fuel system, electrical system, etc,). However, this type of categorization will be replaced by subsets that reflect the shop floor process as the manufacturing processes evolve.

4. Part Information - Each part is described in the company manufacturing resource planning (MRP) software program to include its procurement source, drawing number (with revision), procurement cycle lead time, warehouse location, safety stocking level, and special personnel safety requirements.

5. Procurement - Product procurement is completed using the MRP system, Fishbowl Inventory®, a commercially available software package. Product materials are generally ordered upon receipt of written equipment orders with an automated feature of Fishbowl that compares current inventory levels to the order requirements and generates the PO's for each vendor. Some materials will not require order at this time, as they may have a reserve stock in the warehouse or they may involve expensive pre-purchased components that have been ordered as part of a "blanket order." These types of items are generally items custom made for Tecogen that require the blanket order because of the long lead time or because the vendor requires a special commitment in order to meet Tecogen's price requirements.

6. Quality Control - All Tecogen CHP modules undergo a lengthy, detailed quality control process that culminates with a full-load operational test (see detailed discussion below). Each machine is serialized to a single number that is part of a large number block for that model. As the machine is fabricated, various portions of the assembly are signed-off by the lead manufacturing technician as they are completed. The document that contains all of the steps in the process is the manufacturing "traveler." The traveler is model-specific and will contain not only process steps (and the initialed certification) but also dimensional checks, pressure leak test results, and sensor calibration results. Subassemblies are often pre-checked in advance of joining the main assembly and their process checks will be included with the traveler. The traveler will also include specific serial numbers of key components, such as the engine or generator, for later service reference. This information is databased for later retrieval by the service group, if needed. Final testing includes recording important test data (such as fuel consumption) and this final step requires engineering approval before concluding. A quality control (QC) engineer reporting to company president directly completes the final pre-ship review of the machine and the entire traveler document.

7. Certifications - Tecogen products are generally certified to one or more safety standards, including ones that apply to utility interconnection (UL 1741, IEEE 1547, Rule 21, etc.). For the authors' standard models, Intertek Testing Services ETL/Semko, a third party NRTL[22] Enforces these. As such, certified products must adhere not only to the company's standard QC and documentation control, but also to the specific elements required by the certification standards. Design revisions require approval by Intertek and each machine must undergo specific tests required by the standard. For example, UL1741/IEEE 1547 requires dielectric testing of the key circuits on each machine and also simulation of the utility faults and subsequent controller alarm action. An inspector from Intertek will visit the factory

[22] The Nationally Recognized Testing Laboratory (NRTL) Program, which is a part of OSHA's Directorate of Technical Support and Emergency Management. The program recognizes private sector organizations as NRTLs, and recognition signifies that an organization has met the necessary qualifications specified in the regulations for the Program. The NRTL determines that specific equipment and materials ("products") meet consensus-based standards of safety to provide the assurance, required by OSHA, that these products are safe for use.

unannounced quarterly to review documentation of the tests and confirm the design has not undergone unauthorized changes.

8. Other Product Documents - Tecogen products are generally introduced with certain key documents for use by outsiders. These are:

   - A service manual that includes a detailed product description, process flow and electrical schematics, scheduled service procedures, troubleshooting guide, etc. Service manuals are extremely detailed documents that undergo frequent revision in the product introduction stage and often exceed 300 pages in length.
   - An engineering submittal is a very detailed product specification that is required by the architect and engineer before confirming the product order. This document includes an installation guide for the buyer.
   - A product manual is an application guide to the product for engineers. It describes features of the product in textbook form.

9. Supplier Agreements: Tecogen has supplier agreements for many parts in our system. The ones that are material to this discussion are structured as follows:

   - Expiration will occur after a certain time period (1-5 years) or a certain volume commitment has been achieved.
   - Tooling purchased by Tecogen for the supplier must be exclusive for our products, unless permission provided to the contrary, and be returned upon lapse of contract.
   - Confidentiality terms generally apply and extend beyond contract term.
   - No third-party sales without written permission.

9.1.2. General Plan For Manufacturing

The INV-100 would be assembled and tested in the Tecogen Waltham facility described above. The goal would be to procure the following custom devices pre-assembled from suppliers:

- The inverter/ control cabinet (pre-wired and tested to UL 1741).
- Water-cooled generator.
- The unit base frame with integral oil sump.
- The engine/generator coupling and transition housing.
- Sound enclosure.
- Exhaust heat exchanger/ catalytic converter assembly (catalyst elements purchased separately).
- Various custom wiring harnesses (DC).
- Custom hoses.

- Exhaust assemblies with high-temperature insulation blankets.
- Custom circuit boards designed for INV-100.
- The base engine (7.4 L GM).

Production preparation for these items would require an iterative process of exchanging technical details, quote preparation, and sample evaluation. Vendors are generally selected from pre-qualified ones that Tecogen has used in previous products. The authors' new vendors for the product, Danotek (permanent magnet generator) and The Switch (inverter assembly) were not typical vendors. These suppliers were essentially start-up ventures not currently equipped to produce their respective devices in quantity.

Danotek required special tooling for producing production generators. This investment was approximately $85,000, covering several tooling devices, including casting molds for the housing.

The Switch's scope of supply was to increase in stages. The initial group, or first generation design, of eleven systems would be supplied with a modest scope, a partially wired back-panel containing the specialized power conversion devices of the rectifier, DC boost system, and water-cooled semi-conductors for final AC output. Tecogen would separately procure the electrical enclosure, microprocessor system, power supplies, and complete the final wiring of the power conductors and accessories and plumb the water cooling system. Current production units have the entire inverter control system completely pre-assembled by The Switch and delivered as a tested module. This two-stage implementation process allowed time for careful consideration of the best layout and the development of pre-made bus-bars and wiring harnesses, resulting in a superior system. It was important to finalize all design aspects after the initial production run; units thereafter would be UL listed and fixed in design.

9.1.3. Critical Production Requirements

The INV-100 would, in most respects, be producible in Tecogen's factory with current staff and on-hand equipment. Some exceptions would exist, as described below

- The complex wiring of the inverter and controls would require a highly skilled technician, familiar with panel wiring and standardized practice. The authors would not have this skill set in their factory as they typically procure pre-made harnesses and pre-assembled panels for our existing products. Tecogen was able to hire an experienced individual for this task. Current production does not require this skill set, however, as the panels are supplied complete from The Switch.
- The test facility would require significant upgrades to test new product. Specifically, a second cooling loop was added for cooling the generator and inverter. Also, the wiring service required an upgrade to the kW requirements of the unit and a load bank was included for testing the unit in black-start mode.
- Specialized instrumentation was needed to accurately measure power quality (harmonics, etc) and confirm kW output during pre-ship test conditions.

- The bottleneck in production was determined to be the test booth. Although this was partly due to the learning curve in production – sorting out production errors – we recognize that a second test booth will be needed in the long run. Fortunately, the facility has ample electrical and gas service and we will not be constrained in this regard.
- Additional space may be required if production requirements increase significantly. However, the authors able to expand in the building significantly if needed[23].

9.1.4. Supplier Agreements

Three new supply agreements are required for this product. The first is from Danotek, the supplier of the specialized PMG. The PMG is not readily available from other suppliers, as it is not a traditional type used in other applications. Two successive agreements were signed with Danotek. The first covered the tooling and the initial production-run of 11 units. The second was for the first year production with staggered deliveries. Under the agreement, the generator is exclusive to Tecogen, and the tooling ownership is also retained indefinitely. Pricing is fixed.

The Switch, the inverter supplier, is covered under similar agreements – one for the initial production run and the second for a one-year supply with option for extension of the period and quantity. No tooling was necessary for their scope.

Lastly, the product has required a license from the Wisconsin Alumni Research Foundation (WARF) for the specialized software for microgrid operation. This software was developed under Commission sponsorship for the CERTS Microgrid program. Its patents are assigned to WARF, an affiliate of the University of Wisconsin whose researchers developed the patents. A long-term licensing agreement has been concluded with WARF, exclusive to small-scale engine-driven CHP. Tecogen is the holder of the license, although the licensed software is imbedded in the The Switch system.

9.1.5. Support Systems for Production and Service

During the fabrication of the First Generation units, production support infrastructure was developed. These would be the following:

- A detailed manufacturing QC "traveler" for the product was developed. It has been modified extensively as production processes have evolved and includes a detailed test procedure that includes the UL requirements for certification (see discussion below).
- A detailed bill of material (BOM) has been developed for the product, which has been continuously updated and refined.
- A work order process flow system for the product has been developed. Each machine is processed individually; all direct costs are recorded, labor and material, and job summaries are available in real time through the accounting software.

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[23] Additional space is available in the Waltham facility, although the authors currently sublease the space on a one-year basis to other business entities.

- Detailed production records are recorded and databased for later retrieval by the service group (serial numbers of components, and so forth).
- A detailed service manual has been completed and published.
- Engineering submittals (including an installation manual) has been completed for the product.
- Detailed drawings have been completed for all critical parts and assemblies. Manufacturing drawings for assembly processes are well along but are still in process.

9.1.6. Quality Control and UL 1741 Compliance

A detailed quality control document for the INV-100 is required to assure that the manufacturing process proceeds in proper sequence and that manufacturing quality is incorporated into the production layers. The outline for the multi-page QC record or "traveler" is provided below with descriptive summaries of the essential areas to be covered in each section.

Preface – record unit serial number and nameplate data from major components.

A. General Assembly – mount major components to skid (engine, generator, and so forth) per referenced drawings utilizing torque specifications provided. Note: Engine has been pre-assembled with most accessories.

B. Engine Oil System Assembly and Fill – attach external oil assembly and sensors, fill oil sump and prime oil pump.

C. Engine Coolant System – complete plumbing and pressure test to procedure.

D. Natural Gas System – assemble and pressure check.

E. Electrical Assembly – mount pre-fabricated inverter/microprocessor cabinet to skid and install and rout all harnesses. Wire miscellaneous AC devices that are located within engine enclosure (pumps, fans, and so forth).

F. Engine Enclosure – attach all enclosure-mounted devices per referenced drawings, including catalyst/exhaust heat exchanger assembly. Mount enclosure to skid.

G. Exhaust System – install exhaust system piping, blankets and sensors.

H. Final assembly – add final accessories and current software to main microprocessor.

I. Electrical Checkout – review/compare listed circuit boards for correct jumpers and dual in-line package (DIP) switch positions. Check fuse ratings against master list. Power microprocessor up and complete detailed check of analog/digital input/output (I/O), calibrate power supplies and program engine governor.

J. Factory Testing – operate engine under no load and confirm various settings and analog readings. Confirm inverter is operational. Connect to load bank, operate in standby

(isolated, black start mode) in steps of increasing power and verify proper operation. Repeat tests in grid-tie mode. Record performance and affirm passing grade.

K. Prepare for Shipment – drain and winterize fluid systems, plug connections, install tags and labels,

L. Final Approval by QC engineer – Final review of unit and documents.

The INV-100 QC procedure has been completed and is under company documentation control (revision 6). The specific steps for UL 1741 certification are completed by TSI in their production process. These include dielectric testing (high voltage) as well as simulated conditions of utility faults (to confirm required alarms for certification). Tecogen is the certified facility for the product, subject to quarterly inspections[24]. The Switch QC travelers are archived with the authors' internal documents for review by the inspectors.

9.1.7. Commercial Launch Investment

As discussed, the INV-100 is being introduced into a family of pre-existing products manufactured by Tecogen and supported by a factory owned service group. The service group has seven locations, which overlay the likely territories for the new model's introduction (i.e., the high electric tariff regions). The INV-100 product shares many common features with our existing products – the engine, engine accessories, sensors, lubrication oil, filters, etc. – which is a significant advantage in the product introduction phase. The factory and service groups, normally requiring significant learning curves during product introduction, are better positioned at the outset for a successful outcome.

The commercial launch investment would involve integrating this new product into the company' existing models. The tasks and approximate costs are presented in Table 21.

[24] The certification of the facility by Intertek Testing Services, ETL/Semko is a significant part of the certification process. This requires a detailed review of the company processes, especially those relating to the ongoing integrity of manufacturing and engineering. Fortunately, the Tecogen manufacturing facility has pre-existing certification from earlier product certifications.

Table 21. Commercial Launch Investment

Item	Task	Investment	Notes
1	Procure tooling for generator	$ 86,000	Required by Danotek for castings, etc.
2	Negotiate supply agreements	$ 50,000	Includes WARF one-time fee ($10k) and outside legal assistance
3	Develop Service Manual	$ 32,000	
4	Service Training Seminars (3)	$ 16,000	For regional service personnel
5	Develop QC "Traveler"	$ 15,000	
6	Prepare Production Design Drawings/BOM	$ 50,000	
7	Purchase Special Test Equipment	$ 15,000	Load Bank, Power Analyzer
8	Upgrade Test Facility	$ 8,000	
9	Prepare Marketing Materials	$ 20,000	Trade show booth, presentations, flyers
10	Prepare Engineering Submittal Package	$ 20,000	
11	UL 1741Cerification	$ 180,000	Includes ETL/Semko service fees, testing costs, inhouse labor (TSI, Tecogen)
12	UL 2200	$ 50,000	Not yet completed
13	First Year Support (Engineering)	$ 150,000	Post product launch effort to corect/upgrade design, QC, support materials, upgrade units
	Total	**$ 692,000**	

Source: Tecogen, Inc.

9.1.8. Implementation Plan/Schedule

The production implementation plan is summarized in the schedule shown below. The plan revolved around two production runs. The first run represented an early group of units that were to include the program's field test unit and the NYSERDA counterparts in NY. These units were nearly final production units except that it was anticipated that design improvements/upgrades would reveal themselves in the course of their construction and subsequent testing. These changes would be made to the second production group that would, thereafter, be ongoing. The second run was to be the certified modules, which brought the design under strict control; changes thereafter would require a more difficult process.

Figure 34 presents the production readiness schedule. As shown in the schedule, the initial production run shipped in 2007 Q4, while the final production began output in 2008 Q3. Delays in UL certification required some units to be shipped in advance of the process; these units may be certified retroactively by an Intertek Testing ETL/Semko field inspector[25]. Most of the items in the schedule have been discussed and for these we will not elaborate further. We have recently completed the 50 Hz model development and shipped a unit to an EU dealer. Trade show graphics are in process (a dedicated booth design) and we will develop a specialized Web page for the Inverdé product in mid-2009.

[25] This process requires a detailed design conformance review, but no testing. As the units were made to the final design specification (ultimately certified) the process would not require any field changes.

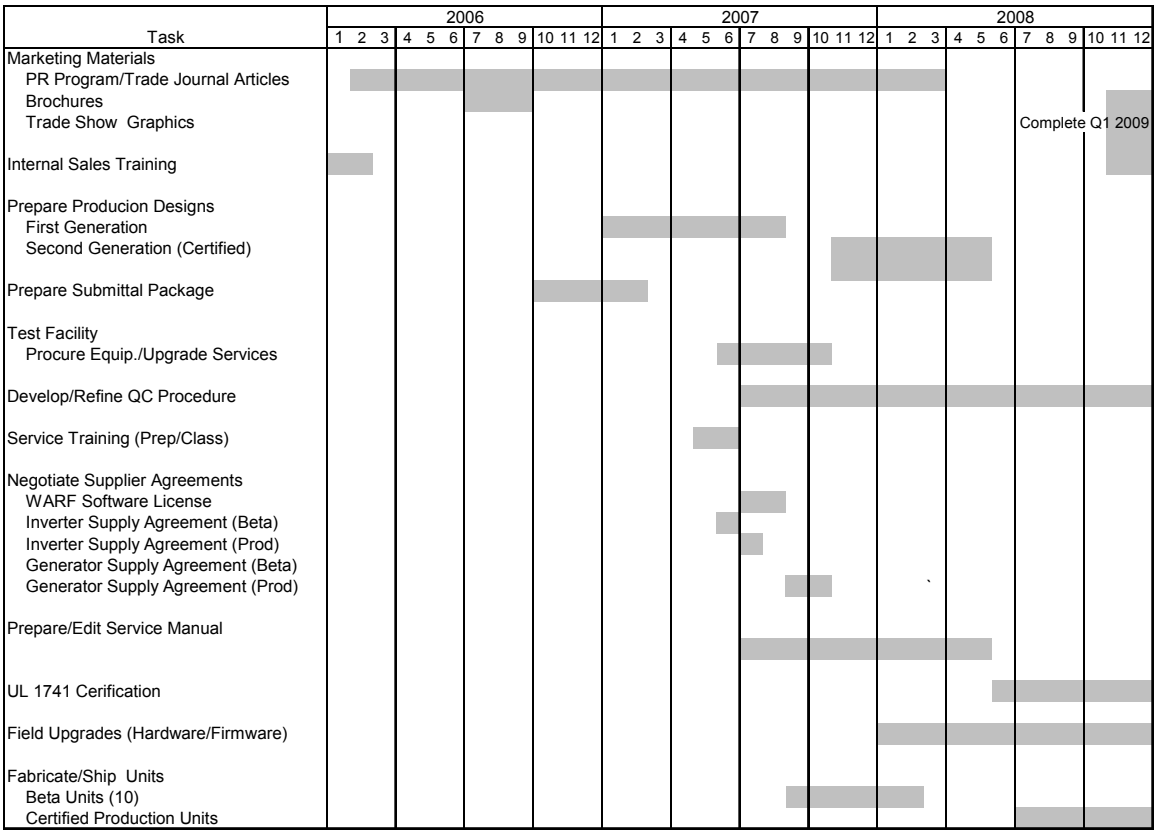

Figure 34. Production Readiness Schedule

Source: Tecogen, Inc.

9.2. Product Costs

9.2.1. Program Goals Versus Current Sell Price

The INV-100 production costs have been well documented internally by Tecogen's manufacturing group. At this time, Tecogen management has established the product's "sell-price" at approximately $130,000 ($1300/kW) for a fully equipped module. At this value, Tecogen is able to achieve strong gross margins that would make this business segment profitable even at very modest sales volumes (< 50/year).

Table 22 summarizes the INV-100 pricing currently in place at Tecogen relative to the project goals of six years ago. The first column lists the baseline pricing of Tecogen's pre-existing cogeneration module, a 75 kW unit equipped with conventional driveline and electrical generation system. The 75 kW sell price of $60,000, that was used in the authors' proposal, is valid today. An option the authors frequently sell with the base unit, a pump and valve (P&V) system, has been added to the unit cost, bringing the total to $68,000 ($907/kW). The reason the P&V accessory was included is that the final INV-100 module includes this option in the base design; as such, its inclusion equalizes the product scope for this discussion.

When the credit for the pump and valve option is included, the proposal price target for the INV-100 module was $83,000 ($830/kW). The "stretch" goal, a more ambitious long-term value,

was $5,000 less or $780/kW. The authors are currently, therefore, about 60% higher than our original target.

Table 22 Product Selling Price (INV-100) Relative To Project Goals

	CM-75 Current Cogeneration Module	INV-100 Program Goal Near Term	INV-100 Program Goal Stretch	INV-100 Program Goal Actual (2009)
kW Rating	75	100	100	100
Base Unit Sell Price	60,000	75,000	70,000	130,000
Additional Cost Pump/Valve (P&V) System	8,000	8,000	8,000	Included
Total Unit Cost with P&V System	68,000	83,000	78,000	130,000
Total Unit Sell Price with P&V System/kW	907	830	780	1,300

Source: Tecogen, Inc.

9.2.2. Company Profitability, Gross Margin, and Sales Volume

To properly develop a strategy for cost reduction, it is necessary to understand the relationship between product cost, selling price, unit sales revenue, and the company profit margin. Company profit, the true measure of the product's success in the market, will be determined by the difference between product cost and its sell price multiplied by the quantity sold, less the fixed expenses of the company. This relationship is represented by the simple formula:

$$\text{Profit} = [\text{Quantity Sold} \times (\text{Price} - \text{Cost})] - \text{Expenses}$$

The difference between price and cost is the gross margin. Tecogen defines the cost as the authors' direct costs – the factory labor expended in producing the machine plus the purchase price sum of the material used in its fabrication. For the purposes of this analysis, indirect expenses may be assumed as fixed over a significant change in company revenue, especially for the product discussed here[26].

The profitability of the company may be increased by increased unit sales or by improving the gross margin. The latter can be accomplished by either raising the price or reducing the cost (or combination of the two). Increasing price may negatively impact sales, while lowering price may have the opposite effect. Assuming the gross margin is positive, more sales will always increase the absolute company profit (in dollars). However, increased company profits in absolute dollars would be undesirable if the profit as a percentage of the company cash requirements were too low.

[26] The manufacturing process for the INV-100 at Tecogen is, in essence, a final assembly of components procured from vendors. The indirect expenses are those of maintaining the factory (rent, utilities, insurance, etc) and the indirect labor force — supervisors, engineers, accountants, and management. These fixed expenses are relatively unaffected by increase sales volume as the factory can tolerate a far higher throughput.

For the INV-100 it is possible to look at these relationships in meaningful analysis because the product cost is known and the company in to which it has been introduced has a well-established financial cost structure. More specifically, it is possible to analytically superimpose the INV-100 into the Tecogen business financial model and determine the effect of various pricing and cost scenarios. This will provide a clear picture for accessing the products viability and establishing a strategy for achieving the ambitious sales goals we hope to achieve.

Figure 35 presents the results of this analysis for a moderate but realistic range of sales 25 to 200 units annually. Shown are results of calculating the company INV-100 sales needs for different price levels in order to achieve a certain reasonable level of profitability, assumed for the analysis as 7.5%[27]. The authors have plotted three cases for the analysis: (1) no cost improvement achieved, (2) a 10% cost improvement, and (3) a 20% cost improvement. As an example of how this figure is to be interpreted, consider the first case: From the upper curve, the company will realize a 7.5% profit if any of the plotted combinations of price and quantity are achieved. If the sell price is set at $900/kW, the authors' our profit goal requires 200 units be sold annually. Likewise, a price of $1000/kW will necessitate a quantity of 70 units.

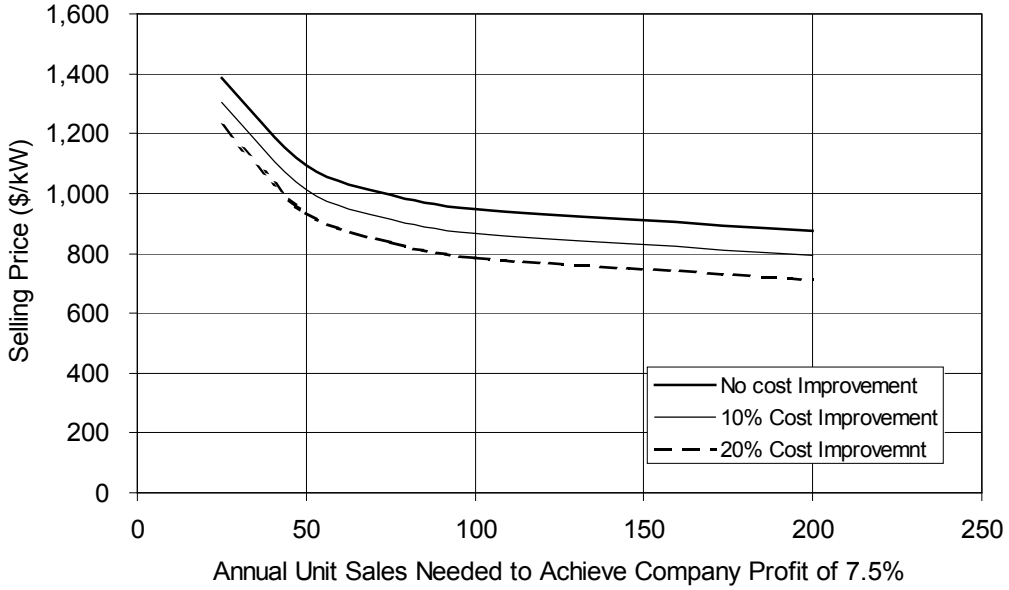

Figure 35. Effect of Annual Sales on Pricing Requirements
Source: Tecogen, Inc.

[27] This profitability level is, in the authors' opinion, typical for capital equipment suppliers in mature, competitive markets, such as air-conditioning products. This can be verified by checking public companies in these business areas such as ITT, Ingersoll Rand, etc.

From the analysis, it is possible to project with fair accuracy that the authors' price goal, of about $800/kW for the product is attainable with relatively modest cost reduction and sales volumes. More specifically, a cost reduction of 10% coupled with an annual sales volume of 200 units would result in a company profit of 7.5%. If the authors are able to obtain greater cost reduction – to the 20% level – their sales point for the same profitability would be halved, 100 units per year.

9.2.3. Cost Reduction Strategies

Tecogen would, of course, desire the lowest cost possible to maximize the opportunity for increased profits and revenue growth. To that end, the authors would identify the following specific areas for cost reduction:

- Reduced Labor Costs — The current configuration for the product requires Tecogen to complete a relatively simple final assembly and test. For example, the most complex portion of the unit, the power electronics/control assembly, is completely fabricated by our supplier and should therefore require only a brief fit-up. As this process becomes smoother, we anticipate the labor content to steadily shrink to about 50% of it current value. This will require no special tooling but rather a combination of typical "learning-curve" factors – more timely procurement, improved suppler quality, and increased understanding of the product by line workers. The labor content of the product is relatively small and the overall cost saving from this improvement will be about 5%.
- Quantity Discounts —Secondary Materials — The secondary suppliers of material – weldments, sensors, hardware, enclosures, will likely offer discounts for quantity orders. The authors anticipate this would provide at least another 5% reduction, especially given the current slower economy.
- Quantity Discounts — Primary Suppliers — The major cost items for the product are the generator and power electronics (inverter and related controls). Both items have been custom designed for the INV-100 and were significantly more expensive than originally projected. The suppliers, Danotek and The Switch, appear willing to reduce their price for higher quantities. If production rates were to double or triple, a 10-15% price reduction would seem reasonable. As mentioned above, the worldwide economic slowdown has significantly decreased some raw material costs; this downward price trend may be beneficial to the authors' procurement relative to The Switch and Danotek, especially if it applies to copper, "magnetics", and semi-conductor (silicon).

The product cost goals set forth in the proposal do seem attainable in the short term if the product achieves even modest success (100-200 units annually) and the authors are able to reduce costs 10-20%. Tecogen's strategy will be pragmatic: we will carefully price the product to balance the company's need to be profitable, while at the same time concede reduced price where needed to expand our market. The authors are especially sensitive to the negative consequences of expanding too quickly with a new product and would, in any case, maintain prudent production limits at these early stages.

Weighing all these factors, a reasonable goal for the INV-100 would be to achieve the limits of Figure 35 in 2-3 years; that is, annual sales of 200 units per year and pricing at $800/kW, supported, of course, by an underlying cost reduction of at least 20%.

9.3. Field Experience (RAMD)

In 2008, the first generation design of the INV-100 unit gained field operating experience. In addition to this PIER program's field test unit at the Claremont Club, Tecogen had nine additional units operating in the state of New York as part of a NYSERDA grant program. This program offered funding incentives to facilities for the demonstration of DG-CHP systems. These DG units had to have the emergency power capability, among other requirements with regards to efficiency, emission, and grid interconnection. The INV-100 unit fit the criteria, resulting in the accelerated introduction of additional field test units. Also, Tecogen had a commercial sale of one unit that was placed in a local hotel in Massachusetts.

The following sections will present the data that has been gathered to reflect the reliability, availability, maintenance, and durability (RAMD) of the premium power unit.

9.3.1. Reliability and Availability

Table 23 presents a summary of the field operating experience of this fleet of first generation design units. The group accumulated over 50,000 operating hours in approximately one year's time. The average capacity was 78 kW with an average operating time of 13 hours per day. The availability ranged from 80%– 97.3% with an average of 89%. The availability is defined as the ratio of number of hours the unit is in an "Alarm" state versus the total number of possible hours of operation.

Table 23 Field Test Units Availability

		Commissioning Date	Hours as of 2/15/09	Average Capacity [kW]	Average Hours Per Day	Availability
300001	Madison Oneida #1	2/7/2008	4240	61	11.4	91.5%
300002	Madison Oneida #2	2/7/2008	3974	84	10.7	86.2%
300003	Madison Oneida #3	2/7/2008	4211	78	11.3	92.3%
300008	Madison Oneida #4	2/7/2008	4219	77	11.3	88.2%
300009	Madison Oneida #5	2/7/2008	4144	81	11.1	90.7%
300010	Madison Oneida #6	2/7/2008	4233	80	11.3	80.2%
300004	Jewish Home & Hospital #1	2/12/2008	6496	85	17.6	94.3%
300005	Jewish Home & Hospital #2	2/12/2008	4587	86	12.4	95.5%
300006	Jewish Home & Hospital #3	2/12/2008	7101	80	19.2	97.3%
300007	Claremont Club	4/21/2008	4250	86	14.5	76.4%
300011	Indigo Hotel	6/27/2008	3452	58	15.1	84.4%
	Fleet Total Hours:		50,907	78	13	89%
	Fleet Averages:					

Source: Tecogen, Inc.

Given the understanding that these units were essentially prototype field test units, the 89% average availability was tolerable for the authors' customer-base. However, Tecogen recognizes that this number needs to improve to around 95% in order to achieve a successful commercialization of this product. This is based upon the authors' 25 years experience of selling and servicing more than 1500 CHP units to a similar customer base.

The plan to improving the availability involved cataloguing the issues of each of the units over their operating history. This was done by reviewing service records, as well as downloading data via the RMCS. Each unit was equipped with a modem and a phoneline so that Tecogen's service and engineering personnel could have remote access for troubleshooting and diagnostics. The RMCS also allowed us to develop a database of alarms so that we could methodically determine the most prevalent alarms, as well as the frequency of these alarms, over the entire fleet. With the RMCS data, the authors were able to formulate a plan by prioritizing the most pressing issues, based on actual data, rather than anecdotal reports from service personnel and customers.

A listing of the most significant reliability issues, along with their resolutions, is presented as follows:

1. Generator Failure – As presented in Section 3.2.2, the Danotek generator had some significant design flaws in the early design. First, there was the problem where magnets became detached from the rotor, causing a catastrophic failure. Nearly half of the generator population (5 units) failed during operation, causing downtime to the customer (approximately 2 weeks). However, the remaining units were changed prior to failure, resulting in significantly less downtime (1 day).

The second problem experienced with the generator was the bearing failure. This failure mode happened during operation to 2 of the 11 units, causing significant downtime (approximately 1 week). The remaining units were pro-actively changed out, again resulting in less downtime (approximately 1 to 2 days).

Danotek resolved both of these problems with design upgrades, which have proven to be successful. Most of these generators now have several thousands hours of operation.

2. CAN Bus Communications Faults – As described in Section 4.2, the premium power unit's master control system communicates with the PCS via the CAN bus communications link. The master control system uses this interface to enable/disable the PCS and provide it a power setpoint when the system is grid connected. The PCS then relays all of the AC power related information back to the master control system, including the voltage, current, frequency, and power factor.

   Although the CAN system was tested on bench simulations, as well as in the laboratory, it was not until the premium power units experienced hundreds of hours of operation in the field where the CAN bus problems began to surface. The symptoms were not always apparent as a CAN problem because various faults, of different names, would occur as a result of information not being transmitted properly. This resulted in many nuisance faults and downtime for reasons that were not always apparent.

   In order to resolve the problem, a highly methodical approach to diagnostics and troubleshooting was required, including trap software routines and laboratory simulations. It also took hundreds of hours of field operation to refine the intricacies of this interface, such as the timing of software handshakes and eliminating noise on the line. The solutions to the CAN us problems proved to be a combination of software changes, improved grounding on the printed circuit boards, and noise suppression. At the present time, CAN bus faults have been basically eliminated.

3. Boost Capacitor Bank Failures – The AC output from the permanent magnet generator is rectified to DC power in the range of 200 - 300 volts. This DC Boost circuit takes this lower voltage power and raises it to 830 volts. It includes two boost modules, one positive and one negative, each equipped with a two capacitors. Out of the 11 units in the field, there have been 5 occurrences of these capacitors failing after thousands of hours of operation. In addition to the downtime incurred, another negative aspect of this failure mode is that these capacitors burst, which in some cases caused incidental damage of other components within the PCS enclosure (Note: The second generation PCS design now includes a Plexiglas shield in front of the power electronics panel for personnel safety, as well as to minimize damage from these types of incidents).

   The action taken to resolve this issue was laboratory analysis of the failed capacitors and a series of electrical measurements of production units, as well as field units, to ensure that operation was within the specifications. It was concluded that the ripple currents, which are an AC component of the total current within a capacitor, were higher than expected. These

excessive ripple currents resulted in an internal temperature rise, causing these capacitors to prematurely fail.

The planned remediation of this problem is to add two additional capacitors to each Boost module, which is expected to extend the capacitor life to 50,000 hours. A retrofit program will take place over the next few months, both in the field and with the units presently in production, to resolve this issue going forward.

4. Board Failures – The PCS has three printed circuit boards, while the master control system has another four. However, since the boards on the master control system have been field qualified on other Tecogen products, they proved to be very reliable in this application. However, since this was the first volume production run and extended field operation of PCS boards, these proved to be more problematic.

   The PCS has three printed circuit boards: the DC boost control board, the inverter control board, and the microgrid control board. Two out of the three, the inverter control board and the microgrid control board, had excessive failure rates. The symptoms included the reporting of incorrect information, failure to phase lock, and freezing up requiring a reboot. In most cases, the board would be replaced in the field with a new one, correcting the problem, without ever knowing the root cause.

   In the past several months, Tecogen and The Switch have devised a return material authorization (RMA)process so that going forward, the authors can determine and remedy the causes of the faults. These boards will be bench tested, repaired, and then factory-tested in production units to ensure thorough qualification. Recertified boards will be used as warranty replacements.

5. Power Electronics Modules – Two units, from the fleet of the first eleven, experienced a failure of the primary power electronics components, the boost module. The failed components were sent back to the manufacturer in Germany (Semikron) and it was determined that these were part of a bad batch of components. As a precaution, Tecogen instrumented several of the field units with thermocouples on the boost modules, as well as the inverter module, to ensure these components were not overheating. Since these are water-cooled devices, an air vent was also installed on the cooling plates to ensure there was no air entrapment. No abnormal findings were collected from the field data.

9.3.2. Maintainability and Durability

The maintenance schedule for the INV-100 unit is presented in Table 24. It is divided into five intervals and given letter designations of A through E. The intervals are defined by both operating hours and equivalent full load hours, whichever occurs first.

Table 24. INV 100 Maintenance Schedule

Category	Interval	Item	Action
A	750 EFLH[1] or 1000 operating hours (whichever occurs first)	Engine lube oil	Replace
		Engine oil filter	Replace
		Engine air filters[1]	Replace
		Spark plugs	Replace
		Air inlet filters[1]	Inspect & clean or replace as necessary
		PCV valve	Inspect
		Battery	Inspect and clean terminals
		Timing	Check & adjust if necessary
		Coupling	Inspect
		Engine mounts	Inspect
		Condensate trap	Clean
		Ventilation fans	Verify operation
		Safety circuit[2]	Verify operation (DSHT, PSHT)
		General	Check for leaks, check electrical connectors
		Catalyst	Monitor emission levels
B	1500 EFLH[1] or 2000 operating hours (whichever occurs first)	"A" Items	
		Distributor cap	Replace
		Rotor	Replace
		Distributor	Check for shaft bushing wear
		Ignition wires	Replace
		PCV valve	Replace
		Engine evaluation	Blowby & compression test (omit on first "B" service)
		Engine valves	Adjust
		O_2 sensors	Replace
C	6000 EFLH[1] or 8000 operating hours (whichever occurs first)	"A" and "B" items	See above
		Generator	Grease bearings
		Cylinder heads	Replace (if necessary)
		Catalyst	Inspect, wash or replace every other interval (that is, 16,000 operating hours)
D	Typical life	Engine, partial	Replace as indicated by blowby and compression tests
E	As required items	Thermostatic valve	Replace thermostatic element
		Water pump	Replace shaft seal

Notes:

1. A dusty environment may require more frequent service for air filters.

2. The Safety Circuit acts as a redundant safety to ensure safe shutdown in the event of a microprocessor failure.

3. Typical engine life with proper service is 16,000-20,000 EFLH

Source: Tecogen, Inc.

The engine life is expected to last 16,000 to 20,000 hours, with cylinder heads required at 6000-8000 hours. It is still early in the life cycle for most units, but it is encouraging that we have not seen any premature failures of cylinder heads or engines.

The power electronics and generator should, in most cases, survive the life of the unit. However, as discussed in Section 7.4.1, the authors have seen premature failures in both of these areas, caused by design shortcomings. Now that those problems have been resolved, the authors will learn more about the life expectancy of these components with operating experience.

At the present time, the authors' service pricing remains at their baseline number, which was presented in the proposal, of $0.02/kWh. The authors have yet to meet their stretch goal of $0.0175/kWh. One reason is a result of the significant rise in automobile fuel costs over the past two years. With the current economic uncertainty, adjusting this price down at this time is not likely.

The authors are also investigating extending the oil change interval to more than 1000 run hours. Oil samples have been taken on many of the units with consistent results. At the current oil change interval, the viscosity, wear elements (metals), and other contaminant elements are all within acceptable ranges. The only questionable parameter is the total acid number (TAN), which is a measure of the amount of acid present in the lubricant. An increase in the acid number is an indication of an increase in oxidation, which could jeopardize engine corrosion protection. Until the authors learn more about the long-term effects of compromising this parameter, they continue to keep the oil change interval at this level. However, stretching out this interval could provide significant savings in maintenance costs.

10.0 Conclusions and Recommendation

10.1. Conclusions

The project met its objectives and, in particular, was successful in developing a commercial product. In addition, the authors have formed the following conclusions:

- Utility reaction to the inverter design approach has been highly favorable. This is true for East Coast utilities as well as those in California. We have successfully interconnected to the Consolidated Edison Company (New York City), Niagara Mohawk (upstate New York), NSTAR Electric and Gas Corporation (Massachusetts), and Connecticut Light and Power Company (Connecticut) and Southern California Edison (California). No units have been permitted as "certified" product at this time (certification was just obtained). The authors are hopeful that certified units, which have just begun to ship from their factory, will qualify for simplified interconnection processes in California and other states, which have copied the Rule 21 process.
- The "Black-start" operation feature has been incorporated into all installations thus far. Tecogen's pre-existing products (CM-60 and CM-75 modules) were without this feature, so we were uncertain as to how widely it would be used. In would appear to be a major sales driver for the product. Notably, black-start operation is a necessary requirement for qualification for NYSERDA CHP grants.
- The InVerdé product has quickly overtaken the authors' pre-existing products in sales by about 2 to 1. While the authors do not anticipate the obsolescence of these older models, they do anticipate the inverter product will dominate.
- The California CHP market has been highly depressed due to largely unfavorable economics; electric rates, while quite expensive, are poorly structured for CHP and the expiration of the SGIP has been particularly negative. The InVerdé product is generating renewed interest and we are hopeful of a mild sales resurgence. However, if the SGIP were reinstated and other economic drivers were to improve (carbon credits, improved tariff structure, expiration of legacy costs, etc.), then we would anticipate very strong sales of the product.
- The disbanding of the Rule 21 Working Group is unfortunate relative to obtaining the authors' Rule 21 certification. The authors expect that it will return under CPUC management at some point. In the meantime, the authors are hopeful that the California utilities will regard the product as certified since the criteria for certification – UL 1741 certification – has been met. Approval by the working group is essentially a formality.
- Selling price of the product is currently $1300-1400/kW, about 30% greater than the authors' conventional CHP modules and their program goal. Reaching this goal will require better pricing from our key suppliers, Danotek and The Switch. Higher volumes and secondary sources will help significantly.

10.2. Recommendations

The InVerdé successfully addresses the significant shortcomings of pre-existing CHP technology – most notably, utility safety and power quality concerns, utility outage ineffectiveness, and poor part-load performance. Under favorable market conditions (such as in the Northeast) it would have very rapid and significant market penetration. In order for its benefits to be effective in California, however, CHP needs to be better integrated across applicable state regulations and legislation in order to maximize its cost, environmental, reliability, and grid benefits. In particular,

- The Self-Generation Incentive Program for CHP needs to be restored. Its current status, whereby certain technologies are favored, has been particularly negative.
- Utility tariff barriers need to be removed. These would include legacy costs (standby rates, departing load charges, etc.) and tariff structures that are strongly biased toward fixed and demand charges and are, therefore, anti-efficiency in nature.
- Utility interconnection requirements need to be simplified to enable inadvertent export and simple means for utility sell back of excess power. Power export control should never be required for the InVerdé product as it is fully certified with anti-islanding protection. To do so for the simple reason that the utility will not participate in a sell back program is highly objectionable given the energy and societal benefits of CHP.
- The microgrid aspect of the InVerdé product is a very significant feature that should be further developed. The authors would recommend program(s) to further develop the solid-state switching device needed to connect/reconnect to the utility seamlessly in outage conditions. Also, suppliers of PV systems should be encouraged to offer microgrid-compatible versions of their inverters so that they can participate in microgrid installations.

10.3. Public Benefits

The benefits of CHP are well established: fundamentally, CHP is an efficiency measure; overall fuel usage relative to conventional processes is dramatically reduced. Customers realize a significant reduction in their overall utility bills, while society benefits from conserving its valuable hydrocarbon resource (natural gas, typically). In particular, the electric grid is relieved of carrying that portion of the electric load and carbon emissions are reduced proportionally to the efficiency improvement. Here the authors will quantify these benefits on a per module basis, then extrapolate their proposal sales to determine the overall benefit.

For a single CHP module, the fuel benefit is calculated from the general formula:

$$A = B - C \qquad (1)$$

where, A = the fuel benefit for the CHP module.

C = fuel expended by the CHP module in providing its thermal and electrical energy.

B = the fuel that would required to provide the same useful electric and thermal energy by conventional means (i.e., electricity from the grid, low-grade heat from a boiler/water heater).

Therefore,

$$A = \frac{E}{\eta_{pp}} + \frac{Q}{\eta_{boiler}} - \frac{E}{\eta_{elec}} \qquad (2)$$

where, E = electrical output of the CHP module

η_{pp} = power plant efficiency

Q = thermal output of CHP module

η_{boiler} = boiler efficiency

η_{elec} = electrical efficiency of CHP module

It is useful to normalize the formula (convert the benefit to a percentage) relative to overall fuel usage of the module. To do so, each term is divided by the total CHP fuel use, which is equivalent to its electrical output divided by its electrical efficiency. This operation is completed below:

$$A' = \frac{A}{[CHP_fuel_use]} = \frac{A}{E/\eta_{elec}} = \frac{\eta_{elec}}{E}\left[\frac{E}{\eta_{pp}} + \frac{Q}{\eta_{boiler}}\right] - 1 \qquad (3)$$

From which,

$$A' = \frac{\eta_{elec}}{\eta_{pp}} + \frac{\eta_{thermal}}{\eta_{boiler}} - 1 \qquad (4)$$

This equation is expressed graphically using the INV-100 specifications and typical boiler/water heater efficiency (75%) in Figure 36.

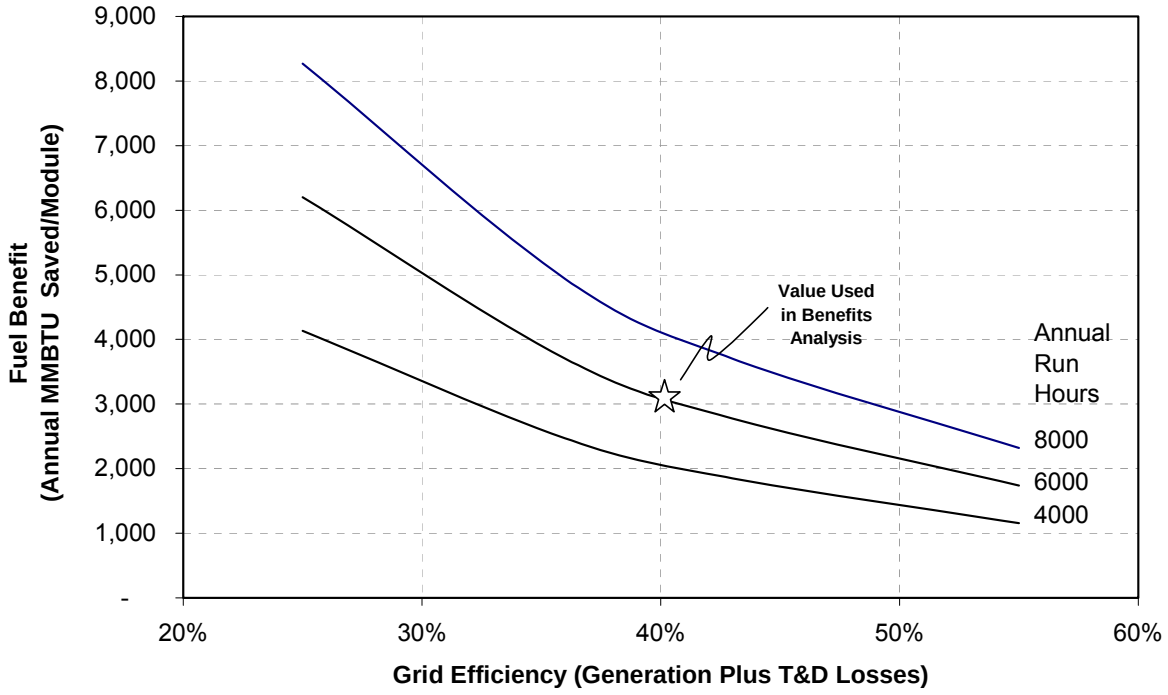

Figure 36. Fuel Benefit for Various Grid Efficiencies

Source: Tecogen, Inc.

Using the standard carbon content of 117 pounds per million BTU's for natural gas, the annual carbon benefit of a single unit is directly obtained and shown in Figure 37.

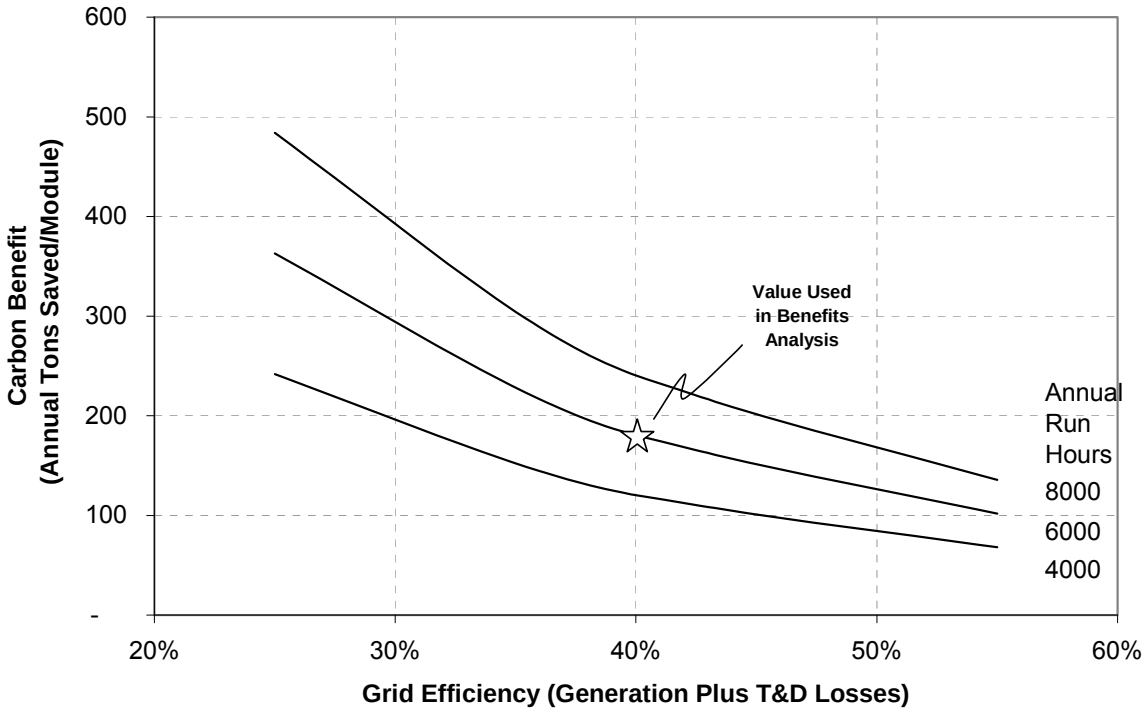

Figure 37. Carbon Benefit for Various Grid Efficiencies

Source: Tecogen, Inc.

From the two figures, it is clear that the grid efficiency is an important variable in determining the fuel and carbon benefit. The grid, of course, is comprised of multiple power sources using various fuels – coal, natural gas, nuclear material and renewable resources (hydro, etc.). For this analysis, the comparison will be made to natural gas fired sources, the primary source of new power and power displaced by the distributed resources, such as CHP.

Figure 38 depicts the relationship between efficiency and carbon emissions for natural gas electric grid sources. Two points are highlighted that coincide with notable benchmarks: the first, lower point is the lower limit imposed by California Senate Bill 1368, while higher point is the current upper limit for conventional power plant design, the so-called best-in-class two-cycle turbine. SB 1368 sets the power plant carbon output limit at 1100 pounds/megawatt-hour, which coincides with 36% efficiency. If the transmission and distribution losses are included, the effective value of these benchmarks is depressed about 8 percent (3-4 percentage points)

Using these benchmarks and including the effects of grid loss, reasonable grid efficiency to use in the benefits analysis would be roughly mid-way or about 40%. Likewise, the authors need to assign an average run-hour usage for each machine. The mid-range value will be used, 6000 hours, which now fixes the annual fuel and carbon benefit for each module installed at 3000 MMBTU and 180 Tons, respectively. (See these points highlighted in Figures 10.1 and 10.2).

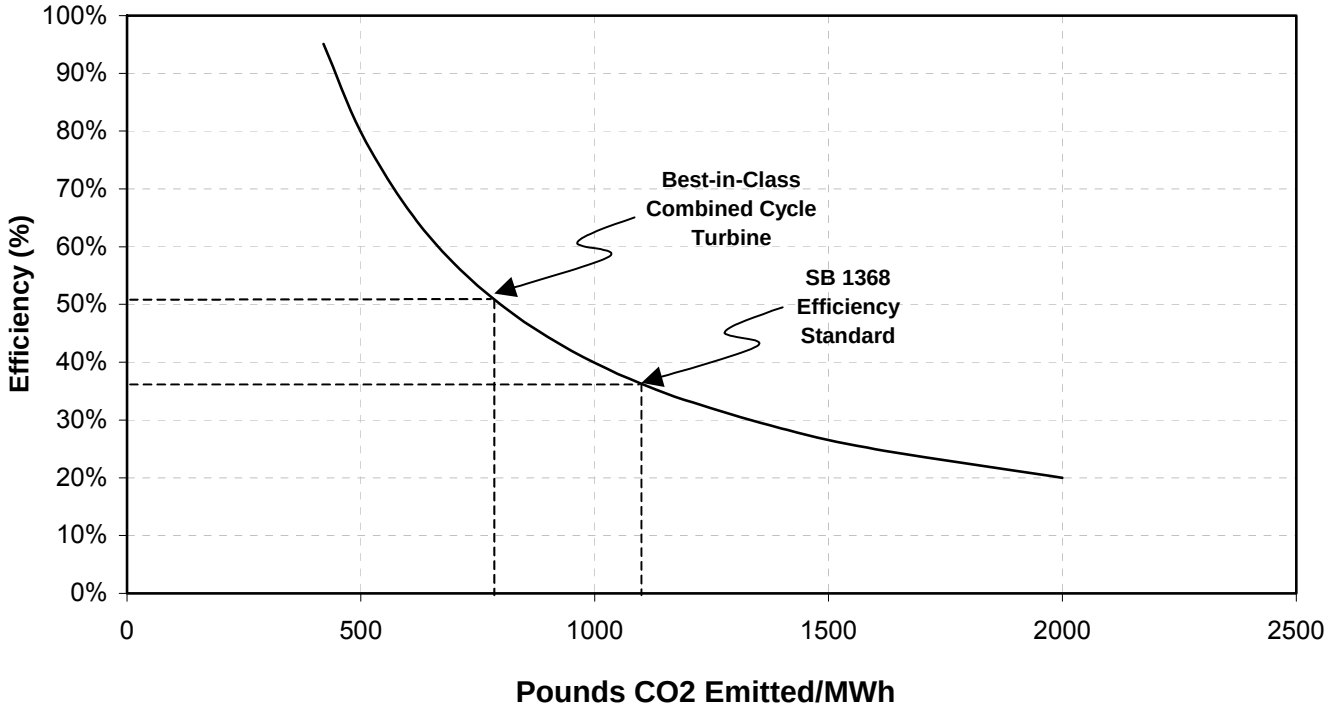

Figure 38. CO_2 Emissions vs. Generation Efficiency

Source: Tecogen, Inc.

To complete the analysis, sales projections from the proposal will be used. These are given in Table 25. Using these sales projections and applying the benefit calculated for fuel and carbon, the annual benefit is easily determined. These results are provided in Table 26[28].

Table 25. California INV-100 Sales Projection (# of Units)

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Simple Interconnect	40	80	100	120	120	120
Plus Grid Isolated Capability	20	40	60	70	80	80
Plus Demand Response		5	10	40	100	150
PV Platform			5	20	50	70
Total Annual Sales	**60**	**125**	**175**	**250**	**350**	**420**
Total Installed Base	**60**	**185**	**360**	**610**	**960**	**1,380**
Effective Units Operating*	**30**	**123**	**273**	**485**	**785**	**1,170**

* For this calculation, it is assumed that the new units introduced in a given year are brought online on a continuous basis, but spread throughout the 12-month period. Hence, their average operation for that first year is 6 months (50%).

Source: Tecogen, Inc.

[28] Assumptions used in Table 10.2: Grid efficiency = 40%, annual run time 6000 hours, annual CO_2 saved = 180 tons per module, annual fuel saved = 3000 MMBTU/Module, Availability = 80%.

Table 26. Summary of California Benefits By Year

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Effective Units Operating	30	123	273	485	785	1,170
Carbon Savings (Tons)	5,400	22,050	49,050	87,300	141,300	210,600
Fuel Savings (MMBTU)	90,000	367,500	817,500	1,455,000	2,355,000	3,510,000
Fuel Savings (bcf))	0.1	0.4	0.8	1.4	2.3	3.4
Electricity Savings ($M)	2	7	16	29	47	70
Peak reduction (mW)	2,400	9,800	21,800	38,800	62,800	93,600

Source: Tecogen, Inc.

10.3.1. Public Benefits Summary

The public benefits for the project will be realized with the deployment of the INV-100 module that begun in 2009 with a few initial units, followed by a ramp-up of sales in California and elsewhere. California's investor-owned utility ratepayers will realize significant near-term benefits from this project can be summarized as follows for Year 6 (2015):

- Annual carbon reduction of approximately 200,000 tons (as CO_2).
- Annual fuel reduction of approximately 3.5 million BTUs (3.4 Billion cubic feet, bcf).
- Annual electricity savings of approximately $70 M (6000 hours/module x 10 cents/kWh x 100 kW x 1170 modules operating).
- Grid peak reduction of approximately 93 megawatts (80% of 1170 units operating x 100 kW each).
- Commensurate reduction in deferred central station plant and transmission costs.
- A strengthening of California's economy and energy security.

Glossary

A/F	Air / Fuel
AEP	American Electric Power
BOCES	Board of Cooperative Educational Services
BTU	British thermal unit
CAN	Control area network
CARB	California Air Resources Board
CERTS	Consortium for Electric Reliability Technology Solutions
cfm	Cubic feet per minute
CHP	Combined heat and power
CL&P	Connecticut Light & Power
Con Ed	Consolidated Edison
CPUC	California Public Utilities Commission
dBa	Decibel - A scale
DER	Distributed energy resources
DG	Distributed generation
DR	Distributed resources
DSR	Demand side response
EFLH	Equivalent full load hours
EHR	Exhaust heat recovery
EMF	Electromagnetic field
EMI	Electromagnetic interference
EPS	Electric power systems
ETL	Electrical Testing Labs
EU	European Union
EUT	Equipment under test
GHG	Greenhouse gas
gpm	Gallons per minute
GT	Grid tie
HHV	Higher heating value
Hz	Hertz

I/O	Input / output
IC	Internal combustion
IEEE	Institute of Electrical and Electronic Engineers
IGBT	Insulated-gate bipolar transistors
IOU	Investor-owned utilities
kVA	KiloVolt Amperes
kW	Kilowatt
LBNL	Lawrence Berkeley National Laboratories
LE	Light Engineering
MAP	Manifold absolute pressure
mS	Milisecond
MW	Megawatt
MWh	Megawatt hours
NOx	Mono nitrogen oxides
NRTL	Nationally Recognized Testing Laboratories
NYSERDA	New York State Energy Research and Development Authority
NYSIR	New York State Interconnect Requirements
O_2	Oxygen
OSHA	Occupational Safety and Health Administration
P & V	Pump and valve
P/F	Pass / fail
PCB	Printed circuit board
PCC	Point of common coupling
PCS	Power conditioning system
PI	
PID	Piping and instrumentation diagram
PIER	Public Interest Energy Research Program
PLL	Phase lock loop
PMG	Permanent magnet generator
PO	Purchase order
psig	Pounds per square inch gauge

PV	Photovoltaic
QC	Quality control
RAMD	Reliability, availability, maintenance and durability
RD&D	Research development and demonstration
RMA	Return material authorization
RMCS	Remote monitoring and control system
RMS	Root mean square
rpm	Revolutions per minute
SA	Standalone
SCAQMD	South Coast Air Quality Management District
SCE	Southern California Edison
SGIP	Self-Generation Incentive Program
T & D	Transmission and distribution
TES	Thermal energy storage
THD	Total harmonic distortion
TSI	The Switch, Inc.
VFD	Variable frequency device
WARF	Wisconsin Alumni Research Foundation