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FINAL PROJECT REPORT

Low-Cost Microscale Distributed Generation and Combined Heat and Power for Use in Laundry Facilities

Edmund G. Brown Jr., Governor

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PREFACE

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

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

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

Low-Cost Micro Distributed Generation and Combined Heat and Power for Use in Laundry Facilities is the final report for the project PIR-13-004 conducted by UC Irvine. The information from this project contributes to Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

This project successfully developed a 49 horsepower combined heat and power system using a laundry facility as an example application. To accomplish this, the research team modified an automotive rotary engine to operate on natural gas and mated it to a generator. The system was packaged into a unit containing all necessary connections and balance of plant. Emission testing indicated good performance when operated on natural gas, but required the use of a catalytic converter to achieve the desired emissions levels. Hundreds of hours of operational experience were accumulated on two engines. One engine was retained at the laboratory of the Advanced Power and Energy Program at University of California, Irvine, while the second was used at a commercial laundry facility. The testing indicated some challenges remain with integrity of the heat exchanger system and the generator. One concern, the integrity of the seals of the rotary engine, was removed as analysis of wear suggested adequate life. Emission levels below those required by the California Air Resources Board could be attained for oxides of nitrogen and carbon monoxide with appropriate engine tuning. Regarding demonstration testing, the original demonstration site was unable to support the test due to changes in management. Deployment at the alternative site was straightforward, although the heat demand at the alternate site was significantly less than that of the original. This precluded desired long-term testing at the alternate site. The engine at the laboratory, however, was operated for long periods and proved reliable aside from the heat exchanger and generator issues mentioned. Analysis projected for the original site with the larger thermal load indicated possible total savings of about $1,300 per month in the winter and $2,080 per month in the summer, based on relevant utility rates.

Keywords: Micro DG/CHP, laundry, Mazda rotary engine, stationary automotive engine applications, low-cost DG/CHP

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EXECUTIVE SUMMARY

Introduction

The overtaxed electric grid in the Southern California service area has been further stressed by the permanent closure of the San Onofre Nuclear Generation Station (San Onofre), taking nearly 3,000 megawatts (MW) off of the grid. Widespread use of new, low-cost, clean, reliable distributed generation with combined heat recovery can provide grid reliability support to Southern California while addressing the efficient use of natural gas and other local resources, particularly in the Greater Los Angeles and San Diego areas affected by the closure of San Onofre. Distributed generation with combined heat recovery is composed of small generator systems that also provide usable heat. They can help provide additional generation capacity to the distribution grid level or reduce grid load and demand by providing generating capacity at the user level.

Project Purpose

This project helps drive deployment of distributed generation with combined heat recovery by focusing on a microscale distributed generation with combined heat recovery system (roughly 30 kilowatt [kW] output), using a unique automotive industry-based engine (the Mazda rotary engine), and targeting laundries as a significant market for the technology. By focusing on low power output, the intent is to minimize issues with siting the equipment at the facilities; the output exempts the system from traditional reciprocating engine air quality permitting issues and will likely minimize issues of electric power export. By using a production Mazda rotary engine, the intent is to capitalize on economies of scale for the prime mover production as well as capitalize upon the small size and extreme reliability provided by the rotary design. By focusing on laundries, the intent is to target a previously unrecognized market (more than 3,700 facilities in the San Onofre-affected territory, more than 8,000 in California) that need hot water and hot air (for washing and drying) concurrent with the need for electricity.

Project Process

The rotary engine-based distributed generation with combined heat recovery system offers users the opportunity to implement a cost-effective system with a comfort level and technology understanding of a mobile technology-based reciprocating engine. The attributes of the rotary engine include simplicity, along with reliability and durability. Coupled with waste heat recovery, the target system overall efficiency is over 67 percent. To accomplish this, the engine had to be adapted and integrated with an appropriate balance of plant.

The first step in the process was to obtain all the relevant mechanical interface information of the rotary engine from Mazda, as well as specifications for the balance of plant necessary for the engine operation, and to conceptualize and develop the mechanical and control system interconnection between the rotary engine and the generator. With the design completed, the research team carried out component development with the specific tasks of adapting the engine for use on natural gas, interfacing the engine with an appropriate generator, integrating an inverter, and installing all aspects of the balance of plant, including heat exchangers and controls.

The research team adapted two engines, the first of which was configured in an open frame, convenient test package to allow operational performance to be evaluated and the system components to be evaluated and modified as necessary. This engine was used for tuning to attain low pollutant emissions levels.

The second engine was packaged into a cabinet representing more of a commercial look and feel and was ultimately used at the evaluation site (Anteater Recreation Center at University of California, Irvine), where it was used to displace electricity from the grid and provide all the hot water needed by the laundry facility as well as showers at the site.

Project Results and Lessons Learned

The program successfully modified a production automotive gasoline rotary engine for natural gas operation using medium-pressure natural gas and incorporated electronic engine management and fuel injection. A solar panel inverter was used with a novel alternator to provide output power from the system.

The research team encountered several challenges. Multiple alternators were damaged due to electrical short circuiting, which sometimes suspended testing due to the somewhat custom nature of this component. After the second generator electrical short, the manufacturer supplied an external fan for the alternator that greatly improved thermal management. Other major events included, in particular, finding a new host site halfway through the project.

The exhaust heat exchanger developed a leak at an internal weld that was not repairable. As a custom part, it had a long lead time for replacement, which affected full system testing.

After managing these weaknesses in the system, the emissions were able to get very close to California Air Resources Board limits for stationary generators. The system is able to accomplish this while having a minimum repeatable overall efficiency of 75 percent, which is impressive for such a small scale. Specific tests yielded more than 80 percent overall efficiency. These numbers easily surpassed the 67 percent efficiency goal set at the beginning of the project.

The overall efficiency at 75 percent helped yield an indicated possible total savings potential of roughly $1,300 per month in the winter and $2,080 per month in the summer, based on relevant utility rates.

Technology/Knowledge Transfer/Market Adoption

The demonstration site did not have enough thermal demand to allow long-duration testing to be fully evaluated, so a longer-term demonstration and evaluation is necessary. However, this project indicates that the system has a high potential as a production unit. The system is expected to provide a unique penetration of low-cost engines into the small to medium wastewater treatment marketplace. For any chance of market penetration, distributed generation/combined heat and power systems must be easy to site (e.g. minimization of difficulty with local permitting issues) and economically viable to purchase and operate. When compared to the de facto California Air Resources Board-certified combustion distributed generation system, the Capstone C65 iCHP Microturbine, the overall cost of ownership ($/kW-hr generated) is about 25 percent less for the rotary engine system. Further, the perceived familiarity of the reciprocating engine in general and the rotary engine in particular will have a positive influence on the decision makers and ultimate use of these systems. The proposed microscale distributed generation/combined heat and power system, in a final configuration, is expected to be a modular offering rated at nominally 35 kW (below the South Coast Air Quality

Management District 50 horsepower permit threshold) within a volume of approximately half that of a Capstone C65 iCHP system.

Benefits to California

The rotary engine distributed generation/combined heat and power system can operate at 24 to 30 kW of power and provide 400 kilowatt-hours (kWh) a day assuming 16 hours of operation. Excess energy (kWh) and power (kW) are assumed to be used in other areas of the recreation center (outside the laundry) in addition to being stored for use during non-operation of the system. The costs associated with operating the system include fuel input of about 494,714 British thermal units per hour (Btu/hr) with natural gas as the fuel at a cost of 41.687 cents/therm, and an estimated operation and maintenance cost of $0.02/kWh. Along with the electrical savings due to the on-site energy (kWh) and power (kW) generation, the research team assumed that the facility will also use the estimated 294,790 Btu/hr in waste heat recovery. Considering all these conditions, the ideal operation of this system will result in about $3,010 in net energy savings during the five months covered in this analysis.

Regarding economic benefits, the total system capital cost, net of incentives, is about $19,500, and when taking into consideration the natural gas costs and retail electricity rates discussed in the life-cycle economic analysis, the simple payback period is calculated to be roughly 1.9 years.

CHAPTER 1: Motivation and Goals

Motivation and Opportunity

The future of energy production in a carbon-constrained world will hinge upon (1) increased overall thermal efficiency, (2) increased use of low-/no-carbon-impact fuels, including renewable fuels, and (3) the availability and use of transmission and distribution grid infrastructure to accommodate the increased power production by conventional and renewable power production to meet increased energy demands. Distributed generation (DG) will play a major role in easing the power grid "gridlock" and help to reduce the need for grid improvements. DG will help reduce the nominal 11% transmission and distribution losses[1] by allowing power generation to be distributed across the grid at or near the points of use. The *2012 Integrated Energy Policy Update (IEPR Update)*[2] identified the potential for distributed generation/combined heat and power (DG/CHP) applications as 4,000 MW in additional capacity on top of the existing 8,500 MW of capacity by 2020 in California alone. Other sources have placed this same potential in capacity number approaching 8,000 MW.[3] Finally, Governor Edmund G. Brown Jr. in his Clean Energy Jobs Plan, has called for an additional 6,500 MW by 2030.

Beyond California's energy goals, the closure of the San Onofre Nuclear Generating Station (San Onofre) and the immediate loss of 2,246 megawatts (MW) of generation capacity will greatly impact the power available to its service areas of the Greater Los Angeles Area and San Diego County. The area has managed to ride out this upset in deliveries over the past few years with conservation measures and mild weather. However, continued growth in demand in the affected areas of about 400 MW/year and a programmed reduction in power generation capacity through the elimination of once-through-cooling power plants[4] portend grid support and reliability issues that cannot be sustained with purely conservation measures and wishful hopes for mild weather.

This program seeks to develop and promote the further deployment of distributed generation systems in this region which will provide much needed grid reliability.

1 Kosanovic et.al. 2005. "The Influence of Distributed Energy Resources on the Hourly Clearing Price of Electricity for Industry in a Restructured Market." ACEEE Paper 145. *American Council for an Energy Efficient Economy Summer Conference on Energy Efficiency for Industry*.

2 California Energy Commission. 2012. *2012 Integrated Energy Policy Report Update (IEPR Update)*. http://www.energy.ca.gov/2012publications/CEC-100-2012-001/CEC-100-2012-001-CMF.pdf.

3 Electric Power Research Institute. 2005. *Assessment of California CHP Market and Policy Options for Increased Penetration.* California Energy Commission. Publication Number: CEC-500-2005-060-D.

4 State Water Resources Control Board. Water Quality Control Policy on the Use of Coastal and Estuarine Waters for Power Plant Cooling, Resolution No. 2010-0020.

Using DG/CHP while providing promising benefits for energy, the environment, and end users, is falling short of the State goals for additional capacity despite the market opportunities available. DG/CHP system offerings in general have been limited to turbines/microturbines, fuel cells, and large (>400 kW) reciprocating engines. After several years of use experience, the low number of these technologies can be summarized as issues of (1) interconnection with utilities, (2) perception of technology, (3) local air quality permits (4) matching of electric and waste heat loads for maximum efficiency, and (5) initial and continuing operations and maintenance (O&M) costs. While this project cannot address specific interconnection hurdles with local utilities other than to ensure that any developed system would comply with Rule 21[5] interconnection mandates, this project looked to develop and use a microscale DG/CHP system that meets all the other placement issues.

A key issue for a successful application of a DG/CHP system is to find an appropriate load or "sink" for the captured waste heat. One sector that stands out as an application and seemingly one that has had very little attention is commercial laundry facilities. The specifics of what defines a commercial/industrial laundry are somewhat nebulous. They would include laundry facilities that are located at and support the laundry generated at hotels, hospitals, and jails/prisons. They would also include businesses focusing exclusively on laundry services that would accept material from off-site or otherwise provide material services on their own (for example, uniform supply companies). Finally, for the consideration of this project, the research team included Laundromats in the sectors as they have a large number of machines and can see reasonably high public use. In the cases outlined, the laundry facilities are used for long periods each day through the week, have an ongoing demand for hot water for the washing machines, and hot air for drying. Further, the operations of the washing machine and dryer motors, irons, presses, and so forth provide a concurrent and significant load that can be effectively met with DG/CHP

In California, as a whole, and the Greater Los Angeles Area and San Diego County in particular, the opportunities to support laundry facilities are significant. For jails/prison/correctional facilities, hotels, hospitals, and Laundromats® (a definitive list of stand-alone industrial/commercial laundries has not been found), the numbers of facilities in California and the San Onofre service territory are presented in Table 1. All generate laundry load, and expectations are that each facility has an on-site laundry. (Alternately, they would ship the laundry out to a local commercial laundry, for which specifics are not immediately available)

Focusing in on one sector and one specific facility to assess energy and waste heat loads, the University of California, Irvine, Advanced Power and Energy Program (UCI-APEP) monitored the electric energy consumption for three months (July – October 2008) at a local Orange County hotel (a candidate host site for the deployment of the developed system).[6] Figure 1 shows the average 15-minute electric energy demand through the day for the laundry in this

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5 Electric Rule 21 is a set of regulations that describes the interconnection, operating, and metering requirements for generation or storage facilities to be connected to an investor-owned utility's distribution system.

6 Akbari, Amin, Marc Carreras Sospedra, Richard Hack, Vince McDonell, and Scott Samuelsen, UC Irvine, 2011. *Realistic Application and Air Quality Implications of Distributed Generation and Combined Heat and Power in California*, California Energy Commission Publication CEC-500-2015-032.

facility. Initial observations are (1) there is a cyclic load profile with a minimum (but not zero) in the early morning hours and (2) an average demand of about 45 kW.

Table 1: Probable Laundry Facilities in California and San Onofre Territory

	California Facilities/Beds	San Onofre Territory Facilities/Beds
Jail/Prison[7]	108 / n/a	18 / n/a
Hotel[8]	5509 / 501,544	2390 / 252,420
Hospital[9]	394 / 80,600	181 / 46,000
Laundromat[10]	n/a	1100+

Source: University of California, Irvine

7 http://app4.lasd.org/iic/maps/Prisons-ALL-MAPS1.html.

8 Smith Travel Research Inc.

9 California Health Care Foundation.

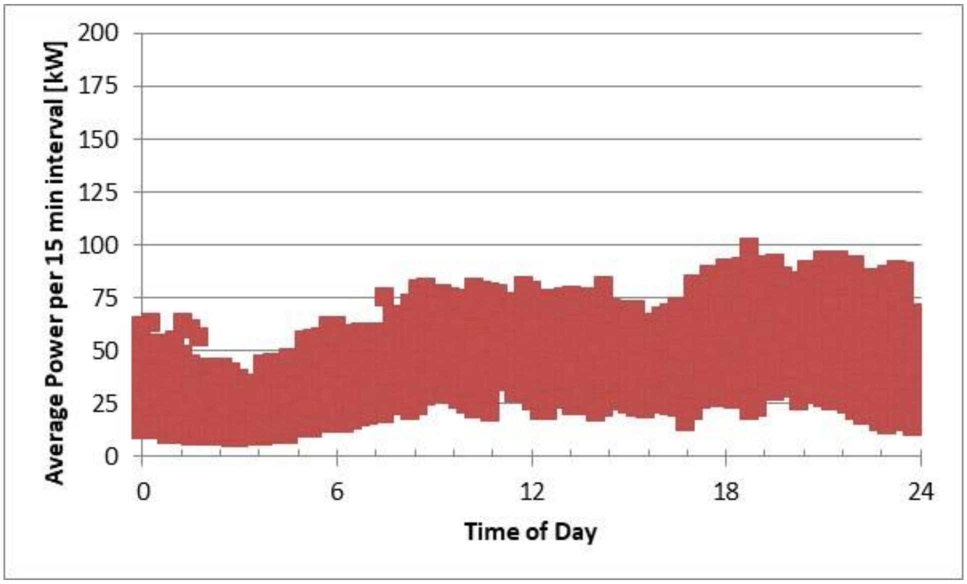
10 Coin Laundry Association.

Figure 2 shows the maximum electric demand as measured for each 15-minute window; the average "peak" power is about 75 kW, roughly a factor of 1.7 over the average value. However, a review of the specific measured intervals reveals a maximum factor of about 4.8 between the peak and average interval powers measured. Clearly, the on/off cycling of equipment results in significant power spikes throughout the day.

The hotel laundry facility in this example consists of six large gas-fired dryers and eight washing machines. Five dryers are 175 lb.-capacity units with a 450,000 Btu/hr. firing rate and nominally 4.5 kW (6 HP) electric demand while the sixth is a 540 lb.-capacity, 1.6 MMBtu/hr., and 25 HP unit. The washing machines are nominally 60 lb. units with 5 HP motors. Specific energy consumption for the washers was not monitored at the time of the electric power monitoring. It is known that the machines are supplied with 140 degrees Fahrenheit water from the hotel's central plant water heaters. (Injection of steam, also generated on site, is used during the wash cycle to bring up the temperatures appropriate for washing). The supply temperature for the water is 60 F; assuming about five gallons of water per wash cycle (wash and multiple rinses), the nominal energy content of each wash cycle is 200,000 Btu/load minimum, not including any steam injection energy. The research team monitored typical dryer operations by logging the duty cycle of the gas control valve. While highly dependent upon load size, room temperature, and humidity, the burners typically operated at roughly 25% duty cycle (such as rated at 450,000 Btu/hr at 25% duty cycle = 112,500 Btu consumed for each hour of operation).

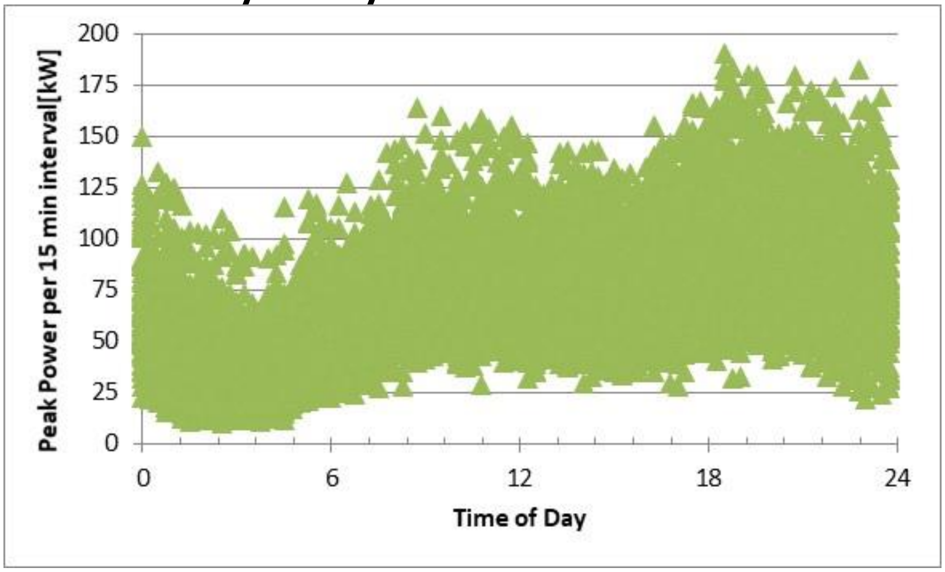
An issue with DG/CHP use is matching heat to electric needs or, more importantly, ensuring maximum use of waste heat without electric power export. The measured parameters of this specific candidate host site suggested that this would not be an issue. While an aggregate measured history of the hot water/washer and hot air/dryer energy demands was not available, the numbers and duty cycles suggest that 100% of the waste energy from the DG/CHP system can be used. Figure 3 shows the proposed system energy balances. Further, in the host site installation and likely typical of other sector installations with the possible exception of Laundromats, there is far more energy load on the customer side of the meter that would mitigate any issues of grid export.

Figure 1: Hotel Laundry Facility: Average 15-Minute interval Electric Demand



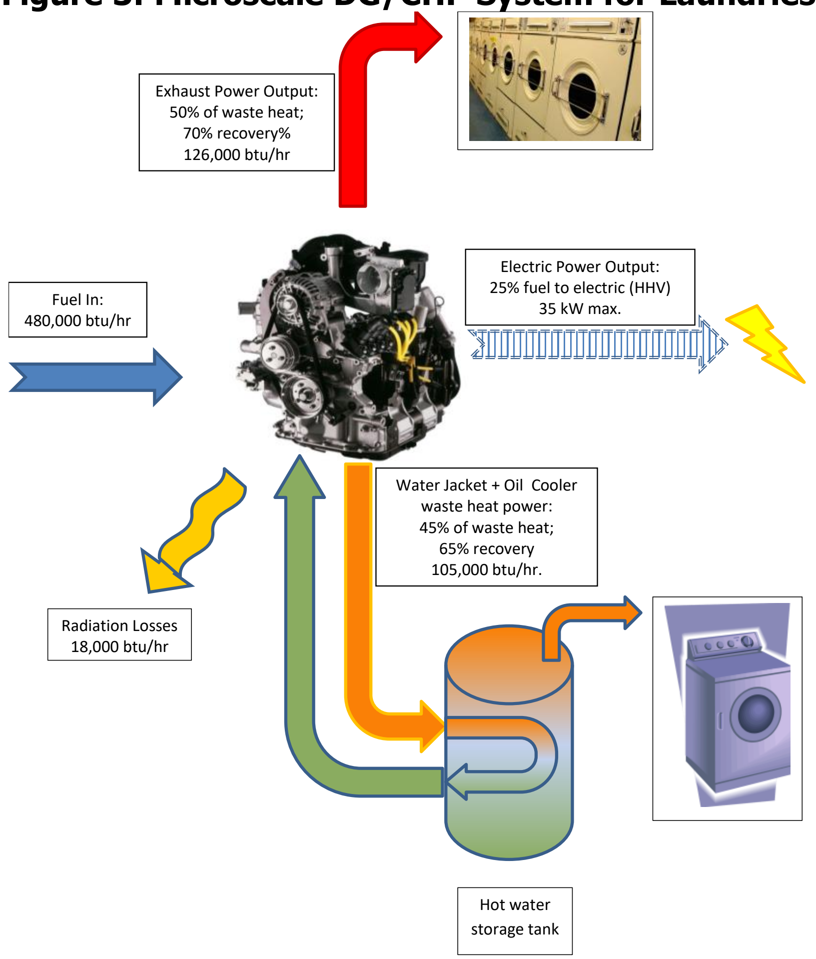
Source: University of California, Irvine

Figure 2: Hotel Laundry Facility: Peak 15-Minute Interval Electric Demand



Source: University of California, Irvine

Figure 3: Microscale DG/CHP System for Laundries



Source: University of California, Irvine

Of these three broad categories of fuel-based DG systems (turbines/microturbines, fuel cells, reciprocating engines), reciprocating engines continue to see generally wide (albeit still limited) acceptance, whereas fuel cells and turbines/microturbines seem to be hindered by not only the realities of cost, but the perception of reciprocating engines being ubiquitously associated with power production, whether in automobile/truck, construction equipment, or backup generator. Reciprocating engines hence enjoy a perceived "comfort level" advantage place in the minds of the public since these engines power virtually all land-based transportation systems. With more than 100 years of development and refinement, current reciprocating engines, especially those used in mobile applications in general and in the automobile sector in particular, are tremendously refined systems offering longevity, durability, very low emissions, state-of-the-art controls, and low cost. However, reciprocating engines for DG/CHP systems are dominated by very large engines (e.g. Caterpillar, Jennbacher, Cummins) that are costly for application at smaller energy demand facilities. Further, the exhaust emissions associated with reciprocating engines can be problematic in securing necessary air quality permits, especially in the south coast air basin (SoCAB). An alternate source of reciprocating engines of particularly low cost is the automotive industry. Reciprocating engine developers for automobile applications, with more than 100 years of experience, have engineered longevity, durability, manufacturing techniques, controls, and economies of scale to produce highly efficient, clean, and relatively inexpensive prime movers that seem well-suited for application in DG/CHP systems.

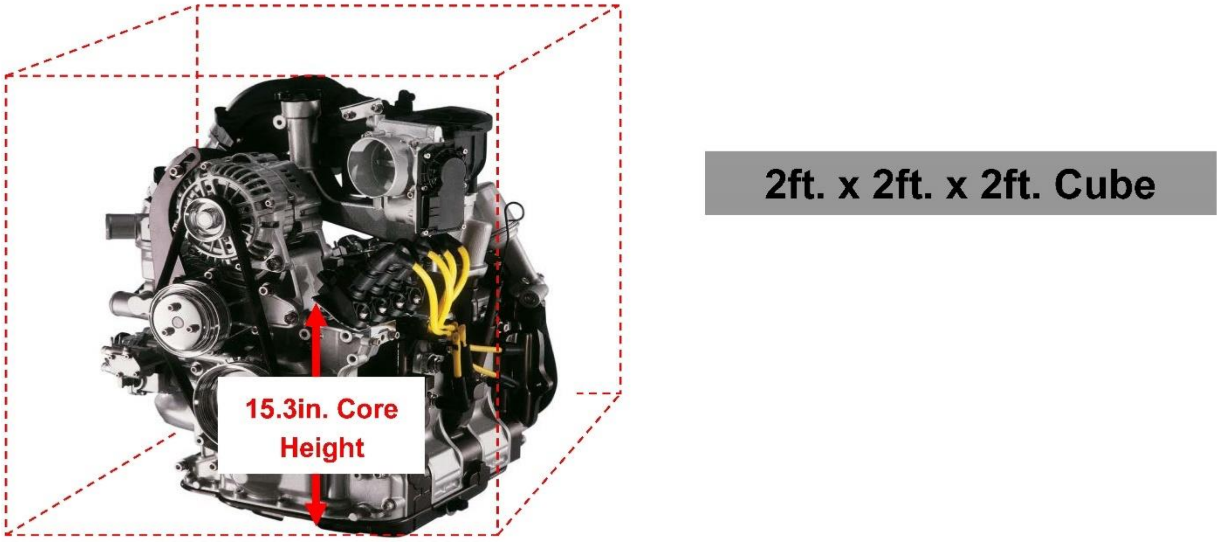
To date, reciprocating engine deployment has emphasized "larger" applications typically greater than 400 kW, although TecoGen offers engine systems with capacities down to about 75 kW (100 HP). In the South Coast Air Quality Management District (SCAQMD) territory, these engines have found limited acceptance owing to the need for air quality permits (SCAQMD output threshold for permitting is 50 HP or greater).[11] Whether real or perceived, potential applications with customers were likely hindered by a general fear of SCAQMD permitting issues, essentially thwarting application.

Economic and Performance Goals

As a subset of reciprocating engines, the Wankel rotary engine (RE), exclusively produced by Mazda Corporation for automotive use, offers many advantages beyond the more typical piston/crankshaft engine. With a fraction of the total number of parts and an even smaller fraction of moving parts to wear out or break versus a piston engine, the engine has higher reliability and longer life. The rotary motion reduces the acceleration and deceleration forces on the components compared to the piston/crankshaft engine, where piston and valve components accelerate, stop, and change directions. The result is significantly reduced wear on and failure of components. The engine has inherently high power density (output versus physical volume), low noise, and low vibration, all highly desirable for a DG system. The current generation of rotary engine, the Renesis 13B (1.3-liter displacement), has been used in the current version of the Mazda RX-8 vehicle in the United States and throughout the world. The RX-8 has a total production of more than 170,000 units since its introduction in 2003. As used in the RX-8, the engine is rated at 197 HP and 238 HP for "standard" and "high power" versions, weighs only 275 lbs, and fits into a 2-foot on a side cube (Figure 4). For reference, a cross section of the engine is shown in Figure 5, which clearly shows the rotary component. The size and weight advantage compared to conventional V-configuration automobile engines are presented in Table 2.

11 Rule 219, South Coast Air Quality Management District.

Figure 4: Mazda Rotary Engine



Source: University of California, Irvine

Figure 5: Cross Section of Rotary Engine

Source: University of California, Irvine

Table 2: Comparison of Rotary Engine to V-Configuration Automobile Engines

	Renesis 13B (1.3 liter)	4.3 liter V-6	5.7 liter V-8
Length [inches]	22	30	43
Width [inches]	21	30	30
Height [inches]	24	36	36
Weight [pounds]	275	780	888
Power [HP]	197 and 238	190	260

Source: University of California, Irvine

For the RE, lean burn[12] and exhaust gas recirculation (EGR)[13] are adopted to reduce nitrogen oxide (NO_x) emissions. NO_x is primarily reduced by lean burn at low engine speeds and by EGR and a three-way catalyst at high engine speeds. The three-way catalyst is the same as the system used with the standard gasoline automobile engine. Optimal and appropriate use of lean burn and EGR satisfies the goals of high output and low emissions.

The RE as commercially available in the present configuration is used in automobiles. Table 3 summarizes the RE specifications, "current" for the automobile application and "target" for the application as a natural gas-fueled DG/CHP system. Applying the conversion factor derived, Table 4 illustrates the expected calculated emissions in both the "current/expected engine" configuration and the "target engine" configuration compared to the CARB 2007/2013 standards. The emissions presented in the current RE configuration represent the road-going gasoline-fueled version of the engine and not that of a constant speed generator application operating on a methane or methane-rich fuel. Significant improvements were expected because of the constant-speed operation via optimizing engine operating parameters that are otherwise required to address the highly variable engine speed and shaft power output of the automobile engine application. Further, operation on methane or methane-rich fuels was expected to result in even greater reductions in emissions (as evidenced by general classification of compressed natural gas (CNG) vehicles as "clean air" vehicles with greatly reduced emissions as compared to gasoline counterparts).

In addition to possible improvement in engine operating conditions and the inherent combustion-related emissions, in a stationary application, the size of the three-way catalytic converter is not as constrained as on a vehicle; a larger, catalyst could be employed to further reduce emissions. Finally, the expected waste heat recovery was conservative; additional waste-heat-recovery methods were evaluated during program development. Any increase in waste heat recovery reduces the emission levels presented (specifically emission index form - lb/MW-hr).

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12 Lean burn operation uses excess air in the fuel/air mixture compared to rich burn that operates at stoichiometric fuel/air ratio.

13 Exhaust gas recirculation works by recirculating a portion of the engine exhaust gas back to the engine air intake. This decreases the oxygen in the incoming air and decreases the temperatures in the combustion chamber.

Table 3: Mazda RE Specifications; Current and Target

Specification	Current/ Expected*	Target*
Shaft Power	30 kW	35 kW
Electric Power (85% efficient generator)	26 kW	30 kW
Emissions (EGR & Catalyst, based upon shaft power)		
CO	~0.04 g/kW-hr	~0.02 g/kW-hr
VOC	~0.14 g/kW-hr	~0.03 g/kW-hr
NOx	~0.1 g/kW-hr	~0.08 g/kW-hr
Efficiency (HHV)	22%	25%
Engine Life		20,000 hr
Operations and Maintenance Cost for Expected Life		$10 K
Engine Efficiency (to shaft power) [%]	22	25
Shaft Power Output [kW]	30	35
Generator Output (85% efficiency of generator) [kW]	26	30
Fuel Input (shaft power / (1-efficiency)) [Btu/hr]	465,300	477,750
Fraction of Waste Heat Recovery [14]	60%	60%
Waste Heat Recovery [Btu/hr]	217,600	215,000
Total Energy Output (waste heat + electric power) [Btu/hr]	306,300	317,300
Overall Efficiency (CARB mandate >60%) [%]	65.8	66.5
Emissions Conversion Factor Inclusive of Waste Heat Recovery Credit: [lb/MW-hr per g/kW-hr]	0.72	0.825

∗ "Current/Expected" values are based upon existing deployment of the RE in a gasoline-fueled, road-going RX-8 application, and measurements of existing engine performance. "Target" values were anticipated parameters operating on natural gas due to the optimization for constant speed operation efforts identified in Tasks 5 and 6 and as measured in work Task 7.

Source: University of California, Irvine

14 Waste heat distribution and recovery: Water jacket: 35% of total waste heat; 60% recovery -- Oil system: 10% of total waste heat; 75% recovery -- Exhaust: 50% of total waste heat 70% recovery -- Engine radiation: 5% of total waste heat; not recoverable

Table 4: Calculated Emissions Versus CARB Emission Standards

Constituent	Current H2RE		Target Engine		CARB 2013 biomass limit
	Emissions	Calc. CHP	Emissions	Calc. CHP	
	[gr/kW-hr]	[lb/MW-hr]	[gr/kW-hr]	[lb/MW-hr]	[lb/MW-hr]
NOx	0.1	0.072	<0.08	<0.066	0.070
CO	0.04	0.028	<0.02	<0.017	0.1
VOC	0.14	0.1	<0.03	<0.021	0.02
PM	unknown				

Source: University of California, Irvine

Table summarizes the projected lifetime operational costs for the Capstone microturbine and the system developed in this project and is based upon the following assumptions:

1. A nominal duty cycle of 50% (representative of operating the engine, 16 hours/day, 5 days a week (M-F); no operation during low/off-peak periods and weekends).
2. Nine years = 40,000-hour operating life
    a. Capstone has engine replacement at end of 9-year life
    b. RE has engine replacement at Year 4.5 and at Year 9

Table 5: Lifetime Operational Cost Comparison

	Capstone iCHP	RE DG/CHP
Electric Power Output rating [kW]	65	30
System Capital Costs [$]	135,500	32,000[15]
System Capital Costs [$/kW]	2,100	1070
Engine Life [hours]	40,000	20,000
Replacement Engine Cost [$]	45,000	5,000[16]
Operations and Maintenance Costs [$] over life of engine		$10,000
Operations and Maintenance Cost [$/kW-hr]	0.005 – 0.025	0.017
Amortized Net Present Value of system + engine replacement [$/kW-hr generated]; 5% cost of money	0.065	0.035
Total Cost for Operation [$/kW-hr generated];	0.07 – 0.09	0.052

Source: University of California, Irvine

The performance goals of the RE system development were gauged first against meeting the CARB 2007/2013 emissions standards. Second, the engine operational characteristics (efficiency, power output, waste heat recovery, operational stability) were evaluated as compared to expected values. Engine efficiency and waste heat recovery are integral to the

15 Specs for target engine and inverter system with integral heat recovery.

16 The target costs projections are for production of >10,000 units annually and is based upon the current cost for the gasoline fueled rotary engine of approximately $5,000.

CARB standards and the operational characteristic evaluation. All these operational parameters are successfully evaluated via the Association of State Energy Research and Technology Transfer Institutions (ASERTTI) test protocols. Evaluation of the engine life was made through post-long-term operational engine teardown and measurement. Levels of wear and any unexpected consequences of the long-term operation were noted, and a prediction of engine life expectancy versus the target number was assessed.

Ratepayer Benefits

Developing and using the RE DG/CHP system that complies with the CARB 2007/2013 emission standards will:

- Improve fuel use as compared to current consumption levels for power generation and process needs. Reductions in fuel consumption relate directly to lower emissions of carbon dioxide compared to current levels.
- Increase use of DG/CHP systems to reduce deterioration of area wide air quality while meeting increased energy demands compared to deployment of additional central power plants in the air sheds. Studies of widespread deployment of DG/CHP systems for the Los Angeles Air Basin (SoCAB)[17, 18] reveals:
    - Realistic DG scenarios for 2010 show that peak basin wide 1-hour ozone concentration does not increase due to DG installation. For comparison, deployment of additional central power plants to meet energy needs would result in about 6 parts per billion (ppb) ozone (O_3).
    - There are discernible increases and decreases in **local** concentrations of ozone and fine particulate matter ($PM_{2.5}$) that can be attributed to DG installation in SoCAB in 2010
    - Observed **maximum local** changes in air quality due to realistic DG scenarios are < 3 ppb O_3. For comparison, deployment of additional central power plants to meet energy needs would result in **maximum local** changes in air quality <10 ppb O_3
- Provide owner/operators additional choices in acquisition of energy (e.g. purchase from the grid or make it on site) for improved reliability or reduced costs or both. This would have particular merit with time-of-use metering or real-time pricing, wherein peak energy and demand charges could be mitigated. Reductions in the cost of doing business can trickle down to reduced costs for consumers.
- Provide carbon dioxide emission reductions for the 3,700 sites in the San Onofre territory as a result of both grid electric power displaced by the systems, and by

17 Samuelsen, Scott, Donald Dabdub, Jacob Brouwer, Marc Medrano, Marco Rodriguez, and Marc Carreras-Sospedra (University of California, Irvine). 2005. *Air Quality Impacts of Distributed Generation*. California Energy Commission. Publication Number: CEC-500-2005-069-F.

18 Samuelsen, Scott, Donald Dabdub, Jacob Brouwer, Marc Carreras-Sospedra, and Satish Vutukuru (University of California, Irvine). 2010. *Air Quality Impacts of Distributed Generation in the South Coast Air Basin and San Joaquin Valley*. California Energy Commission. Publication Number: CEC-500-2009-070.

operation of washers and dryers on waste heat rather than using natural gas in water heaters and furnaces. This represents a nominal savings of 90,000 to 180,000 lbs carbon dioxide equivalent per hour (CO_2e/hr) of operation (based upon the connected grid load of 130 to 260 MW). Assuming a nominal 16 hr/day operation, 6 days a week, of potential market would be roughly 0.20 to 0.40 million metric tons (MMT) CO_2 per year,[19] furthering the goals of the Global Warming Solutions Act (Assembly Bill 32, Núñez, Chapter 488, Statutes of 2006).

- Defer the installation of new power generation systems and transmission and distribution lines to handle the power. This deferment has been estimated[20] as having a value of >$350/kW-yr of energy generation. If applied to the projected 130 to 260 MW DG/CHP installed capacity need, this represents an approximate value of $52.5 million to $105 million.
- Support the grid reliability goals in the San Onofre- impacted area and California Independent System Operator (California ISO) Preliminary Reliability Plan calling for 3,250 MW of local generation.

Commercialization Path

The RE DG/CHP system is expected to provide a unique penetration of low-cost engines into the small to medium wastewater treatment marketplace. For any chance for market penetration, DG/CHP systems must be easy to site (e.g. minimization of difficulty with local permitting issues) as well as economically viable to purchase and operate. When compared to the de facto CARB-certified combustion DG system, the Capstone C65 iCHP Microturbine, the overall cost of ownership ($/kW-hr generated) is about 25% less for the RE DG/CHP system. Further, the perceived familiarity of the reciprocating engine in general and the rotary engine in particular will have a positive influence on the decision makers and ultimate deployment of these systems. The proposed microscale DG/CHP system, in a final configuration, is expected to be a modular offering rated at nominally 35 kW (below the SCAQMD 50 HP permit threshold) within a volume of approximately half that of a Capstone C65 iCHP system.

Overall project tasks are focused on finalizing component development as previously described above.

- Individual components are working in harmony with each other.
- Outputs are better than anticipated in all cases, especially exhaust emissions.
- Prototype units show capacity to produce more electrical power and capture more heat than current regulatory limits of <50 HP allow.

Details on readiness are described in the associated Production Readiness Plan developed as part of the project and contained in Appendix B.

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19 117 lb CO2/MMBtu methane, 33% aggregate fossil fuel California power plant efficiency; 70% aggregate water heater + dryer thermal efficiency.

20 Kosanovic et.al; "The Influence of Distributed Energy Resources on the Hourly Clearing Price of Electricity For Industry in a Restructured Market." ACEEE Paper 145: *American Council for an Energy Efficient Economy Summer Conference on Energy Efficiency for Industry*, July 19-22, 2005.

CHAPTER 2: Approach and Objectives

General Approach

The RE DG/CHP system offers end users the opportunity to implement cost-effective DG/CHP with a comfort level and technology understanding of a mobile technology-based reciprocating engine. As designed, the conservative overall thermal efficiency was expected to exceed 70%, and waste heat recovery would be about 48% of the total natural gas energy input. The system would consist of an engine, water jacket, and oil-cooling waste heat recovery to a storage tank via a liquid to liquid heat exchanger, and exhaust energy directed to the dryers. As shown in the diagram, the engine exhaust could conceptually be used directly; however, it was highly likely that for better control and to insure cleanliness of the load, that an air-to-air heat exchanger would be implemented to preheat the feed air before entering the dryer.

Based upon the measured and predicted needs for washers and dryers in possible host facilities, the waste heat streams seemed well balanced. The water jacket energy would provide significant if not 100% support of the hot water needs (about 100,000 Btu/hr versus an estimated need of about 200,000 Btu/load). The fact that the engine output is a continuous feed versus the variable need of the washing machine(s) suggested that the discrepancy may not be as severe as presented by the numbers. Further, in as much as the microscale DG/CHP system heat recovery (both water and exhaust) would operate in parallel to the existing service, the current hot water supply from the site central plant could provide the augmentation, as necessary. For the dryer, the duty cycle-corrected energy consumption by the dryer is in line with the exhaust energy output. Much like the washers, the dryers work in batch processing modes and do not need a continuous stream of energy. Unlike the hot water, no means of storing the gas energy was available. Rather, the expectation was that the exhaust energy could be used to supply multiple dryers. An alternate configuration would divert some of the exhaust energy to augment hot water energy, if needed. A final consideration was the disposition of the engine exhaust. The dryers, whether at this facility of others, are firing natural gas for the heat and must have an exhaust system. The plan was to use this same exhaust plenum as the exhaust for the engine.

As designed, the RE would be mated to a generator. Most likely, a high-frequency alternating current (AC) alternator would be used, in which case the engine would not be operated at a fixed “synchronous” speed dictated by 60 Hertz (Hz) grid support but allowed to float to allow for more efficient power reduction and load-following capability. As such, the nonsynchronous AC output would be rectified to direct current (DC) and then fed to a commercial, grid-connect-approved, 480 volt, three-phase output, solar photovoltaic (PV) inverter (nominally 50 kW rated). The inverter would possess the entire grid protection mechanisms required by Rule 21 interconnect guidelines. The general trend for DG systems is a move toward inverter-based systems as the preferred method, as Rule 21 limits on power quality for grid-connected systems are tightened.

The plan focused on low-pressure fuel supply (for example < 5 psig, which is typical of commercial and industrial distribution). The goal of this development was to use the RE DG/CHP directly within or immediately adjacent to a given laundry facility. Using the existing gas infrastructure without requiring a gas compressor reduces overall cost and eliminates another source of unreliability/system failure. Finally, while fire safety codes vary, the introducting high-pressure gas into enclosed spaces can be an added complication or ultimately a prohibitive hurdle that would prevent the placement of the RE DG/CHP next to laundry facilities. Introducing fuel into the intake manifold would involve the collaboration/purchase of commercially available systems used for natural gas, propane, and digester gas offered by IMPCO (California company), Commercial Controls Corporation (California offices), Quantum Fuel Systems (California company), and others.

The engine controls and exhaust emissions system would rely heavily upon the existing Mazda RE equipment. Applying the exhaust oxygen sensor system would provide the necessary feedback for engine management and a closed-loop fuel-control system. Because of the low and relatively constant power operation envisioned for the microscale DG/CHP system, Mazda's expectation was for the ability to tune the exhaust treatment system for this narrow and consistent operating band (as compared to the compromises necessary for an automotive application with the engine operating from 0 to 200+ HP output and the need for the exhaust treatment system to compensate for this variation while maintaining a regulated emission level). Further, because there are no space constraints (as in an automobile), the exhaust system could be sized, configured, and optimized for lowest emissions and capacity without compromises necessitated by automotive applications (for examp[le multiple catalysts in parallel or other scenarios). Finally, recent publications by TecoGen[21] have demonstrated an exhaust intercooling treatment scenario that provides necessary carbon monoxide and volatile organic compound (VOC) emissions reductions without the counterproductive reformation of NO_x.

Initial performance tests would be conducted at UCI's distributed technology test facility (DTTF) to provide information on any operational deficiencies of the system, as well as identify the primary fuel injection strategy to be incorporated in the "updated" second generation system for installation at the host site.

Operation at the host site would begin when the updated system was ready. Site modifications would be necessary to interconnect electrical and natural gas service to the unit. Site modification would also include the placement of a heat exchanger and hot water storage tank (for use in the wash machines) and tie into the hot water service supply to the machines. Finally, the site modifications would include duct work for the engine exhaust to be used directly in the dryer or through a gas to air heat exchanger to preheat room air being used in the dryer.

Goals

The goals of this project were to

- Develop a microscale DG/CHP system based upon an automotive-sourced rotary engine.
- Demonstrate the applicability of the developed RE microscale DG/CHP system for commercial laundries.

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21 Roy, J., Panora, R., Gehret, J., Roser, R. et al. 2012. *Exhaust Temperature Control Enhances Dual-Stage Catalyst System Performance on Engines Fueled With Low-Pressure Natural Gas*. SAE Technical Paper 2012-01-1730.

- Demonstrate that the RE microscale DG/CHP system will meet all emission standards.
- Demonstrate advantages in size, noise, vibration, initial capital cost, and lifetime operational and maintenance costs compared to existing benchmark systems.
- Demonstrate the applicability of the RE microscale DG/CHP concept for applications beyond commercial laundries.
- Through widespread deployment of developed product and support of Mazda in production and marketing, promote the opportunity for the application of the low-cost RE microscale DG/CHP system to the more than 3,700 commercial laundry sites in the San Onofre territory and to nearly 10,000 commercial laundries in California.

To achieve these goals, the following tasks were carried out.

Project Initiation

This task established and confirmed willingness/availability of the host site for the demonstration. Activities included the following:

- Verify that the proposed demonstration host site can still host the project. If the primary choice for the host site is unable to support the demonstration, the identified backup host site will be confirmed.
- Finalize as necessary an appropriate program-specific nondisclosure confidentiality agreement between UCI and Mazda. The research team, through the proposal process, has an informal working confidentiality agreement, but full system details have not been provided.
- Initiate site instrumented measurements for electric power, gas, and water consumption, as well as emission measurements directly associated with the laundry facility.

Design of System Integration

This task obtained all the relevant mechanical interface information of the rotary engine from Mazda, as well as specifications for the balance of plant necessary for the engine operation and conceptualize and develop the mechanical and control system interconnection between the rotary engine and the generator. Activities included the following:

- Obtain engine specifications from Mazda associated with:
  - Mechanical interface points.
  - Engine controls including but not limited to:
    - Fuel/air specifications over the range of the anticipated load.
    - Fuel injection control.
    - Emission/oxygen sensor feedback control.
- Work with Mazda to integrate load signal with ECM.
- Identify generator and grid-compatible three-phase inverter that will provide the electric generation balance of plant to which the RE will be mated.
- Engineer and produce an engineering package including, but not limited to, development drawings for necessary mechanical interface components or identify

existing commercially available hardware that can be used for the mechanical connection.

- Develop a parts list and preliminary work plan for the control systems integration.

Engine/Generator Mating

This task mechanically interconnected the RE with the donor generator. Activities included the following:

- Take delivery of two production Renesis 13B rotary engines and all ancillary equipment.
- Purchase and take delivery of the generator system.
- Issue purchase orders for commercial products or custom machining work necessary for the mechanical interface or both.
- Monitor fabrication of equipment and provide engineering support to the manufacturer, as necessary.
- Take delivery of mechanical interface hardware.
- Integrate mechanically, the RE with the generator.

Balance of Plant Design/Integration

This task completed the balance of plant integration of the RE/generator to provide a complete, operational system ready for tests. This task acquired current electric, water, and gas consumption measurements in the host laundry facility, as well as exhaust emissions measurements from the dryers at the host site to provide a full understanding of the energy and emission characteristics of the site before system installation. Finally, this task began designing the balance of plant at the host site (storage tank, heat exchangers, and duct work integration) in anticipation of the system deployment. Activities included the following:

- Assess the control systems and balance of plant from the donor generator and develop a revised part list and working plan based upon what is available and compatible with the proposed control system integration plan.
- Purchase the balance of the system components necessary to complete the system construction and control system development/integration. Purchased parts can include but are not limited to:
    - Electronic speed governor for primary engine speed control to maintain desired output frequency over varying load ranges.
    - Air-to-water heat exchanger for exhaust waste heat recovery.
    - Auxiliary radiator (water to water heat exchanger) for water jacket waste heat recovery.
    - Auxiliary radiator (liquid-to-water heat exchanger) for oil system waste heat recovery.
    - ECM, with MC guidance, for overall engine control
    - Commercial, interconnect-approved solar system inverter with all protective functionality for grid connectivity
- Integrate control components with mated RE/generator package.

- Thoroughly review all system integration and, to the extent possible, test control systems in a simulated environment (without starting engine) to verify operational control. Specifically look for positive control and unstable operational scenarios and rectify as necessary.
- Initiate the design of the balance of plant necessary for the system integration at the laundry facility.

Initial Operational Tests

This task conducted initial operational testing of the RE DG/CHP system at the UCI APEP test facility and conduct a preliminary performance evaluation. Activities included the following:

- Prepare a field performance test plan based upon the ASERTTI performance testing protocols.
- Operate and test engine in accordance with the performance test plan and:
  - Confirm stable engine operation within manufacturer specifications, acceptable generator output.
  - Adjust engine tuning and operational parameters as necessary to achieve proper engine operation.
  - Once acceptable operation is achieved, conduct tests.
  - Monitor and characterize the waste heat energy streams (exhaust, water jacket, oil cooler) as a function of engine load
- Conduct team meetings (UCI/Mazda/Technical Advisory Committee) as necessary to review and evaluate operational and performance results.
- Prepare the initial field performance test report documenting the initial performance test results. This report shall include, but not be limited to:
  - CHP system description and specifications.
  - Test plan.
  - Test results.
  - Graphical representations of key test data.
  - Analysis of the test results, focusing on the degree to engine generator system performed as predicted. Of particular interest are operational characteristics, engine heat rate, system waste heat recovery, and emissions.
  - Evaluation of the system performance and noting any departure of results from predictions, any unusual findings, and the impact on CHP system design.
  - Recommendations for system upgrades to rectify any deficiencies noted in the performance.
  - Photographs as appropriate.

System Upgrade/Modifications

This task identified and incorporated modifications to correct operational and performance deficiencies noted in the initial operational tests in preparation for the site demonstration test. This task also addressed any modifications to the site balance of plant design initiated as necessary based upon any of the identified system upgrades. Activities included the following:

- Purchase, fabricate, modify and otherwise implement the system upgrades.
- Provide a notification letter of completion of modifications/readiness for test upon completion and verification/validation of modification.

Upgraded System Tests

This task tested the upgraded RE DG/CHP system at the UCI APEP test facility and evaluated system performance consistent with the ASERTTI protocols before long-term deployment. Activities included the following:

- Operate the engine at UCI APEP.
    - Conduct "shakedown" tests to confirm satisfactory operation after transfer. Take particular note of:
        - Stable engine operation within manufacturer specifications,
        - Acceptable generator output
- Remove, disassemble, and evaluate the engine upon completion to quantify dimensional variations (e.g. wear) because of operation and note any anomalies.
- Conduct team meetings (UCI/Mazda/Technical Advisory Committee) as necessary to review and evaluate operational and performance results.
    - Evaluate condition of engine relative to wear and tear. If acceptable and engine is anticipated to perform well through the long-term testing, engine will be reassembled and readied. If not, a new engine with modifications deemed necessary to provide the desired performance will be installed
    - Evaluate exhaust emissions control system and replacing items as necessary.

Beta Testing

This task moved the microscale DG/CHP system to the host site for operation and performance assessment to gain operating hours and evaluate the performance. Activities included the following:

- Work with the host test site and prepare the facility for placement of the DG/CHP system.
    - Develop a plan with the host site for location, plumbing modifications, and electrical connections, as necessary.
    - Confirm that the interconnect agreement is in place.
    - Move the DG/CHP system into position.
- Operate the engine at host site.
    - Conduct "shakedown" tests to confirm satisfactory operation after transfer. Take particular note of
        - Stable engine operation within manufacturer specifications.
        - Acceptable generator output.
- Initiate continuous engine operation at host site for period of acceptance to the site.

- Evaluate the heat rate, overall efficiency (i.e. inclusive of waste heat recovery), and possibly emissions at nominal maximum load.
- Conduct a post-long-term operational test engine teardown and evaluation to quantify dimensional variations (e.g. wear) because of the operation and note any anomalies.
- Evaluate the life expectancy of the engine relative to the target life expectancy.

Evaluation of Product Benefits

This task evaluated the actual benefits derived from the project

Technology Transfer

This task developed a plan to make the knowledge gained, experimental results, and lessons learned available to the public and key decision makers.

Production Readiness

This task determined the steps that will lead to the manufacturing of technologies developed in this project or to the commercialization of the project results.

CHAPTER 3: Component Development

Engine

The Mazda Renesis 13B engine used for this program is a standard automotive gasoline-fueled, automatic transmission, "first-generation" variant found in the RX-8 from 2006-2008. In this configuration, the engine has a maximum output rating of 212 HP (158 kW). To modify the engine from gasoline to natural gas to meet the program target goals, a few modifications were made as described below.

Apex Seals

Unlike piston engines with ring seals on the piston, the rotor on the rotary engine poses unique sealing challenges. The predominant seals are the rotor side seals and the apex seals (the seals at the tips of the rotor). Over the years, Mazda has developed these seals into highly reliable components. The 1980s research reports suggest that the stock iron seals are sufficient for 20,000 hours of operation. In the ensuing years, advances in material technology have produced long life and stronger seals. While the Renesis engine uses iron side and apex seals, for this program, ceramic (silicon nitride) apex seals developed for high-performance racing were substituted for the stock iron apex seals at Mazda's recommendation. The expectation is the harder seal will provide longer life with less degradation compared to the stock seals. The side seals remain the stock iron material, given the lower expected wear rates. Design Ideas assessed the wear of the IAS, as well as other stock seals. The assessment report is included here as Appendix A.

Oil Injection (Metering Oil Pump)

Another unique aspect of the rotary design is the inability to route lubricating oil to the seals. In a piston engine that typically has two compression rings and one oil "wiper" ring, lubricating oil is sprayed from passages in the crankshaft/piston rods onto the cylinder walls for lubricating the sealing rings. The architecture of the rotary engine does not permit the flow of oil to the trochoid surfaces. Rather, the rotary engine employs an oil spray into the intake portion of the rotor motion through the side wall to provide apex and side seal lubrication. The precise control of this oil stream is critical for seal life while not producing excessive "burnt" oil emissions. In the first-generation Renesis engine, oil is injected through an electronic metering pump controlled by engine management system that draws from the engine oil sump. For the RE microscale DG/CHP system, the oil sump supply line was bypassed and replaced by a separate reservoir. Experience with the automotive Renesis engine indicated a potential for carbon buildup in the side case exhaust ports. While the exact cause of this buildup is unknown, two potential causes were considered: (1) conventional engine oil does not burn as cleanly and results in the carbon deposits on the convoluted exhaust passages, and (2) the oil injection rates dictated by the engine management system are too liberal and result in excess oil injection. For this program, a two-cycle synthetic lubricant was employed for the seal lubrication reservoir, the belief being that two-cycle oil is designed for cleaner combustion in two-cycle applications. The research team also adjusted the operation of the metering oil pump through the engine management system to reduced levels reflective of rates seen in the 1980s endurance tests. The belief is that constant load and relatively constant speed of operation will permit operating with reduced oil flow compared to the dynamic load variations of an automotive application. The research team assessed the premise of using two-cycle oil and changing the oil flow during this program.

Fuel Injection

Perhaps the biggest change necessary for natural gas operation, especially at the desired 4 psig maximum supply pressure, is the fuel system. The stock engine has four liquid (gasoline) fuel injectors. These injectors are not suitable for gaseous fuels. The engine was modified to accommodate Quantum Fuel Systems Technologies' gaseous fuel injector (#100078) designed specifically for CNG applications on vehicles. While designed specifically for use with 50 psig supply natural gas for typical vehicle applications, the manufacturer confirmed that the injector would work (or more specifically seal) at the desired lower 4 psig supply pressure. The flow rating of the injector, when scaled back to the supply pressure and the needed gas flow at the estimated engine efficiency, suggested eight injectors would be necessary. Due to the different size/configuration of the CNG injectors versus the gasoline injectors of the standard engine, the intake runner required modification (Figure 6) to accommodate the additional injectors. The unique configuration of the intake runners on the Renesis engine allowed the injectors to be divided into two groups of four, one group for each rotor.

Figure 6: Fuel Intake Runner

This is Version 1, where the two stock locations on the case were used. Version 2 located all eight injectors on this manifold.

Source: University of California, Irvine

Engine Control Unit

Unlike the tests of the early 1980s, the Renesis engine benefits from electronic fuel injection and a vast array of other electronic engine controls. In the automobile application, the RX-8 has a vehicle specific electronic control system to oversee and control a wide range of vehicle functionality as a whole, including the engine operation. However, this electronic system is sealed and generally non-editable. To provide the desired flexibility in tuning the engine for operation on natural gas, as well as refining and optimizing the other engine operating parameters for stationary generator application, the research team employed an aftermarket engine management system. The team chose a MoTeC Engine Management System (M800 with peripheral expansion ports and display unit) for the system. The MoTeC M800 has an operational map for the Renesis engine that formed the starting point for modifications to support natural gas operation. The system also provides extensive data-logging operational and user-defined parameters of interest, including fuel injector duty cycle, throttle position, coolant and water jacket temperatures, and wide-band lambda fuel/air ratio. For this application, 26 channels of data are gathered at a rate of 10 Hz.

Additional Upgrades from Stock Engine

The research team made a smaller water pump pulley to overdrive the water pump by 25% to assist in cooling at the recommendation of Racing Beat (an engineering and development company specializing in rotary engines and performance parts used in race cars).

For dynamometer testing and general assessment of engine operation over the long term, the engine has several sensors beyond the traditional. In the exhaust manifold, three wide-band lambda sensors are installed, one to measure the fuel/air ratio for each rotor and one for the combined "bulk" flow. Moreover, exhaust gas thermocouples are installed in the same locations to monitor temperatures. A narrow band oxygen sensor installed in the combined exhaust allows control for the three-way catalytic converter.

The research team tested a stock Mazda RX8 catalytic converter at first; however, it was not performing well with natural gas, so a natural gas Honda Civic catalytic converter was used and performed better. Again, without the weight and size constraints for the automotive converter, a larger more effective system could also have been considered.

Design of Extra-Capacity Oil Pan

A stock 13B engine holds about 4 quarts of oil. To allow the unit to run longer before requiring service, the research team designed an extended oil pan. The new design was increased to 12 inches deep, maintaining a similar footprint as the stock pan. The stock oil pickup was lengthened for the new pan. This provided a 5-gallon capacity compared to the stock 4 quart. A second wall was added around the main pan for leak containment. The team added NPT bungs, so float switches could be implemented for "low" and "empty" sensors in addition to drain plugs for both layers of the pan.

Oil Life

More testing needs to be done to better understand the oil life. The research team used synthetic oils at the beginning of testing. However, after buildup issues were discovered during tear down of the first engine, the change was made to conventional oils. The oil life can vary because oil needs to be added due to consumption, thereby diluting the existing oil. Even with the metering oil pump (MOP) oil being isolated to a separate tank, for this application, engine sump oil was measured at a consumption rate between 25 cc/hr and 50 cc/hr. Consumption varied from engine to engine as well. This project did not discover why the variation in the consumption exists. However, the initial oil quality analysis suggests that the oil can be used for at least 1,000 hours.

Originally the first engine was run with Mobil Pegasus 1 synthetic gas engine oil SAE 15W-40 in the oil pan and Castrol Power RS TTS 2T synthetic oil for the MOP injection oil. The second and third engines used almost exclusively Pennzoil 5W-30 conventional oil and Valvoline Marine 2 cycle oil for the sump and MOP, respectively.

Inverter

To provide grid interconnection, the DC power from the alternator/rectifier must be inverted back to 60 Hz AC. Rather than develop an application-specific inverter, the program opted to employ commercially available solar PV inverters. With the tremendous growth in PV installations worldwide, the cost of grid-compliant inverters has plummeted. Inverters capable of 36 kW are available for less than $5,000. Incorporating a commercially available inverter also insures that the system has all the necessary grid protective functions (over-/undervoltage, over-/underfrequency, etc.) required by typical grid interconnection rules (Rule 21 in California). However, since these inverters are optimized for PV installations, they are not necessarily directly compatible with a generator application.

An SMA SunnyBoy STP 24000TL-US-10 (Figure 7) was tested first. As higher generator output was achieved during the progress of the program (discussed below), the research team learned that this inverter could not take the full load onto a single channel. In addition, the single generation source could not be split across the two channels. As a result, the research team ultimately acquired and used a Yaskawa–Solectria PVI 36TL inverter. It had multiple channels; however, they were able to be bridged and ran in parallel mode, allowing the maximum full single load to be processed.

Figure 7: SMA Sunnyboy and Solectria Inverters

Source: University of California, Irvine

Initial operation on the inverter with the test bed engine (after the dynamometer testing) resulted in limited power output (only 12 kW rather than the desired 30+ kW). The inverter manufacturer was at a loss to provide guidance since the application was so different from a photovoltaic system design. Ultimately, changing the stator to a higher voltage output (480 VDC at 3,000 rpm versus the original 300 VDC) resulted in the inverter operating more as expected, ultimately permitting power generation of more than 30 kW and requiring the Yaskawa unit.

Heat Exchangers

The research team used three heat exchangers in the system, oil-to-water, coolant-to-water, and exhaust gas-to-water. Water is the medium used for the waste heat recovery, with design target temperatures of 120° F entering and 160° F exiting. Tube and shell heat exchangers were initially used for the oil and coolant, and a spiral heat exchanger for the exhaust gas. The original selections for coolant and exhaust were acceptable after testing; however, the oil heat exchanger was discovered to be too small and to not remove enough heat

shows the mounted locations of the three original heat exchangers, with the oil one tucked away under the coolant one on the top left. The exhaust heat exchanger is to the right of the muffler that is the center top of the image. A larger tube and shell heat exchanger for the oil was installed, which was still not enough and didn't show a significant temperature rise across the water. The team then implemented a stacked plate heat exchanger, which kept the oil cool enough and showed a multiple degree temperature rise in the water. The estimated distribution of waste heat is shown in Table 6.

Figure 8: Three Original Heat Exchangers

Source: University of California, Irvine

Table 6: Preliminary Fuel, Power, and Waste Heat Distribution

Item	kBtu/hr	%
Fuel Input [HHV]	640 kBtu/hr	
Engine Power	35 kW/120 kBtu/hr	18.8%
Waste Heat		
Exhaust	180 kBtu/hr	28.1%
Water Jacket	120 kBtu/hr	18.8%
Oil	20 kBtu/hr	3.1%
Waste Heat Total	320 kBtu/hr	50%

Source: University of California, Irvine

Electric Generation/Engine Operational Speed

Traditional reciprocating engines generators (as well as larger gas turbines) use synchronous generators that operate at a fixed rotational speed (typically 1,800 rpm for 60 Hz U.S. grid frequency). With a fixed speed and the need to maintain very tight control of the generated frequency for grid interconnection, prime movers mated to synchronous generators are required to operate within a very narrow and well-controlled speed to maintain the appropriate generator rotational speed and output frequency. For two primary reasons, this program opted for a different approach.

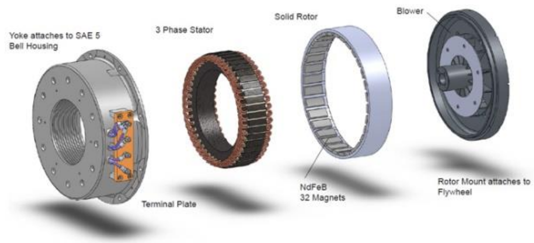
First, with little knowledge of the operation and necessary tune for the Renesis engine in microscale -DG/CHP application, defining a specific engine speed was not a realistic goal. Operating a rotary engine on natural gas with fuel injection as such low supply pressure had never been attempted. Initial discussions with Mazda and Racing Beat suggested that the engine may not have much power/torque at low rotational speeds, so a target of 4,500 +/- 500 rpm was set. However, as the operation and tuning/testing on the dynamometer progressed (as described in the section Dyno Results and Emissions), the engine performance was better than expected, exhibiting the ability to generate 50 HP as low as 2500 rpm. Hence the initial target speed of about 4500 rpm was reduced to a new target – 3,000 rpm, the lower speed ideally reducing the wear and tear on the apex and side seals as well as the internal surfaces. While it is possible to operate at 2,500 rpm, the engine was able to reach just 50 HP at this speed, maximizing the duty cycle on the fuel injectors and leaving no margin for any additional adjustments. Further, at 2,500 rpm the engine did not have a smooth "comfortable" sound which admittedly qualitative led the research team to feel that the low speed did not seem conducive to long operation. In contrast, the engine seemed very content at 3,000 rpm, with the injectors operating at roughly 75% duty cycle, permitting minor adjustments, if necessary, to maintain 50 HP operation, given variations in ambient conditions.

Second, utilities are becoming more reticent to provide interconnection agreements with synchronous generators, preferring inverter-based connections. Following the general approach promulgated by Capstone's microturbine, this effort looked to a nonsynchronous "high-frequency" AC alternator, rectification to high-voltage DC, and then use of a grid-compliant DC-to-AC photovoltaic inverter to provide grid interconnection.

To keep the overall system size small as well as deviate from the need to operate at synchronous speeds, conventional generators were not considered for this project. Rather a unique, compact 8000 Series AC alternator offered by Polar Power (Gardena California) was chosen.

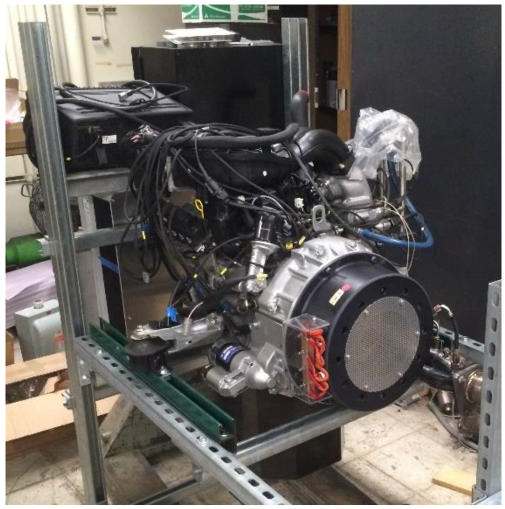
Figure 9 shows a diagram of the unit. Very compact, the 5-inch-deep by 14-inch-diameter stator section bolts directly to the back of an engine bell housing. The rotor, composed of 32 niobium iron boron magnets, connects to and cantilevers off the engine flywheel and surrounds the stator section. The three-phase power voltage is directly proportional to the engine speed. The voltage/speed characteristics can be varied through different stator winding strategies. The original generator purchased for the system has a voltage output of about 265 VDC (after passing through a three-phase rectifier) at 3,000 rpm and 30 kW power. However, a different stator with a higher voltage output is a likely modification in the near future. Figure 10 shows the compactness of the alternator mounted to the shortened bell housing being about equal lengths.

Figure 9: AC Alternator



Source: University of California, Irvine

Figure 10: AC Generator Installed on Engine



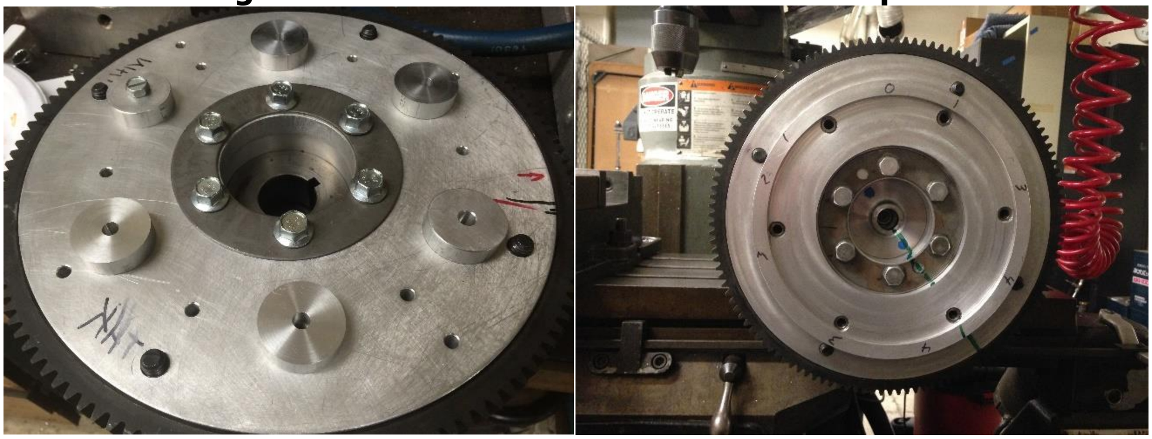
Source: University of California, Irvine

Design of Alternator/Generator Adapter

An adaptor for mating the generator rotor to the stock flywheel was required. The research team designed alternate versions after the original design was found to have excessive vibration. The first was a half-inch aluminum plate with six half-inch-thick (machined down to have equal thickness within 0.005 inch) by 1.5-inch-diameter pucks welded on, equally spaced, around a 7.875-inch bolt circle. To avoid any tolerance stacking issues in the revision, it was machined out of a single billet. On both alternate versions, threaded inserts (Heli-Coil® and TIME-SERT®) were used to strengthen the treads holding the cantilevered rotor on.

Figure 11 shows the original adapter before welding on the left and the single billet adapter on the right. Figure 12 shows the components necessary to mount the alternators magnetic rotor (top of left image) to the engine and them assembled.

Figure 11: Two Versions of Alternator Adapter



Source: University of California, Irvine

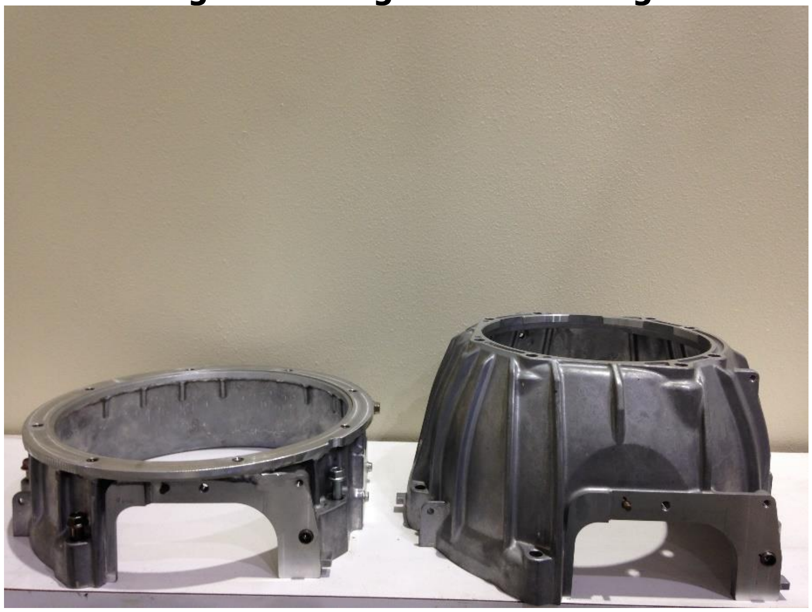
Figure 12: Components for Mounting Alternator Rotor to Engine

Source: University of California, Irvine

Design of Modified Bell Housing for Generator

For mounting the stator to the engine, the research team used a stock Mazda automatic transmission bell housing. After determining the required length, the research team cut down the stock housing and welded a flange onto it for the stator to bolt to Figure 13 shows the modified and stock bell housing on the left and right, respectively.

Figure 13: Engine Bell Housing



Source: University of California, Irvine

Thermal Management

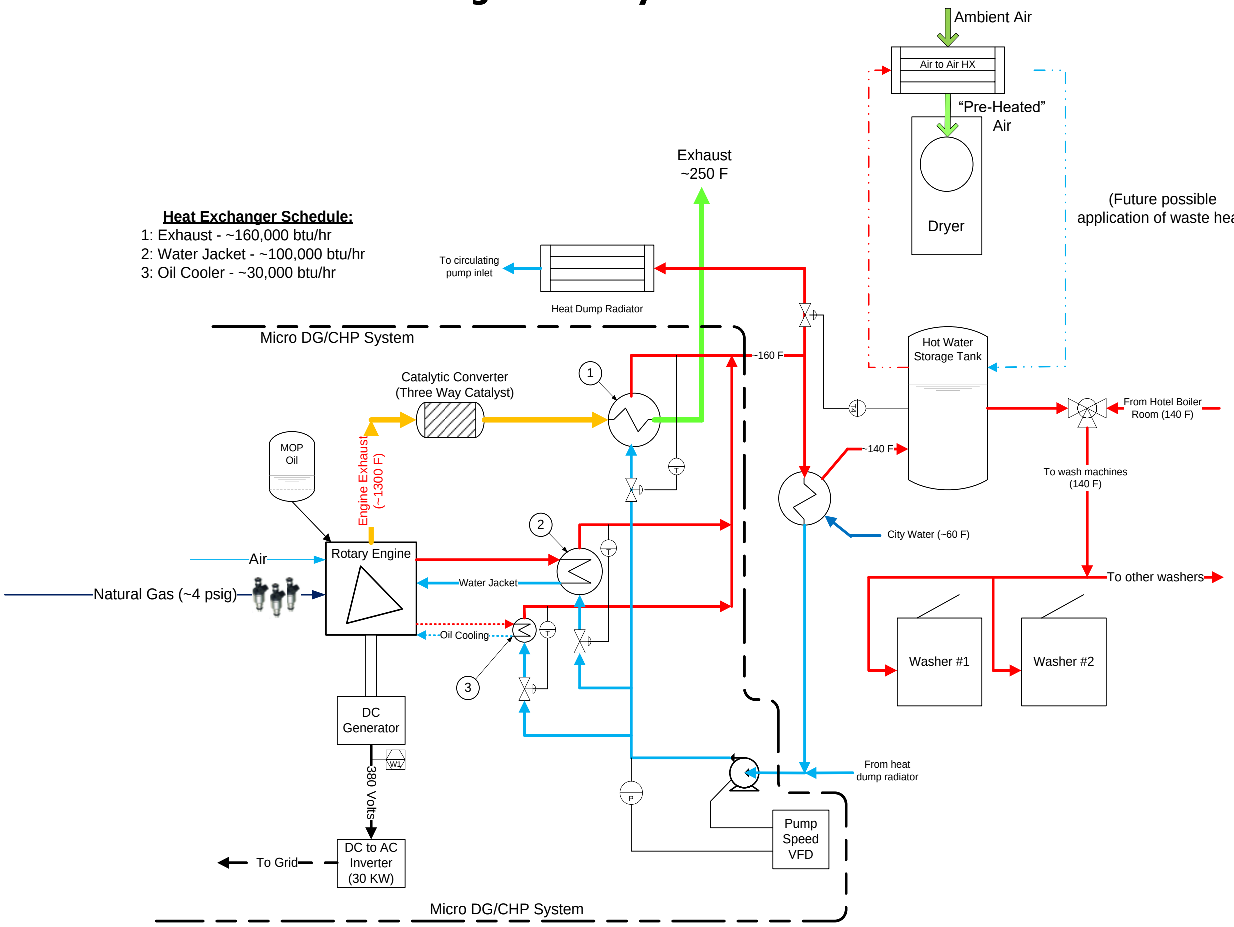
Thermal management was important on both RE units. On the open frame test mule, the proximity of the exhaust heat exchanger to the alternator required additional heat shielding and the addition of a fan to the alternator. For the housing packaged demonstration unit, the component layout was more spacious which kept components from affecting each other. However, with the housing being an enclosed cabinet, air changes were required. This was achieved with two electric automotive radiator fans pressurizing the cabinet and vent holes on the roof. Further, with the additional confinement of the demonstration site, a large exhaust fan was added to the roof of the unit to expel the hot air from the room to avoid recirculation.

CHAPTER 4: System Integration and Initial Results

Balance of Plant Design/Integration

The stand-alone microscale DG/CHP unit in this project encompasses an automotive engine with electrical generation and waste heat recovery. All that is required for it to run is 5 psi industrial natural gas service, a 480 VAC grid connection, and connection to a water heat load. Figure 14 is a pictorial representation.

Figure 14: System Schematic



Source: University of California, Irvine

The waste heat recovery system has a built in circulating pump. This makes sure it cools the engines coolant and oil since it does not have a radiator. This water from the coolant and oil heat exchangers, as well as the exhaust heat exchanger, is recovered and pumped out of the unit to its load. Water flow meters were installed on each of the three circuits, as well as an overall one for verification.

For electrical generation a DC alternator is used that mounts directly to the engine. The generated power goes into a commercially available solar inverter. This was done since the solar inverter had grid connection safety checks and interlocks.

Some of the components, mainly instrumentation, that were installed on these two prototype units would not be required on a production unit, which reduces the cost and complexity.

Test Mule/Demonstration Unit Differences

The test mule, which was used for initial testing and development of the system, was built on a strut channel frame to allow adjustability as it was being built and configuration options as more components were added. After knowing the balance of plant items required, the demonstration unit was packaged into a preexisting cabinet. Since the demonstration unit was offsite, the cabinet acted as protective barrier against people injuring themselves on moving or hot components.

Initial Testing

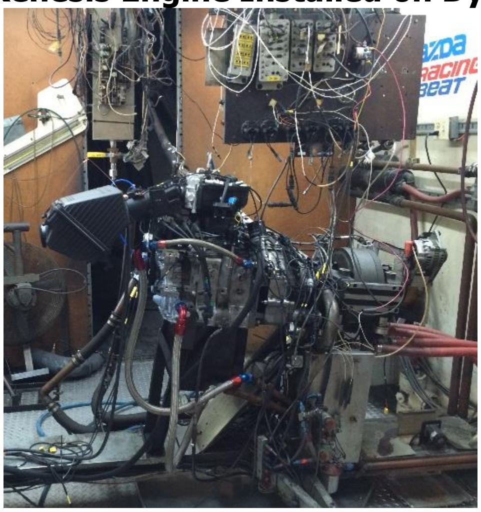
The Renesis engine for this program was initially tested at Racing Beat (Anaheim, CA) since they also assembled them, incorporating the modifications previously outlined.

Dynamometer Testing

The research team installed the engine, without the AC alternator, on Racing Beat's water brake dynamometer (Figure 15).

To provide natural gas service at the desired 4 psig pressure, Southern California Gas provided a high-pressure CNG trailer. The trailer stores 80 gasoline gallon equivalent of natural gas at 3,000 psig maximum. A two-stage pressure reduction process provided 4 psig to the fuel injection manifold of the engine.

Figure 15: Renesis Engine Installed on Dynamometer



Source: University of California, Irvine

Aside from the normal dynamometer system instrumentation, the engine was outfitted with a thermal mass flow device to measure natural gas flow. The dynamometer has a liquid flow rate device but not a gaseous one. For the exhaust gas measurements, the research team used a Horiba PG-250 portable gas analyzer. A water-cooled probe extracted a sample of exhaust gas that passed through an ice bath for water dropout before entering the sample pump. The PG-250 analyzer drew a slip stream of the exhaust gas on the pressure side of the sample pump. The PG-250 analyzer incorporates all EPA accepted protocols for O_2, CO_2, NO_x, and CO. The analyzer does not measure hydrocarbons. However, typical combustion behavior and processes will have low hydrocarbon emissions when CO emissions are low (good, "complete" combustion).

The engine operated in a "rich burn" mode as opposed to lean burn operation found for many reciprocating engines. Essentially, the engine operates at the proper stoichiometric fuel/air ratio, and oxygen concentration in the exhaust is "0"; by comparison, lean burn engines typically run at roughly 4% oxygen in the exhaust. As such, a three-way catalyst is necessary in the exhaust to reduce criteria pollutant emissions. The operating fuel/air ratio of the engine is controlled and dithered on either side of stoichiometric based upon the feedback from narrow band oxygen sensor. In response to a "rich" signal from the narrow band sensor, the engine management reduces fuel. Once lean, the fuel is increased, and the system is back to a rich condition. The frequency at which this occurs is a function of the sensor and the engine tuning. The engine management system has several tuning parameters associated with the rate of change of fuel injector adjustments that can be used to alter the behavior for the desired effect. The narrow band sensor teeters on either side of perfect stoichiometry, alternating between slightly rich and slightly lean, driving the engine management to operate the engine essentially 180 degrees out of phase with the sensor. The result of this seesaw process occurring at 100+ Hz is a pool of exhaust compounds and radicals that provides the necessary gas composition to the catalytic converter to reduce NO_x compounds and to oxidize CO and hydrocarbon emissions.

Initial tests and tuning used a standard Mazda automobile three-way catalyst designed for gasoline operation. While tests showed very low emissions of either NO_x or CO, the emission reductions were mutually exclusive (such as low NO_x, high CO and vice versa). The testing also showed a very delicate knife-edge of operation that would flop rapidly from one emission profile to another with the slightest, and sometimes undetectable, change in operating parameters. This lack of stability was not acceptable. The research team replaced the gasoline converter with a three-way catalytic converter designed specifically for natural gas. This system proved to be far more stable in operation and was retained for the balance of the dynamometer testing.

One concern is the use of a conventional gasoline automotive narrow band sensor for the engine control. The presence of higher concentrations of hydrogen in the exhaust can lead to poisoning of the narrow band sensor and lead to drifting in the operational stoichiometry and, ultimately, excessive emissions.[22] Admittedly, operational hours for the sensor were limited (fewer than 100 hours), but to this point, no evidence of calibration drift or general poisoning was noted. As a cross check of the narrow band sensor operation, a Bosch Lambda 4.9 wide-band oxygen sensor was installed immediately adjacent to the narrow band sensor to monitor the exhaust equivalence ratio. Although the researchers do not have evidence that the wide-band lambda sensor is immune to any potential poisoning and operational compromise, the ability to measure the fuel/air specifically should provide an early indicator of any issues with the narrow band sensor. Furthermore, as indicated earlier, two additional wide band oxygen sensors, one for each of the two rotors, allow monitoring of the individual rotor equivalence ratio for any airflow deviations or fuel injector issues. With the independent fuel injector banks

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22 Takushi Toda, Masato Matsuki, Tadanobu Ohmori, and Yuji Yamamoto. "Development of a 1.7 L CNG Engine for the 2001 Civic GX."; Honda R&D Co. LTD. *Honda R&D Technical Review*, Vol 14 No 1 (April 2002)

(i.e. two groups of four), one for each rotor, the fuel injector operation/duty cycle for each rotor can be adjusted to account for any rotor-to-rotor variations.

Dynamometer testing/tuning encompassed about 60 hours. The target maximum operating condition was 37 kW (50 HP). However, loads of 30 kW and 25 kW were also tested and tuned. The original target operational speed of 4,500 rpm was chosen based on consensus (UCI, Mazda, and Racing Beat), believing the high-revving but low torque engine would have difficulties producing the desired power at lower speeds. However, this perceived lack of low-end power was in error; the engine readily provides 50 HP operation at 2,500 rpm, although at this level, the throttle is wide open. Based upon a sweep of operating engine speeds ranging from 2,500 to 4,500 rpm, the target operating speed was changed to 3,000 rpm. At 3,000 rpm, the engine has a comfortable "ease" in its operation and offers additional throttle position and fuel injector duty cycle margin. The throttle is roughly 70% open, injector duty cycle about 75% at 3,000 rpm/50 HP. At 3,000 rpm, the maximum measured power output was 70 HP (100% throttle open), with a natural gas supply pressure of 4 psig.

While a discussion of all the testing and tuning efforts is beyond the scope of this report, key results of the final tune setting are shown in Table 7.

Table 7: Final Tune: Measured Engine Parameters

	Measured	**CARB Limits** **(@ 72% overall efficiency)**
Power [kW]/[HP]	37 / 50	
Fuel Flow [g/sec]		
Efficiency [LHV] / [HHV]	24% / 22%	
Exhaust Gas Temp	1250 F	
Emissions (corrected to 15% O2)		
NOx	<1 ppmvd	< 4 ppmvd
CO	<3 ppmvd	<10 ppmvd
HC	Not measured	<3.5 ppmvd
CO2	11.7	

Source: University of California, Irvine

Figure 16 are photos of the PG-250 emission readings displayed on the MoTeC screen. Admittedly, these values of "non-detect" NO_x and 0 CO seem "impossible", but they are real. It is remarkable to the team that the emissions achieved are as low (non-existent) as was measured. Yet, the measurement protocols, instrument calibration, and operations all follow appropriate engineering practices. These measurements are not just a snapshot in time; rather, the engine operated at the load for over four hours at steady state at these same levels. Admittedly, these are the results of a relatively short test on a new engine. Additional testing throughout the program will be tracked to assess the stability of these observations. These results are exceptionally encouraging for the program and the application of the rotary engine as the prime mover for a microscale DG/CHP system.

Figure 16: ECU Control System Display Screen Shots Including Emissions Analyzer Values at 25, 30, and 50 HP Settings

Credit: University of California, Irvine

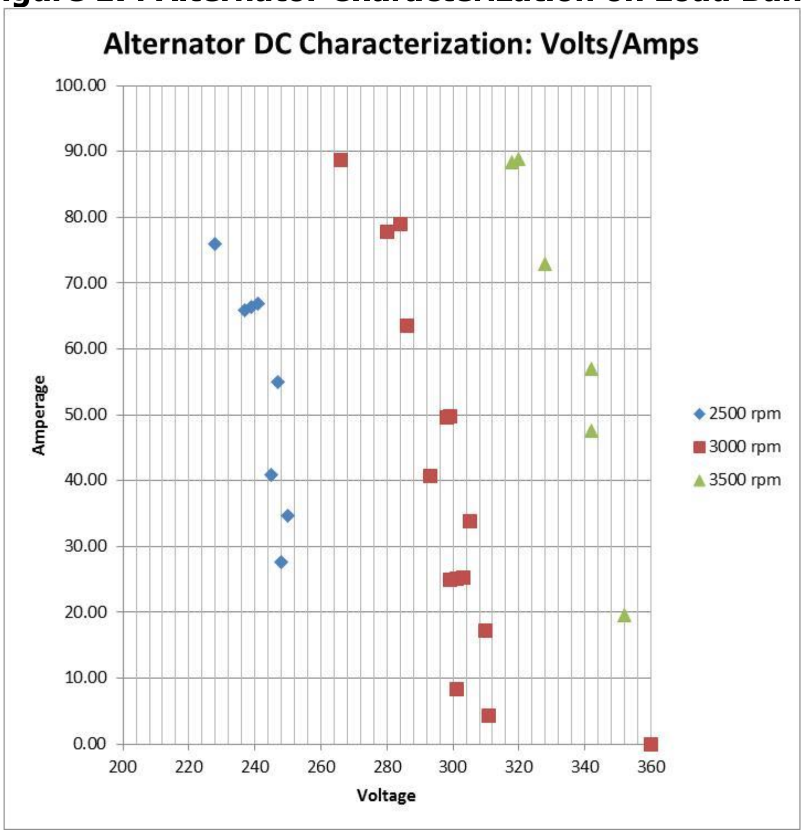
When the dynamometer testing was finished, the engine was mated to the AC alternator, the waste heat recovery heat exchangers installed, and the balance of the plant assembled and connected to the grid.

Test Bed Evaluation

As shown in **Error! Reference source not found.**, the system is about 34 inches wide, 60 inches long, and 54 inches tall. Once installed, the system was operated, and some initial performance data were obtained. The results of initial testing of the test bed unit are presented in Table 8. These values are early indications of performance of the system. At this point, the test bed is far from optimized, with many pipes and other heat loss paths. With the engine operation deemed consistent and reliable, further steps can be taken to reduce heat losses and improve overall thermal efficiency toward a goal of >70%. Figure 17 shows the first data collected from the alternator production using a DC load bank. The load bank was used to vary the load in addition to understanding what the alternator could do before connecting to the inverter.

Figure 17: Rotary Engine Microscale DG/CHP Test Bed

Figure 17: Alternator Characterization on Load Bank



Source: University of California, Irvine

Table 8: Initial Testing Results

Speed	AC Power	Fuel Flow	Electric Efficiency	Waste Heat			Overall Efficiency
			(at grid)	Exhaust	Water Jacket	Oil	
[rpm]	[kW]	[scfm]	% HHV	[Btu/hr]	[Btu/hr]	[Btu/hr]	%HHV
2750	21.2	6.20	19.4	94500	75650	6300	66
3000	25.1	7.46	19.7	103500	89460	6300	64
3250	30.4	8.67	20.0	121500	102250	6300	64

Recommendations for Upgrades

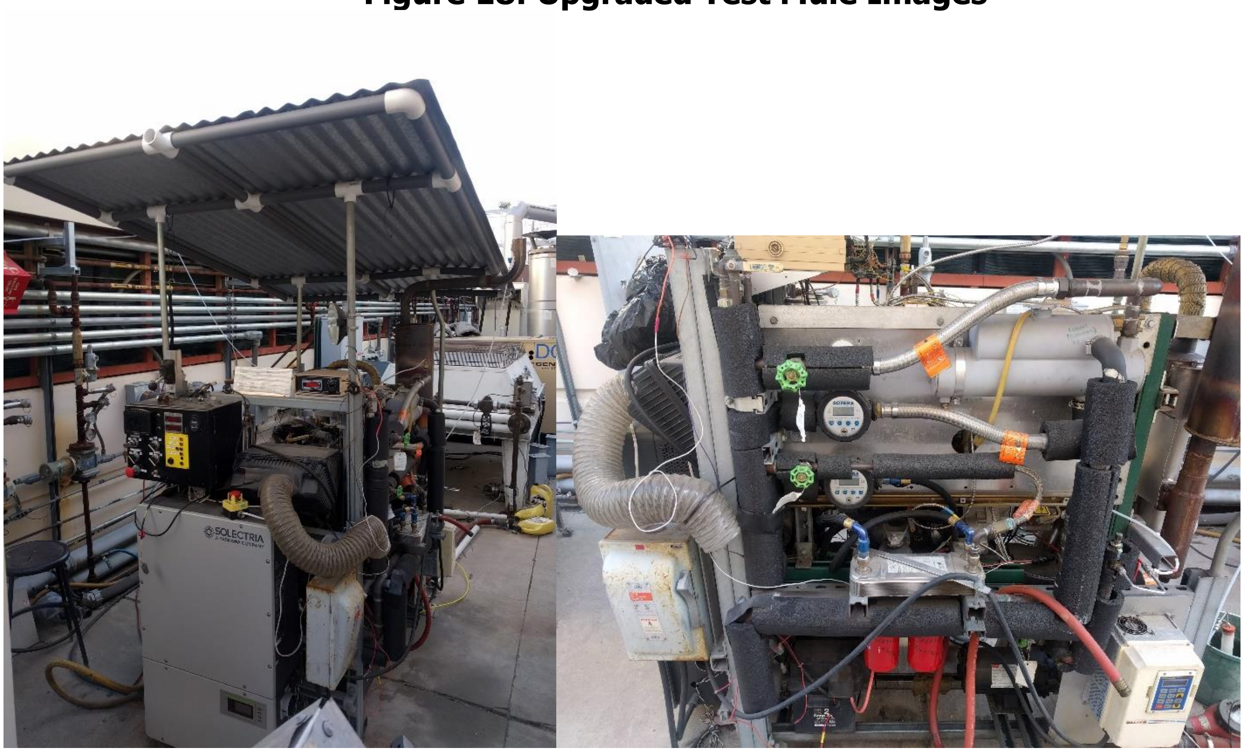
From the preliminary data, it is apparent that the oil system was producing more heat than originally estimated. The oil heat exchanger capacity needed to be increased. Another concern was the thermal couple readings. The research team discovered at times that the connections at the readout became contaminated causing the readings to be off a few degrees centigrade occasionally. When the overall water temperature change was 10 degrees centigrade, a few degrees affected the performance drastically. Secondary temperature checks need to be performed at times to verify the readings. Changes in alternators and heat exchange strategies were also warranted, but generally the initial tests indicated reasonable performance, especially for emissions. These changes were implemented and the resulting upgraded test mule system was further evaluated.

CHAPTER 5:
System Performance Testing

Instrumentation/Setup

For the system performance testing of the upgraded system, ROOTS® meters (rotary type positive displacement gas meters) were used in conjunction with a pulse counter and temperature and pressure gauges to measure the fuel energy input. For heat recovery, Sotera water flow meters were installed at the inlet to the three heat exchangers, along with thermal couples at the exit of the heat exchangers. In addition, an OMEGA™ water flow totalizer metered the overall flow going into the rig with additional thermal couples for overall temperature differential. The Yaskawa-Solectria inverter provided DC voltage and current input, as well as AC kilowatt output. Horiba PG 250/350's were used to measure emissions. Figure 18 is the upgraded test mule configuration. The right image shows the flat plate oil heat exchanger just above the two red oil filters at the bottom center of the image.

Figure 18: Upgraded Test Mule Images



Source: University of California, Irvine

Results

Following are results of testing the test mule during a 15-minute window after it reached equilibrium.

Efficiency

With upgrades to the oil heat exchanger and different alternators, the overall efficiency was improved up to 75% (Table 9).

Table 9: Upgraded System Testing Results 1

Speed	AC Power	Fuel Flow	Electric Efficiency	Waste Heat			Overall Efficiency
			(at grid)	Exhaust	Water Jacket	Oil	
[rpm]	[kW]	[scfm]	% HHV	[Btu/hr]	[Btu/hr]	[Btu/hr]	% HHV
3030	24.6	7.21	18.9%	114505	104095	29741	75.2%

Source: University of California, Irvine

Emissions

Table 10 lists the limits for stationary generation for CARB certification. It also lists the average limits allowed for automobiles to pass the California smog check as a comparison of the stringent regulations. Table 11 summarizes the emission results with all of the upgraded components installed. Unlike what was observed on the dynamometer testing, these emission numbers are likely more representative of typical operation. It is noted that these numbers were obtained prior to additional tuning of the MoTeC ECU. While the CO is higher than allowed, the NO_x is about 11% of the CARB level. Since CO and NO_x are inversely proportional, this does indicate room for tuning to be done to decrease the CO and increase NO_x as a result.

Table 10: CARB Certification Limits

	Emission Max Concentration Allowed (ppmvd) @15% O2		
	Engine Only (w/o heat recovery)	Engine + 225,000 Btu/hr heat recovery (η=70%)	CA Smog Check[23]
NOx	1.0	4	400 - 500
CO	2.5	9.7	4000 - 5000
HC	0.9	3.4	50 - 75

Source: University of California, Irvine

23 Actual emission levels for smog checks depend upon the make, model and year of vehicle. These numbers represent the typical range.

Table 11: Emissions From Upgraded System Test

	Emission Max Concentration Allowed (ppmvd) @15% O2
NOx	0.45
CO	66.9

Hydrocarbons were not measured for this test; however, HC typically track with CO; low CO -> low HC

Source: University of California, Irvine

Availability

The availability of this microscale DG/CHP unit is high. A quantitative value was not assessed; however, the test mule unit had multiple stints of running for multiple weeks 24 hours a day 7 days a week. Being an automotive engine, it is also capable of multiple on/off cycles a day to follow demand.

CHAPTER 6: Demonstration Testing

Site Overview

riginally, the St. Regis Monarch Beach Resort was planned to be the demonstration site (Figure 20). The resort was working on its own water reclamation project that would allow the microscale DG/CHP unit to add on with minimal infrastructure additions. Onsite electrical data were collected from the laundry, and past use data for the utilities were provided. The laundry load was near the 30 kW of anticipated generation from the microscale DG/CHP unit, which made for an excellent match. Unfortunately, during the project, the resort was sold, and management was changed. It was not an ideal time for the new management to host a research project demonstration. In reaction, other sites were sought after. With limited time to find a new site, the Anteater Recreation Center (ARC) in Irvine, California became the most feasible for demonstration and the personnel involved were very receptive and interested in the project (Figure 21).

Figure 20: Example of St. Regis Laundry Equipment

The ARC is a multiuse building with offices, gymnasium, and a pool. It has its own laundry facility onsite to support towel and uniform service. It was previously serviced by two 120-gallon, 400,000 Btu/hr water heaters plumbed into a recirculating 300-gallon (approximate) hot water storage tank. This hot water also provided service to the 20 showers contained within the locker room.

Figure 19: ARC Installation

The installation is located through the open door in the lower right of Figure 19.

Credit: University of California, Irvine

Specific Concerns

Depending on the installation site, different concerns will arise. The original installation location at the hotel site was going to be in a parking garage which eliminated concerns with noise within the laundry facility itself as well as providing ample space for positioning and access. Access to the needed electrical and water utilities was extremely convenient. The ARC site revealed new concerns.

Sound Pollution

The room where the demonstration unit was installed had an open roof and was adjacent to the pool. This brought up a main concern from the facility; the demonstration unit could not disrupt the pool users.

Modification to Site

The ARC site had the required infrastructure; however, it was not located in the installation room. Water had to get plumbed through the wall since the hot water storage tank was in the next room. Three–phase, 480 VAC power with neutral and ground had to be run into the room. A five psi natural gas line was running through the room, so it just needed to be tapped into. An outside contractor approved by the facility performed all the construction. Figure 20 shows the added infrastructure to the host site.

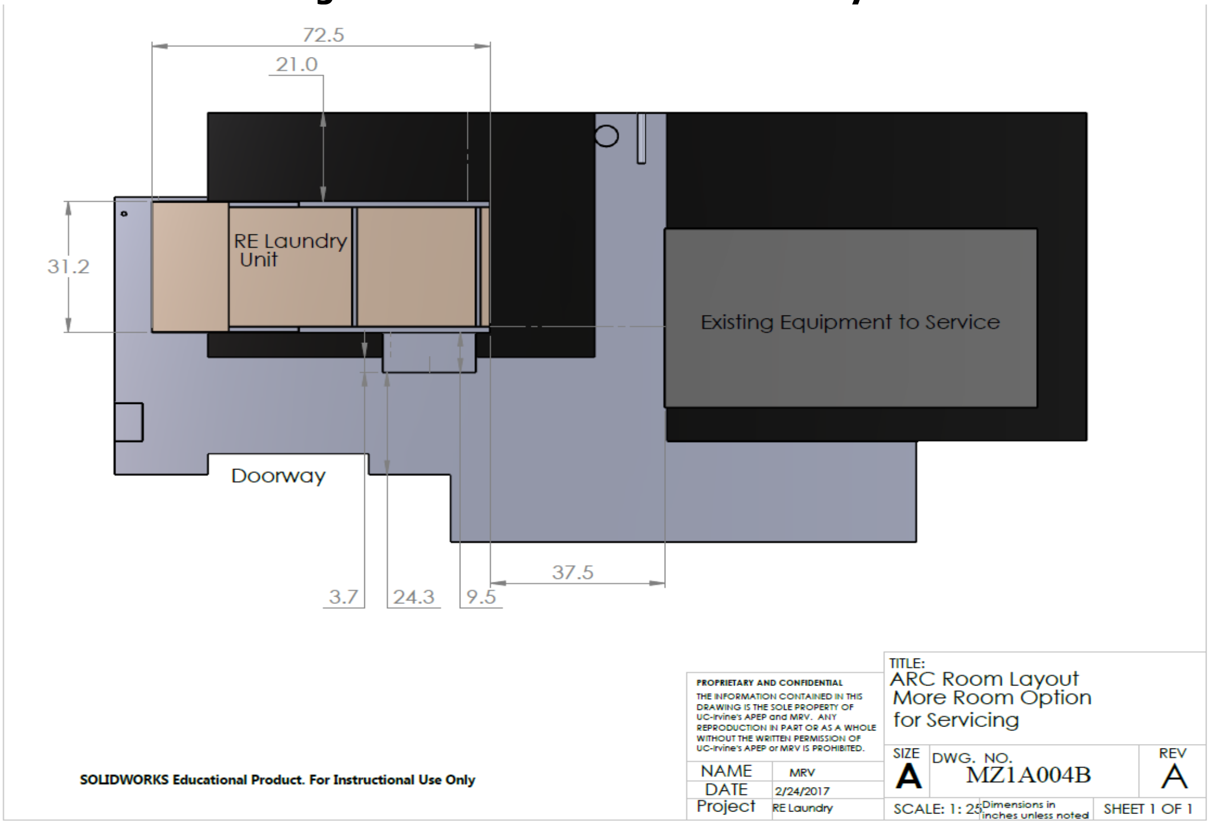
Figure 20: Electrical, Gas, and Water Installation at the Host Site for Demonstration Unit

Credit: University of California, Irvine

Installation Aspects

Moving the demonstration unit into place was challenging. The only access to the room was through a single door with an 8-inch-high threshold. In addition, there was roughly six feet to the back wall from the doorway. From there, the unit had to be rotated 90 degrees to the installation location (Figure 21 and 24).

Figure 21: Demonstration Room Layout



Source: University of California, Irvine

Figure 22: Images of Moving the Demonstration Unit to the ARC

Credit: University of California, Irvine

Results

This section presents the results from the demonstration site. The emphasis was on attaining performance information in terms of overall efficiency.

Spot checks of sound generated were taken with a cell phone application.[24] In late evening with the ARC facility closed to users during a break, the outside measurement was 55 decibels (dB) with the engine off. Since this test was done after hours, none of the normal equipment

24 Decibel X by SkyPaw Co. Version 6.1.

was on that would increase this baseline value. Ninety-five dB were measured inside the enclosed room (~2 feet from the unit) while the unit was fully loaded. Outside with and without the access door closed yielded a reading of 63 dB. Qualitatively, it was a different tone than the normal equipment with a similar level. Acoustic mitigation could be readily accomplished with added damping material to the system enclosure.

To mitigate any concerns with impact on facility operations, the initial running of the demonstration unit at the ARC required coordinating times with the facilities manager. On a night when the building closed at 6 p.m. instead of 1 a.m., the demonstration unit was finally able to be run. The traditional hot water heaters were shut off hours before to allow the hot water storage tank to cool down. This was necessary so the unit could be fully loaded right away without overheating. The engine was started when the hot water tanks temperature was at 77 degrees Fahrenheit. Some hot water was bled off as the demonstration unit was getting going. Even doing so, the hot water tank got back up to 96 degrees Fahrenheit 34 minutes after starting, illustrating that the relatively small thermal load would require considerable cycling of the engine to avoid overheating. While beyond the scope of the current project, other thermal loads within the ARC property (e.g., pool heating, space heating, both of which have separate services) could provide a means to allow a higher engine duty cycle.

Efficiency

Performance results from the demonstration unit test can be seen in Table 2. Comparing the demonstration unit test to the test mule tests yielded expected similarities. The electrical efficiencies are within 0.4% of each other at 19.3% and 18.9%. The alternators between the two units are slightly different windings, which is one reason the AC power is 27.05 kW on the demonstration unit instead of 24.6 kW on the test mule. Fuel flow is within 0.5 scfm, since both engines operated near 3,000 rpm and with similar alternators. The research team added more controls with the MoTeC system on the demonstration unit to have fixed rpm ranges with the throttle. In addition, the heat recovery splits are nearly the same for the exhaust and oil, while the water jacket waste heat was significantly greater for the demonstration unit. The plumbing was approached slightly differently for the two units. The test mule used mainly copper pipe, while the demonstration unit used convoluted hose with JIC connections from Brown and Miller Racing Solutions for convenience in taking the connections on and off and flexibility in tight spaces. The results for the demonstration unit, although from limited testing, shows overall efficiency in excess of 80% which is very impressive. Emissions testing was not conducted due to the short duration of the run.

Table 12: Demonstration Testing Results

Speed	AC Power	Fuel Flow	Electric Efficiency	Waste Heat			Overall Efficiency
			(at grid)	Exhaust	Water Jacket	Oil	
[rpm]	[kW]	[scfm]	% HHV	[Btu/hr]	[Btu/hr]	[Btu/hr]	% HHV
3000	27.05	7.79	19.3	109,747	155,480	28,938	80.9

Source: University of California, Irvine

Availability

The availability of the demonstration unit was not able to be tested due to limits of the demonstration site. The ARC was an alternate demonstration site after an unforeseen sale of the previous demonstration site made it an inopportune time to deploy new equipment there. The hot water tank of the ARC feeds the laundry as well as the showers. The building is open on average 19 hours a day, and the facilities managers did not want to affect the water temperature. Testing times had to be arranged when the tank could be made cold to allow the heat recovery to be captured. As mentioned, future effort could involve having the demonstration unit offset other thermal needs such as pool heating and space heating for the facility.

CHAPTER 7: Project Benefits

System Operating Conditions

This analysis aims to summarize the economic benefits for operating a natural gas-fueled rotary engine (RE) based distributed generation system with waste heat recovery with the goal of providing heat and power for use at the laundry facility at the UC Irvine Anteater Recreation Center (ARC).

The system is expected to generate about 25 kilowatts (kW) at 17% engine efficiency of energy conversion to shaft power. An estimate of 294,790 Btu/hour was determined for possible waste heat recovery, in the form of water/oil jackets and exhaust heat exchangers. Essentially, this low power DG/CHP[25] will be operated to assist with the electricity and hot water loads of the laundry during hours of high demand. The electricity that is produced will decrease costs associated with both energy usage (kilowatt-hours, kWh), as well as monthly demand charges (kilowatts, kW). As for hot water demand, the waste heat recovery will be able to serve the average base load during peak hours and decrease natural gas fuel costs associated with increased use of boilers the facility uses to meet the hot water demands. The only costs coupled with operating the DG/CHP system are the fuel (natural gas) required, as well as a $0.02/kWh estimated cost to account for routine maintenance over the life of the system. The following summary examines the most important factors to consider for the deployment and operation of the system in question and offers an evaluation of the overall economic benefits of the system in the present year.

Installation Site

The location for implementation of the system as previously described is the laundry facility at the UC Irvine Anteater Recreation Center (ARC) in Irvine, CA. Metering equipment was installed at the facilities to record electricity usage at five-minute intervals beginning in July 2016. The location of the ARC is within the service areas of the Southern California Gas Company (SoCalGas) for delivery of natural gas and Southern California Edison (SCE) for delivery of electric power. For this analysis, all costs associated with the gas or electricity provided were determined using available data from each of these utilities, unless stated otherwise.

Electricity Costs

For determining the costs of electricity, it is important to understand the rate structure provided by SCE. The rate that utilities charge depends on the month of the year, the hour of the day, and the type of electricity used. Table 13 summarizes the rate schedule chosen to understand the electricity costs associated with the ARC laundry facility.

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25 Distributed generation/combined heating and power.

Table 13: SCE Monthly Electricity Rates (TOU-8 Option B, Effective June 1, 2017)

	Service Level	Type	Winter Rate	Summer Rate	Rate Unit
Delivery	Peak	energy	$0.00000	$0.02336	$/kW-hr
Delivery	Semi-peak	energy	$0.02336	$0.02336	$/kW-hr
Delivery	Off-peak	energy	$0.02336	$0.02336	$/kW-hr
Generation	Peak	energy	$0.00000	$0.07072	$/kW-hr
Generation	Semi-peak	energy	$0.04579	$0.04730	$/kW-hr
Generation	Off-peak	energy	$0.03645	$0.03165	$/kW-hr
Generation	Peak	demand	$0.00	$18.97	$/kW
Generation	Semi-peak	demand	$0.00	$3.58	$/kW
Delivery	Facilities Related	demand	$18.34	$18.34	$/kW

Source: University of California, Irvine

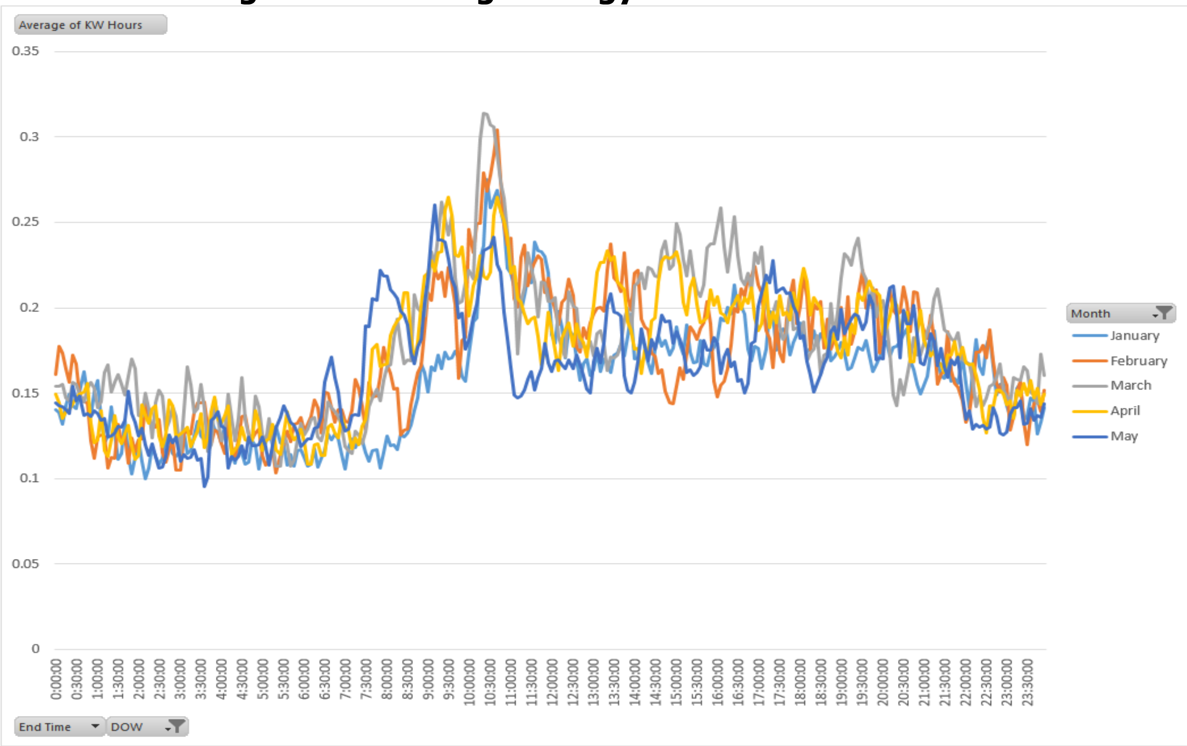
It is important to first make the distinction between how SCE differentiates the summer and winter period for each year. SCE considers only four months, June through September, as summer months, and the other eight months is considered the winter period. As can be seen, summer rates differ from winter rates in that they are generally higher and they include a "peak" service level, whereas there are no "peak" charges during the winter period. Next, it is important to differentiate the different service levels with respect to the hour of the day. For SCE, "peak" hours occur only during summer weekdays, during the hours between 12 p.m. and 6 p.m. "Semipeak" hours for a summer weekday are 8 a.m. to 12 p.m. and 6 p.m. to 11 p.m., while for a weekday during the winter period, the "semipeak" hours are from 8 a.m. to 9 p.m. These hours are characterized by higher costs per kilowatt-hour for energy use and per kilowatt for maximum demand. All other hours of operation, including weekends and holidays, fall under the "off-peak" service level. In the following energy cost and benefit analysis, the focus is on data collected during the winter period (January 2017 through May 2017) as the data collected during this period is complete.

Current Energy Costs

Before calculating the electricity costs, it is helpful to understand the typical power load of the laundry facility being investigated. In

Figure 23 and Figure 24, the average electrical load (in kWh per five-minute interval) is plotted for each month during the winter period of the current year. For a typical weekend day (Saturday or Sunday), there seems to be a consistent trend throughout the year of low electric power use in the early morning hours following by a spike in energy use between 10 a.m. and 11 a.m. The load curve for a weekend differs from a typical weekday load curve because on a weekday, there is no obvious spike in energy use. During the week, the energy use in kWh is slightly greater on average than on the weekend, with most of the use occurring during the semipeak period.

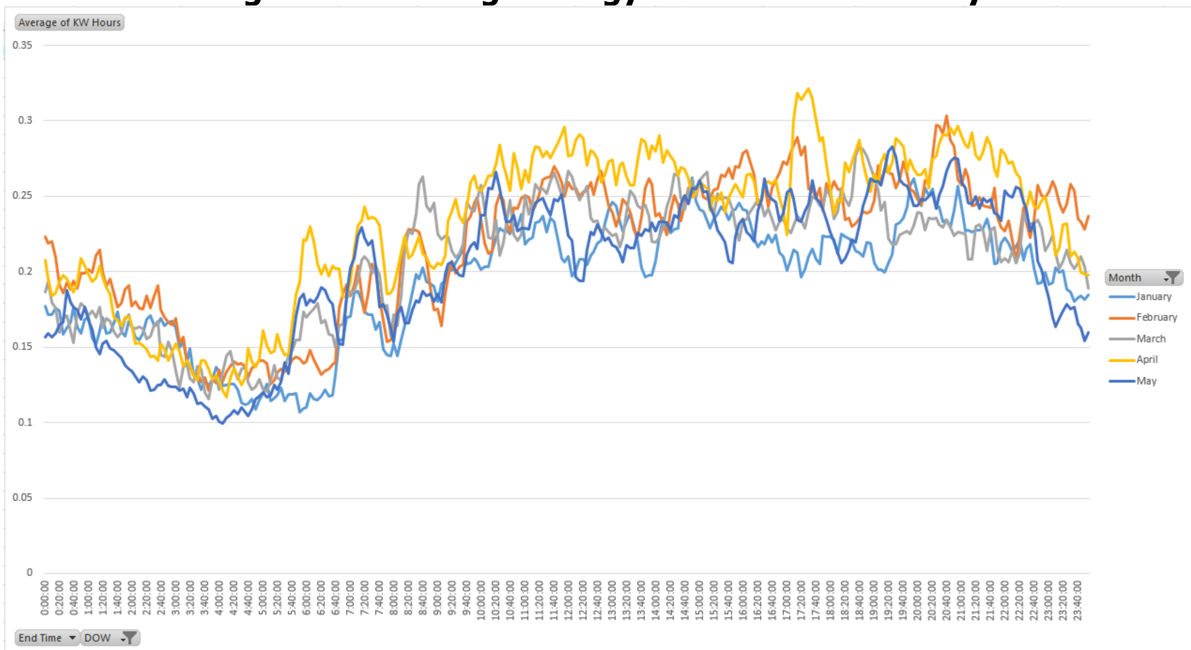
Figure 23: Average Energy Use Winter Weekend



Average energy use (kWh per five-minute interval) for ARC laundry for a typical Saturday/Sunday during the winter period

Source: University of California, Irvine

Figure 24: Average Energy Use Winter Weekday



Average energy use (kWh per five-minute interval) for ARC laundry for a typical weekday during the winter period

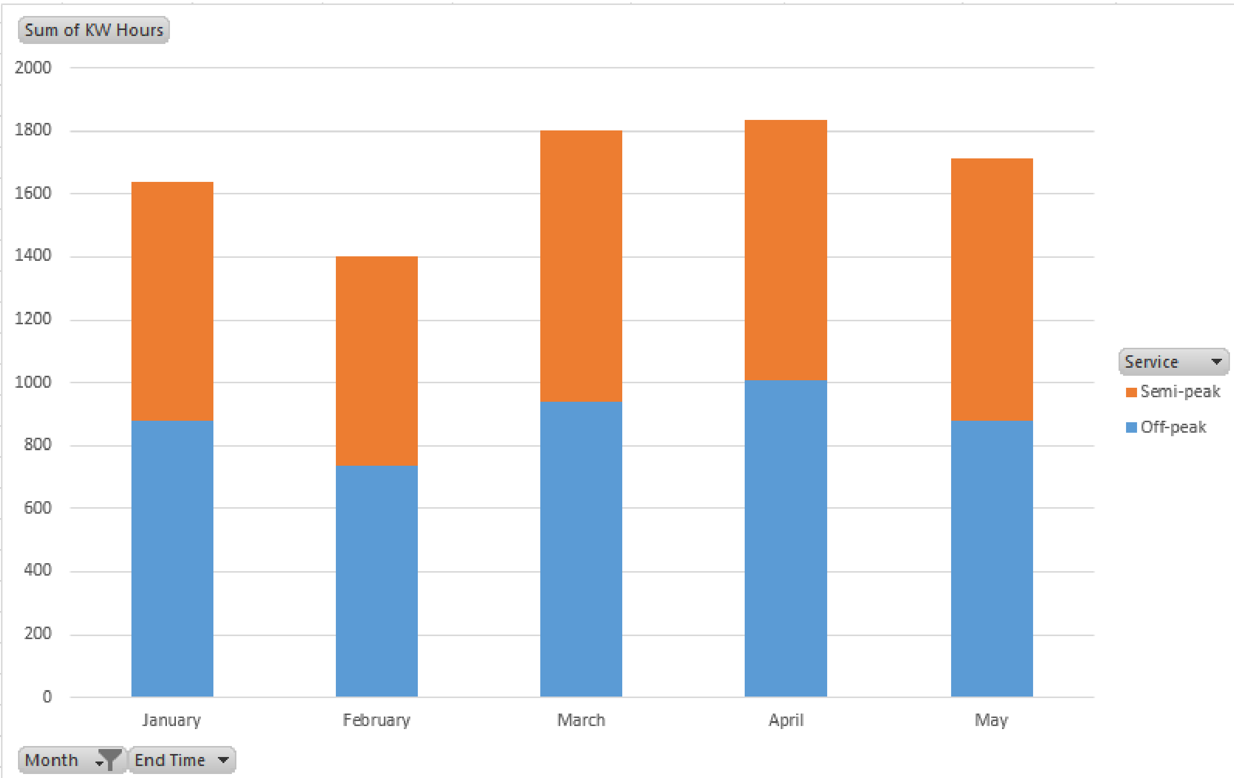
Source: University of California, Irvine

To assist with the cost analysis, calculations of the total energy use (kWh) per month, as well as the maximum power (kW) recorded per month, were done and are shown in Figure 25 and Figure 26.

Combining these results and using the winter rate schedule provided in Table , the total electricity costs are calculated and summarized in Source: University of California, Irvine

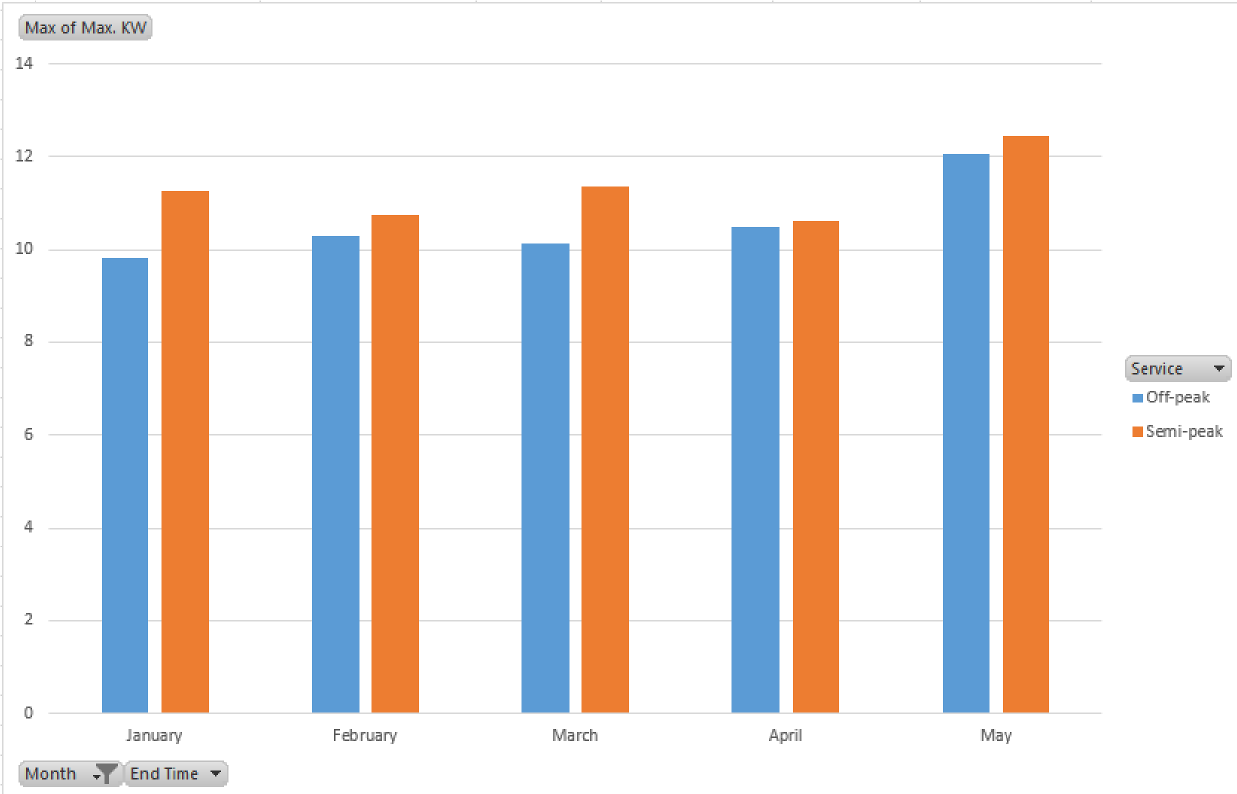
Table . From this table, it is evident that most of the cost is due to the demand charge, which is calculated based on the maximum power demand (in kW) at any hour for a given month. In the next section, the approach for implementing the RE DG/CHP system is discussed in detail, with the largest savings benefit resulting from a decrease in the demand of the entire laundry facility load.

Figure 25: Comparison of Total Energy Use (kWh) per Month During the Winter Period



Source: University of California, Irvine

Figure 26: Comparison of Maximum Load (kW) per Service Level per Month during the Winter Period



Source: University of California, Irvine

Table 14: Electricity Use Costs for the ARC Laundry Facility During the 2017 Winter Period

Month	Energy (kWh)	Demand (kW)	Total
January	$104.98	$386.55	$491.53
February	$90.12	$385.47	$475.59
March	$115.61	$393.69	$509.29
April	$117.33	$387.23	$504.56
May	$110.09	$449.79	$559.88
Grand Total			*$2,540.85*

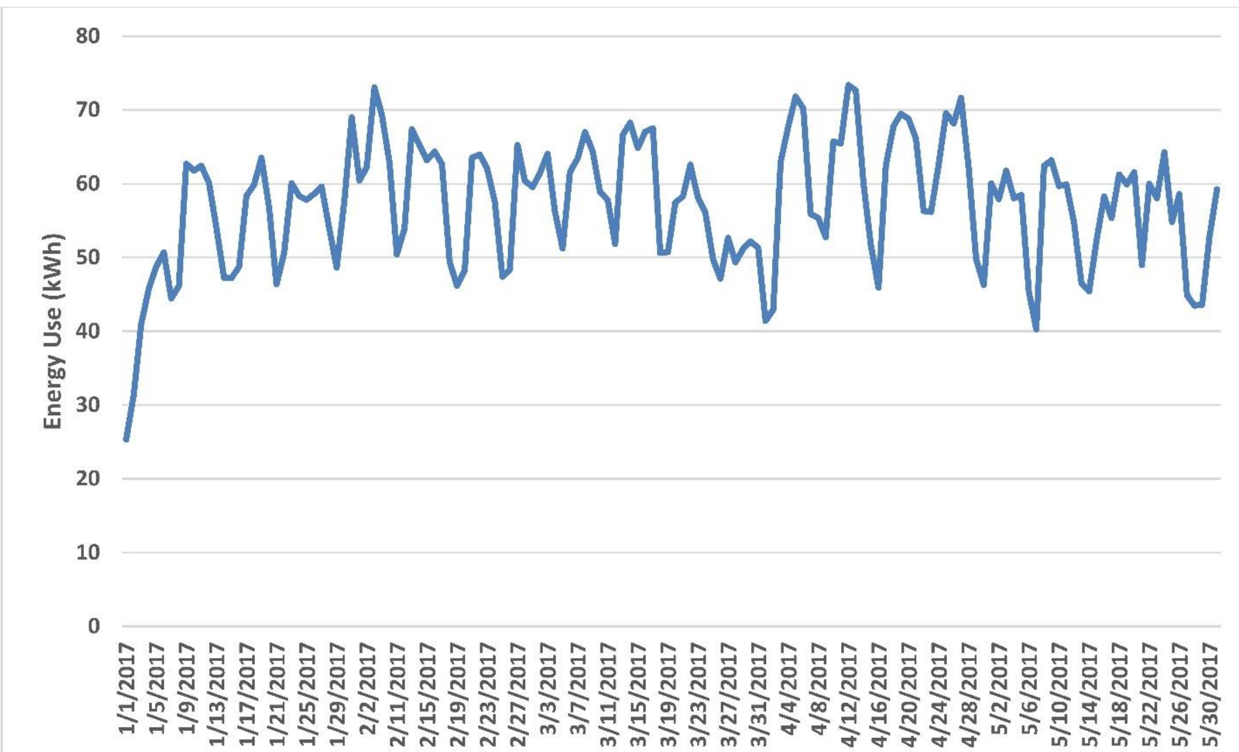
Source: University of California, Irvine

Evaluation of Costs and Benefits

For this analysis, the amount of hours of operation for the system was determined based on maximizing use of the system while allowing for down time for occasional maintenance and to promote a longer engine life. This analysis based calculations on 16 hours per day operation of the RE DG/CHP, geared toward operating only during semi-peak and on-peak hours during the week, which is when the highest rates for electricity are charged. During the summer, the schedule would cover the 15 hours of semi-peak and on-peak electrical service, and the 13 hours of semi-peak service in the winter. Given that the main focus of this analysis is on data collected during the winter months, the preliminary schedule was chosen to be 6 a.m. to 10 p.m., where 6 a.m. to 8 a.m. are off-peak hours, 8 a.m. to 9 p.m. are semi-peak hours, and 9 p.m. to 10 p.m. is another off-peak hour. For consistency, the same schedule was applied to weekends.

The RE DG/CHP system was assumed to operate at a constant generator power output of 25 kW; therefore, the electrical output for a 16-hour day on average would be 400 kWh. Recalling the total energy use of the laundry facility in kilowatt-hours per month calculated and presented in Figure 25, the RE DG/CHP system would need to operate for only 3-5 days for 16 hours each day to meet the required capacity of the facility (roughly 1,200 kWh to 2,000 kWh per month). This is further exemplified in Figure 27, where the average energy use per day during the winter months ranges only from about 40 kWh to 75 kWh. For the current installation, the system capacity is deemed larger than necessary; however, this is only when compared to the electrical load of the laundry facility. Considering this facility is within a larger recreation center, the excess energy produced (kWh) by the generator will be useful and accessible to other facilities within the same building.

Figure 27: Total Energy Use (kWh) per Day During the Winter Months of the Current Year

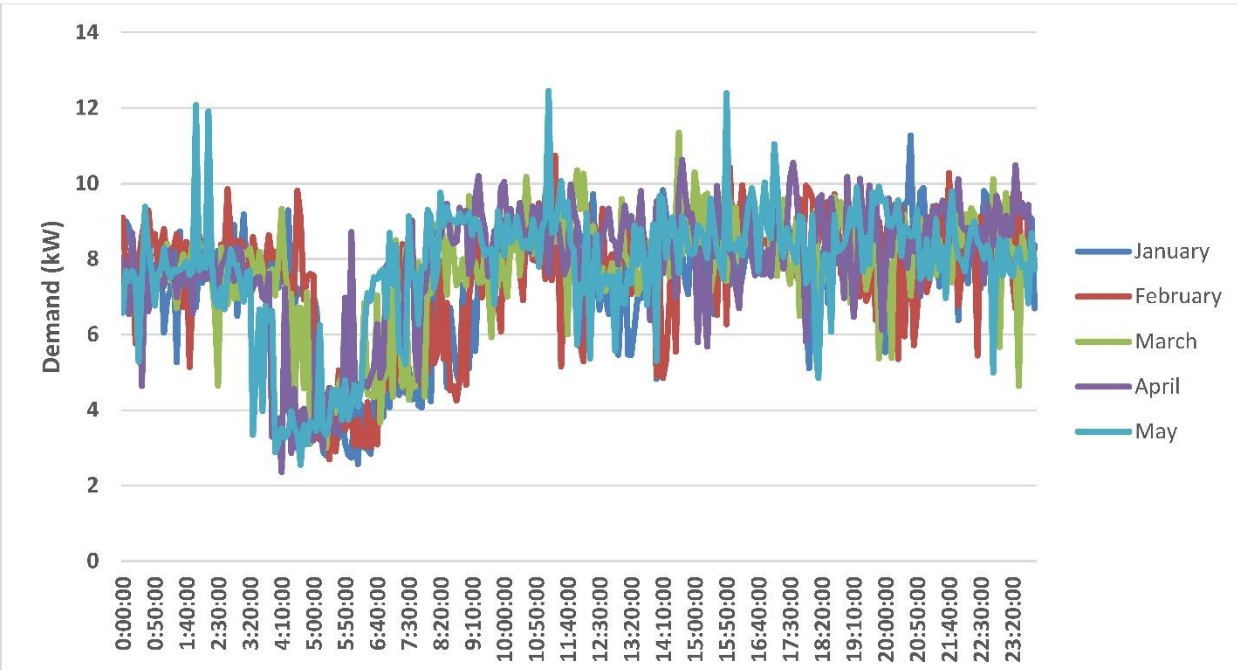


Source: University of California, Irvine

As was shown in Table , the electric power demand (kW) charges can be on average 3.75 times the cost of total energy use (kWh). It is evident that lowering the maximum monthly kilowatt demand (maximum electric load averaged on a 15-minute interval) is the deciding factor for economic benefits. This is especially true for operation during periods of high demand charges, such as in the summer.

Figure 28 shows the maximum power demand (kW) for each 5-min interval in a given day for each 2017 winter month for the current installation. For this laundry facility, it is clear that the 25 kW RE DG/CHP system will be more than enough to completely cover the highest power demand; however, with a 16-hour schedule for operation, the intended prevention of demand charges may not be achieved. For example, if the RE DG/CHP system were to have been operating 6 a.m. to 10 p.m. every day in January, the demand charge would decrease since the demand peak occurred around 9 p.m. However, if the system were to have operated on the same schedule during May, there would be a minimal, if any, decrease in the demand charge as there were very large demand peaks during the early hours of at least one day in May.

Figure 28: Maximum Power Demand (kW) for Any Given Hour/Day During the Winter Months of the Current Year



Source: University of California, Irvine

To achieve the maximum savings for the RE DG/CHP system, it is imperative to use the electricity provided by the generator to meet the power demand and electrical energy use throughout the entirety of each day instead of only during a 16-hour window. In practicality, the only option to achieve this is to supplement the RE DG/CHP system with energy storage, which would discharge during the non-operative system hours of each day. After analyzing the electrical data for this winter period, the required capacity to manage the electrical load during the 8-hour "overnight" period is about 26.7 kWh. A new schedule was also proposed where the system would run for 23 hours (for example start at 7 a.m., end at 6 a.m. the next day), allowing one hour of downtime. For this scenario, energy storage is still necessary, although the required amount of storage is smaller than the previous case at approximately 4.4 kWh. Further investigation into the type of energy storage as well as to the nature for charge/discharge is necessary before confirming an appropriate size.

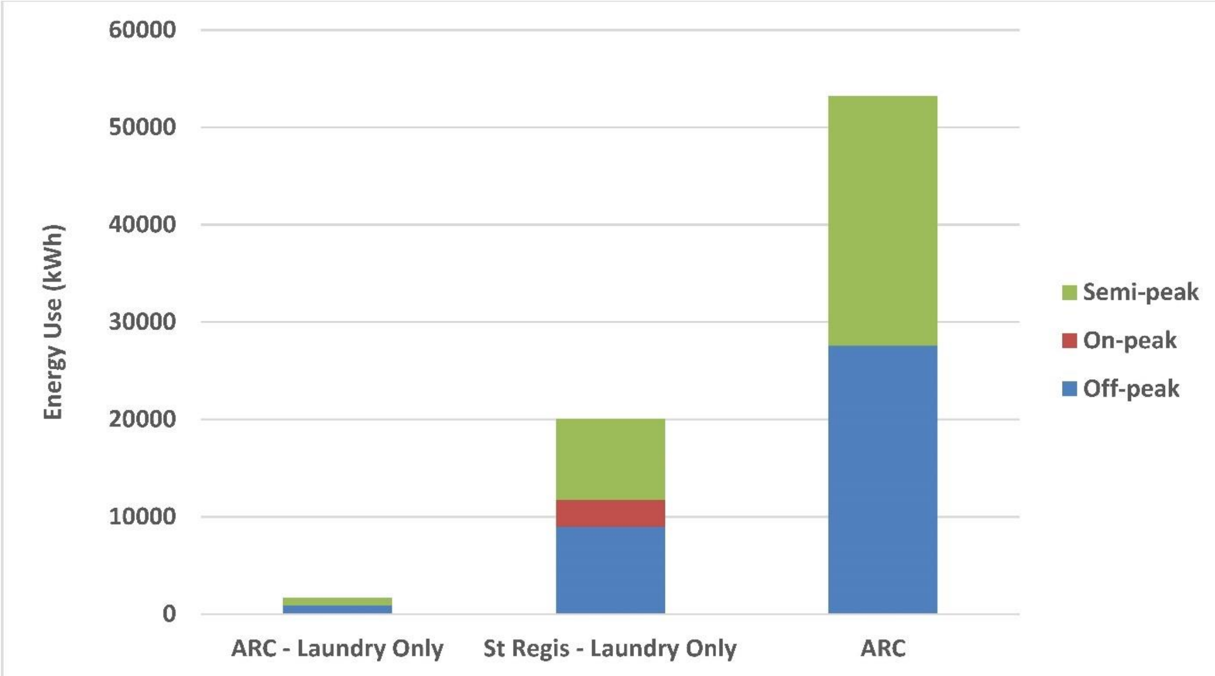
Overall, although the RE DG/CHP system is "oversized" for the electrical energy and power demand of the laundry facility for this demonstration, benefits for the system were still able to be determined under the following assumptions. The RE DG/CHP system will operate at an optimal 25 kW of power and provide 400 kWh a day assuming an operating schedule of 16-hour per day. Excess energy (kWh) and power (kW) are assumed to be used in other areas of the recreation center (outside the laundry) in addition to being stored for use during non-operation of the RE DG/CHP system. The costs associated with the operation of the RE DG/CHP include fuel input of 494,714 Btu/hr, with natural gas as the fuel at a cost of 41.687 cents/therm, and an estimated O&M cost of $0.02/kWh. Along with the electrical savings due to the on-site energy (kWh) and power (kW) generation, it is assumed that the facility will also make use of the estimated 294,790 Btu/hr in waste heat recovery. Considering all these conditions, the ideal operation of this RE DG/CHP system will result in about $3,010 in net energy savings over the five-month period covered in this analysis.

System Sizing Relative to Installation Site

The laundry facility at the ARC is one of many possible installation locations for this RE DG/CHP system. Due to the relatively small energy use and power demand of this laundry facility, the system has been deemed oversized and certain challenges are presented with respect to the full use of the generated power and available waste heat. The benefits of the RE DG/CHP system can be better demonstrated by matching the maximum generated power and waste heat of the engine more closely with the energy use and power demand of the installation site. In addition to the laundry site at the ARC, electrical data were also collected at the laundry facility of the St. Regis Monarch Beach Resort in Dana Point, California as this facility was originally proposed as the RE DG/CHP demonstration site. The following figures compare the total energy use (kWh), maximum power demand (kW), and typical daily electrical load curves for the two previously discussed potential installation sites for the RE DG/CHP system.

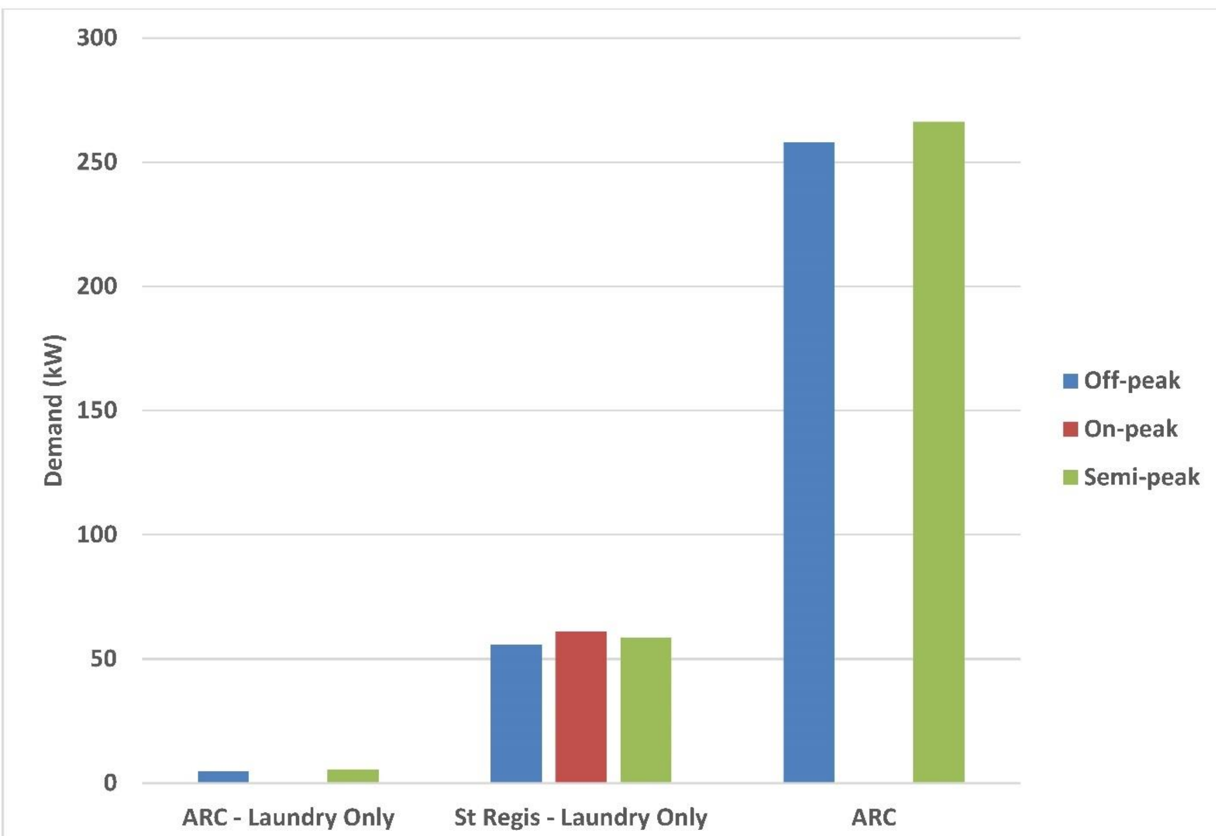
From Figure 29 to Figure 32, the three sets of data that are analyzed and plotted are from the load of the laundry facility at the ARC, the total electrical load of the entire ARC facility, and the load of the laundry facility at the St. Regis hotel. In Figure 29 and Figure 30, it is clear that the laundry facility at the ARC uses a small amount of energy and requires a much smaller demand relative to the entire facility (roughly 3% of the monthly energy use in kWh, and about 1.9% of the monthly demand in kW). The laundry facility at the St. Regis hotel has an electrical load more than 10 times larger than the laundry facility at the ARC and contributes more to the total energy use and demand of the entire hotel (about 6.6% of the monthly energy use in kWh and roughly 9.8% of the monthly demand in kW). As previously mentioned, the RE DG/CHP system will provide 400 kWh a day, assuming a 16-hour per day operation schedule, which translates to an average of 12,000 kWh a month available for use by the installation facility. Figure 29 confirms that this system is oversized for the ARC laundry; however, the energy demand of about 20,000 kWh a month of the St. Regis laundry validates the choice of the St. Regis facility as a more appropriate choice for the installation location. The claim is supported by comparing the power demand of each facility in Figure 30. The optimal generated power of the RE DG/CHP system is 25 kW, which is about five times greater than the maximum power demand of the ARC laundry facility. The average maximum power demand of the St. Regis laundry is slightly greater than 50 kW, which would make it a more suitable candidate as an installation location for the RE DG/CHP system.

Figure 29: Comparison of Total Energy Use (kWh) by Location in January



Source: University of California, Irvine

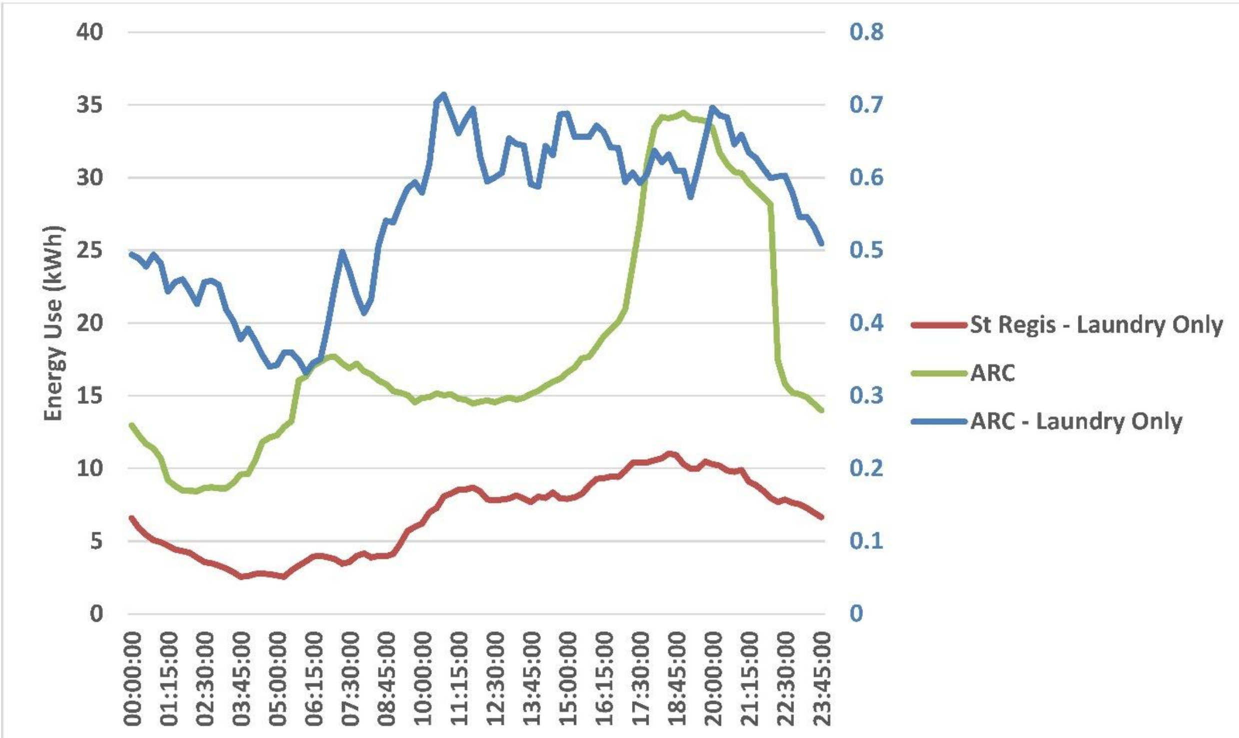
Figure 30: Comparison of Maximum Demand (kW) by Location in January



Source: University of California, Irvine

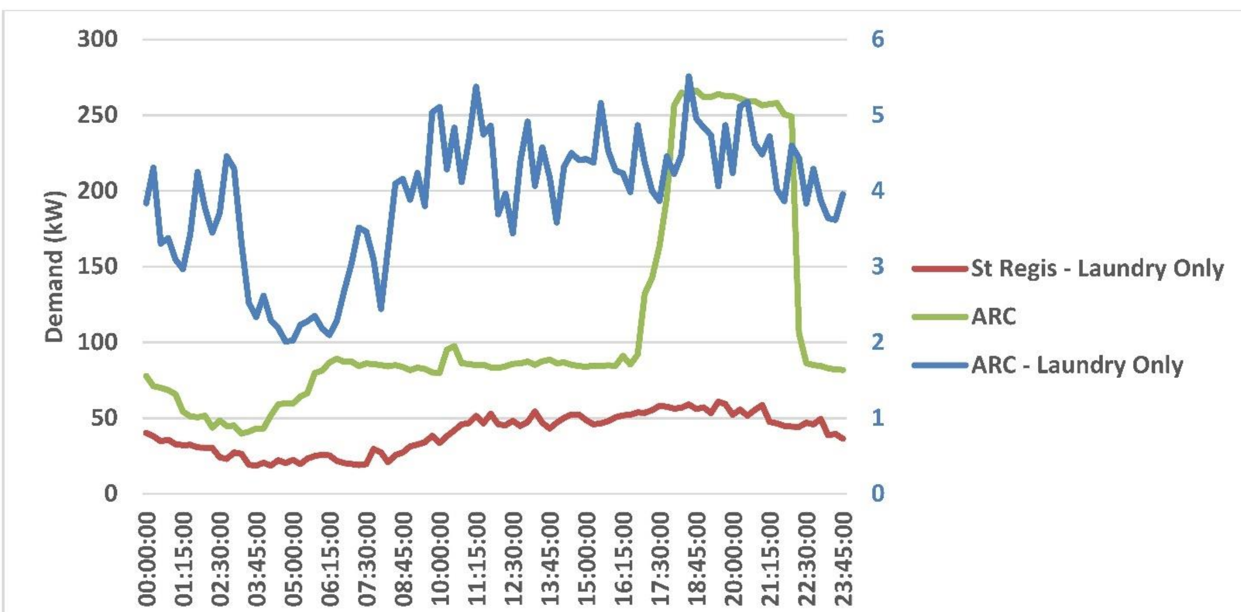
Figure 31 and Figure 32 further demonstrate that an installation location with similar energy and power demand to the St. Regis laundry is optimal for this RE DG/CHP system. Figure 31 shows the average energy use, in kWh per 15-minute interval, for a typical day during January, with the ARC laundry electrical energy load plotted on a second y-axis due to the relatively small magnitude compared to the other loads. Per 15-minute interval, the RE DG/CHP system will provide about 6.25 kWh of electrical energy for use by the laundry facility. When compared to the electrical energy profiles of the ARC and St. Regis laundry facilities, it is clear that this amount satisfies the St. Regis profile best and is on average 10 times oversized for the ARC laundry facility. From the electrical data collected from the St. Regis, the shape of the daily load profiles was consistently higher in the on-peak and semi-peak hours and lower in the off-peak hours. This type of load profile is optimal for implementing this RE DG/CHP system since the proposed schedule is 16 hours a day only during the on-peak and semi-peak hours, as discussed earlier. Nominally, the RE DG/CHP system will provide 6.25 kWh of energy to be used by the St. Regis laundry during peak times, resulting in optimal energy cost savings when the energy is completely used by the laundry or excess energy is stored for use during off-peak hours. Figure 32 shows the maximum power demand profile for a typical day during January and confirms the St. Regis facility as the most appropriate installation location for the RE DG/CHP system. The cost savings associated with the maximum monthly power demand would result from shifting the maximum demand (kW) from where it typically occurs, during either the on-peak or semi-peak period, to the off-peak period. From the electrical demand data for the St. Regis facility in January, this reduction of the maximum power demand would be from roughly 60 kW to 35 kW, resulting in potential total cost savings of about $1,300 per month for a winter month. This estimate assumes the unit is running for the entire 16 hours shift and using the SCE rates. Extrapolating this to the summer months, the total cost savings increase to about $2,080 per month under the same conditions. Overall, although the benefits of the RE DG/CHP system discussed in the previous sections for the installation at the ARC laundry seemed promising, it is clear that the benefits are improved when the maximum generated power and waste heat of the RE DG/CHP system is more closely matched with the energy use and power demand of the installation site.

Figure 31: Average Energy Use (kWh per 15-Minute Interval) for a Typical Day in January



Source: University of California, Irvine

Figure 32: Maximum Demand (kW) during 15-Minute Interval for a Typical Day in January



Source: University of California, Irvine

Utility Infrastructure Implications

To address the goals of grid reliability in the San Onofre Nuclear Generating Station (San Onofre) territory, this program seeks to develop and deploy an RE microscale DG/CHP system.

As shown in Table 15, there exists a potential market in the San Onofre territory of roughly 3,700 installation sites at hotels, hospitals, jails/prisons, and Laundromats representing a conservatively estimated 130-260 MW of electric grid support. The system addresses small power "need" markets in the range of < 50 kW per installation, with the optimal power output previously mentioned at 25 kW. The goal would be to be able to package the RE DG/CHP system for this power output and be able to combine with identical units to increase the system capacity by increments of 25 kW.

From the previous benefits analysis and discussion, the size of the current RE DG/CHP system was matched with an optimal electrical load of a facility that would benefit the most from this system. The St. Regis laundry facility used about 20,000 kWh of electricity per month and had a monthly power demand of about 60 kW, which aligned well with the 25 kW capacity and 16-hour operating schedule of the proposed system. The St. Regis Monarch Beach Resort contains about 400 rooms, which puts the laundry facility electrical load into perspective. The average hotel in the San Onofre territory has about 105 rooms. Depending on the type of hotel/resort, it may have 200+ rooms, which would be more suitable for considering the installation of this RE DG/CHP system as it would most closely match the electrical load of the St. Regis laundry facility. Regarding the installation of this system at laundries at other locations, it is important to consider the overall electrical load of the laundry. At locations such as hospitals and Laundromats, the use of the laundry facilities is potentially greater than at a hotel. Therefore, hospitals and Laundromats merit further investigation and determination of the electrical load of the associated laundries to confirm that they are optimal locations for installing the proposed RE DG/CHP system. Investigating other sectors that can benefit from DG/CHP applications, along with the widespread deployment of such a system within the San Onofre service territory, will provide the desired grid support sought in the solicitation.

Life-Cycle Economic Analysis

The research team evaluated the overall economic benefits of the RE DG/CHP system over the projected life cycle. The analysis was accomplished using the CHP calculator tool provided by the California Energy Commission. Table 15 shows the economic data necessary to perform the analysis, as well as the estimated values associated with the CHP system. As mentioned, the proposed schedule of operation for the CHP system is a 16-hour day, which is 5,840 hours a year. The total system life is projected to be 40,000 hours, which is about seven years for the economic life of the CHP system. The remaining estimated values are economic data estimates provided by the Energy Commission for illustration that were left unchanged; thus, the results of this analysis are based on these financial assumptions.

Table 15: Estimated Values for the Economic Analysis

Symbol	Terms	Unit of Measure	Inputs
CC	Capital cost of the CHP system	\$/kW	1,070
FOM	Fixed operations & maintenance costs	\$/kW-year	100
VOM	Variable operations & maintenance costs	¢/kWh	1.5
L	Economic life of the CHP system	years	7
Decom	Decommissioning cost of the CHP system	\$/kW	200
Fin_{debt}	Fraction of financing from debt	%	60
R_{debt}	Interest rate paid on debt (real)	%	3
R_{eq}	Desired rate of equity return (real)	%	6

Source: University of California, Irvine

In addition to the estimated values provided in the above table, baseline values for costs such as fuel and electricity were necessary to complete the set of inputs before performing the economic analysis calculations. Table 16 shows these baseline values, most which are Energy Commission-provided default values and were left unchanged. These default values included the Self-Generation Incentive Program (SGIP) incentive of about \$0.42/W and the combined state and federal income tax rate of roughly 40%. The value for the cost of natural gas fuel in Table is the average retail cost for natural gas delivered by SoCalGas between January 2017 and December 2017. The team determined the retail rates of electricity using the most up-to-date time-of-use schedule (TOU-8) provided by SCE.

Table 16: Baseline Values for the Economic Analysis

Symbol	Terms	Unit of Measure	Inputs
FC_{ng}	Cost of natural gas fuel	\$/MMBtu	3.59
ARR	Avoidable retail rate of grid electricity	\$/kWh	0.12
EXT	Tariff paid for exported electricity	\$/kWh	0.11
SGIP	Self-Generation Incentive Program (SGIP) incentive	\$/W	0.42
ITC	Federal Investment Tax Credit (ITC)	%	0
TAX	Combined State & Federal Income tax rate	%	40
DSCR	Debt service coverage ratio	-	1.25

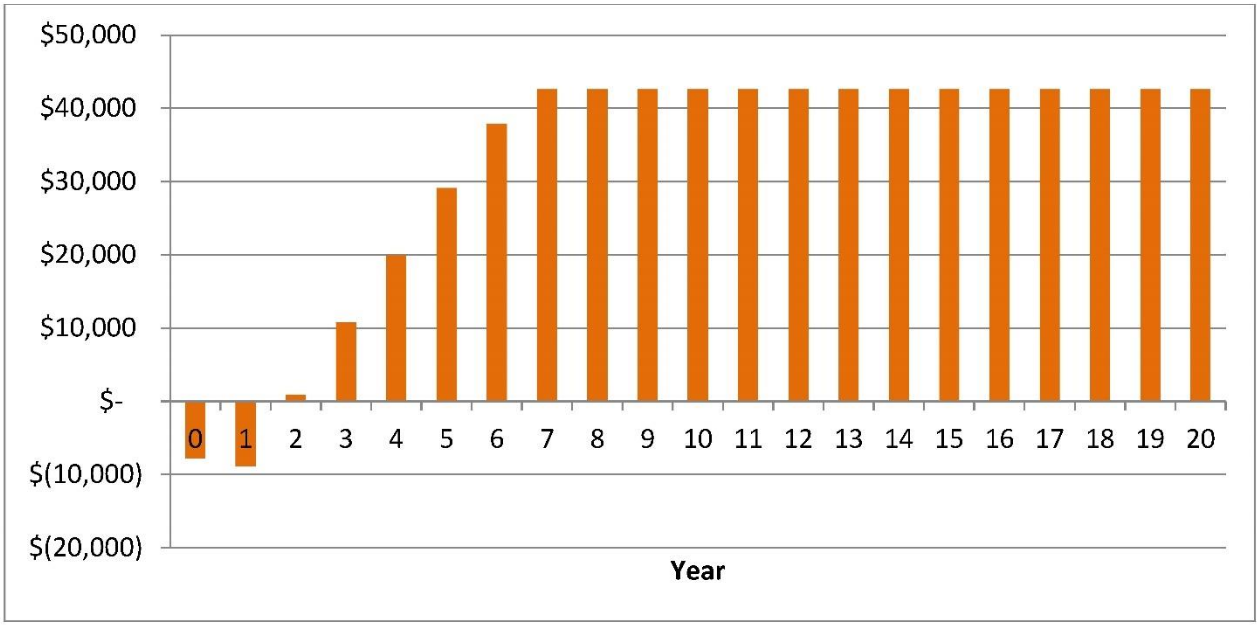
Source: University of California, IrvineTable 17 shows the results of the economic analysis for the life cycle of the RE DG/CHP system. Key results from this life-cycle economic analysis include the total system net capital cost of \$19,500, the net present value of the CHP system of \$31,132, and the simple payback period (SPB), which is determined to be about 1.9 years. In addition to this table of results and calculated values, Figure 33 provides a representation of the cumulative cash flow versus time for the RE DG/CHP system. The economic life of seven years for the CHP system is clearly shown, as well as the resultant simple payback period of almost two years. It is important to note the effect of the cost of natural gas and/or electricity costs on the SPB metric. If the natural gas cost is doubled to $7.18/MMBtu, the SPB only slightly increases to about 1.97. While the SPB has a weak dependence on the cost of natural gas, a variation in the electricity costs causes a large variation in the SPB. If the avoidable retail rate of grid electricity is doubled to $0.24/kWh, the SPB drops more than 60% to about 0.7. Overall, the results of the life-cycle economic analysis support the use and installation of the proposed RE DG/CHP system in the San Onofre territory, with an additional increase in benefits possible if there is an increase in the retail rate of grid electricity.

Table 17: Calculated Values for the Economic Analysis

Symbol	Terms	Unit of Measure	Inputs
CC_{total}	Total System Capital Cost, Net of Incentives	$	19,500
$Debt_{b,0}$	Debt Balance in Year 0	$	11,700
Eq	Initial Equity Investment / Down Payment	$	7,800
NPV	Net Present Value of CHP System	$	31,132
IRR	Internal Rate of Return	%	64
BCR	Benefit-Cost Ratio	-	5.0
SPB	Simple Payback Period	years	1.9

Source: University of California, Irvine

Figure 33: Cumulative Cash Flow



Source: University of California, Irvine

Summary of RE DG/CHP Benefits

Overall, the preceding benefits analysis provides firm support for the proposed RE DG/CHP system to be a successful CHP application with respect to serving the San Onofre territory. With the cost of electricity steadily increasing and a rise in the demand for distributed generation that can be met with the use of efficient natural gas-fueled CHP systems, the proposed RE DG/CHP system will be able to provide low-cost electricity locally and would address small power "need" markets in the range of < 50 kW per installation. **Error! Reference source not found.** summarizes the key results of this benefits analysis, including total electrical and thermal output, net change of emissions, and the cost and estimated payback of the proposed CHP system.

Table 18: Key Results and Benefits of the RE DG/CHP System

Symbol	**Terms**	**Unit of Measure**	**Inputs**
E_{CHP}	CHP system electrical output	kWh / year	170,937
F_{CHP}	Total fuel used by CHP system	MMBtu / year	2,961
T_{CHP}	CHP system thermal energy output	MMBtu / year	2,280
$\eta_{CHP,t}$	Thermal efficiency of CHP system	%	75
$CO_{2\ net}$	Net change in CO_2 emissions	metric tons /year	- 97.30
$NO_{x\ net}$	Net change NO_x emissions	kg / year	- 3.33
CO_{net}	Net change in CO emissions	kg / year	206.88
CC_{total}	Total system capital cost, net of incentives	$	19,500
SPB	Simple Payback Period	years	1.9

Source: University of California, Irvine

The CHP system electrical output that was calculated based on the aforementioned 16-hour daily schedule is 170,937 kWh/year, while the calculated thermal energy output is 2,280 MMBtu/year. Although the total fuel used by the CHP system is large, the benefits of locally producing low-cost electricity as well as waste heat greatly outweigh the fuel costs. The thermal efficiency of the CHP system that was achieved was 75%; however, this value can potentially be improved on with improvements to the balance of plant after additional testing. In general, the net change of emissions is encouraging, where negative values represent emission reductions and positive values indicate emission increase. The overall emission reduction for CO_2 is about 97.30 metric tons/year, and the reduction for NO_x is about 3.33 kg/year. Although the net change in CO emissions is positive, this can be managed with the addition of an oxidation catalyst or other exhaust treatment system, or further engine tuning. Regarding economic benefits, the total system capital cost, net of incentives, is about $19,500. When considering the estimated values and baseline values, such as natural gas costs and retail electricity rates discussed in the life-cycle economic analysis, the simple payback period is about 1.9 years. The proposed RE DG/CHP system is well-suited for installation at a facility with low to moderate power demands and high demands for waste heat (such as hot water, steam, etc.). For maximum economic benefits, the ideal installation location must have access to inexpensive natural gas to fuel the CHP system, but most importantly, the retail rate of grid electricity must be significantly high or increasing. Along with these economic benefits, consumers will also benefit from a highly energy-efficient system that also maintains emissions to a minimum to meet stringent air quality standards. The RE DG/CHP system is ideal for deployment and installation in the San Onofre territory for the reasons mentioned in the previous benefits analysis and throughout this report. Moreover, it has the potential to serve any other area in need of clean, low-cost power generation, as well as a significant amount of waste heat that can be used for a diverse number of applications.

CHAPTER 8: Conclusions and Recommendations

Conclusions

This project developed the initial design for a low-cost microscale DG/CHP system centered on a Mazda rotary engine and unique AC alternator concept. The program has successfully modified a production rotary engine for natural gas operation using medium-pressure natural gas (~5 psig) and incorporating electronic engine management and fuel injection. Dynamometer testing has shown extremely low emissions levels due to the sophisticated engine management system. Installed in the test bed located at UCI, the engine performance is nearly to the target levels with room for improvement with better waste heat management. The subsystems of high-speed AC alternator/DC rectifier/PV grid connect inverter have been fine tuned to provide reliable grid connect capability.

The most challenging and recurring aspects of the prototype system were the alternator and heat exchanger (Table 19). The loss of two instrumental members of the team also took some time from which to recover. A solid foundation had been laid; however, the pieces needed to be integrated and used.

Table 19: Major Events During the Project

2014		2015					2016									2017			
Q3	Q4	Q1	Q2		Q3	Q4	Q1	Q2		Q3		Q4				Q1	Q2	Q3	Q4
July 2014 Project Start			April 2015 First Engine Dyno Tested	May 2015 Host Site Letter of Commitment (St. Regis)	September 2015 Test Mule Running			May 2016 Engine 1 Failed	June 2016 Host Site Change of Location	September 2016 Generator Failed - Ordered replacement	September - October 2016	Construction for utility connections at ARC	November 2016 Generator Failed - Ordered a second	December 2016 **Rich Hack** (Technical Lead) Passed Away	December 2016 **Jim Mederer** (Engine Guru) Passed Away	January 2017 Received 2 Replacement Generators	May 2017 Demonstration Unit Installed at Host Site		December 2017 Project End

Source: University of California, Irvine

Multiple alternators were damaged due to internal electrical shorts, which suspended testing at times. This was due to long lead times of the built-to-order alternator. An external fan was added to the alternator from the manufacturer toward the end of the project that greatly improved the thermal management of the alternator.

The exhaust heat exchanger was the only heat exchanger to have a failure. It developed a leak at the weld that was not repairable. It had a long lead time to replace as well, which delayed full system testing.

After the research team managed the weaknesses in the system, the emissions were able to get very close to CARB limits for stationary generators. The project was able to accomplish this while having an overall efficiency of 75%, which is tremendous for such a small scale. While a higher efficiency of 81% was achieved on the demonstration unit, the test mule had more consistent long-term testing. There the minimum expected efficiency was 75%, and any increase results in an accelerated payoff.

The overall efficiency at 75% helped yield an indicated possible total savings potential of roughly $1,300 in the winter and $2,080 per month in the summer, based on relevant utility rates.

Regarding economic benefits, the total system capital cost, net of incentives, was about $19,500. When considering the natural gas costs and retail electricity rates discussed in the life-cycle economic analysis, the simple payback period is about 1.9 years. In addition, CO_2 emissions are reduced by more than 97 metric tons per year using the California Energy Commission CHP Calculator.

Recommendations

Various generators must be tested to find a balance of temperature and electricity production.

The demonstration site had too low of a thermal demand to allow long-duration testing to be fully evaluated, so a longer-term demonstration of six months or more would be useful. Conceivably this could be accomplished at the demonstration site if additional thermal load present (such as pool heating, space heating) could be connected to the system.

The units must be run more; however, this project indicates that the system has a high potential as a production unit.

LIST OF ACRONYMS

Term	Definition
Btu	British Thermal Unit
California ISO	California Independent System Operator
CARB	California Air Resources Board
CNG	Compressed natural gas
CO	Carbon monoxide
DG/CHP	Distributed generation/combined heat and power
ECU	Engine control unit
HC	Hydrocarbons
HHV	Higher heating value (natural gas = 1000 Btu/scf)
IAS	Iannetti Apex Seals
MOP	Metering oil pump
NOx	Oxides of nitrogen
PG&E	Pacific Gas and Electric
ppmvd	Part per million volume dry
Psig	Pounds/square inch gauge
RE	Rotary (aka Wankel) engine
Rpm	Revolution per minute
SCAQMD	South Coast Air Quality Management District
SCE	Southern California Edison
scfm	Standard cubic foot per minute
SDG&E	San Diego Gas & Electric
SoCAB	South Coast Air Basin
San Onofre	San Onofre Nuclear Generation Station
VAC	Volts – alternating current
VDC	Volts – direct current
η	efficiency

APPENDICES

Appendix A: Apex Seal Longevity Analysis (Publication Number CEC-500-2018-030-APA) and Appendix B: Production Readiness Report (Publication Number CEC-500-2018-030-APB) are available upon request by contacting Chuck Gentry at Chuck.Gentry@energy.ca.gov.