CHP INTEGRATION (OR IES): MAXIMIZING THE EFFICIENCY OF DISTRIBUTED GENERATION WITH WASTE HEAT RECOVERY

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Abstract

A laboratory facility for testing combined cooling/heating and power (CHP) or more currently referred to as Integrated Energy Systems (IES) has been commissioned at the Oak Ridge National Laboratory (ORNL). The scope of the facility is to test distributed generation (DG) with thermally-activated (TA) technologies for waste heat recovery. The designation of the IES Laboratory Facility as a "National User Facility" provides industry with greater access and control to various IES testing that can be conducted at the laboratory.

The IES laboratory test facility is concluding the testing of a 30 kW microturbine generator (MTG) with a first generation heat recovery unit (HRU), direct and indirect-fired desiccant dehumidification systems and an indirect-fired 10-ton single-effect absorption chiller. The MTG has been operated individually to obtain its baseline performance characteristics as well as in combination with various waste heat recovery configurations to test an MTG-based IES.

The dynamic and steady-state electrical, thermal, and emissions performance of the MTG has been measured over the power output range of 3 to 30 kW as well as during startup and shutdown. The heat recovery process has been found to reduce the energy efficiency and power output of the MTG slightly due to the increased backpressure on the MTG's exhaust.

However, the overall MTG-based IES system produces a 35-60% efficiency vs. the ~23% efficiency of the individual MTG. A number of key results have been produced by the laboratory and are leading to IES recommendations. Also, performance issues related to the MTG have been identified and are being addressed.

Keywords

Distributed Generation (DG); Cogeneration; Combined Cooling/Heating and Power (CHP); Waste Heat Recovery; Desiccant Dehumidification; Thermally-Activated Technologies.

1. Introduction

The problems caused by deregulation of the electric energy market in the United States and other developed countries have created an important opportunity for distributed energy technologies [1]. In the report prepared in 2001 by the National Energy Policy Development Group, the concept of Combined Cooling, Heating and Power (CHP) or Integrated Energy Systems (IES) is identified as a strategy for addressing increased energy demands and peak power issues [2]. Recent developments in distributed generation (DG) technologies have opened new opportunities for relatively small-scale IES that can be used in commercial buildings. DG in combination with thermally-activated (TA) desiccant dehumidification and/or absorption cooling or heat recovery technologies, which use waste heat directly for heating purposes, provide a viable IES technology for buildings [1].

A laboratory for testing IES has been commissioned at the Oak Ridge National Laboratory (ORNL). During the summer, the IES Test Laboratory was formally designated as a National User Facility. The scope of the facility is to test DG with TA technologies for waste heat recovery. The objectives of the laboratory include:

(1) Collect performance data on current DG and TA technologies both individually and operated as an integral part of an IES,
(2) Develop models of the individual devices and based on integrated operation verify an IES model,
(3) Rate the performance of current IES technologies, and
(4) Develop testing protocols and rating standards for assessing current IES technologies.

The goal is to increase the overall efficiency of DG systems by integrating them with waste heat recovery and TA technologies. These use the DG's heat generated exhaust, a by-product of the power generation process, to produce heating/cooling or to regenerate desiccant material used by dehumidification systems. The recent designation of IES Laboratory Facility at ORNL as a "National User Facility" provides industry with greater access and control of various IES testing that can be conducted at the laboratory.

The IES Laboratory Facility is quite flexible in the configuration of the DG unit with the various heat recovery systems. The exhaust gas from the DG can either be used directly and/or routed to an air-to-water heat exchanger. Also, the air and water flows from the heat recovery process can be varied and directed via automated damper controls to test various IES configurations and operating modes. The laboratory is concluding the testing of a 30 kW microturbine generator (MTG) with a first generation air-to-water heat exchanger or heat recovery unit (HRU), direct and indirect-fired desiccant dehumidification systems and an indirect-fired 10-ton single-effect absorption chiller. The MTG has been operated individually as well as together with various waste heat recovery configurations.

2. Test Equipment

The IES Laboratory Facility is a flexible test bed consisting of a 30-kW MTG configured and instrumented to operate with or without waste heat recovery from the MTG exhaust. Although, the laboratory is currently using an MTG it is certainly not limited to just this type of DG or size of DG. The heat recovery components consist of a first generation HRU, both an indirect-fired and a direct-fired desiccant dehumidifiers, and an indirect-fired (hot water) 10-ton single-effect absorption chiller (Figure 1). A duct network from the MTG exhaust to the HRU and/or to the direct-fired desiccant dehumidifier, a water loop from the HRU to the indirect-fired desiccant dehumidifier and absorption chiller, and an air mixing chamber leading to the duct network (for mixing outside air with exhaust air to lower its temperature and/or supplement its volume) provide for flexible testing of various waste heat recovery conditions and loadings as well as exhaust heat-by product producing DGs. The HRU, which is designed to capture the waste heat from the MTG, is used to produce hot water for the indirect-fired desiccant dehumidification (IFDD) system or absorption chiller. The insulated duct system along with outside air mixing is used to provide hot air for the direct-fired dehumidification (DFDD) unit.

The MTG, which is located on the outside of the IES Laboratory Facility's building, is a three-phase 480-VAC/30-kW rated unit that can operate at 50 or 60 Hz when connected to the grid. A stand-alone option, which allows the MTG to start and generate power without electric utility service, is also available, although it was not employed or studied in these tests. The gas microturbine and the electric generator are on the same shaft. The MTG, which is designed to operate at a maximum speed of 96,000 rpm, produces high-frequency AC power that is rectified to DC and converted to 50 or 60-Hz AC power by the power conditioning electronics of the digital power controller [3].

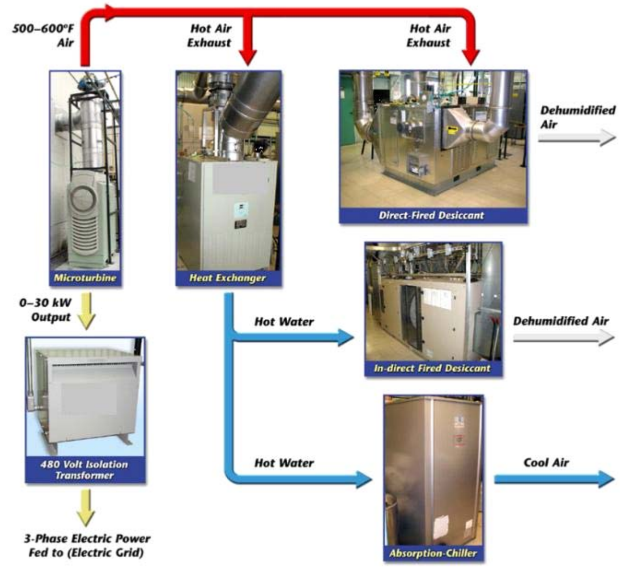

Figure 1. IES Test Facility.

The MTG is designed to produce a continuous phase current of 36 A at 480 VAC and to produce unity power factor (the amount of real power divided by the total power) when the unit is grid connected. The unit's nominal phase-to-neutral voltage is 277 VAC. The MTG is connected to the grid (through a 480-VAC electrical panel which is connected to the local distribution system) via a 480-VAC/45-kVA three-phase delta/wye-grounded isolation transformer. The unit's power controller incorporates protection functions that will shut down the MTG if the phase-to-neutral voltage sags (or drops) to less than 208 VAC for more than 10 seconds. Islanding of the MTG (or separation of the unit from the grid) is detected within milliseconds from the loss of current control. The MTG also includes over-voltage, over/under frequency, and rate of frequency protection functions to protect the unit and to prevent islanding of the unit.

In the IES mode, the flue gas from the MTG exhaust, which is at a temperature of ~527^{o}F is directed to the heat recovery components located on the inside of the IES laboratory building. The exhaust passes through the HRU and transfers heat to the water loop. The flue gas leaving the HRU has a temperature of ~255^{o}F and can still be used to regenerate the desiccant materials in the DFDD. The maximum water flow rate through the HRU is ~26 gpm with a maximum water temperature of ~196^{o}F (actual temperature depends on several parameters such as MTG output, ambient temperature, and HRU water flow rate). The hot water is directed to the regeneration heating coil of the IFDD which restores the dehumidification capability of the desiccant wheel (Figure 2).

The IFDD system brings in outside air and passes it through a desiccant material, removing moisture and increasing the temperature of the process air [4, 5]. Next, the air flows through a heat recovery wheel to lower the temperature of the dry air to a more "space neutral" temperature, and in the same process, preheats the regeneration air to decrease the amount of thermal energy required to raise it to the regeneration temperature. Some additional post-cooling of the dried process air is usually required before it can be used for building ventilation. The desiccant wheel is constantly turning to allow the desiccant to move between process and regeneration airstreams. In order to regenerate the desiccant, outside air is brought in and passes through the rotating heat recovery wheel, where it picks up heat from the process air stream prior to entry into the regeneration heating coil. Air passing through the regeneration heating coil rapidly increases in temperature prior to entering the desiccant wheel, where it removes the absorbed moisture. The warm, moist air is then discharged to the atmosphere. The test instrumentation that was used in the testing is described in detail in the previous baseline performance studies [4, 5, 6].

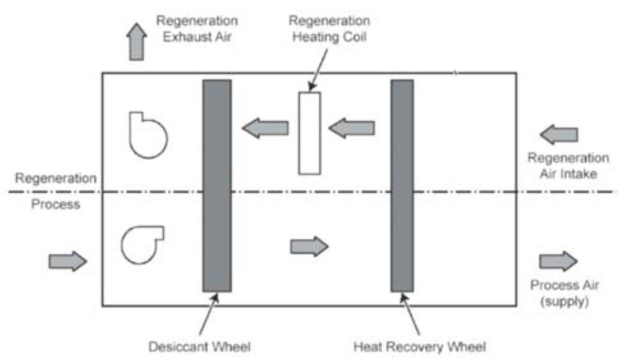

Figure 2. Diagram of Indirect-Fired Desiccant Dehumidifier (IFDD).

3. Test Procedures

Tests were performed at the IES laboratory facility to determine the effects of varying the power output of the MTG, air flow rate, and desiccant wheel speed on the latent capacity (LC) and latent coefficient of performance (LCOP) of the IFDD, as well as on the overall IES efficiency. The LC is calculated using the following equation [6]:

$$Q_{latent} = Q_{total} - Q_{sensible} \quad (1)$$

where total cooling capacity Q_{total} (Btu/h) and sensible cooling capacity $Q_{sensible}$ (Btu/h) are as follows:

$$Q_{total} = 60 \cdot \rho_{air} \cdot G_p \cdot (h_{pout} - h_{pin}) \quad (2)$$

$$Q_{sensible} = 60 \cdot C_{Pair} \cdot \rho_{air} \cdot G_p \cdot (t_{pout} - t_{pin}) \quad (3)$$

where G_p is the flow rate of the process air (scfm); h_{pin} and h_{pout} are the process inlet and outlet enthalpies (Btu/lb of dry air); ρ_{air} is the density of air at standard condition (0.075 lb/ft^3); C_{pair} is the air heat capacity (0.24 Btu/lb·^{o}F); and t_{pin} and t_{pout} are the process inlet and outlet dry-bulb temperatures (^{o}F).

The LCOP, a measure of the IFDD efficiency, is calculated by the ratio of the LC to the total energy input to the IFDD, including the HRU input on the regeneration heating coil side and electrical parasitics (such as the energy use of the desiccant wheel motor, fans, and electronics).

The overall IES efficiency is determined by the ratio of the sum of the net electric power output generated by the MTG (total minus the auxiliary power consumed by the unit) and LC of the IFDD to the total energy input to the IES, including the gas input to the MTG (based on the higher heating value or HHV of natural gas) and the electrical parasitics (all the power used by the fans, pumps, and electronics of the MTG, HRU, and IFDD).

The tests were performed at the following conditions:

- MTG net power output: 10 – 25 kW (limited by ambient conditions);
- HRU flow rate: 26 gpm;
- IFDD dry/wet bulb temperature at process and regeneration inlet: 95^{o}F/75^{o}F;
- IFDD process/regeneration air flow rate: 2,000 and 2,700 scfm;
- IFDD desiccant wheel speed: 58 and 76 rph.

4. Test Results

The specific results of varying the MTG output and IFDD speeds and flow rates on the latent cooling capacity and energy efficiency of the IES system are given below.

4.1. Desiccant Wheel Speed and Air Flow Rate

Ideally, the desiccant wheel should be rotated at a speed where the desiccant will be near total saturation at a point just before it rotates out of the process air stream into the regeneration air stream [4]. Wheel speeds that are too high will result in incomplete utilization of the active desiccant for process-side moisture removal, and speeds that are too low will allow saturated desiccant to remain in the process air stream too long resulting in excess heating of already activated desiccant. In both cases LC and efficiency losses are observed. In addition to the desiccant wheel speed, the process/regeneration air flow rates, air temperatures and humidity levels can also influence the LC and efficiency of the desiccant unit.

Figures 3–5 present the data on the LC, LCOP, and overall IES efficiency produced during the tests at various desiccant wheel speeds and air flow rates, while the MTG power output, HRU water flow rate, and IFDD air inlet conditions were maintained constant for the tests. LC and LCOP increased with increasing desiccant wheel speed, similar to the results obtained in the baseline performance study [4]. Although at the higher air flow rate the effect of the wheel speed is not as significant. It should be noted that further increase in the desiccant speed may actually result in reduction of both LC and LCOP due to ineffective utilization of the desiccant material [4].

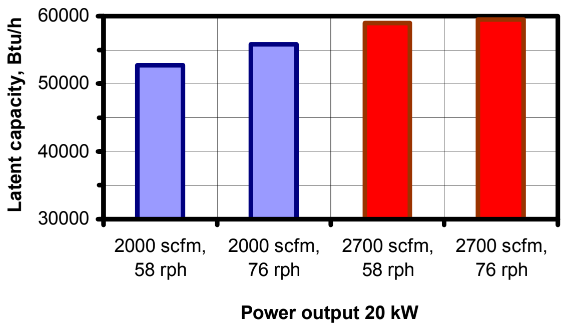

Figure 3. Effect of Air Flow Rate and Wheel Speed on the Latent Capacity of the IFDD.

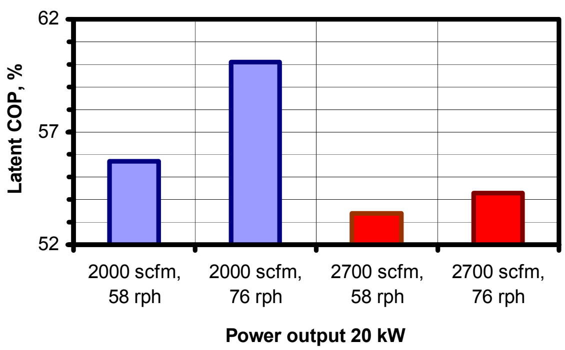

Figure 4. Effect of Air Flow Rate and Wheel Speed on Latent COP of IFDD.

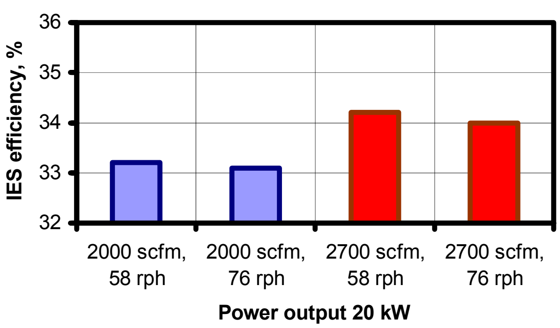

Figure 5. Effect of Air Flow Rate and Wheel Speed of the IFDD on IES System Efficiency (MTG + HRU + IFDD).

Figure 3 shows the effect of the air flow rate on the LC. As expected, the LC increases with the air flow rate. It should be noted that while LC is increasing with increasing air flow rates, the extent of air drying is actually decreasing (grains/lb of dry air is less). It is just that more mass of air "G_p" is being pushed through the system. The data presented in Figure 4 indicates that at 2,700 scfm the LCOP is lower than at 2,000 scfm. As expected, the LC and parasitics of the IFDD increased with the air flow rate. However, the rate of increase of LC is lower than that of the parasitics which would result in an optimum LCOP with respect to the air flow rate. This optimum was found in the previous study [4] to be at a flow rate of 2,500 scfm which is in agreement with the results presented here.

The overall IES efficiency data is shown in Figure 5. Results show increasing overall IES efficiency with increasing air flow rate and decreasing desiccant wheel speed.

Another important factor influencing the overall IES efficiency is the ambient temperature. As indicated earlier, the MTG is located outdoors and these test runs were performed at ambient temperatures ranging from 77°F to 86°F. The importance of this factor will be discussed later in this paper.

4.2. MTG Power Output

The effect of the MTG output on the LC, LCOP, and the overall IES efficiency is shown in Figures 6 and 7. For comparison, Figure 7 also shows the effect of the MTG output on the individual unit's efficiency and the combined MTG and HRU (MTG + HRU) efficiency. The MTG + HRU efficiency is the efficiency of the IES without the IFDD. The data are given for the IFDD air flow rate of 2,700 scfm and a wheel speed of 58 rph.

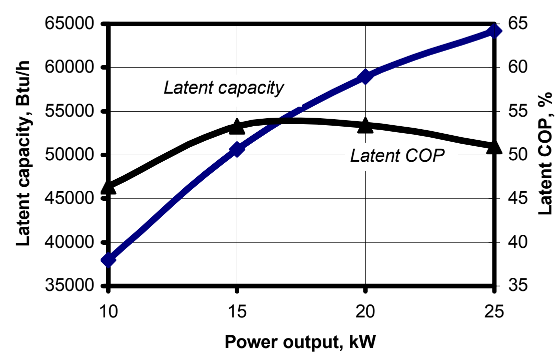

Figure 6. Effect of MTG Output on Latent Capacity and Latent COP of IFDD.

The results indicate that an increase in the MTG output leads to higher LC of the IFDD. Regarding the efficiencies, the effect is much less pronounced. Moreover, after an MTG output of 20 kW both LCOP and IES efficiencies start to fall.

The major reason for the fall off, as already noted, is the significant impact of ambient temperature on operating parameters of the MTG and the heat recovery equipment. As was previously mentioned, the current test runs were performed at ambient temperatures ranging from 77°F to 86°F. The MTG used in this study controls the net power output by adjusting the turbine speed. However, this turbine has a maximum allowable speed limit of 96,000 rpm (maximum speed allowed by the MTG controller). Upon reaching this limit at the "critical" ambient temperature (>60°F), there is no more turbine speed remaining to compensate for any further increases in ambient temperature, so eventually the net power of the MTG decreases (Figure 8). For the 25 kW output setting this "critical" ambient temperature is ~70°F. The exhaust gas temperature continues to increase with increased power output, but with a smaller increment (Figure 9).

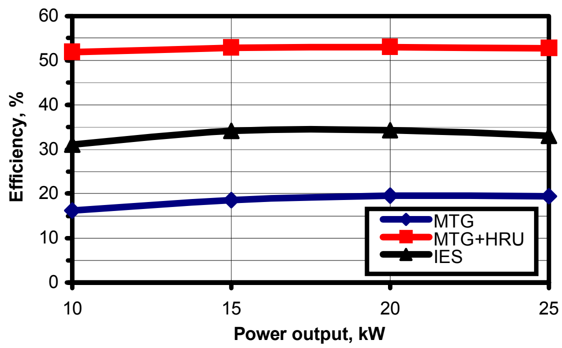

Figure 7. Effect of MTG Output on the IES Efficiency.

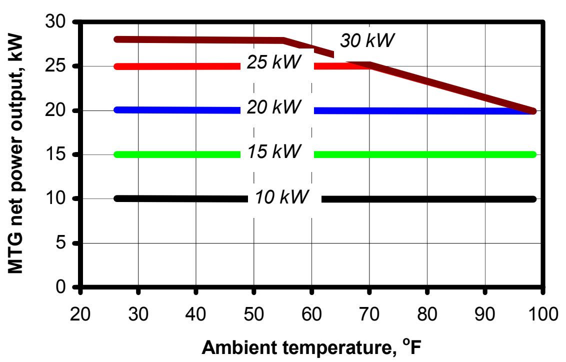

Figure 8. Effect of Ambient Temperature on MTG Net Power Output.

Analysis of Figure 7 shows that addition of the IFDD to the IES system does not increase its overall efficiency: it drops from 53% (MTG + HRU system) to 34% (MTG + HRU + IFDD system). It should be noted that the drop in efficiency is due to the parasitic losses in the IFDD. Comparison of this current data with the data produced with the direct-fired desiccant dehumidifier (DFDD) for the same desiccant inlet conditions (dry/wet bulb temperature of 95/75°F) show that use of the MTG/HRU exhaust gas to drive the DFDD can increase the overall IES efficiency up to 60% (Figure 10) [7].

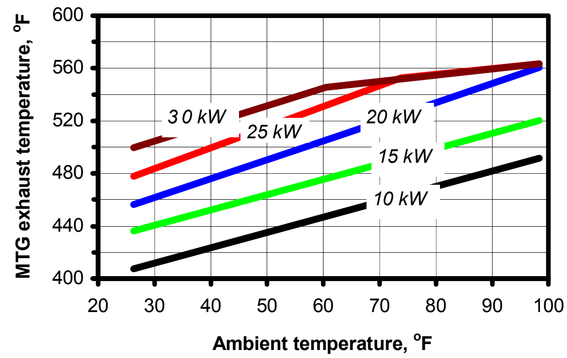

Figure 9. Effect of Ambient Temperature on MTG Exhaust Temperature.

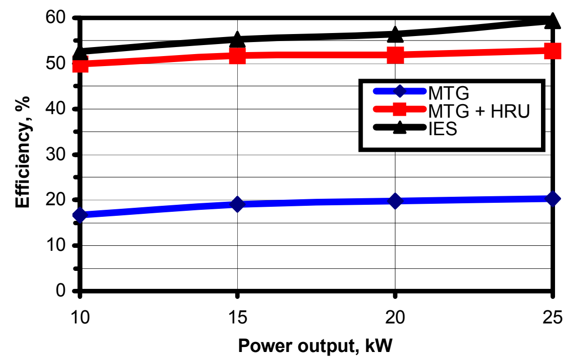

Figure 10. Effect of MTG Power Output on IES Efficiency (MTG + HRU + DFDD).

Thus, maximum overall IES efficiency is obtained with the recovery of as much exhaust heat as possible in the HRU and then the utilization of the remaining available heat in a direct-fired desiccant unit.

5. Conclusions

Testing of a MTG-based Integrated Energy System (or Combined Cooling/Heating and Power System) was conducted at the IES Laboratory Facility at ORNL. The heat recovery components consist of a first generation HRU, both an indirect-fired and a direct-fired desiccant dehumidifiers, and an indirect-fired (hot water-fired) 10-ton single-effect absorption chiller. The objective of these tests was to determine the effects that different MTG outputs, air flow rates, ambient temperature, and desiccant wheel speeds of an indirect fired desiccant dehumidification (IFDD) unit have on the latent capacity (LC) and latent coefficient of performance (LCOP) of the IFDD, as well as on the overall IES (MTG + HRU + IFDD) efficiency. Results show that addition of the IFDD to the IES system would result in a decrease in its overall IES efficiency from 53% (MTG + HRU system) to 34%

(MTG + HRU + IFDD system). However, the overall IES efficiency could be improved by adding a direct-fired dehumidification unit to the IES. This addition could increase the overall IES efficiency to 60%, compared to the ~23% efficiency of the individual MTG based on a higher heating value of the natural gas.

The first generation HRU that has been in operation at the IES Laboratory Facility for over a year was recently replaced with a second generation HRU. The second-generation unit has a heat transfer area that is double in size to improve the HRU's efficiency. The modification was made to the HRU by the manufacturer based in part by backpressure testing conducted by the IES Laboratory Facility at ORNL that showed minimal effect on the performance of the MTG up to 8"wc (0.02 atm). The new HRU unit is expected to improve the overall IES system efficiency as well as that of the HRU.

In the near future, the IES laboratory facility at ORNL will be used to test larger MTGs since the industry is moving in the direction of larger units to make them more attractive to the commercial/industrial markets. Although, the immediate testing at the IES Laboratory only includes MTG-based IES; it will be extended in the future to encompass many other DG systems such as reciprocating engines and fuel cells.

The designation of the IES Laboratory as a National User Facility greatly increases our flexibility to work directly with business and industry in developing and testing the performance of effective designs of IES. This laboratory capability is important for meeting both near-term and future needs for IES systems. In the Laboratory's role as a National User Facility, its purpose is to model and test modular IES package systems for industry to improve the technology and accelerate its introduction to the market. Recent competitively awarded contracts by the U.S. Department of Energy to seven industry teams for the development of packaged IES provide an opportunity for the IES Laboratory to test MTG-based IES from industry. The systems include those with MTG in the 30 to 80 kW range. The industry partners which are cost sharing the design and development costs include: Burns and McDonnell, Capstone Turbine Corporation, Gas Technology Institute, Honeywell Laboratories, Ingersoll-Rand, NiSource Energy Technologies, and the United Technologies Research Center [8]. An expanded future role for the IES Laboratory in conjunction with its designation as a National User Facility includes the assessment of IES controls and advanced diagnosis and thermal energy storage.

6. Acknowledgements

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