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COGENERATION SYSTEM PERFORMANCE MODELING

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ABSTRACT

A bioDiesel fueled engine generator with heat recovery from the exhaust as steam and from the coolant as hot water has been installed in the Intelligent Workplace, the IW, of Carnegie Mellon's School of Architecture. The steam and hot water are to be used for cooling, heating, and ventilation air dehumidification in the IW. This cogeneration equipment is a primary component of an energy supply system that will halve the consumption of primary energy required to operate the IW.

This component was installed in September 2007, and commissioning is now underway. In parallel, a systems performance model of the engine generator, its heat recovery exchangers, a steam driven absorption chiller, a ventilation unit, fan coil cooling/heating units has been programmed making use of TRNSYS transient simulation software. This model has now been used to estimate the energy recoverable by the system operating in the IW for different characteristic periods, throughout a typical year in Pittsburgh, PA.

In the initial stages of this modeling, the engine parameters have been set at its design load, 27 kW, delivering up to 17 kW of steam and 22 kW of hot water according to calculation. The steam is used in the absorption chiller during the summer and in hot water production during the winter. Hot water is used in desiccant regeneration for air dehumidification during the summer, in IW heating during the winter, and in domestic hot water product year around. Systems controls in the TRNSYS

simulation direct the steam and hot water produced in the operation of the engine generator system to meet the IW's hourly loads throughout seasons.

Keywords: cogeneration, biodiesel, performance modeling, TRNSYS, heat recovery system

INTRODUCTION

According to the U. S. Energy Information Administration [1], buildings; residential, commercial; and institutional; are responsible for 40% of the United States primary energy consumption. Developing measures to reduce energy consumption in the building sector is crucial to meeting global energy saving objectives.

Cogeneration has long been recognized for its high efficiency [2]. This project incorporates also the use of various renewable fuels, along with the recovery and use of waste heat at two different temperature levels.

For all these reasons, cogeneration is an attractive energy supply feature for buildings, linking high efficiency and environmental benefits.

This paper describes the computer modeling of the cogeneration system to evaluate its performance at the design power load. Beyond this objective, the model will be used to evaluate the performance for other operating modes, such as following the thermal load or the electric load of the IW.

Building description

The IW is 600 m² of office and conference room space. The average height is about 3.1 m, including the raised floor and average height of roof. The open space is subdivided by partition walls and furniture in 13 offices and 2 conference spaces. The building has operable windows, window blinds, and horizontal solar reflectors on the east and west facades. The floor plan is shown in Figure 1.

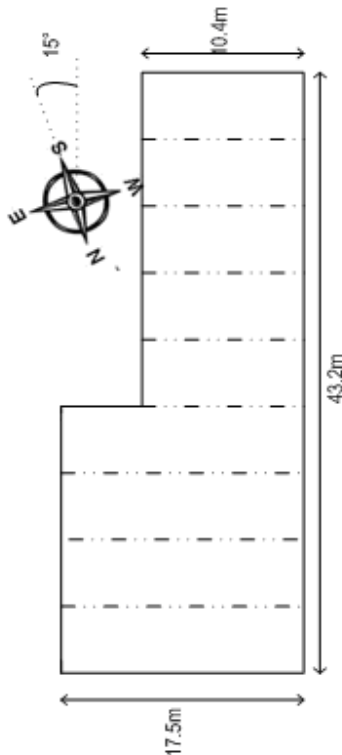


Figure 1. IW floor plan

Internal Loads

This workplace is occupied throughout the day by faculty and students. The internal loads including lighting, plug loads such as computers, and occupants contribute to the overall cooling requirements. The maximum occupancy is 30 people. Most of the occupants arrive between 9AM and 10AM and leave the building between 5PM and 8PM. The equipment heat gain is 100 W per computer (one per person) and 50 W for one printer. The total heat gain of the artificial lighting is 17 W/m². The lights are seldom turned on due to the architectural integration of day lighting features (skylight, windows) of the space.

HVAC System

Ventilation and air conditioning are separate functions in order to reduce the amount of air circulated. Ventilation handles only the latent and sensible loads of the outside ventilation air supply and the latent load of the space. While space cooling/heating by fan coils handles the sensible loads of the space.

Ventilation: Fresh air is supplied to the IW by a ventilation unit that includes an enthalpy recovery wheel, an air based heat pump, and a desiccant wheel. The outside ventilation air enters the space through diffusers in the floor at a rate of 34 m³/hr per person in accord with the American Society of Heating, Refrigerating and Air-conditioning Engineers – ASHRAE-standards [3]. The outside air is supplied throughout the year at a temperature 3°C to 6°C below the set point temperature and at a humidity that maintains comfortable room conditions and permits effective operation of space cooling units in summer.

The heat requirements for regeneration of the desiccant of the ventilation unit are shown in Fig. 2.

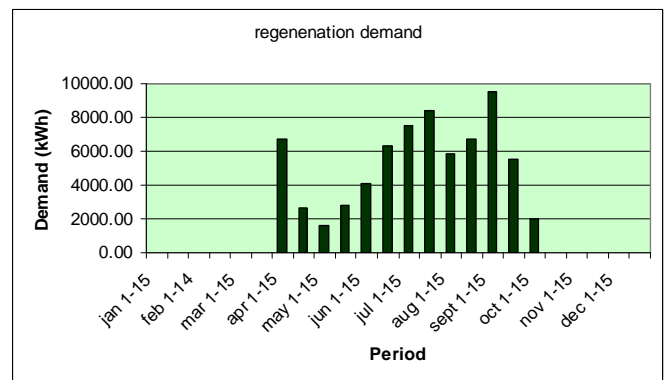


Figure 2. Regeneration bi-monthly loads [4]

Heating: Heat for the IW can be provided by any of 3 sources:

- An exchanger that recovers heat from the engine coolant to produce hot water at 40 – 60 °C, circulated to the convective and radiative heating units in the IW.
- A converter: that uses steam from the cogeneration system in heating and intermediate season and produces hot water stream.
- Otherwise steam from the main campus steam grid is used this converter.

The heating loads of the IW are shown in Fig.3.

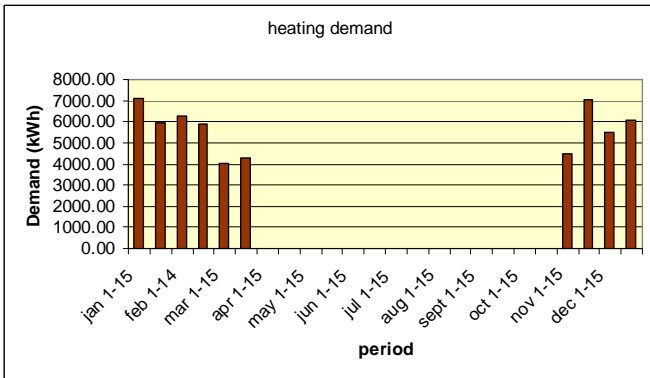


Figure 3. Heating bi-monthly loads

Cooling: Cooling is provided by a steam driven double effect absorption chiller delivering chilled water at 7°C to convective and radiant cooling units mullions and fan coils, in the IW. The cooling loads are shown in Fig. 4.

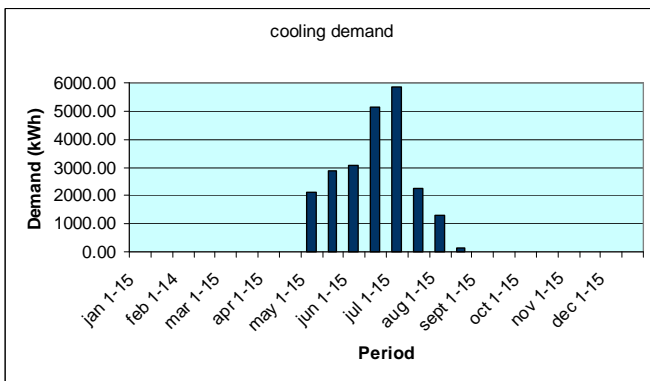


Figure 4. Cooling bi-monthly loads

Cogeneration system installation

The cogeneration system has been installed for safety and practical reasons in the 2d basement of the building in which the IW is located on the 4th floor.

The cogeneration system includes the engine generator, the steam generator, absorption chiller, steam converter, coolant heat recovery exchanger, and a fan cooled radiator to reject unused heat from the engine as shown in Figure 5.

System operation, and control

In the operation of the system various operating conditions are adjusted to control temperatures:

- The coolant flow rate is adjusted by a thermostatic valve to maintain the coolant temperature at the engine outlet of 94°C, avoiding coolant boiling and keeping the engine at an appropriate operating temperature.
- The inlet coolant flow into the heat recovery exchanger is regulated by a valve to keep the hot water outlet at a temperature set point,

- The air fan flow rate in the radiator is adjusted by a variable speed drive to remove the excess heat from the coolant.
- The engine exhaust flow rate to the steam generator is regulated by a by-pass valve to maintain the steam pressure in the steam generator at a set point value at varying steam flows to the IW.

Seasonal modes

Heating season: The heating season starts 1st November and ends 1st April. During the winter, the hot water is circulated to the mullions and fan coils, flowing at 40°C and 19,300 kg/hr. , the hot water is heated by the coolant hot water heat exchanger, or if needed by the steam converter.

Cooling season: The cooling season begins 1st May and ends 1st September. During the summer, the hot water is circulated at 90°C and 5450kg/hr to regenerate the desiccant wheel for ventilation air dehumidification. Again, the hot water is heated by the coolant hot water heat exchanger, or if needed by the steam converter fed by the steam grid. Steam from the cogeneration system is used to drive the two stage absorption chiller.

Intermediate season: The two intermediate seasons extend from 1st to 30th April and 1st September to 30th October.

When no heating or cooling is required in the IW, all the energy recovered is used for the ventilation. Both the coolant hot water heat exchanger and the converter are operating. The hot water flows to the regeneration wheel at 90°C at 5450kg/hr.

In addition, excess steam and hot water can be fed to the campus and building grids.

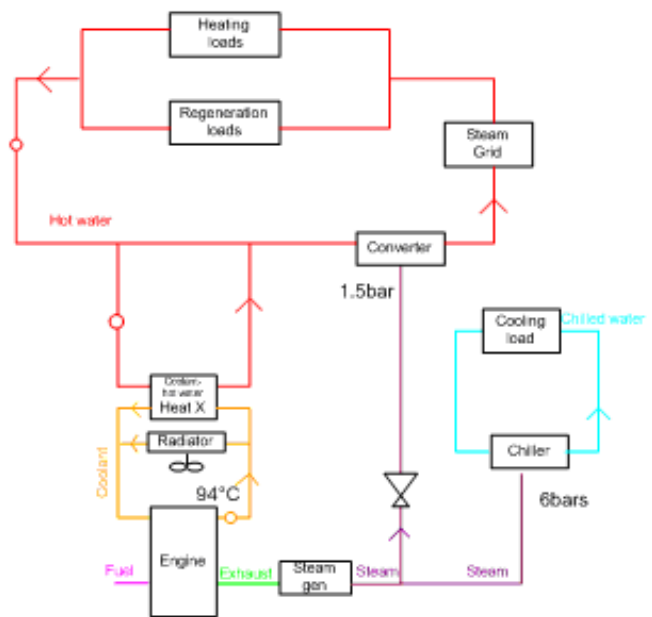


Figure 5. Cogeneration: system flow diagram

Operational mode

For the calculations reported here, the engine operates continuously at its design load and at its maximum electrical efficiency. Then controllers regulate the fluid flows to satisfy the cooling, heating, and ventilation loads and to reject excess heat from the engine in the exhaust stack and the radiator.

Different operating modes of the system will be studied in the future.

TRNSYS MODEL

Modeling option

The objectives of this cogeneration system simulation are to:

- Estimate the performance of this system in the IW.
- Validate equipment design and modeling simulation assumptions through comparisons of experimental data and modeling calculations..
- Anticipate the behavior of the system in different modes for different seasons.

Different direction can be followed to model a cogeneration system: Based on thermodynamic law with model develop in Simulink, like Banetta et al. [5], Gatecycle computer software code like Witzani and Petchtl [6] or based on normalized experimental results like in this study.

Modeling tool

The software program selected to model the IW loads and its cogeneration system is TRNSYS [7]. This software supports detailed simulations of multi zone buildings and their energy supply equipment. The TRNSYS equipment library includes: sophisticated building models; many of the equipment components commonly found in building thermal energy systems; components that facilitate input of weather data and of occupancy, equipment, and set point schedules; and components that support output of simulation results. Exercise of the TRNSYS simulation tool enables the search for an optimal system configuration, equipment design and operational mode.

Modeling approach

The overall system including the IW; the cogeneration energy supply, as shown in Figure 5; and the overall operation and control system includes 8 main devices and 5 fluid streams – exhaust gas, steam, coolant, chilled, and hot water. Components of the overall system have been first modeled separately and when validated, connected.

Model assumptions

Calculations: The first calculation from the model has been made simulating a commissioning test period, at nominal design operating conditions. Then calculations for operation at a constant design power and varying cooling, heating, and ventilation IW loads throughout a year have been carried out.

Due to several continuous controls in the system, the time step has been chosen very small, to simulate reasonably the operation of a control system.

TRNSYS engine component: The engine component developed by TESS [8] for TRNSYS was not applicable in this IW cogeneration model. It does not accurately provide for all of the energy outputs of the engine as a function of power load. A new TRNSYS engine component has been created to meet the requirements of the IW cogeneration system model.

This component has been designed as a look up table to indicate the shaft power, the electric power, the thermal energy to the coolant, to the exhaust, the exhaust flow rate and temperature for a given inlet fuel flow rate and fuel heat of combustion for each engine.

The engine characteristics are shown in Table 1 whereas the ASHRAE [9] value are shown in Table 2.

Table 1. Engine component parameter and inputs

Combustion heat	42565	kJ/kg
Cp exhaust	1.078	kJ/kg.K
Inlet Fuel Flow Rate	8.1	kg/hr
Rated exhaust flow rate	192.24	kg/hr
Rated electric power	97200	kJ/kg

This engine model uses external data files to provide for a given fuel flow:

- The shaft power of the engine.
- The mechanical and electrical efficiency.
- The fractions of input energy of the fuel distributed by the engine to the coolant, the exhaust, and the environment.
- The exhaust temperature.
- The exhaust flow rate.

The data required to construct this model is provided by ASHRAE [9] for an internal combustion engine with oil cooler. The Diesel engine installed for the IW cogeneration system has no such cooler; the small quantity of heat rejected in the oil cooler is assumed to be negligible.

Heat is rejected directly by the engine either to the circulating coolant stream or directly to the surroundings by convection to the air.

Table 2. Heat fraction in the engine and efficiency (ASHRAE Values)

Fuel flow rate	Nominal electric power fraction	Coolant heat fraction	Exhaust heat fraction	Environment heat fraction	Electrical efficiency	Mechanical efficiency	Nominal exhaust flow rate fraction
0.0	0.00	0.40796	0.437811	0.154229	0.00	0.000	0.2
2.0	0.25	0.376108	0.446936	0.176957	0.80	0.228	0.1
4.0	0.50	0.355072	0.456522	0.188406	0.86	0.313	0.6
6.1	0.75	0.337287	0.451446	0.211268	0.89	0.325	0.8
8.1	1.00	0.330396	0.447871	0.221733	0.92	0.323	1.0

Coolant loop: The components of the engine coolant loop are:

- The engine itself, in particular the cylinders walls.
- The coolant pump and the thermostatic valve.
- The coolant-water heat recovery exchanger.
- The coolant heat rejection radiator and its air fan.
- the coolant piping and control valves

The coolant is a 50 - 50 wt % propylene glycol - water mixture. Its properties are shown in Table 3. It circulates between the engine and the coolant-water heat recovery exchanger and/or to the radiator where heat is removed.

Table 3. Coolant properties

T	T _{boil}	C _p	r	k	μ
[°C]	[°C]	[kJ/kg.K]	[kg/m ³]	[W/m.K]	[mPa.s]
94	106	3.611	1033.6	0.3824	0.86

The engine model provides the heat added to the coolant in the engine.

The thermostatic valve adjusts the coolant flow provided by the coolant pump to maintain a set point temperature at the outlet of the engine, 94°C. When engine operates at the design power, a minimum flow of 20 % of the total flow is set to insure a minimal cooling. Coolant flow through the radiator with the air fan on occurs when the cool outlet temperature exceeds 94°C.

All the coolant loop components are available in TRNSYS library. The coolant heat recovery exchanger is simulated by a counter-flow heat exchanger model with a constant effectiveness of 0.7.

Exhaust branch: The components of the exhaust branch are

- The steam generator and muffler.
- The generator by-pass valve and exhaust piping.

The exhaust gas flow rate and temperature from the engine are provided by the engine model. The pipe model calculates the pressure loss. The model of the steam generator [10] calculates the energy required from the exhaust flow to raise steam from the condensate at the rated conditions (Table 4). It determines the inlet exhaust gas flow rate, outlet temperature, and the exhaust gas flow that goes directly to the surroundings.

Table 4. Steam generator TRNSYS parameter and inputs

Specific heat of the heating fluid	1.078	kJ/kg.K
Specific heat of the condensate	4.187	kJ/kg.K
Saturated steam temperature	160.8	°C
Saturated steam pressure	618.8	kPa
Saturated steam flow rate	100	kg/hr
Heating fluid inlet temperature	517	°C
Condensate inlet temperature	100	°C
Maximum heating gas flow rate	192.4	kg/hr

Steam loop: The components of the steam condensate loop are:

- The steam piping including the pressure reduction valve in the line to the converter.
- The converter.
- The two-stage absorption chiller.
- The IW space cooling load on the chiller.

The steam loop with its condensate return lines operates with predictive control: Each component sets the inlet steam flow rate needed to reach the desired outlet conditions. The converter or the chiller calculates the inlet steam flow rate needed to achieve the outlet set point value for hot or chilled water. The thermal losses in the steam pipes and consequent losses in steam flow are calculated by a piping model.

The converter model is based on the steam generator component model developed in our work; it calculates the energy needed to heat the hot water by steam condensation.

The absorption chiller is simulated by a TESS type 676 model. It makes use of 4 external files containing tables with full load capacity, nominal capacity, design energy input fraction data and condensate temperature for different fluids characteristics as shown in Table 5.

Hot water loop: The components of the hot water loop are:

- The coolant-water heat recovery exchanger.
- The steam converter.
- The campus steam grid, supplementary heat source
- The IW ventilation system, desiccant regeneration heat load.
- The IW space heating load.
- The hot water piping, valves, and pumps.

Table 5. Chiller TRNSYS parameters and inputs

Rated capacity	58212	kJ/hr
Rated COP	1.21	
CHW fluid specific heat	4.16	kJ/kg.K
CW fluid specific heat	4.16	kJ/kg.K
Auxiliary electrical power	2000	kJ/hr
Chilled water inlet temperature	14	°C
Chilled water flow rate	2044	kg/hr
Cooling water inlet temperature	29	°C
Cooling water flow rate	4088	kg/hr
Steam inlet temperature	160	°C
Steam inlet gauge pressure	617.8	kPa
CHW set point	7	°C

The hot water piping has been modeled to account for heat losses. The campus steam grid as a supplementary heat source to the converter has been included in the system model to facilitate calculations.

In winter, the hot water temperature to the fan coil/mullions heating units is 40°C. In summer, the hot water temperature to the ventilation unit for desiccant regeneration is 90°C. Heating and regeneration are, therefore, not carried out simultaneously.

Table 6. Converter TRNSYS parameter and inputs

Specific heat of the condensate	4.187	kJ/kg.K
Steam Temperature	112.2	°C
Steam Pressure	149.6	kPa
Hot water outlet temperature set point	40 or 90	°C
Hot Water inlet temperature	40	°C
Hot Water Flow rate	5450 or 19300	kg/hr
Maximum steam flow rate	800	kg/hr

PERFORMANCE RESULTS

Primary study

Initially, the overall TRNSYS model of the IW and its cogeneration system was run with the power and heat recovery components operating at their design maximum levels, recovering all the rejected heat of the system (Figure 6):

- 28.4 kW from the engine; 25.0 kW from the generator.
- 21.9kW in the coolant-heated water heat recovery exchanger
- 20kW in the steam generator; 100% of the cooling loads

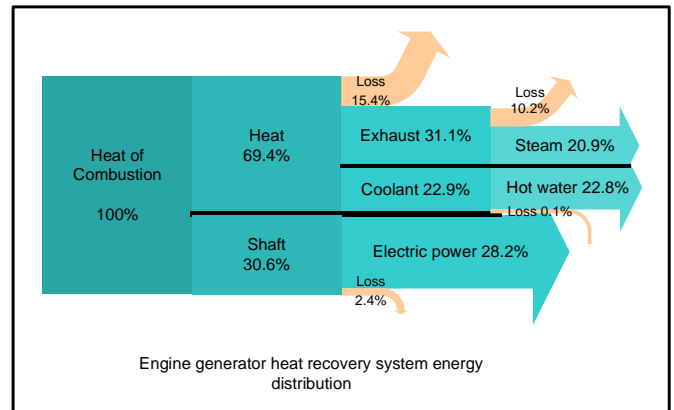


Figure 6. Energy repartition in the cogeneration system

Observation: This preliminary calculations from the overall model provided significant, miscellaneous information about the operation of the system:

- Heat losses from the steam piping losses are important: 3.9kW.
- The system, none the less, is able to operate the absorption chiller at its full load, 16kW.
- Up to 72% of primary energy of the fuel is available as power, steam at 160°C, and hot water at 89°C.
- The average coolant temperature is 93.3°C, with a peak at 97.2°C significantly below the boiling point of the glycol – water mixture
- The temperature difference in the coolant – hot water heat recovery exchanger is 3.5°C.

Legislation: According to the Federal Energy Regulatory Commission – FERC [11] the ratio between system output and input for a qualified cogeneration system based on fuel lower heating value has to be

$$FERC_{eff} = \frac{\text{Electric output} + \frac{1}{2} \text{ used thermal output}}{\text{Fuel input}} \geq 42.5\% \quad (1)$$

If the IW cogeneration system were run in the full heat recovery mode, this ratio would be 50.1% (based on LHV).

Diesel results

Description: Now that reasonable results have been obtained from the model, calculations have been run to evaluate how much of the thermal output of the Diesel engine generator operating at full, design power can be used to provide hourly building loads of the IW.

The following input parameters for the engine have been used:

- Diesel heat of combustion: 42565kJ/kg.
- Nominal electric power 27kW.

Performance analysis: The IW cogeneration system very nearly provides sufficient thermal energy for the various IW building loads as shown in Fig.7.

- 95.0% of space heating.
- 82.8 % of ventilation desiccant regeneration.
- 80.3% of cooling

Calculation based on Equation (2)

$$\text{coverage} = \frac{\text{Heat provided}}{\text{Loads}} \quad (2)$$

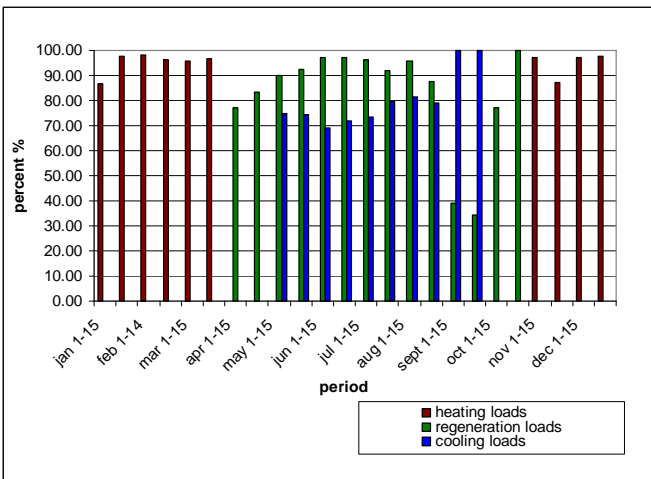


Figure 7. Diesel load coverage

Legislation: According to calculation results, shown in Fig. 8, the system satisfies the federal legislation criteria from 15th June to 31st July. During this period, the regeneration and the cooling load are both high. The maximum heat is recovered, but the system needs supplementary heat from the campus steam grid.

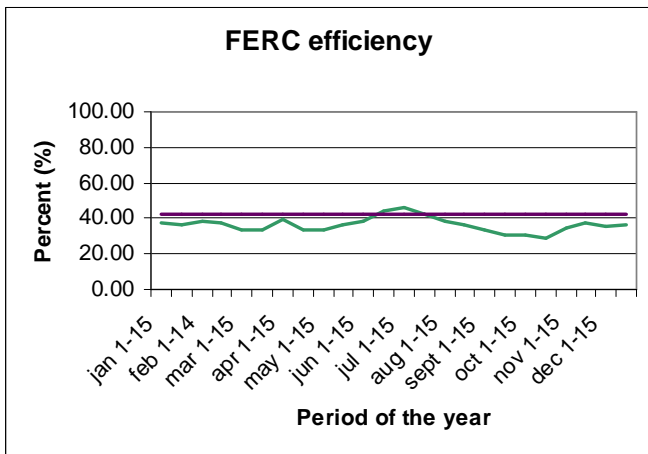


Figure 8. Achievement of legislation ratio for diesel

Biodiesel B100 results

Description: The IW cogeneration system is intended to be run on 100% bioDiesel fuel, B100. Calculations have been

made to evaluate the system performance on B100 with its heat of combustion of 37,216kJ/kg.

It has been assumed that the system will generate 24kW power instead of the nominal 27kW due to the lower fuel heat of combustion. This assumption will be adjusted when the results of our experimental program are available in several months.

Performance analysis: The cogeneration system provides thermal energy for the various building loads along the years to a certain extent, results from the calculation shown on Fig.9 are:

- 93.6% of space heating.
- 81.3% of ventilation desiccant regeneration.
- 80.4% of cooling.

As expected, the results are slightly lower than those for Diesel fuel.

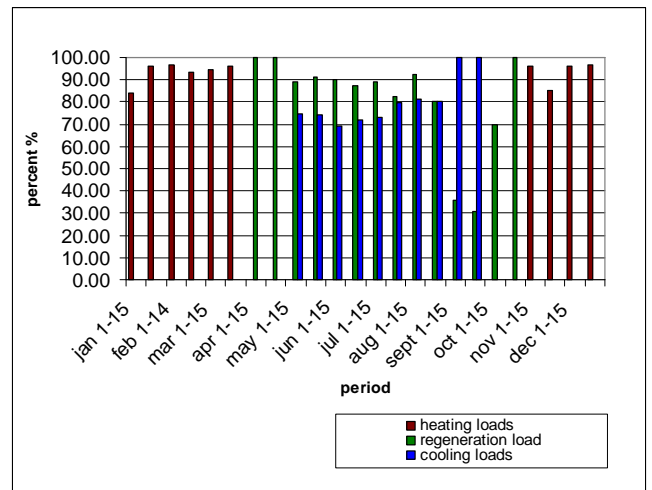


Figure 9. Biodiesel load coverage

Legislation: The system meets the federal Public Utilities Code standard in summer from 15th June to 31st July, according to Fig.10.

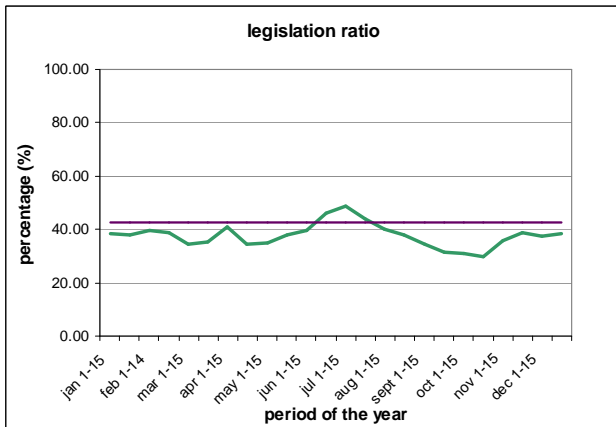


Figure 10. Achievement of legislation ratio for biodiesel

Further work

Partial mode: Additional studies will be run at various electrical power loads to evaluate the overall system efficiency in these modes.

Thermal load adjusted mode: In these calculations, the engine will be run to follow the regeneration, heating or cooling demand which imply to redefine a control strategy.

Electric Power Adjusted mode: The engine will be run following the building electric demand.

CONCLUSION

The modeling of the engine generator, heat recovery system of the IW provides valuable information regarding its performance throughout a typical year based on its design, its loads, and its operating mode.

The simulation calculation shows that full use of the thermal load of the system results in an overall system efficiency of 72%.

The high percentage of various IW thermal loads covered indicates that the system can provide heat for the majority of the year, but supplementary heat from campus grids is required for high demand days.

This study also underlines that a cogeneration system has to be completed by the grid to supply the demand variations while the cogeneration system provides for baseload requirements, to be used at its optimum efficiency.

Further consideration should be given achieving higher electrical generation efficiency and increased recovery of thermal heat in order to consistently meet federal standards. It appears likely that additional heat is available from the engine exhaust gases leaving the steam generator. Further consideration should also be given to evaluate the costs and the economic benefits of this cogeneration system.

ACKNOWLEDGMENTS

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NOMENCLATURE

Electric output	electric power produced by the engine generator
Used thermal output	heat used in the hot water/coolant heat exchanger + heat used in the steam generator
Fuel input	fuel based on lower heating value (LHV) of the fuel
Heat provided	calculated heat transferred to the heated/chilled water stream (in the desiccant unit, in the chiller ...)
Loads	estimated building loads (regeneration, cooling ...)

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