

A Final Report to the U. S. DOE/EERE/NETL

**Advanced Building Efficiency Testbed Initiative/
Intelligent Workplace Energy Supply System; ABETI/IWESS**

DE-FC26-06NT42798

10/1/06 through 31 May 08

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FOREWORD

This final report on ABETI/IWESS is presented in three sections

- a word description of the work and its accomplishments.
- a presentation of the work originally conceived in PowerPoint.
- a comprehensive listing of the formal documents prepared during the course of the work: reports, theses, and publications. These documents are grouped according to their general subject in what has been termed Appendices. They are publically available and all can be found posted on the website of the ABETI/IWESS project: <http://cmu.edu/iwess/>.

The helpful contributions of DOE/EERE personnel, Paul Giles, Project Officer, and Kelly McDonald, Project Administrator, are greatly appreciated and acknowledged here.

David H. Archer
18 September 2008

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INTRODUCTION

ABETI/IWESS is a project carried out by Carnegie Mellon's Center for Building Performance and Diagnostics, the CBPD, supported by the U.S. Department of Energy/EERE, to design, procure, install, operate, and evaluate an energy supply system, an ESS, that will provide power, cooling, heating and ventilation for CBPD's Intelligent Workplace, the IW. The energy sources for this system, the IWESS, are solar radiation and bioDiesel fuel. The components of this overall system are

- a solar driven cooling and heating system for the IW comprising solar receivers, an absorption chiller, heat recovery exchanger, and circulation pump.
- a bioDiesel fueled engine generator with heat recovery exchangers, one on the exhaust to provide steam and the other on the engine coolant to provide heated water.
- a ventilation system including an enthalpy recovery wheel, an air based heat pump, an active desiccant wheel, and an air circulation fan.
- various convective and radiant cooling/heating units and ventilation air diffusers distributed throughout the IW.

PROJECT GOAL

The goal of the ABETI/IWESS project is to demonstrate an energy supply system for a building space that will provide a healthy, comfortable environment for the occupants and that will reduce the quantity of energy consumed in the operation of a building space by a factor of 2 less than that of a conventional energy supply for power, cooling, heating, and ventilation based on utility power and natural gas fuel for heating.

PROJECT ACCOMPLISHMENTS, STATUS

This project has installed and has successfully operated all of the components of the IWESS. It has completed also the test and evaluation of all of the components, except the cooling/heating units with their advanced control system. Mathematical performance models have been programmed for each of the IWESS components based on their fundamental scientific and engineering principles. These models have been used in analyzing performance data obtained in testing of the components. Systems performance models that include the IW, the IWESS components, the building operation schedules, the outdoor ambient conditions, and the system operating algorithms have also been programmed and used in the design of system components, the test of operating algorithms, and the evaluation of the performance of the IWESS in reducing the energy demands for operating the IW throughout the course of a typical year in Pittsburgh.

The ABETI/IWESS project has been carried out over three years with \$2.7 million in funds from the U. S. Department of Energy responding to a Congressional directive sponsored Congressman Mike Doyle of Pennsylvania. It has also received support from the Pennsylvania Department of Environmental Protection, the U. S. Department of Defense, and a number of industrial sponsors. Paul Giles has ably served as the DOE Project Officer.

The project has received significant technical contributions from the Milwaukee School of Engineering/Sierra Nevada College, the Texas A&M University, and the University of Maryland.

PROJECT FUTURE

The IWESS equipment has been installed, operated, and tested, but funding from the U. S. DOE has been interrupted. Further work on the ABETI/IWESS is required to achieve the full energy conservation, economic, and environmental benefits of this work on ABETI/IWESS. Three significant tasks still remain.

Control automation, operation integration and optimization.

Up to now PhD graduate students have been responsible for operating independently the solar thermal cooling/heating and the bioDiesel fueled power supply/heat recovery systems. The operation of these two systems must now be automated to provide for start up, load follow, and shut down of the systems. Systems diagnostics will be required to provide for emergency shut down and for maintenance advisories. The operation of these two systems must be integrated with the IWESS and with the campus power, chilled water, and steam grids to provide reliably and efficiently the power and cooling/heating energies needed by occupants and by the ventilation system of the IW.

In parallel, the operation of the ventilation system and the cooling/heating units needs to be examined and optimized. The development of advanced controls must be continued to consider a variety of features in their operation: the measurement and consideration of occupancy, CO₂ levels, humidity, and multiple temperatures; the adoption of set back temperatures; the coordination with operable windows, blinds, and solar reflectors; the use of weather predictions and night cooling.

It is expected that these efforts in control automation, integration, and optimization will result in a further reduction of energy consumption in the IW by a factor of 1.5.

Economics: reduction of equipment, installation and operating costs.

The significant reduction of energy consumption and the associated environmental emissions resulting from the adoption of an ESS for operating a building seems clear. But a critical questions remain concerning the cost of designing, procuring, installing, and operating such systems and the pay back for such costs based on reduced energy requirements. An effort that must be made to calculate such costs and to consider carefully and in detail how they might be reduced in both new and retrofit ESS installations. Such considerations need to include not only the ESS itself but also the building in which it is installed in order how costs might be minimized.

Dissemination, commercialization, deployment

In order to realize the full benefits of this ABET/IWESS project in significantly reducing the energy consumed in U. S. buildings and in providing enhanced economic activity, the knowledge gained and the lesson learned must be disseminated. The technical advances achieved must be commercialized. And the technology represented in IWESS – distributed power generation and combined cooling, heating, and power, CHP, production for buildings – must be deployed.

To date, dissemination has been fostered through presentations, publications, and the IWESS website. Seven graduate students have been or are being trained. This effort will be continued. But further work must be explored and planned for dissemination through education – students, professionals, and the public.

Eight commercial firms have donated substantial equipment items and/or services to the IWESS project. Six additional firms have been involved in a substantial way. These firms have continued to work closely with the program so that there are existing channels for commercializing the advances made in the work. Further work in commercialization must be considered and planned.

Deployment, first addressed through proposed building projects at Carnegie Mellon and at Texas A&M University needs to be pursued and facilitated through a number of efforts: the preparation of design guides, procedures, and tools for ESS components and

systems; contacts in architects, builders, and developers; efforts with legislators, regulators, and code writers regarding provisions for increased effectiveness and efficiency of buildings.

ABET/IWESS TECHNOLOGY HALVES THE ENERGY REQUIRED FOR BUILDING OPERATION

A primary objective of the Advanced Building Efficiency Testbed/Intelligent Workplace Energy Supply System, ABET/IWESS, Project is to develop and demonstrate measures that

- reduce by half the energy required to provide power, cooling, heating, ventilation, and domestic hot water to a commercial building
- provide an environment in a building that promotes the health, productivity, and comfort of its occupants.

The specific measures for energy consumption reduction being employed in the IWESS are

- separation of ventilation air supply and space cooling/heating; control of ventilation air temperature and humidity for health, comfort, and effective operation of cooling/heating units, avoiding condensation.
- enthalpy recovery: heat and moisture exchange between ventilation air supply and air exhaust;. Enthalpy recovery reduces by 70-80% the energy required to cool/heat and dehumidify/humidify the ventilation air.
- hydronic space and ventilation air cooling/heating, replacing air based cooling/heating distribution: chilled/heated water supply to radiant and/or convective units distributed in the building space. Hydronic cooling/heating eliminates the fan energy required to circulate air in an air based distribution system and reduces the air duct size in the building by a factor of 5 to 10.
- distributed power supply from a renewable liquid or natural gas fueled engine generator with heat recovery from the exhaust gas and engine coolant
 - in summer for chilled water production in a two stage absorption chiller and desiccant regeneration in a ventilation air dehumidifier.
 - in winter for heated water production for space heating.
 - year around for domestic hot water supply.

The reduction in the energy required for operating a building from these measures obviously depends upon the specifics of the building, its location, and its operation. But some indication of the possible savings can be obtained by considering the following

illustration. Table 1 presents statistical data from the U. S. EIA 1995 on the current average delivered energy intensity, kWh/m²yr, of commercial buildings in the U. S. for space and ventilation air heating and cooling, electrical energy for lighting, equipment, pumps, and fans; and water heating. These building energy requirements are summed in the left section of the table in terms of total thermal and electrical delivered site energy intensities after each of the IWESS energy savings measures is successively adopted. The total reduction of delivered site energy is 60.1%, a factor of 2.5. If it is assumed that utility power is delivered to the building at an overall efficiency of 30%; that the efficiency of an engine generator located at the site is 35%; and that heat is delivered as natural gas, used at an efficiency of 80%, then the reduction of primary energy is 50.7%, a factor of 2.0.

The table thus shows that IWESS technologies result in a 50% reduction in the total primary energy required for building operation; and a 60.1% reduction in delivered site energy, if solar thermal energy is available to supply the heat not available from power generation. It also shows that because of the balance between the building power and heat requirements that a slightly less efficient power generation system could be employed in the building energy supply system without compromising the overall efficiency of the system.

Again it can be emphasized that these considerations are based on an averaged situation. Specific buildings in specific locations

- having various power generation components with their heat recovery systems
- coupled with different thermal based cooling systems and heating systems
- supplying chilled/heated water to various radiant/convective cooling/heating units and a ventilation air cooling/heating/circulation unit with humidity control
- incorporating also a solar photovoltaic or thermal energy recovery unit

can operate with source energy reductions greater or smaller than 50%. The important factors are the integrated design and operation of building and its energy supply system.

Automation, integrated operation, and advanced control of the various components of the IWESS are the factors that will be investigated in the next phase of ABET/IWESS project as funding is provided. It is projected the energy intensities can be further reduced, by a factor of 1.5 or more.

Table1. Effect of ABETI/IWESS Technologies on Reducing the Energy Required to Operate a Commercial Building

	Energy Intensity															Notes
	Total Energy			Low Temp. Thermal			High Temp. Thermal		Electrical							
	Site	Thermal	Electrical	Space Heating	Ventilation Heating	Water Heating	Cooling	Ventilation Cooling	Cooling	Cooking	Ventilation	Lighting	Refrigeration	Office Equipment	Other	
Consumption (kBtu/ft2-Year)	101.2	44.2	57.0	33.2	0.0	11.0	0.0	0.0	11.4	1.4	6.1	18.9	0.3	11.1	7.8	Reference [1]
Consumption (kWh/m2-Year)	319.3	139.4	179.8	104.7	0.0	34.7	0.0	0.0	36.0	4.4	19.2	59.6	0.9	35.0	24.6	Conversion to Metric
Thermal & Electrical Loads	369.6	226.6	143.0	83.8	0.0	27.8	115.1	0.0	0.0	3.5	19.2	59.6	0.9	35.0	24.6	Assumptions 2 and 3
Separate Space/Ventilation Heating/Cooling	369.6	226.6	143.0	71.2	12.6	27.8	97.8	17.3	0.0	3.5	19.2	59.6	0.9	35.0	24.6	Assumption 4
Hydronic Energy Distribution	354.1	226.6	127.4	71.2	12.6	27.8	97.8	17.3	0.0	3.5	2.9	59.6	0.9	35.0	25.4	Assumption 5
Enthalpy Recovery	333.2	205.8	127.4	71.2	3.8	27.8	97.8	5.2	0.0	3.5	2.9	59.6	0.9	35.0	25.4	Assumption 6
Absorption Cooling	323.8	196.4	127.4	71.2	3.8	27.8	88.9	4.7	0.0	3.5	2.9	59.6	0.9	35.0	25.4	Assumption 7
Thermal & Electrical Demands	323.8	196.4	127.4	102.8			93.6						127.4			Assumption 8
CHP Applied to Electrical & Heating Requirements	134.3	6.9	127.4	1.7			5.2						127.4			Assumption 9
Solar Thermal	127.4	0.0	127.4	0.0			0.0						127.4			Assumption 10

Assumptions:

- 1) Average consumption for a standard VAV commercial installation using natural gas and electricity. Other includes elevators and pumps.
- 2) Load: Average boiler, burner efficiency is 80%, therefore the actual load for space heating, water heating and cooking is 20% lower than the consumption [2].
- 3) Load: Average Chiller COP is 3.2 [3]
- 4) Separation: Space heating and cooling is separated from ventilation. 15% of space heating and cooling goes into heating and cooling ventilation air [4].
- 5) Hydronic: Applying a hydronic heating and cooling distribution system rather than a ducted system reduces ventilation fan power by 85% as stated in step 3. Further, the energy consumed by the fans for heating and cooling is reduced by 95% and added to other [5,6]
- 6) Enthalpy: Use of an enthalpy recovery wheel on the ventilation air reduces the heating and cooling loads by 70% [7]
- 7) Absorption: Absorption Chillers are used to cover the cooling load, which changes the electrical input for the chillers to a thermal input using a COP of 1.1 [8]
- 8) DG+CHP: A combined heat and power system is applied to cover the electrical load of 127.4 kWh/m2-year, which will yield 88.4 kWh/m2-year in high temperature heat and 101.1 kWh/m2-year in low temperature heat [9]. Fuel is added in site total, with an efficiency of 80%.
- 9) Solar: Assuming 1 kW/m2 and an efficiency of 0.4 at 6 hours of sunshine per day yields 216 kW of thermal energy. Therefore the balance of the thermal load can be covered by a solar thermal system operating in parallel with the CHP system. [8]

References:

- [1] 1992 Commercial Buildings Energy Consumption Survey, Table 2. Energy End-Use Intensities for All Major Fuels 1992
- [2] http://www.eere.energy.gov/buildings/appliance_standards/residential/pdfs/furnaces_boilers/furnaces_fr_111907.pdf
- [3] http://www.eere.energy.gov/buildings/appliance_standards/commercial/ac_hp.html
- [4] "Hydronic Radiant Heating and Cooling", Lawrence Berkeley National Laboratory, Environmental Energy Technologies, Indoor Environment Department, Energy Performance of Buildings Group. <http://epb.lbl.gov/thermal/hydronic.html>
- [5] Feustel, Helmut E. and Corina Stetiu, "Hydronic Radiant Cooling - Preliminary Assessment". Energy and Buildings 22 (1995) 193-205
- [6] Archer, David H and Fred Betz, "Comparison of Hydronic and Air Based Sensible Heat Transport". Carnegie Mellon University, CBPD 2008.
- [7] Zhai, Chaoqin; "Performance Modeling of Desiccant Wheel Design and Operation", PhD Thesis, Carnegie Mellon School of Architecture, Spring 2008
- [8] Yin Hongxi; "An Absorption Chiller in a Micro BCHP Application Model Based on Design and Performance Analysis", PhD Thesis, Carnegie Mellon School of Architecture, Spring 2005
- [9] Qu, Ming; "Model Based Design and Performance Analysis of a Solar Absorption Cooling and Heating System", PhD Thesis, Carnegie Mellon School of Architecture, Spring 2008



Figure 1: Carnegie Mellon's Intelligent Workplace with Solar Receivers on the Roof

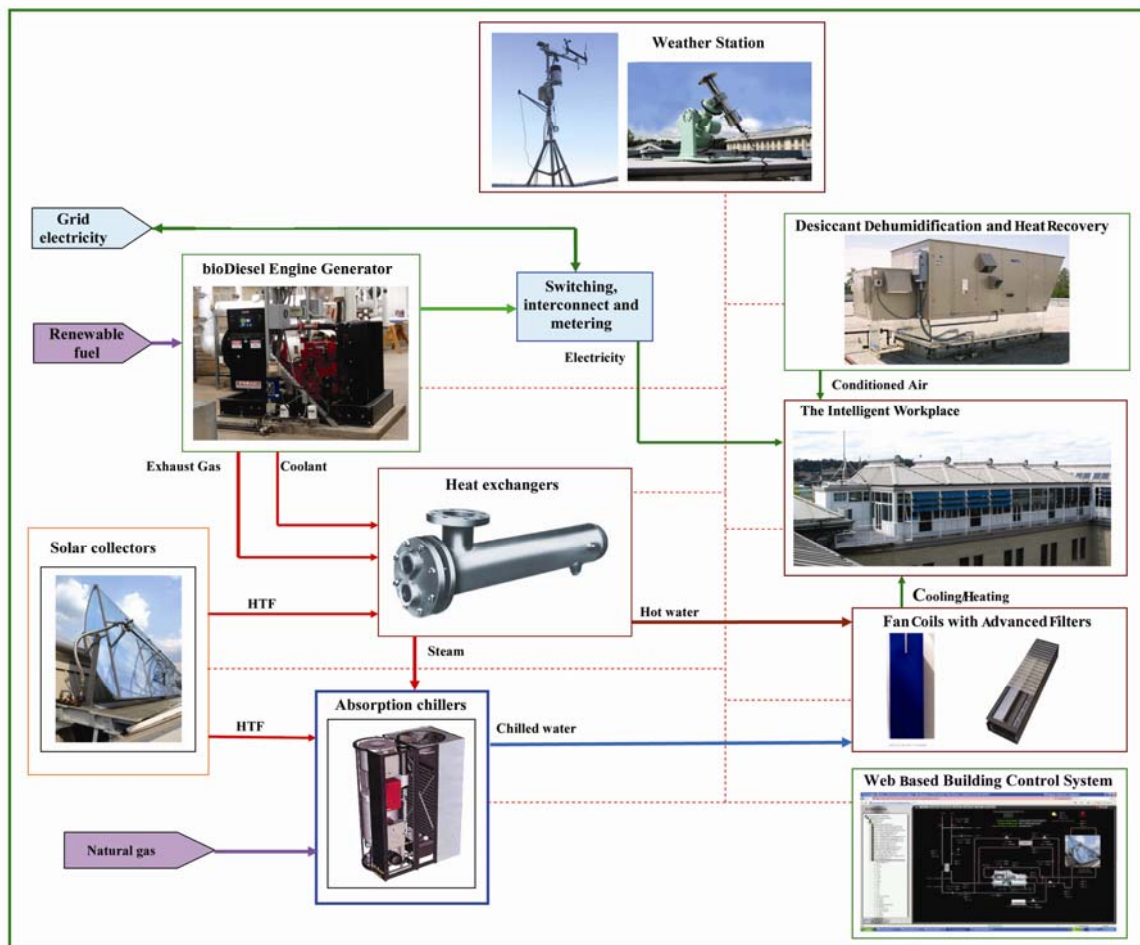


Figure 2: Installed Components of the Energy Supply System of the Intelligent Workplace, the IWESS



Figure 3. BioDiesel fueled engine generator



Figure 4. Heat recovery steam generator



Figure 5. Parabolic trough solar thermal receiver



Figure 6. Two stage absorption chiller

THIS FINAL REPORT

This Final Report for ABETI/IWESS project is comprised of the following

- the brief project summary presented above concluding with the section that presents how the technologies incorporated in the IWESS reduce the energy consumption of a commercial building, both site and source, by a factor of 2 or more.
- a .ppt presentation following describing the current status of the project.
- this reference to the website of the project: <<http://www.cmu.edu/iwess>>
- a collection of eight Appendices: one for each of the four IWESS components; two for modeling studies, one for systems' performance and the other for air flow and temperature in the IW; and one for each of two collaborators, Texas A&M University and the University of Maryland. The work of Sierra Nevada College/Milwaukee School of Engineering is incorporated in the Appendix 2, dealing with the bioDiesel engine generator and its heat recovery exchangers. These Appendices include theses, publications, reports, and computer program files of component and systems models.

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IWESS, CMU's Intelligent Workplace Energy Supply System



Power, Cooling, Heating, and Ventilation
from Solar Heat and a Renewable Fuel

David H. Archer
12 June 2008

IWESS Guidelines

- provide energy for IW operation from the sun and from a renewable fuel
- distribute cooling/heating in the IW by circulating chilled/heated water
- ventilate the IW by ample fresh conditioned, temperature and humidity, air
- generate power for the IW from the renewable fuel; recover heat at suitable temperatures for cooling/heating/ventilation
- install, operate, evaluate, integrate a combined cooling/heating/power/ventilation, CHPV, system, in the IW
- provide energy to the IW at an efficiency twice that of a conventional energy supply
- develop how this system might be cost effective
- assist in disseminating, commercializing, deploying the technology



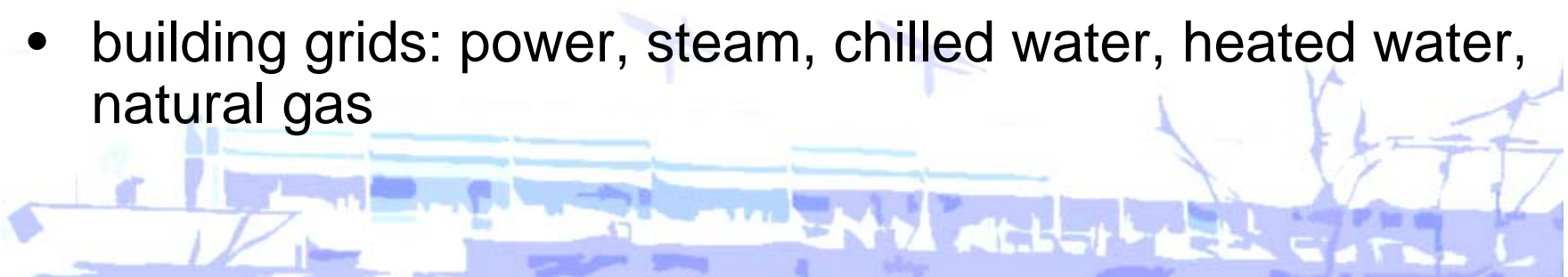
IWESS Rationale

- high energy impact of operating buildings: 40% of primary energy, 70% of power generated
- reduced impact requires architecture, engineering
- distributed generation, combined C/H/P/V, renewable fuel and solar energy
- integrated: system, space, grids, operation/control
- simulation: includes building space, schedules, ambient conditions, equipment, operation/control; calculates performance; effects of design and operation
- develop, demonstrate, specific instance; generalize

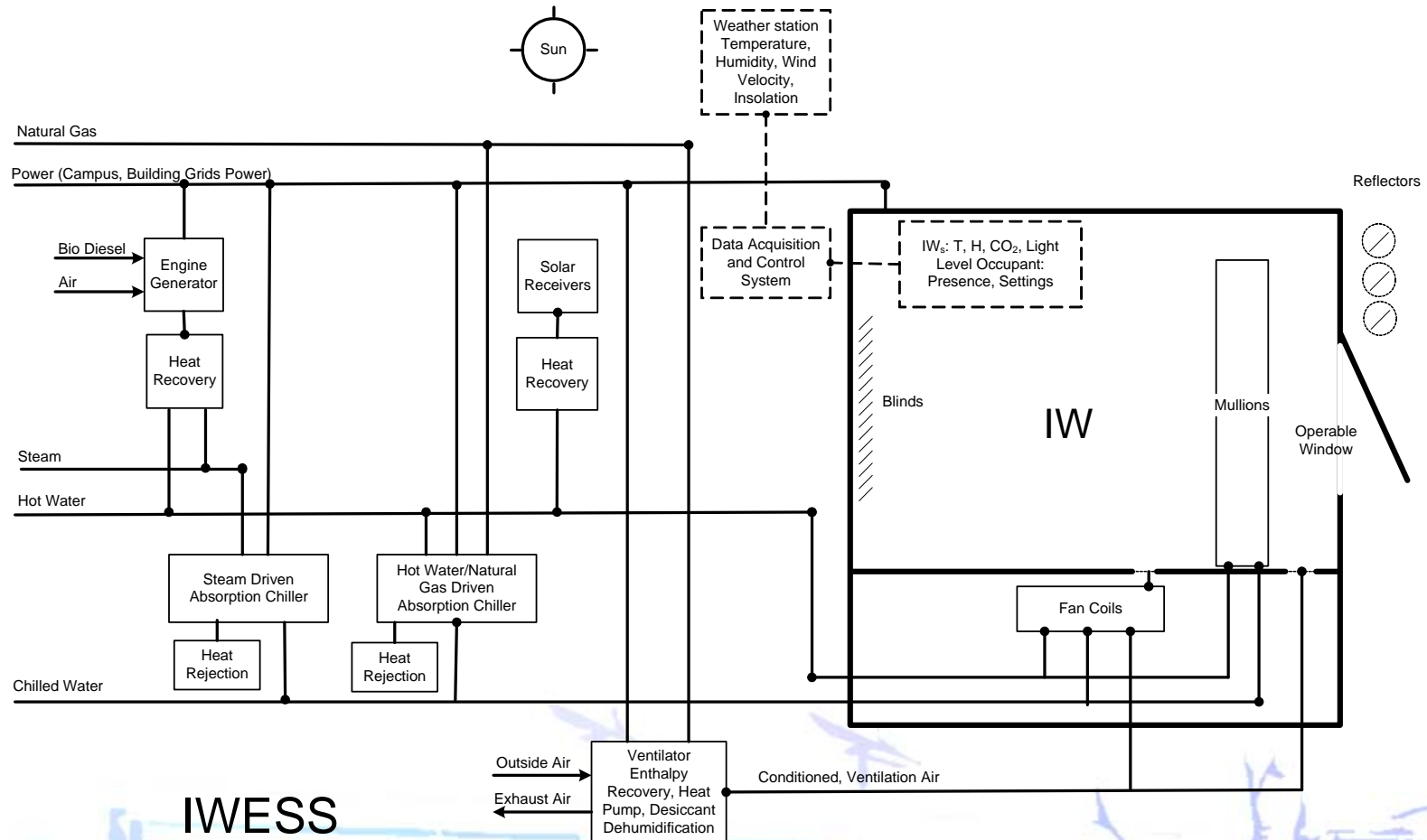


IWESS Components

- solar thermal heat supply with a hot water driven absorption chiller and a heat recovery exchanger
- bioDiesel engine generator with heat recovery equipment for steam and hot water; steam driven absorption chiller
- fan coil and radiant cooling/heating units with advanced controls
- ventilation system with an enthalpy recovery wheel, heat pump, and desiccant dehumidification wheel
- operable windows; other façade elements
- building grids: power, steam, chilled water, heated water, natural gas



IWESS Components Integrated with IW through Grids

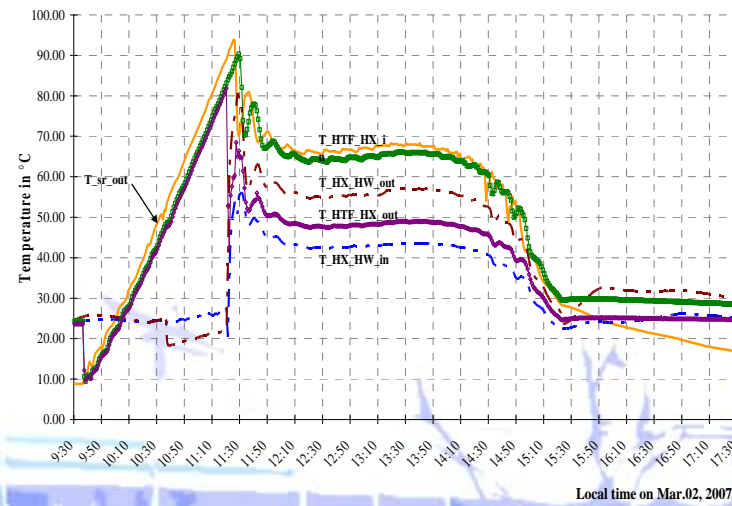
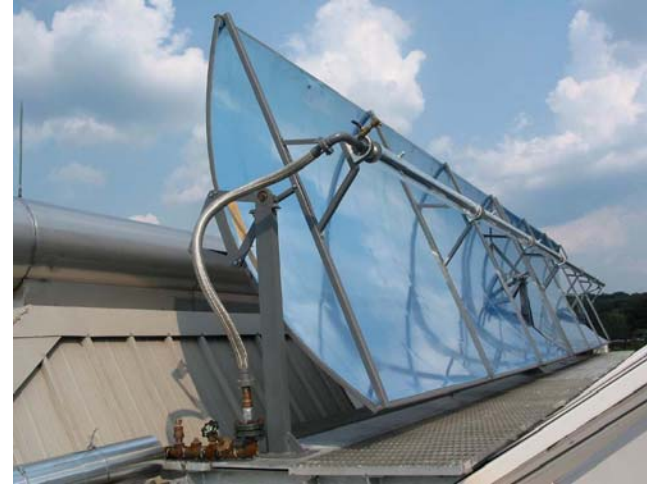


IWESS Status Table

Component	Selected	Preliminary Design	Procurement	Detailed Design	Installation	Test, Evaluation	Operation, Integration*	Optimization, Diagnostics*	Cost	Comments
Solar thermal building cooling/heating									\$387 k	Testing is now complete
BioDiesel engine generator with heat recovery									\$644 k	Commissioning now complete
Steam driven chiller									\$219 k	Renovated, awaiting operation w engine
Ventilation, conditioned air supply system									\$74 k	Operating, awaiting modification
Fan coils with advanced control system									\$314 k	Testing underway, expanded controls
Radiant cooling/heating units; mullions, panels										Modeling for performance studies
Operable windows									\$24 k	Installation underway
									\$1,662 k	

* Require advanced control

IWESS Solar Thermal Building Cooling/Heating System

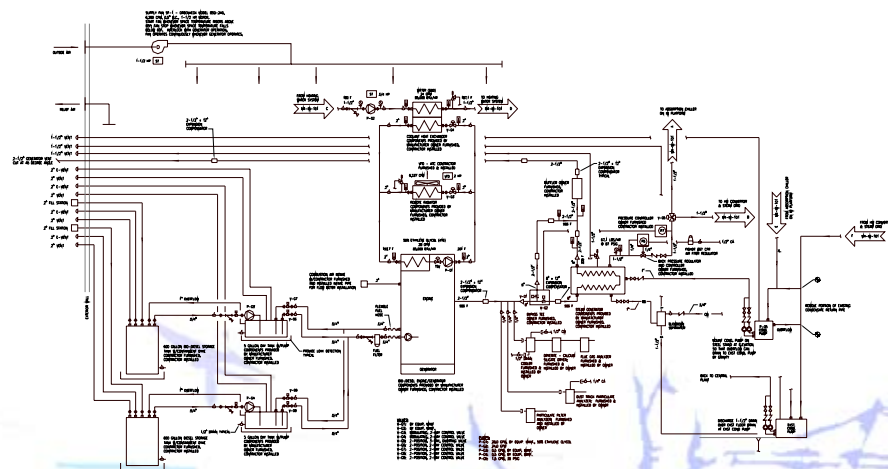


IWESS Solar Thermal Cooling/Heating System

- installed Oct 06; commissioned Feb 07
- testing; 37 sunny days through Sep 07
- tested: receiver efficiency; preheating/postcooling times; heat lost/delivered; summer cooling/winter heating; chiller operation
- accomplished: validation of receiver and system models; performance prediction, equipment design, system operation/control
- Problems identified: receiver focus; receiver heat loss; glass absorptance; system extent/heat capacity
- to do: automation, integration; inclusion of PCM storage and drain back; solar cooling system design, evaluation, cost, marketing, manufacture

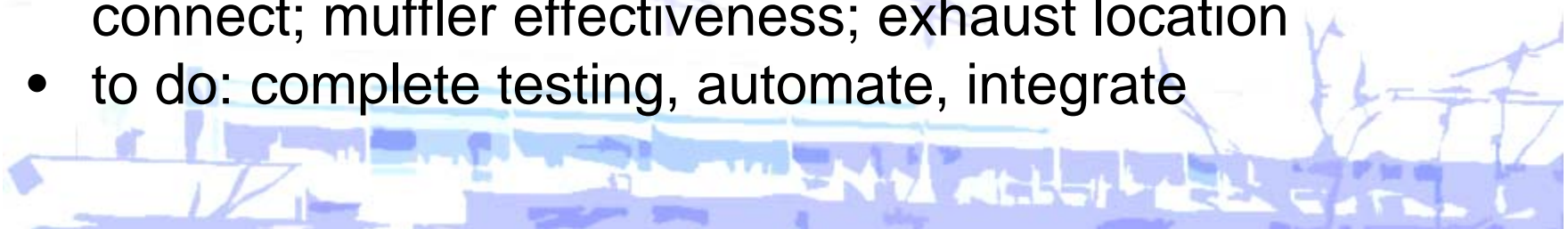


IWESS BioDiesel Fueled Building Power/Cooling/Heating Supply

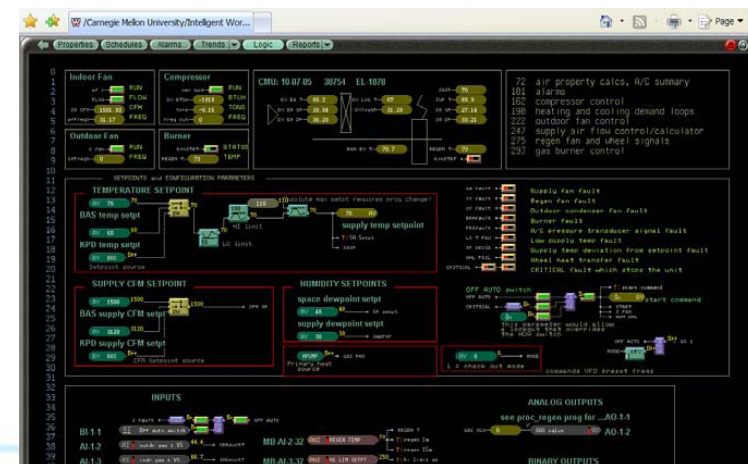
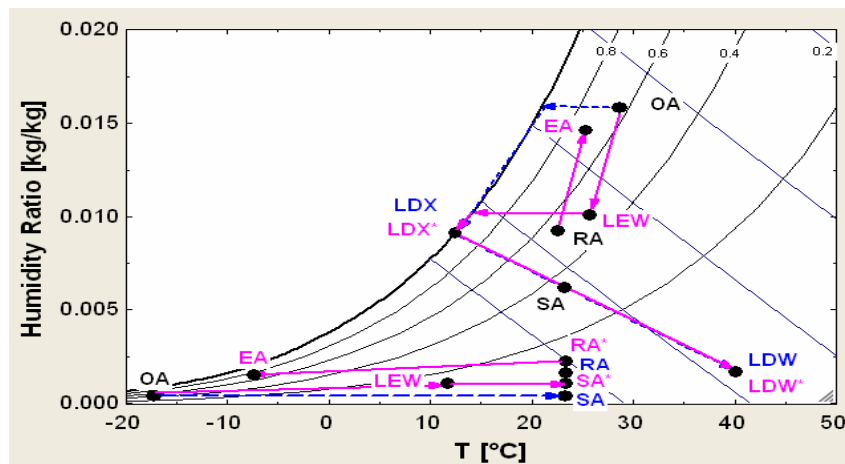
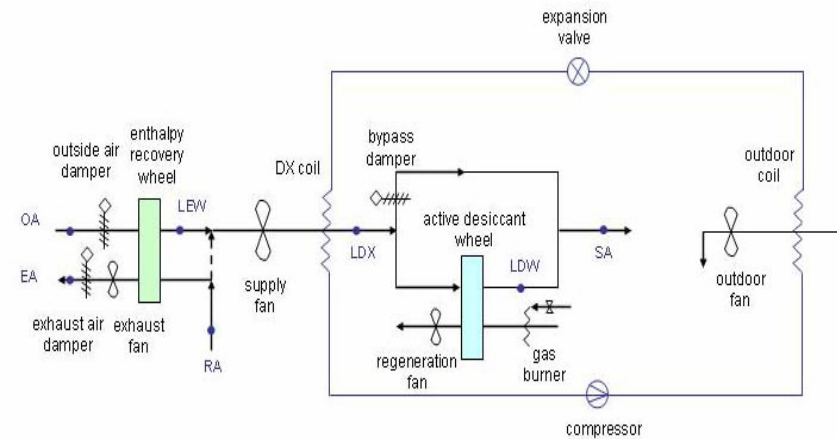


IWESS BioDiesel Fueled Building Power/Cooling/Heating Supply

- procured Jul 06, space allocated, detailed design, installed Sep 07 (3 months late)
- testing: conventional and 4 biofuels; four power load levels
- determine: fuel consumption, steam/heated water production, gaseous and particulate emissions, injection/combustion timing, turbo charger performance
- collaborators: MSOE - particulates, cylinder p-t analysis; Lehigh - turbocharger, heat recovery equipment analysis; CMU - particle analysis
- observations: power/heat compatibility; steam generator/muffler capacity; complexity, cost of grid connect; muffler effectiveness; exhaust location
- to do: complete testing, automate, integrate



IWESS Ventilation Air Supply with Enthalpy Recovery and Desiccant Dehumidification

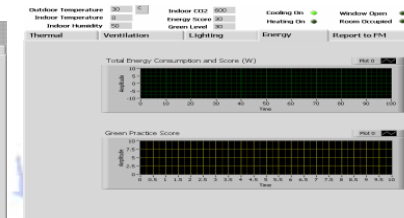
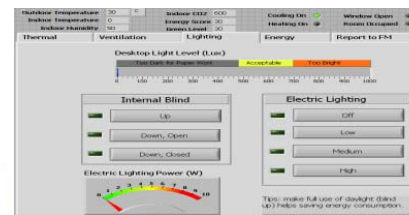
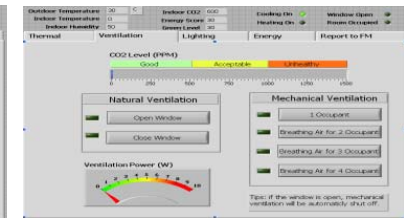
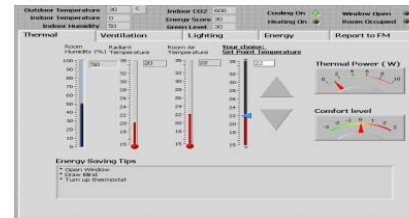
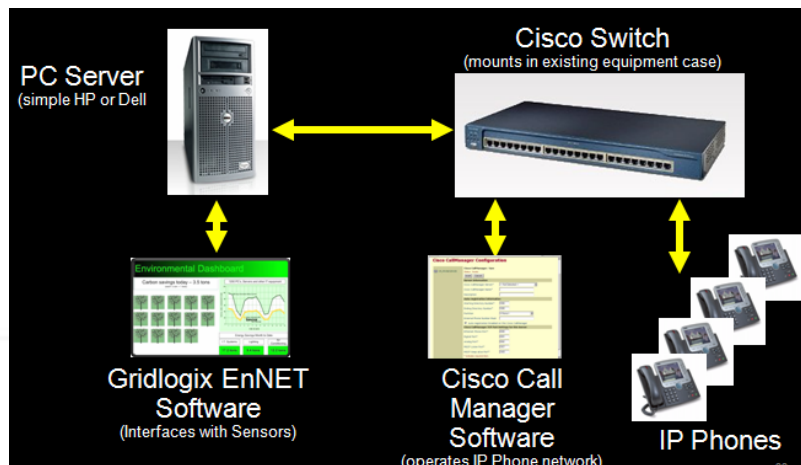
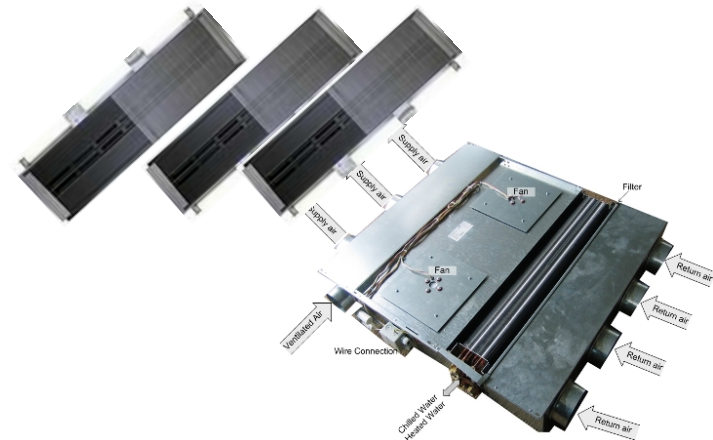
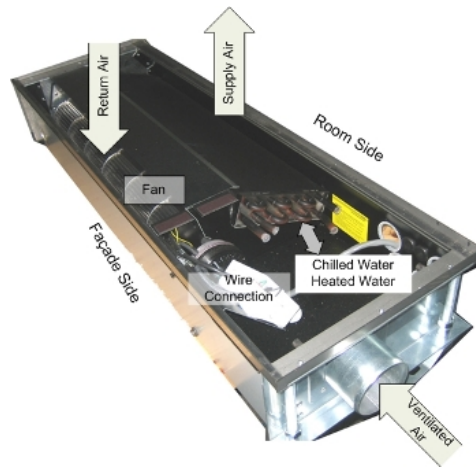


IWESS Ventilation Air Supply

- installed Oct 05; operated, tested to date
- problems: condenser air fan replacement; control adjustments for heat pump reversing valve; heat pump compressor capacity/low freq limit
- accomplished: detailed performance tests for enthalpy exchange wheel, active air dehumidification/heating wheel; material/energy balances, heat/moisture recovery effectiveness; heat/moisture exchange; validation of wheel performance models predicting air stream outlet conditions based on design, operating, inlet conditions
- validated models applicable to performance projections, equipment design, operation/control optimization
- WBDG preparation: enthalpy exchange wheel selection, evaluation
- to do: modify equipment, integrate operation with other IWESS components; add logical algorithms for operation - on/off of system components; adapt system to chilled/heated water supply, not power and natural gas, for ventilation air temperature and humidity control; compare performance with alternate ventilation system designs



IWESS Fan Coil, Office Cooling/Heating, Environment Control



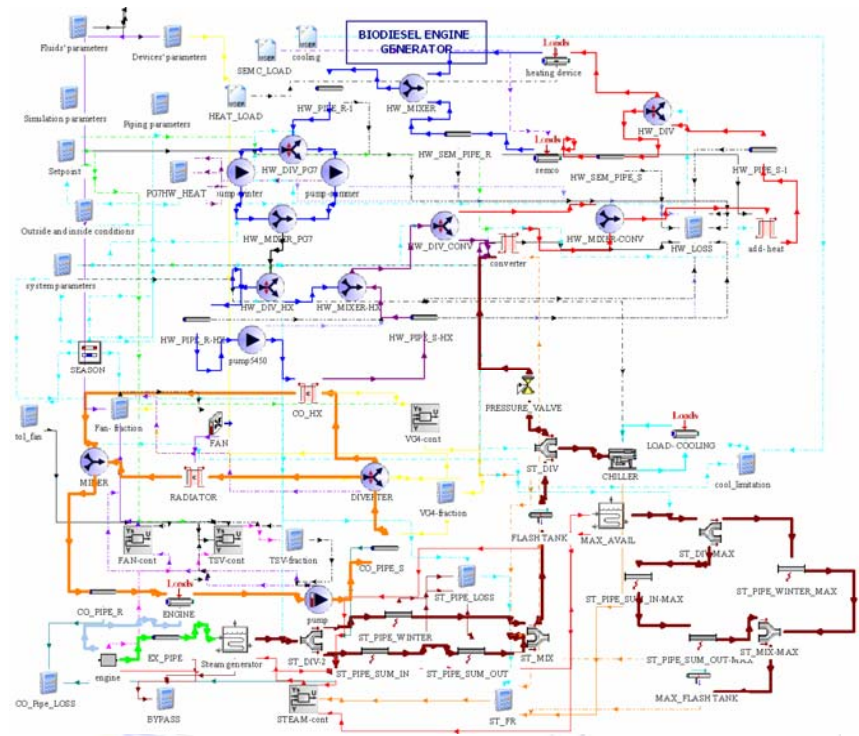
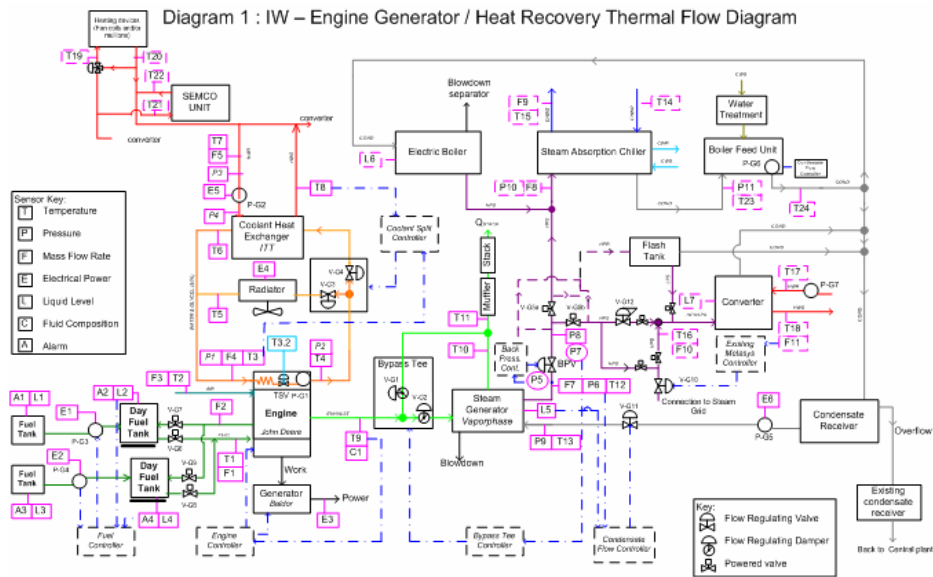
IWESS Fan Coil Cooling/Heating Units

- 22 units, 3 types for IW_s procured from LTG, Oct 06; instrumentation, control promised by Siemens, Oct 06
- detailed design by Astorino; installation bids, \$203 k, Jun 07; Siemens software, hardware did not materialize
- rescope of project: 2 offices not 10; 4 fan coils not 22; 2 pipe cooled/heated water not 4; million water supply; NI Labview advanced control programmed; installation \$56 k not \$203 k.
- tests evaluating the system and its advanced controls underway
- office environment control (cooling, heating, ventilation, lighting, window opening) system proposed; occupant, equipment, administrator communication with Cisco IP phone; occupant satisfaction, energy reduction targeted
- to do: complete installation, continue testing, operation; evaluate
- new areas: Cisco IP phone; CFD evaluation of air flow (fan coil design, location, operation); new fan coils with electrostatic particulate removal, activated carbon impurity absorption from Boad; façade based fan coil ventilation with dehumidification



IWESS Modeling: BioDiesel Power, Steam, Heated Water Energy Supply

Diagram 1 : IW – Engine Generator / Heat Recovery Thermal Flow Diagram

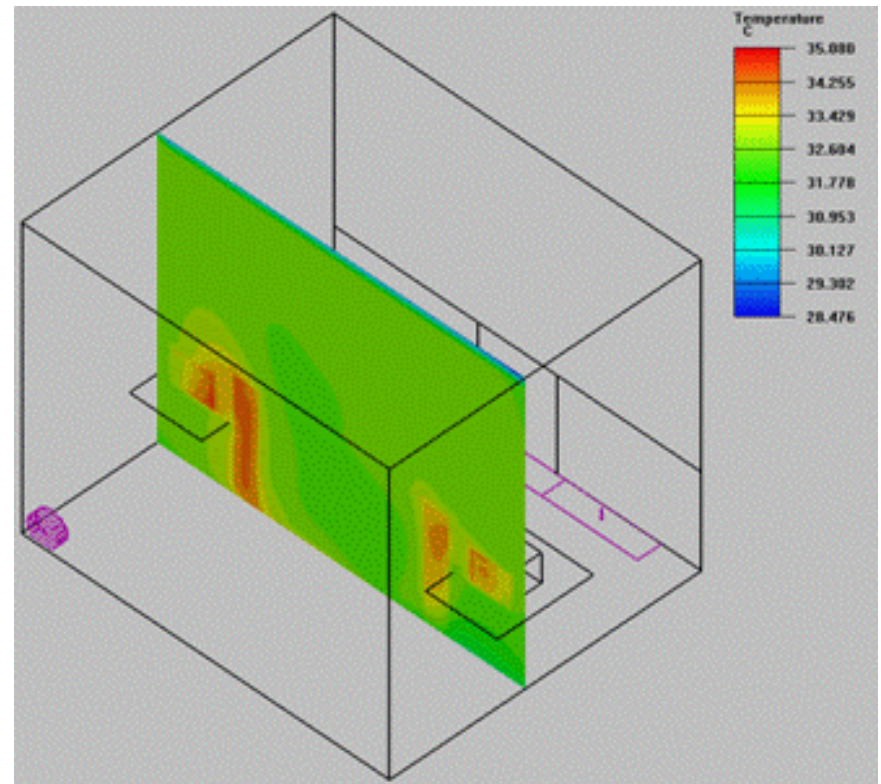
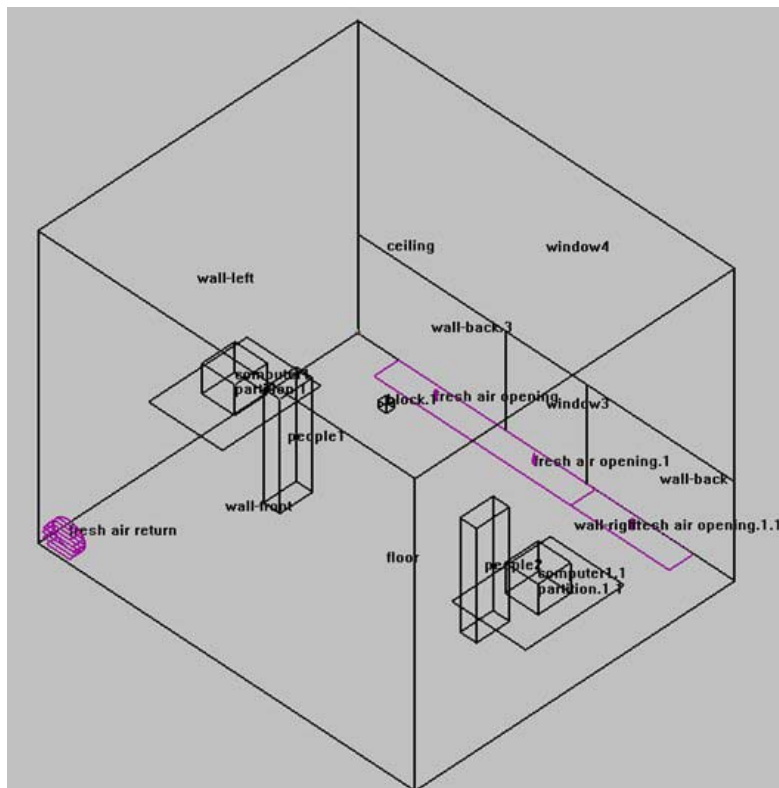


IWESS Systems Studies

- initiated early 05, meeting of TAMU, UMD, CMU, DOE to select platform: Trnsys; Comis, used for air flow between zones
- accomplished: solar thermal IW cooling/heating: design (solar field sizing, orientation, storage capacity, insulation, pipe sizing); performance (solar/gas heat use)
- solar system test: operation, performance of test systems
- window opening: effect of opening windows on cooling, ventilation costs, evaluation of operating algorithms
- bioDiesel engine generator, heat recovery system performance (power, steam, hot water produced following various loads)
- to do: extend current studies; multi zone IW; integrated solar and bioDiesel supply; transition to Energy Plus; extend to tools for system design, performance projection



IWESS CFD Modeling: Air/Heat Flow in an Office



IWESS Collaborators

- TAMU – analysis of IW million cooling/heating system; performance modeling with CFD flow/heat transfer computations, checking with data; analysis of air infiltration into the IW; application of IW, ESS at Laredo site
- SNC/MSOE – procurement of the bioDiesel engine generator system; particulate emissions measurement; operation and performance measurements
- UMD – consultation on modeling; consultation on ESS for the BAPP



IWESS Initiatives for Extended Work

- automate, integrate, optimize IWESS component operation
- develop IW office (IP Phone) advanced control of cooling, heating, ventilation, lighting, window operation: IWESS-occupant interaction
- Install operable windows: evaluate operational strategies in providing comfort reducing ventilation and cooling costs
- initiate cost analysis: economic performance of IWESS; exploration of equipment and operating costs; identification of means for cost reductions
- dissemination
 - publications: web site, papers, WBDG's,
 - education: students, NSF course/curriculum; presentations,
- commercialization (Components, Systems)
 - company contacts: Broad, Semco, Siemens, Astorino, Logical Automation, John Deere
 - tools provided: equipment components, systems
- deployment
 - customers: Giant Eagle, Almono
 - policy
 - codes, standards



IWESS New Funding Initiatives

- NREL: solar power generation with heat storage and recovery (not funded, only utility power generation considered).
- PITA: CFD fluid flow/heat transfer in fan coil installations (not funded)
- PEDA: window opening, mixed natural/mechanical ventilation (funded at \$80 k)
- Broad: advanced fan coil, installation, analysis (funded at \$80 k)
- NSF: course/curriculum on ESS, multi university; use of ESS components for demonstration, experimentation, projects (no announcement; \$500 k requested)
- Heinz Foundation: Almono District Energy System description (funded at \$15 k)
- Broad: gift to CBPD (\$250 k/year for 5 years; gift to CMU (\$250 k/year for 5 years)
- Commonwealth of PA: energy initiative (\$500 k requested)



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David Archer



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**Advanced Building Efficiency Tested Initiative/
Intelligent Workplace Energy Supply System; ABETI/IWESS**

DE-FC26-06NT42798

10/1/06 through 31 May 08

Final Report Appendices: Documents Produced in the IWESS Project

Appendix 1. IWESS Solar Thermal Cooling/Heating System: Parabolic Trough Solar Receivers; Two Stage Absorption Chiller

This system is one of two essential components of the IWESS that receive energy from an external source and provides an energy supply to the IW. Parabolic trough solar thermal receivers operating with a two stage absorption chiller or a heat exchanger for chilled or heated water production have been installed, tested, and evaluated for cooling or heating in the IW. Detailed performance models of the receivers and of the solar cooling/heating system have been programmed based on fundamental scientific and engineering principles. These models have been used in data analysis, equipment design, and performance projection. The documents follow.

- **Thesis:** “Model Based Design and Performance Analysis of Solar Absorption Cooling and Heating System”; Ming Qu., Carnegie Mellon, School of Architecture; Spring 2008
- **Thesis Presentation:** “Model Based Design and Performance Analysis of Solar Absorption Cooling and Heating System”; Ming Qu; Winter 2007
- **Report:** “Test Report of Solar Cooling and Heating System for the Intelligent Workplace”; Ming Qu, David H. Archer; Winter 2007
- **Publications:**
 - ES2008-54200: EXPERIMENT BASED PERFORMANCE ANALYSIS OF A SOLAR ABSORPTION COOLING AND HEATING SYSTEM IN THE INTELLIGENT WORKPLACE; Ming Qu, David H. Archer, Hongxi Yin; Energy Sustainability 2008, Jacksonville, Florida, August 10-14,
 - ES2007-36052: A LINEAR PARABOLIC TROUGH SOLAR COLLECTOR PERFORMANCE MODEL; Ming Qu, David H. Archer, Hongxi Yin; Energy Sustainability 2007, Long Beach, California, June 27-30,

Appendix 2a. IWESS BioDiesel Fueled Engine Generator with Heat Recovery Exchangers from the Engine Exhaust for Steam and from the Engine Coolant for Heated Water

The engine generator is the second of the two essential components of the IWESS. It receives a supply of renewable energy, bioDiesel fuel, and delivers power and heat. This liquid fuel is readily available and easily handled. The engine has reasonable cost and relatively high power generation efficiency; the reject heat is available at a useful temperature. The documents follow.

- **Report:** “BioDiesel Fueled Engine Generator with Heat Recovery”; Fred Betz, David H. Archer; Carnegie Mellon University, School of Architecture; May 2008.
- **Publication:** ES2008-54131: BIODIESEL FUEL ENGINE GENERATOR WITH HEAT RECOVERY; Fred Betz, David Archer, Carnegie Mellon University; Chris Damm, Brian Goodwin, Milwaukee School of Engineering.

Appendix 2b. IWESS Steam Driven Two Stage Absorption Chiller

This chiller was the first of the IWESS components to be received, installed, tested, and evaluated. It is intended to operate with steam provided by the bioDiesel fueled engine. To enable early testing of this system an electrically heated steam supply and a variable cooling load exchanger provided with heated water from the building grid supply were installed. A performance model of the chiller was programmed, validated, and used for performance data analysis. The documents follow.

- **Thesis:** “An Absorption Chiller in a Micro BCHP Application: Model Based Design and Performance Analysis”; Hongxi Yin; Carnegie Mellon, School of Architecture; Summer 2006
- **Thesis Presentation:** “An Absorption Chiller in a Micro BCHP Application: Model based Design and Performance Analysis”; Hongxi Yin, Summer 2006
- **Publications:**
 - THE MEASURED PERFORMANCE AND MODEL BASED PERFORMANCE ANALYSIS OF A 16kW ABSORPTION CHILLER; Hongxi Yin, David H. Archer; CMU Proceedings of
 - ES2008-54209 ES2008: THE HEAT TRANSFER CHARACTERISTICS OF A 16 KW STEAM DRIVEN DOUBLE EFFECT ABSORPTION CHILLER; Hongxi Yin, David H. Archer, Ming Qu; CMU. Energy Sustainability 2008, Jacksonville, Florida, August 10-14,

Appendix 3. IWESS Ventilation System: Enthalpy Recovery Wheel, Air Based Heat Pump, Solid Desiccant Dehumidification Wheel, Air Circulation Fan

The ventilation unit of the IW can serve either as a dedicated outdoor air supply, a DOAS, or it can in addition circulate air from the IW and provide additional cooling/heating for the space. The air dehumidification and the consequent reduction of humidity in the IW provided by this ventilation unit has made it possible to reduce the temperature of the chilled water supply to the cooling/heating units in the IW without risking condensation, and thus has significantly enhanced their cooling capacity.

This ventilation unit is comprised of

- an enthalpy recovery wheel that exchanges heat and moisture between the supply and exhaust air streams of the IW making use of a microporous, zeolite desiccant.
- an air based, reversible heat pump that cools or heats the supply air to the IW.
- an active desiccant wheel that dehumidifies the supply air making use of a silica desiccant regenerated by heated outdoor air
- air fans that circulate supply air, remove exhaust air, and provide heated air for desiccant regeneration.

The unit with its Automated Logic control system was provided by Semco and the U. S. DOE. Its performance in summer and winter operation in the IW has been tested extensively and evaluated. Performance models for both the enthalpy recovery and the active desiccant wheels have been formulated, programmed and validated with experimental data from the unit. These models are based on fundamental scientific and engineering principles: material and energy balances, phase equilibrium, and heat and mass transfer relations. They relate the wheel performance to the design and operating conditions, and thus are useful in optimizing the system.

A Whole Building Design Guide, a WBDG, for the application of enthalpy recovery wheels in building ventilation systems has been written to provide guidelines for their inclusion and selection.

- **Thesis:** “Performance Modeling of Desiccant Wheel Design and Operation”; Chaoqin Zhai; Carnegie Mellon, School of Architecture; Winter 2007
- **Thesis Presentation:** “Performance Modeling of /Desiccant Wheel Design and Operation”, Chaoqin Zhai; Carnegie Mellon, School of Architecture; January 2008

- **Whole Building Design Guide:** “An Enthalpy Recovery Wheel for a Building Ventilation System”, , Chaoqin Zhai, David H. Archer; Winter 2007
- **Publications:**
 - ES2008-54190: INTEGRATION OF THE ACTIVE DESICCANT WHEEL IN CHP SYSTEM DESIGN; Chaoqin Zhai, David H. Archer, John C. Fischer; Energy Sustainability 2008, Jacksonville, Florida, August 10-14
 - ES2008-54185: PERFORMANCE MODELING OF DESICCANT WHEELS (1): MODEL DEVELOPMENT; Chaoqin Zhai, David H. Archer, John C. Fischer; Energy Sustainability 2008, Jacksonville, Florida, August 10-14
 - IMECE2006-13763: THE PERFORMANCE OF AN ENTHALPY RECOVERY WHEEL IN VENTILATION OF CMU’S IW; Chaoqin Zhai, David H. Archer, John C. Fischer; 2006 ASME International Mechanical Engineering Congress and Exposition, Chicago, Illinois, November 5-10,

Appendix 4. IWESS Office Cooling/Heating/Ventilation/Lighting System: Fan Coils with Advanced Instrumentation and Control Integrated with Lighting and Ventilation Operation, IP Phone Operation

The IW has had since its initial opening in 1997 a variety of radiant and convective cooling/heating units distributed in the space – pipes mounted on the mullions of the façade through which either chilled or heated water is directed, radiant ceiling panels in several office and interior areas, ceiling mounted paddle fan units in the large meeting room. These units have provided thermal comfort to the occupants of the IW in winter; but IW cooling in summers has proved inadequate, at least prior to the installation and operation of the ventilation unit with its enhanced dehumidification and cooling capabilities.

It has been decided to install under floor mounted fan coil cooling/heating units with floor level diffusers in several office areas of the IW in order to

- enhance cooling in the space.
- demonstrate alternate convective cooling/heating approaches appropriate to the architectural features of the space.
- develop and demonstrate an advanced approach to cooling/heating/ventilation control that will provide an healthy, productive, comfortable office environment and will also minimize the energy required to accomplish this. This control will make use of a wide variety of instrumentation to detect – occupancy, indoor air and radiant temperatures, humidity, and outdoor conditions. It will employ both feed back and model based feed forward control features.

Under floor mounted fan coils from LTG, have been installed in two IW office areas. An advanced instrumentation, operation, and control together with a data acquisition system has been devised and programmed making use of National Instruments' LabVIEW hardware and software. A Cisco IP Phone system with Gridlogix software has been installed to provide for communications among the office occupants, the cooling/heating/ventilation equipment, and the office administrator.

- **Report:** "The Fan Coil Unit Installation in the IW: Summary of Research Conducted and Experiments Performed; Viraj Srivastava, Yun Gu; Carnegie Mellon University; 20 May 2008

Appendix 5. IWESS Systems Modeling Studies

Modeling has been important in the IWESS project. Performance models of individual IWESS components have been formulated and programmed for the solar receivers, the absorption chiller, the Diesel engine, and the components of the ventilation unit. The construction of these models has been helpful in understanding this equipment and in analyzing its performance data. Systems performance models have also been formulated and programmed. These models include models of the equipment, the IW, the hourly weather and schedules of the IW, and the operation and control system. These models have proved useful in the design of the equipment and system based on projections of its annual performance in maintaining a suitable environment for the IW occupants and in minimizing energy consumption. The documents follow.

- **Reports:**
 - "ABETI/IWESS Systems Modeling Studies, Final Report to DOE/EERE/NETL for ABETI/IWESS", Sophie Masson, Ming Qu, David H. Archer, Fore Marion, Elisabeth Aslanian, Berangere Lartigue, Yun Gu, Viraj Srivastava, Spring 2008
 - "Impact of Hybrid Ventilation in a Bay of the IW on Cooling and Ventilation Energy Requirements for a Typical Summer in Pittsburgh"; Elisabeth Aslanian, Sophie Masson, David H. Archer; January 2008
 - "Performance Modeling of a Biodiesel Engine Generator Heat Recovery System in the Intelligent Workplace at Carnegie Mellon University"; Flore Marion, David H. Archer, Sophie Masson,
- **Publications:**
 - ES2008-54256: COGENERATION SYSTEM PERFORMANCE MODELING; Flore Marion, David H. Archer, Sophie Masson, Frederik Betz; Energy Sustainability 2008, Jacksonville, Florida, August 10-14
 - ES2007-36053: PERFORMANCE MODELING OF A SOLAR THERMAL SYSTEM FOR COOLING AND HEATING IN

Appendix 6. IWESS Computer Fluid Dynamic, CFD, Modeling of Air Flow in
Cooling/Heating/Ventilating Office and Meeting Room Spaces

A series of CFD modeling studies have been carried out to determine how the location and operation of fan coils and ventilation air diffusers in a building space affects the air temperature and flow distribution in that space, the comfort level of the occupants of the space, and the quantity of energy required to reach that level. Three publications have been prepared on this work. Additional work is underway. The documents follow.

- **Publications:**
 - ES2008-54232: COMPUTATION OF AIR FLOW IN CMU'S INTELLIGENT WORKPLACE AND ITS EFFECT ON OCCUPANT HEALTH AND COMFORT; Rong Li, David H. Archer, Yongjie Zhang; ASME 2008 2nd International Conference on Energy Sustainability, Jacksonville, Florida, August 10-14
 - ES2008-54213: NATURAL VENTILATION POTENTIAL IN THE INTELLIGENT WORKPLACE; Rui Zhang, David H. Archer, Khee Poh Lam, Yongjie Zhang; Energy Sustainability 2008, Jacksonville, Florida, August 10-14

Appendix 7: The Texas A&M University, TAMU
Studies of Radiant Cooling/Heating and Air Infiltration in the Intelligent
Workplace, the IW. Application of Intelligent Workplace Energy Supply
System, IWESS, Principles to Building Projects at

TAMU has provided consulting on the commissioning of the various components of the IWESS at Carnegie Mellon. They have also undertaken a series of studies on the radiant, mullion pipe cooling/heating units in the IW and on air infiltration into this space. These studies have significantly contributed to the capability to accurately model IWESS performance and to effectively operate cooling/heating in the IW. In addition, TAMU has taken steps to deploy the IWESS principles in the design of new building on their campus.

Their work and accomplishments are described in a two reports, in two theses, and in a collection of four publications included in this Appendix. The documents follow.

- **Theses:**
 - "Evaluation of Selected Energy Options for a Sustainable Campus in Texas"; Kathryn Elaine Clingenpeel; Texas A & M University Winter 2007

- “Investigation of a Radiantly Heated and Cooled Office with an Integrated Desiccant Ventilation Unit”, Xiangyang Gong, Texas A & M University, Summer 2007
- **Reports:**
 - “A Study of the Advanced Systems at the CMU Intelligent Workplace with an Evaluation of Potential Applications to Texas A&M International University: A Summary Final Report”; David E. Claridge, Xiangyang Gong, Malcolm Verdict, Kathryn Clingenpeel, April 2008
- **Publications:**
 - “Development of a Heat Transfer Model for the Integrated Faceade Heating”, David E. Claridge, Texas A&M; David H. Archer, CMU; Xiangyang Gong , Texas A&M
 - “Infiltration Investigation of a Radiantly Heated and Cooled Office”, David E. Claridge, David H. Archer, Xiangyang Gong
 - ICEBO2006: “Indoor Humidity Analysis of an Integrated Radiant Cooling and Desiccant Ventilation System”, David E. Claridge, Texas A&M; Xiangyang Gong , Texas A&M;
 - “Impact of the Position of the Radiator on Energy Consumption and Thermal Comfort in a Mixed Radiant and Convective heating System”, David E. Claridge, Xiangyang Gong
 - “Sustainability Assessment and Roadmap for a Green Campus Initiative”, Prepared by: Texas A&M International University, Laredo, Texas; Energy Systems Laboratory and Texas Engineering Experiment Station, October 2006

Appendix 8: The University of Maryland, UMD. An Energy Supply System Design for the Building as Power Plant, BAPP

UMD was asked to provide preliminary considerations and recommendations for the energy supply system, the ESS, to be installed in Carnegie Mellon’s proposed new building, the Building as Power Plant, the BAPP.

This task was discussed in a meeting at Carnegie Mellon on 17 May 2007. The agenda for this meeting is included in this Appendix 8 along with Carnegie Mellon presentations regarding the architectural design of the BAPP and estimates of its energy requirements, also included. The University of Maryland responded with a Work Statement and Budget., included, The documents follow.

- **Agenda:** Initial Meeting on the UND IWESS Project’ 17 May 2007
- **Presentations:**
 - Architecture of the BAPP; Azizan Aziz, Aviva Rubin; Carnegie Mellon, May 2007

- Energy Requirements of the BAPP; Chaoqin Zhai, Carnegie Mellon, May 2007
- **Work Statement:** University of Maryland Work on IWESS
- **Report:** “Building as Power Plant Energy System Design”; Joseph Orlando, Reinhard Radermacher; University of Maryland, CEEE: April 2008

Note: The documents listed in this Appendix section of the ABETI/IWESS Final Report are presented in a “memory stick” accompanying the printed version of the report.