

# BUILDING AS POWER PLANT - BAPP

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## ABSTRACT

The Building as Power Plant (BAPP) initiative seeks to integrate advanced energy-effective building technologies (ascending strategies) with innovative distributed energy generation systems (cascading strategies), such that most or all of the building's energy needs for heating, cooling, ventilating, and lighting are met on-site, under the premise of fulfilling all requirements concerning user comfort and control (visual, thermal, acoustic, spatial, and air quality), organizational flexibility and technological adaptability. This will be pursued by integrating a 'passive approach' with the use of renewable energies. The project has progressed through preliminary architectural design and engineering and 5 workshops (Ascending Energy Strategies, Floor-by-Floor Infrastructures, Interior Systems, HVAC systems, and Cascading Energy Strategies). BAPP is designed as a 6-storey building, located in Pittsburgh (a cold climate with a moderate solar potential), with a total area of about 6000 m<sup>2</sup> which houses classrooms, studios, laboratories, and administrative offices. At present, the combined cooling, heating, and power generation option that is being considered for the demonstration building is a Siemens Westinghouse 250 kW Solid Oxide Fuel Cell (SOFC). In this paper, a preliminary engineering concept of the SOFC based energy supply system will be described. The purpose of this preliminary engineering is to determine an energy supply system configuration (flow diagram), equipment selection, and mode of operation that will effectively, efficiently, and economically meet the energy needs of the building occupants. This work will provide guidance for detailed engineering and will serve as a pattern for similar efforts to plan effective overall energy supply systems for buildings.

## INTRODUCTION - A National Need

Almost 40% of the energy in the United States of America is being consumed to heat, light, ventilate and cool buildings (EIA 1995). Adding to this figure, the energy required to fabricate, transport and assemble the materials, components and systems of buildings, conservatively estimated, results in an additional 10% of the US national energy budget.

Substandard building performance, such as buildings that sicken their inhabitants (sick building syndrome), can lead to a reduction of as much as 20% of the productivity of the workforce (Loftness 2002). The Environmental Protection Agency has estimated the cost to the US economy to amount to about \$60 billion annually. During 1993 \$508 Billion for new construction and \$339 Billion for the renovation of existing facilities was spent in the US. This total of \$847 Billion amounted to 12.5% of the US GNP. Considered long-term, 5/8 of the nation's reproducible wealth is invested in constructed facilities. Collectively the US construction industry only expends 0.5% of sales on R&D. The industrial average for the US is 3.5% (Construction Industry Whitepaper, 1994). In summary, commercial buildings in the US require significant resources to be constructed, operated and adapted and are judged by the occupants to fail principal tests. Research and development expenditures are inadequate.

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## THE ROBERT L. PREGER INTELLIGENT WORKPLACE: THE LIVING LABORATORY

The Robert L. Preger Intelligent Workplace™ (IW) (Figure 1) is the result of an unprecedented collaboration between the Center for Building Performance and Diagnostics, a National Science Foundation Industry/University Cooperative Research Center, and its supporting industry and governmental members, organized in the Advanced Building Systems Integration Consortium (ABSIC). The 7000 square foot IW is a living laboratory of office environments and innovations. Completed and occupied in 1997, the IW is a rooftop extension of Margaret Morrison Carnegie Hall on the Carnegie Mellon campus. The project provides a test bed for organizational innovations for the advanced workplace.



Figure 1: The Intelligent Workplace™

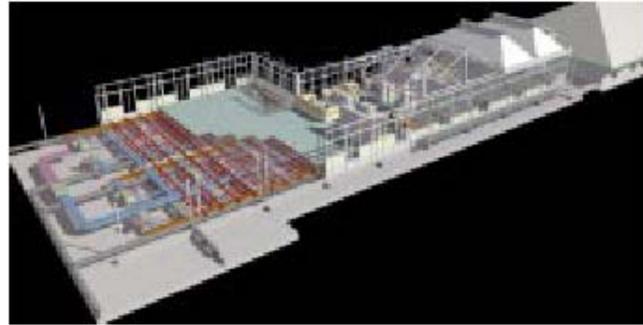


Figure 2: Peel-away view of the Intelligent Workplace™ illustrates the integration of all the building systems

As a “lived-in” occupied office, research, and educational environment, the IW provides a testing ground to assess the performance of new products in an integrated, occupied setting (Figure 2).

## GOALS OF THE ROBERT L. PREGER INTELLIGENT WORKPLACE™

1. *Individual Productivity and Comfort* - both interior system and engineering infrastructures are “plug and play” to ensure that furniture and space reconfigurations for individual productivity and creativity are immediately matched by technology and environment reconfigurations.
2. *Organizational Flexibility* - the community of workplaces be reconfigurable on both annual and daily levels to ensure “organizational re-engineering” for collaboration supporting regrouping and sharing for organizational productivity, creativity and innovation.
3. *Technological Adaptability* - vertical and horizontal pathways for connectivity are accessible and that both interior systems and engineering infrastructures support changing technological demands for horizontal and vertical worksurface, lighting, acoustics, thermal conditioning, and ergonomics.
4. *Environmental Sustainability* - both energy and materials are used effectively over a building’s life cycle. System efficacy, user controls, micro-zoning for flex-time, just-in-time delivery of infrastructures, environmentally sustainable and healthy materials, natural conditioning are demonstrated

The IW is not envisioned as a onetime “show-and-tell” demonstration project, but rather as a dynamic environment for the teaching and evaluation of how integrated building components, systems, and assemblies affect building performance. In-house post-occupancy research is critical to validating predicted performance through simulation and to assessing the performance in the integrated setting. As a test bed of new ideas, and a demonstration center for successful innovations, combined with innovative officing concepts and portable diagnostics, the IW is a unique living laboratory of office environments.

The IW is conceived as a modular system, the units of which can be stacked or reconfigured to adapt to the needs of multiple office settings. The inherent rules of this system – enabling decisions affecting such aspects as building configurations, size of work neighborhoods, cabling and wiring schemes, ratio of shared services and collaborative workspaces to workstations - makes feasible its application on a wider scale.

## BAPP - BUILDING AS POWER PLANT

Building on the concepts of and experiences with the Intelligent Workplace™, a living (always adapted and updated) and lived-in laboratory at Carnegie Mellon University (Hartkopf and Loftness 1999, Napoli 1998), a research, development and demonstration effort is directed at the “Building as Power Plant – BAPP”. This project seeks to integrate advanced energy-effective enclosure, Heating, Ventilation, and Air-Conditioning (HVAC) and lighting technologies with innovative distributed energy generation systems, such that most or all of the building’s energy needs for heating, cooling, ventilating and lighting are met on-site, maximizing the use of renewable energies. Figure 3 schematically illustrates this idea.

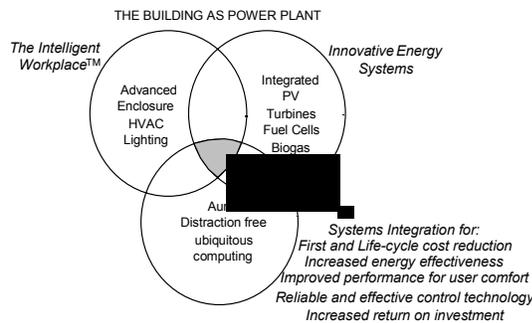


Figure 3: The Building as Power

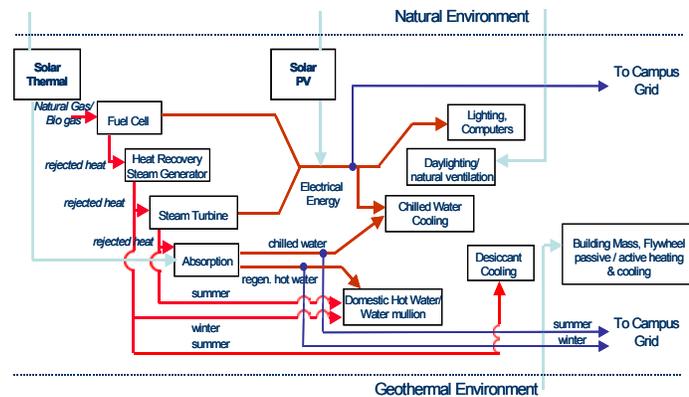


Figure 4: Conceptual scheme for a building-integrated “ascending-descending” energy system

BAPP is designed as a 6-storey extension of the existing Margaret Morrison Carnegie Hall Building with total area of about 6000 m<sup>2</sup> which houses classrooms, studios, laboratories and administrative offices for the College of Fine Arts. It is our intention to develop a building which will be equipped with a decentralized energy generation system in the form of a combined heat and power plant. This will include a 250 kW Siemens Westinghouse Solid Oxide Fuel Cell (SOFC) and absorption chiller/boiler technologies. In addition, advanced photovoltaic, solar thermal, and geo-thermal systems are being considered for integration.

Figure 4 illustrates a conceptual scheme for an “ascending-descending energy scheme” that integrates energy generation and building HVAC and lighting technologies. In an ‘ascending strategy’, fenestration, shading, and building mass will be configured to minimize the lighting, cooling and heating loads and maximize the number of months for which no cooling or heating will be needed. Then, passive strategies such as cross ventilation, stack ventilation, fan-assisted ventilation and night ventilation would be introduced. Passive cooling would be followed by desiccant cooling when humidity levels exceed the effective comfort zone. Geothermal energy will be used to activate the building mass for cooling and heating. As outdoor temperatures or indoor heat loads exceed the capability of these systems, then absorption and finally refrigerant cooling will be introduced, first at a task comfort level. Only the last stage of this ascending conditioning system will be a task-ambient central-system refrigerant cooling system.

Complementing these ‘ascending’ energy strategies is ‘cascading’ energy strategy designed to make maximum use of limited natural resources. In a cascading system, a fuel cell and photovoltaic panels might be bundled for the building’s power generation; reject heat can be converted into steam which can be used to first drive desiccant, absorption and refrigerant systems; and finally the resulting reject heat can be used for space heating and hot water.

Figures 5-8 give an idea of the building design and Table 1 summarizes the dimensional information of the building

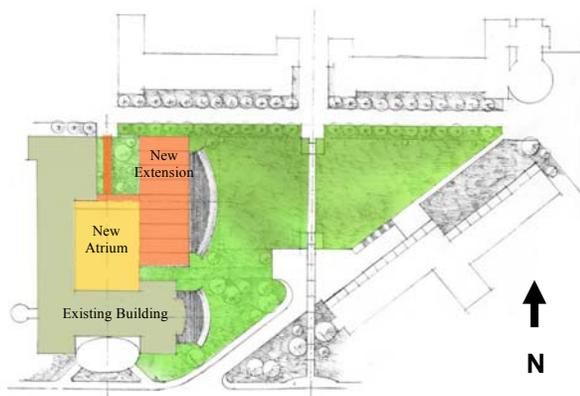
## BAPP WORKSHOPS

Based on a preliminary design described above, BAPP project concepts were further developed with the help of five workshops mentioned below:

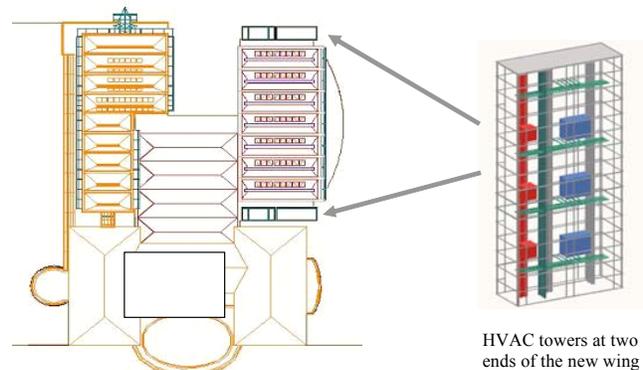
1. Ascending Strategies Workshop, Dec. 4<sup>th</sup>, 2001, Pittsburgh, PA, USA: This workshop analyzed major functions and requirements for the building's facade and roof.
2. Floor-By-Floor Systems Workshop, Jan. 31<sup>st</sup>, 2002, Ottawa, Canada: The objective of the workshop was to develop a set of preliminary strategies for BAPP concerning HVAC, Lighting, and Connectivity.
3. Interior Systems Workshop, Held on April 2<sup>nd</sup>, 2002, Pittsburgh, PA, USA: This workshop focused on developing project concepts and generating new ideas in the area of Interior Systems – 'Collab Kits'.
4. HVAC Workshop, April 4<sup>th</sup>, 2002, Pittsburgh, PA, USA: The objectives were to obtain feedback from experts about HVAC approaches that are being considered for the BAPP in relation to cascading energy systems.
5. Cascading Energy Workshop, May 30<sup>th</sup>, 2002, Pittsburgh, PA, USA: The objective of the Cascading Energy Workshop was to obtain feedback from experts in the field about the Power Generation and Primary Energy Generation system approaches that are being considered.

*Table 1: Building information*

<b>Building Dimensions</b>	
Building Length	49.8 m
Building Width	16.80 m
No. of Floors	6
Area per Floor	836.64 m <sup>2</sup>
Total Area	5019.84 m <sup>2</sup>
Floor-to-Floor Height	4.65 m – in order to connect appropriately with the existing building
Floor-to-Ceiling Height	3.15 m
“Interstitial space” (underside ceiling to surface of raised floor)	1.50 m
Total Building Height	27.9 m above grade (plus roof)
<b>Atrium Dimensions</b>	
Length	32.00 m
Width	22.00 m
Height	3 stories
Area	704 m <sup>2</sup>



*Figure 5: Site plan showing the new extension planned for the BAPP project*



*Figure 6: Building roof plan and a schematic diagram of the plug-and-play service towers*

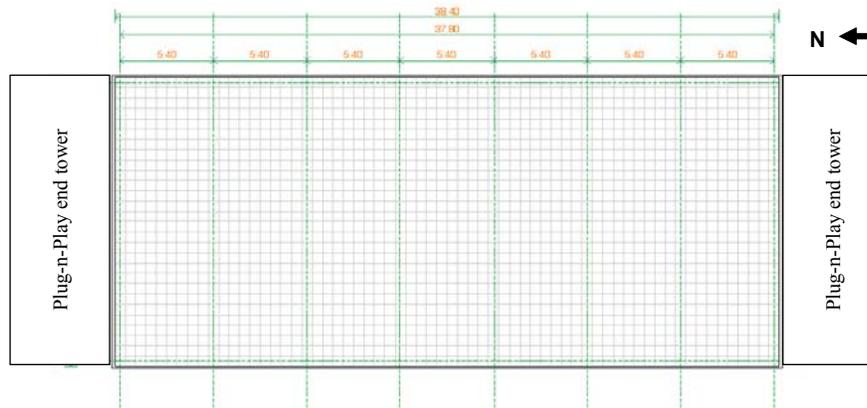


Figure 7: Plan for the new wing (the dimensions are in meters)

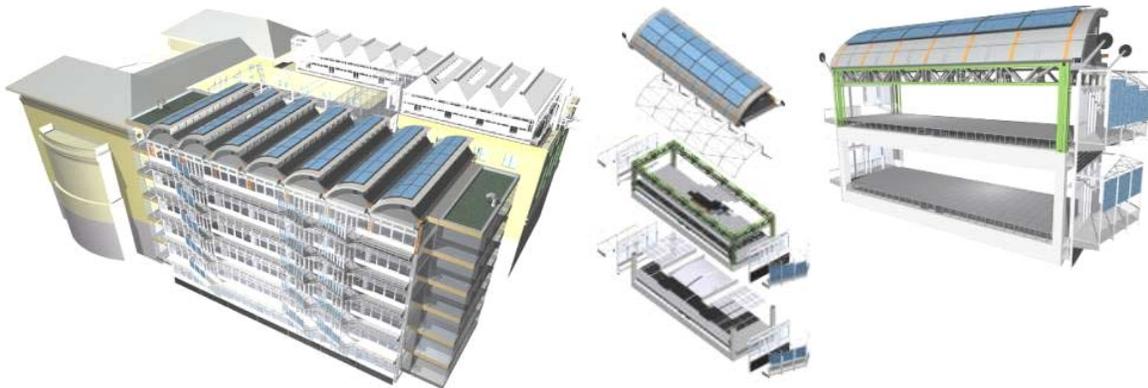


Figure 8: Building as renewable asset and energy generator

## INTELLIGENT WORKPLACE SYSTEMS AND PERFORMANCE ANALYSIS – LESSONS LEARNED

### 1. Reduced waste in the construction of the IW

The IW project exemplifies how the design, engineering, and material selection, can result in 70-90% reduction of emissions and waste during production of the materials used for the exterior wall, floor and roof, compared to a conventional building. There was no on-site waste during most of the construction phase because of the IW's modular design and its off-site fabrication with complete recycling capacity of all by-products.

### 2. Reduced waste in operation

The IW is conditioned for six or more months through “natural” energies alone during daylight hours. In addition to the resource savings of operating a building, there is significant potential to reduce material waste through the management of material and subsystem obsolescence. Demonstrated in the IW, the reconfigurable/ relocatable interior systems, with modular interfaces to the envelope, HVAC, lighting, communication, structure, power systems, enable organizational change on demand, as well as technological change on demand.

The integrated, modular and demountable systems reflect the fact that buildings are made from components that have different life cycles. The envelope as a system should have a life of 50-100 years, with a possibility of exchanging glazing materials, photovoltaic elements and other components, when superior performance becomes economically feasible. The structural system should have a life of 100 years, and when becoming obsolete at a particular site should become redeployable elsewhere (a column is a column, a truss is a truss). Whereas interior systems have considerably less “life expectancy”, down to computing systems that might have a useful life of 2-3 years.

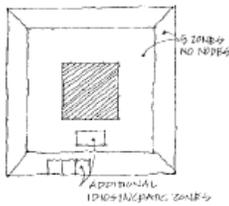
### 3. New design approaches to absorb change and avoid obsolescence: Flexible grid – flexible density – flexible closure

These are a constellation of building subsystems that permit each individual to set the location and density of HVAC, lighting, telecommunications, and furniture, and the level of workspace enclosure. These services can be provided by separate ambient and task systems where users set task requirement and the central system responds with the appropriate ambient conditions.

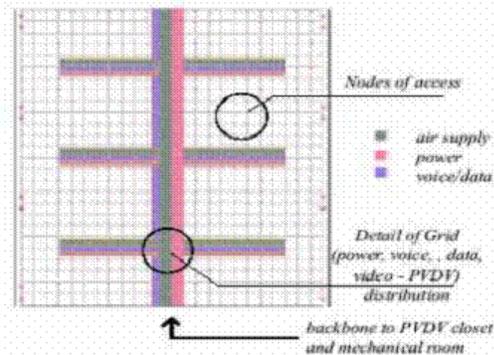
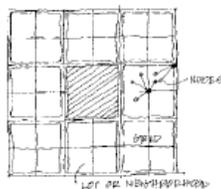
*4. The concept of grids and nodes: ensuring seven basic needs for each individual*

Access to all of the basic needs for a healthy, productive workplace - air, temperature control, daylight and view, electric light control, privacy and working quiet, network access and ergonomic furniture - can only be provided by a shift away from blanket and centrally controlled infrastructures to the concept of grids and nodes (Figure 9). The “grids” establish the overall level of capacitance available to support the working group or neighborhood (fresh air, cooling, power and network capacitance). Then, the “nodes” or user interfaces must be flexible in terms of location, density, and type of service offered.

EXISTING SERVICE/UTILITY



CONCEPT OF GRID & NODES



Nodes of access in the IW



Detail of Grid (power, voice, data, video) distribution in the IW

*Figure 9: Conventional large zone approaches to thermal conditioning and lighting are incapable of delivering adequate environmental quality to accommodate the dynamics of technology, workstation density and teaming concepts*

*Figure 10: Rational underfloor infrastructure distribution allows for just-in-time additions and changes to support the dynamic workplace*

*5. Flexible infrastructures begin with accessible and expandable vertical service*

There should be a significant shift towards distributed systems to support local control by organizational units with differing equipment and occupant densities, or with different work schedules, ensuring appropriate technical and environmental service without excessive costs.

*6. Flexible infrastructures require collaborative horizontal plenum design and relocatable “nodes” of service*

Advanced buildings today demonstrate that floor-based servicing may more effectively support the dynamic workplace (Figure 10). Since networking, ventilation and thermal conditioning needs to be delivered to each workstation, services at floor level or at desktop offer a greater ease of reconfiguration than ceiling-based systems. In addition, floor-based systems such as electrical and telecommunication cabling and outlet terminal units can be continuously updated to meet changing needs.

## 7. Flexible infrastructures can support reconfigurable workstations and workgroups

It is critical to design the furniture/ wall system to support rapid changes between open and closed layouts, between individual and teaming spaces, as well as rapid changes in occupant density, equipment density, and infrastructure/service to match these configurations.

## 8. Smart interior systems

Interactive multimedia and web-based technologies create the possibility to work within ever changing teams, both locally and globally. This requires that built environments must be responsive to ever changing organizational and rapidly evolving technological circumstances.

## 9. Intelligent Workplace energy systems analysis

We analyzed the energy usage and performance of the Intelligent Workplace and its building control systems. The lessons learned during this study can be used to better design and operate the BAPP. The analysis focused on: 1) data acquisition system, 2) building control systems, and 3) building design.

The IW uses several energy systems to provide heating, cooling, ventilation, dehumidification, and lighting (Figure 11 shows the HVAC systems). Heating is provided by warm water mullions on the façade. The cooling is provided through multi-modal strategies consisting of radiant panels, COOLWAVES by LTG, Johnson Control Personal Environment Modules (PEMs), a make-up air unit to supply the PEMs and floor vents, and a SEMCO air handling unit. The SEMCO unit, which is controlled by an Automated Logic system, is an 100% outdoor air system with enthalpy wheel for dehumidification. A JCI Metasys system controls the rest of the HVAC system. The lighting system is controlled by a Zumtobel-Staff LUXMATE system.

The IW uses three different systems to record energy data. Energy Sentry (72 data points) records electrical energy consumption, Metasys (160 data points) is used for HVAC related data and Weather-Station (8 data points) records outdoor environmental data. These three systems record data in different formats in different locations and within the systems, each sensor records data in a different file. To expedite and facilitate the analysis process, it is necessary to bring the data into the same format. As a result, we developed a tool (Figure 12) to collect data from the different systems (that is in different formats and in various locations) and organize it into one common easily usable database. This tool has several features that allow easy analysis of the building data.

The data collected from sensors in the building was analyzed to determine energy usage and trends (Figure 13). It was found that the data contained had missing values. Reasons for this were incomplete documentation of the file storage structure, IP address problems and the system going offline for various reasons. Statistical techniques and simulation were used to fill missing data to make the calculations more accurate. The existing DOE 2.1E simulation model of the IW was calibrated to match the current measured conditions in the IW. This model was then used to predict energy consumption under different scenarios.

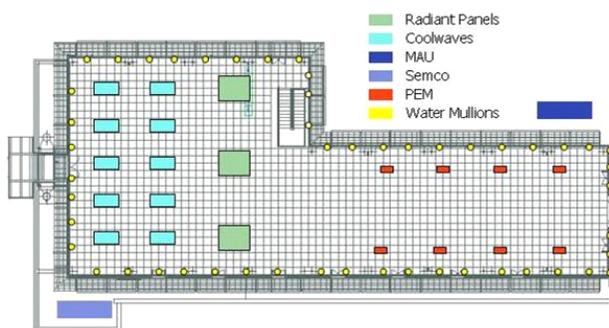


Figure 11: IW HVAC systems

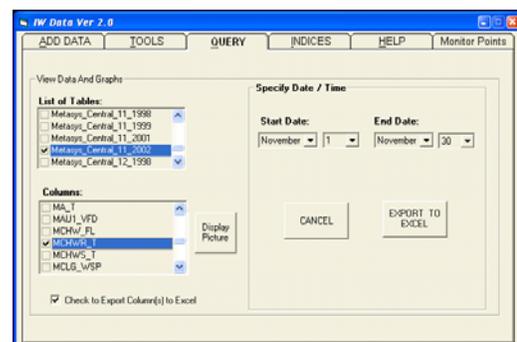


Figure 12: CBPD data acquisition and analysis tool

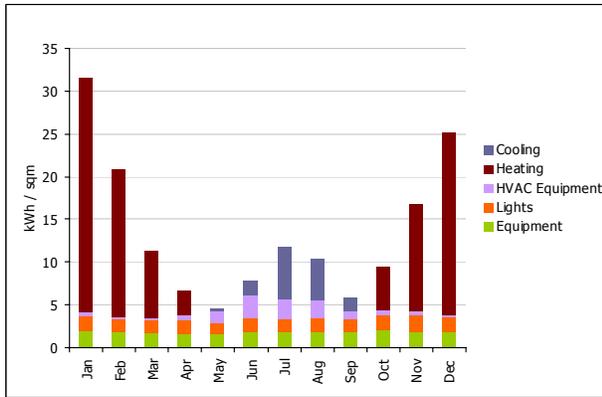


Figure 13: Summary of monthly energy consumption in the IW

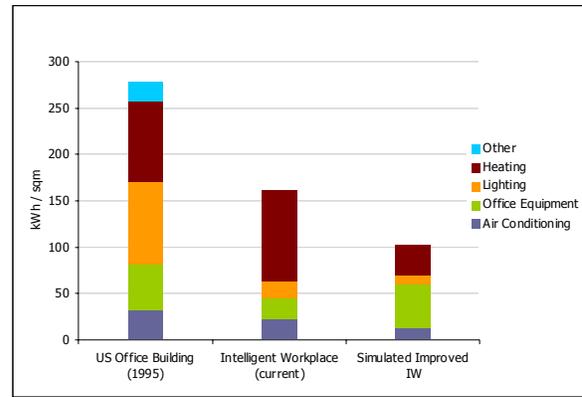


Figure 14: Comparison of IW energy consumption with typical US office building

It was found that although energy usage was less in the IW when compared to standard US office buildings (Figure 14) there were still areas where the energy consumption could be reduced further. Several hypothesis were suggested to explain the results obtained from the analysis. These were based on the design of the building and its mechanical systems.

- The high air infiltration and one un-insulated area in the IW caused the heating load to increase.
- The heating setpoint in the IW is higher than that of a standard office building, which further increased the load.
- The under-floor plenum of the IW contains steam pipes for the floors below that are not measured by the IW systems, this caused a small reduction in the heating load.
- The higher than typical amount of glass and exposed surface area caused an increase in cooling energy.
- This cooling load was increased by the un-controlled operation of windows.
- The unconditioned underfloor plenum was measured to have an average temperature of 31C during the summer. Since it is not insulated from the IW living space, it also increased the cooling load.
- The lighting in the IW is through fluorescent fixtures that use dimmable ballasts. At the time of construction these were available only for 220V therefore transformers were used. It was found that of the total annual lighting load of 18.92 kWh/m<sup>2</sup> (about 1/5<sup>th</sup> of good US practices), 10.12 kWh/m<sup>2</sup> was transformer losses (the “parasitic” load therefore is a 50% of this reduced load).

#### 10. Building control systems

Based on our experience of the control systems in the IW, the goals for the future control system should be to:

- meet the needs of the building users. For the occupants it should be intuitive to use, facility managers should be able to maintain it with their level of knowledge, energy managers should be able to use it to analyze energy consumption, organizational manager should be able to modify it easily, and researchers should be able to extract and analyze the data easily.
- allow for easy expansion to integrate new technologies such as wireless sensors and controllers. The control system should allow equipment to be plug and play installable by untrained installers.
- allow intelligent monitoring and decision support with the ability for continuous process improvement and economic analysis. It should allow for conflict resolution.
- allow for preventive maintenance with the ability to predict future system and component behavior.
- control processes should be interoperable and integrated to allow for management of the whole building and its constituent parts in terms of energy efficiency.
- allow control strategies to be simulated and checked before they are implemented.

## BAPP BUILDING LOADS

Based on the preliminary architectural design of the building and its proposed mode of operation, both annual operating energy consumption and the related emissions have been simulated using EnergyPlus V1.1 (EnergyPlusV1.1.0 2003). In addition to the high office equipment load (due to the high density of computers on two floors housing the Entertainment Technology Center and power tools in the architecture and design shops), typical office equipment load is also being simulated. The energy data for a typical load, instead of high load, office buildings in US and Europe has been used as the baseline for the energy performance analysis. In order to see the effect of ascending strategies, operating strategies and descending strategies, the simulation is carried out step by step, from the case based on ASHRAE Standard 90.1-1999 to the case with distributed power generation. The simulation specifications for ASHRAE case are shown in Table 2.

Table 2. Simulation parameters of ASHRAE case

Parameter	Value	Parameter	Value
R-value: Roof	3.58 m <sup>2</sup> -K/W	Visible Transmittance: Window	0.18
R-value: Above Grade Wall	2.89 m <sup>2</sup> -K/W	Electric Lighting Load	15W/m <sup>2</sup>
U-value: Window	3.15 W/m <sup>2</sup> -K	Office Equipment Load	8.9 W/m <sup>2</sup>
SHGC: Window	0.35	Infiltration Rate	0.2 ACH

Then ascending strategies, such as

- high performance building envelope (R-value of roof: 7.06 m<sup>2</sup>-K/W, U-value: 1.37 W/m<sup>2</sup>-K, SHGC: 0.27, and visible transmittance of window: 0.56, with an infiltration rate of 0.1 ACH),
- daylighting based dimming (lighting setpoint: 500 lux),
- and high performance electric lighting (lighting load: 5.4 W/m<sup>2</sup> [Campbell, 2002])

are applied. In the case with better operating strategies, natural cooling (natural ventilation and night ventilation), and demand controlled ventilation (the ventilation volume is decided according to the number of occupants in the space) are deployed to reduce the annual energy consumption and provide improved thermal comfort as well as indoor air quality.

In addition, a ground source heat pump (GSHP) is also considered as an alternative to a typical chiller-boiler plant configuration. Finally, photovoltaic (PV) on south facing roofs and a 250 kW solid oxide fuel cell (SOFC) are included as distributed power generation strategies.

In Table 3, the percent in the parentheses shows the percentage of site energy, primary energy, operating cost and carbon equivalent compared to those of the ASHRAE case, respectively. The minus sign in operating cost shows that instead of paying more for energy, the construction of BAPP could reduce the energy bill of the campus by \$7,413 per year.

Table 3 Energy Performance of BAPP with Typical Office Equipment Load

	Site Energy (kWh/m <sup>2</sup> -yr)	Primary Energy (kWh/m <sup>2</sup> -yr)	Operating Cost (\$)	Carbon Equivalent (kg)
ASHRAE	122.2 (100%)	381.4 (100%)	\$50,945 (100%)	202,480 (100%)
Ascending Strategies	96 (79%)	225.2 (59%)	\$27,841 (55%)	112,503 (56%)
Operating Strategies	79.3 (65%)	199.5 (52%)	\$25,304 (50%)	101,295 (50%)
GSHP	56.1 (46%)	196.8 (51%)	\$35,505 (70%)	106,551 (53%)
GSHP+PV	45.1 (37%)	158.2 (41%)	\$31,140 (61%)	85,700 (42%)
<b>GSHP+PV+SOFC</b>	<b>80.4 (66%)</b>	<b>80.4 (21%)</b>	<b>-\$7,413 (-15%)</b>	<b>21,270 (11%)</b>
Electric Chiller & Heat Exchanger +PV+SOFC	90.3 (74%)	90.3 (24%)	-\$5,462 (-11%)	23,889 (12%)

The comparison of BAPP with other typical office buildings is shown in Figure 15, which indicates that the primary energy consumption of BAPP is predicted to be only 11% of typical US office buildings.

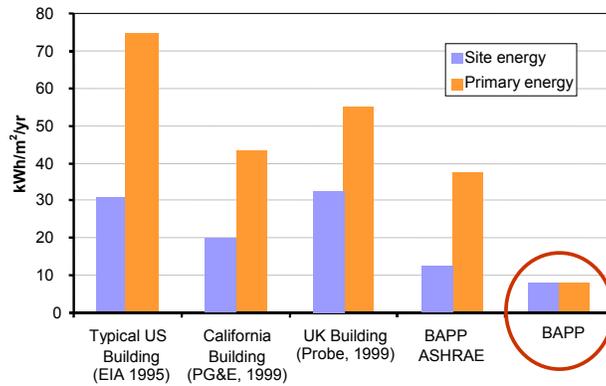


Figure 15: BAPP compared to other office buildings

## ELEMENTS OF THE ENERGY SUPPLY SYSTEM

### SOFC Power Generator

Power generation for the building energy supply system design has focused on a SOFC power system (Figure 16) being developed and commercialized by Siemens Westinghouse Power Corporation, Stationary Fuel Cells Division. The capacity of the commercial system currently envisioned for production in 2006 is 250 kW, approximately the maximum power required by the building. Its electrical efficiency operating on natural gas fuel is 50%. The reject heat from the system, 40% of the fuel energy input, is potentially available from the system as steam and hot water at the conditions and quantity required by this building.

### The SOFC Power Generation and Heat Recovery System

A flow diagram for the natural gas fired SOFC power generation and heat recovery system that serves as the basis of the overall building energy supply system is illustrated in Figure 17. The symbolic representation of the generator shows three cells with hemispherical closed ends. Each of these cells has an internal tube that feeds preheated air at its bottom. The air flows upward inside and fuel outside each cell. As current is drawn and power produced; oxygen is transferred through the cells from the air stream into the fuel stream. At the top of the cells a portion of the largely oxidized, combusted, fuel stream is drawn out of the generator by means of the ejector and mixed with the desulfurized, natural gas fuel feed. The H<sub>2</sub>O in this oxidized fuel gas reacts with, reforms, the methane, CH<sub>4</sub>, in the natural gas fuel producing hydrogen and carbon monoxide.



Figure 16: Siemens Westinghouse Solid Oxide fuel cell, cell bundle, and assembled system.

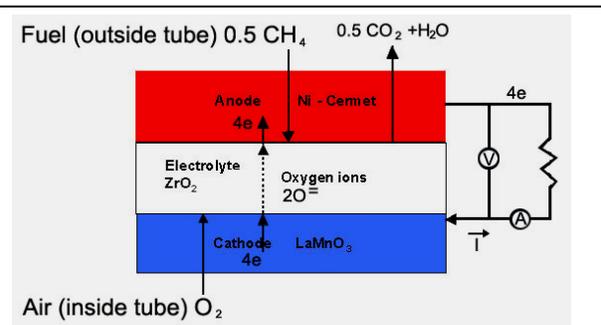


Figure 17: Siemens Westinghouse Solid Oxide fuel cell cross section

The reformed fuel, primarily H<sub>2</sub> and CO mixed with combustion products H<sub>2</sub>O and CO<sub>2</sub>, flows from the reforming passages into the region at the base of the cells and then upward around the cells. The portion of the oxidized fuel gas at the top of the cells not returned and mixed with the fuel feed mixes with the spent air stream leaving the top cells, and the combustion process is completed.

The combustion product gases then are passed to the heat recovery steam generator, the HRSG, comprising sections for superheating, boiling, and feed water heating. The possibility of auxiliary firing

with natural gas fuel provides additional flexibility in operation of the heat recovery system, enhancing steam production or continuing steam production in case of fuel cell outage.

#### *Absorption Chiller, Air Dehumidification Systems*

Both the absorption chiller and the air dehumidifier systems are based on liquid desiccants, an aqueous solution of an inorganic salt such as Lithium Bromide (LiBr) or Lithium Chloride (LiCl). In both systems a concentrated desiccant absorbs water vapor, and the resulting heat release is removed by cooling water. The desiccant is subsequently re-concentrated (regenerated) by heating it with steam and driving off water vapor. Liquid desiccant dehumidifiers, single and multi staged, are under development both in this country and abroad<sup>7</sup>. Their advantage in dehumidification over condensing air coolers is reduction of steam and cooling water usage by a factor of about two.

#### *Cooling Water Supply System*

Cooling water is needed for both the absorption chiller and the air dehumidifier systems. Two possible sources of cooling water are a conventional cooling tower or a geothermal cooling water supply and return system.

#### *Solar Energy Utilization*

The capture of solar energy by photovoltaic and/or thermal energy panels mounted on the façade and roof of the building is also planned. The incremental energy supplied by such systems will be integrated with the building's overall energy supply system, and the incremental cost will be evaluated.

### **MODE OF OPERATION FOR THE BUILDING OVERALL ENERGY SUPPLY SYSTEM**

In the initial phase of operation of the system it is planned to

- operate the SOFC power system continually at its 250 kW design level, interconnected with the campus power grid. The grid will provide for differences between the building power needs and the fuel cell output.
- operate the heat recovery steam generator, HRSG, producing steam at the design pressure, temperature, and flow and providing hot water for heating and for domestic use in the building. The HRSG will be interconnected with the campus steam grid and will interchange steam with the grid as needed at the campus charge rate for steam.
- operate the absorption chiller system when air conditioning is required, producing chilled water at the design flow and temperature conditions. The chiller will be interconnected with the campus chilled water supply and return grid and will interchange with this grid dependent on differences between the building cooling requirement and the chiller output.
- operate the liquid desiccant dehumidifier system and the water evaporation humidifier as needed. The fresh air dehumidification system will remove sufficient moisture to provide comfort for the building occupants, to prevent condensation in the air cooling equipment of the building and fresh air systems, and to compensate for the humidity, latent heat, added by the building occupants.

### **BUILDING ENERGY SUPPLY SYSTEM ALTERNATIVES, FOR EVALUATION**

A number of additional alternatives and extensions were considered. These are to

- Replace the SOFC power generator by a molten carbonate fuel cell, MCFC, generator or by a gas turbine generator.
- Add a small backpressure or condensing steam turbine generator for additional power from the system during spring and fall seasons, in which steam-driven absorption chiller and liquid desiccant dehumidifier are not running or in partial operation.
- Use of exhaust air from the building for exchange of heat and humidity with the incoming fresh, ventilation air. (Presently it is planned to exhaust air directly to an atrium adjoining the building.)
- Consider both single stage and multi stage processing and regeneration of liquid desiccant in both the absorption chiller and the air dehumidification systems.

### **CONCLUSION**

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<sup>7</sup> Dr. Andy Lowenstein and his AIL Research group represent single stage absorber and regenerator, Dr. Jiang Yi and his research group in Tsinghua University, China, are demonstrating multi-stage absorber and regenerator

The work at the Center for Building Performance and Diagnostics, supported by the Advanced Building Systems Integration Consortium, has established and demonstrated the economic and technical feasibility, as well as social/political desirability to create commercial buildings which consume substantially less energy compared to best U.S. practices, while offering the occupants dramatically increased user satisfaction, providing for organizational flexibility, and technological adaptability.

The Building as Power Plant Project demonstration aims to show that the building can be a net exporter of energy. The preliminary analysis of the cascading system shows that the fuel cell produces more power and thermal energy than needed by the BAPP building, which can be exported to the CMU campus. The next steps in this project include the analysis of multi-modal conditioning systems. The process will consist of establishing partnerships with industry and studying the performance and systems integration issues for each of the strategies. A complete design of the building and the systems will be finalized in consultation with project architects and engineers. Preliminary engineering of a novel, solid oxide fuel cell based building energy supply system for a multi purpose building of advanced design at Carnegie Mellon University is now underway. The purpose of this work is to provide economic justification, guidance for detailed engineering, and a basis for the evaluation of new technology.

Their ideas have attracted the attention of the U.S. Congress and are therefore contained in the 2004 Energy Bill, creating the framework for the BAPP to function as a National Test Bed.

## REFERENCES

- Campbell, Steve (2002), "Can Intelligent Office Lighting Systems Really Save 80%" Energy User News, April, 2002
- Construction Industry Whitepaper, (1994), National Science and Technology Council; Committee on Civil Industrial Technology. Subcommittee on Construction and Building. Civil Engineering Research Foundation, April 28, 1994
- EG&G Technical Services, Inc, Science Applications International Corporation, November 2002, "Fuel Cell Handbook", 6<sup>th</sup> Edition, Chapter 7, pp.195
- EIA (1995), EIA: Energy Consumption in Commercial Buildings in 1995. Energy Information Administration, U.S. Department of Energy, 1995
- EnergyPlus V1.1.0 (2003) <http://www.energyplus.gov>
- EnergyPlus Engineering Documents April 2003, pp.262-267
- Hartkopf, V., V. Loftness (1999), "Global relevance of total building performance," Automation in Construction 8 (1999), pages 377-393
- Komor, Paul, (1997), "Space Cooling Demands From Office Plug Loads", ASHRAE Journal, Dec. 1997
- Loftness, V. (2002), "Building Investment Decision Support," U.S. Green Building Council's International Green Building Conference and Expo, Austin, Texas, November 13-15, 2002
- Napoli, L. (1998), "Where Every Worker Is Ruler of the Thermostat," the New York Times, Money and Business, Section 3, Sunday, February 15, 1998,
- Pacific Gas and Electric Company (1999), Commercial Building Survey Report, 1999
- PROBE Strategic Review 1999, Final Report: Technical Review, August 1999
- Shan K. Wang, (2000), "Handbook of Air Conditioning and Refrigeration", 2<sup>nd</sup> Edition, Chapter 14, Chapter 28, McGraw-Hill, New York
- Siemens Westinghouse Power Corporation, Stationary Fuel Cells, (2002), "Solid Oxide Fuel Cells – The New Generation of Power", The CHP250 SOFC Power System
- Streitz, N. A., J. Geißler, and T. Holmer (1998), "Roomware for Cooperative Buildings: Integrated Design of Architectural Spaces and Information Spaces." Cooperative Buildings: Integrating Information, Organization and Architecture, Lecture Notes in Computer Science 1370, N. A. Streitz, S. Konomi, and H-J Burkhardt, eds. Darmstadt, Germany, February 1998, pp 4-21, Springer: Heidelberg.