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). This will be pursued by integrating a "passive approach" with the use of renewable energies. In addition, the project will achieve unprecedented levels of organizational flexibility and technological adaptability. The project has progressed though 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-story building, located in Pittsburgh (a cold climate with a moderate solar potential), with a total area of about 6000 m^2 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 article, we will report a number of integrated solution scenarios and their energy performance.

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. The construction and operation of commercial buildings, which house approximately 50% of the American workforce, is estimated to require 25% of the nation's 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 U.S. 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 U.S. 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.

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, Hartkopf et al. 1997, Napoli 1998, Schmertz 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 1 schematically illustrates this idea.

In this initiative, the systems integration aspect is emphasized, to reduce first costs, increase effectiveness and performance, and maximize the return on investment. We believe that the use of innovative and sustain-

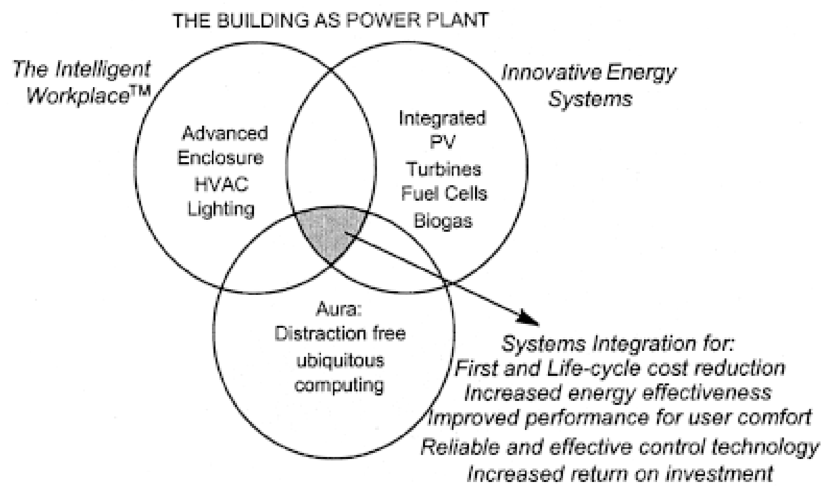


Figure 1. The Building as a Power Plant Concept

able energy systems for buildings will be technologically and economically feasible only if buildings are inherently effective in that they minimize their nonrenewable energy needs. Figure 2 illustrates a conceptual scheme for an "ascending-descending energy scheme" that integrates energy generation and building HVAC and lighting technologies.

BAPP is designed as a 6-story extension of the existing Margaret Morrison Carnegie Hall Building (Figure 3) with total area of about 6000 m^2, which houses classrooms, studios, laboratories and administrative offices for the College of Fine Arts. It is our intention to develop a building that 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 photo voltaic (PV), solar thermal, and geothermal systems are being considered for integration.

In an "ascending strategy," massing, shading, and building mass will be configured to minimize the cooling loads and maximize the number of months for which no cooling will be needed. Then, passive strategies such as cross ventilation, stack ventilation, fan-assisted ventilation and night ventilation would be introduced, which requires the full involvement of mechanical engineers in the early design process. Passive cooling would be followed by desiccant cooling when humidity levels exceed the effective comfort zone. Geothermal energy will be used to

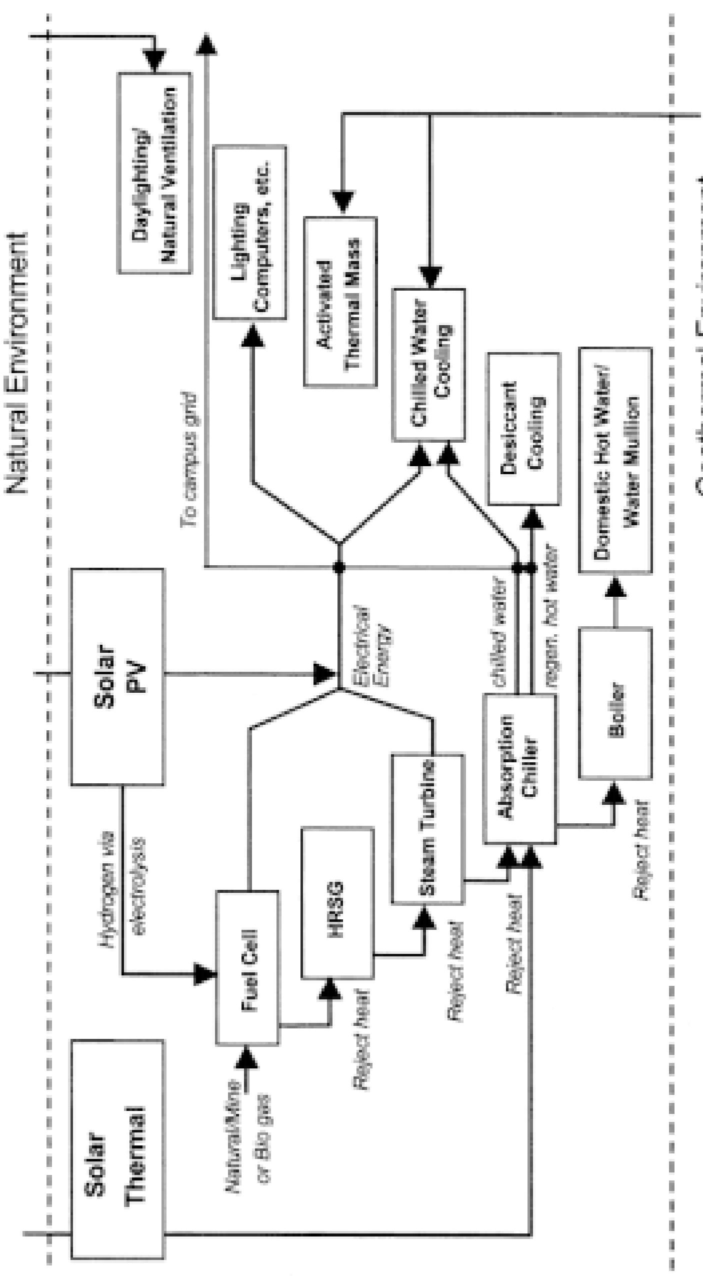


Figure 2. Conceptual Scheme for a Building-Integrated "Ascending-Descending" Energy System

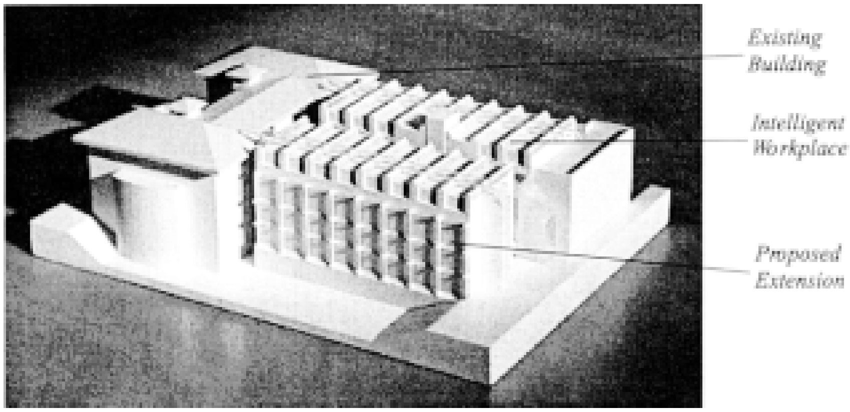


Figure 3. Model of the Existing and Proposed Extension to Margaret Morrison Carnegie Hall

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. Combining innovations of ascending conditioning strategies (load reduction, passive, then active) with innovations in cascading conditioning strategies (the reject heat from each energy process can support the next) - may offer the most environmentally sustainable approach to designing and retrofitting buildings in the future (Hartkopf et al. 2002).

BAPP BUILDING INFORMATION

The BAPP project will be built adjacent to an existing historic building, Margaret Morrison Carnegie Hall (MMCH). Margaret Morrison Carnegie Hall is an L-shaped building with four above ground stories that house classrooms, studios, faculty and administration offices.

Given the specific site conditions on Carnegie Mellon's Campus, the prototypical building will connect to Margaret Morrison Carnegie Hall with a 3-story central atrium that will become a public space. The proposed new wing is north-south oriented, with extensive eastern exposure. The following table summarizes the dimensional information of the building.

Table 1. Building Information

Building Dimensions	
Building Length	49.8 m
Building Width	16.8 m
No. of Floors	6
Area per Floor	836.64 m^2
Total Area	5,019.84 m^2
Floor-to-Floor Height (in order to connect appropriately with the existing building)	4.65 m
Floor-to-Ceiling Height	3.15 m
"Interstitial Space" (underside ceiling to surface of raised floor)	1.5 m
Total Building Height	27.9 m above grade (plus roof)
Atrium Dimensions	
Length	32 m
Width	22 m
Height	3 stories
Area	704 m^2

BAPP WORKSHOPS

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

Ascending Strategies Workshop, held on Dec. 4, 2001, Pittsburgh, PA:

This workshop focused on the enclosure of the building project and was subdivided into two main topical areas: a) Building Facade, and b) Atrium and Building Roof. It analyzed major functions and requirements for the building's facade and roof, including the integration of daylighting, natural ventilation, passive/active solar heating and cooling, as well as energy generation and distribution including access to the natural environment for the user.

Floor-By-Floor Systems Workshop, held on Jan. 31, 2002, Ottawa, Canada:

The objective of the workshop was to develop a set of preliminary strategies for BAPP concerning HVAC, lighting, and connectivity.

Interior Systems Workshop, held on April 2, 2002, Pittsburgh, PA:

This workshop focused on developing project concepts and generating new ideas in the area of interior systems "Collab Kits." It also provided a collaborative environment for design professionals, manufacturers, and government agencies.

HVAC Workshop, held on April 4, 2002, Pittsburgh, PA:

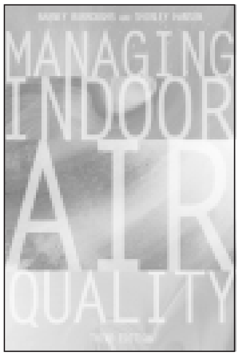
The objective of the HVAC Workshop was to obtain feedback from experts in the field about the HVAC approaches that are being considered for the BAPP demonstration building, especially in relation to the cascading energy systems.

Cascading Energy Workshop, held on May 30, 2002, Pittsburgh, PA:

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.

ENERGY ANALYSIS

The EnergyPlus (EnergyPlus 2002) simulation tool was used to conduct a preliminary analysis of the BAPP building. The comparison between the base case and the best enclosure case is shown in Figure 4. Note that the BAPP building has high internal loads (50.2 W/m^2) com-



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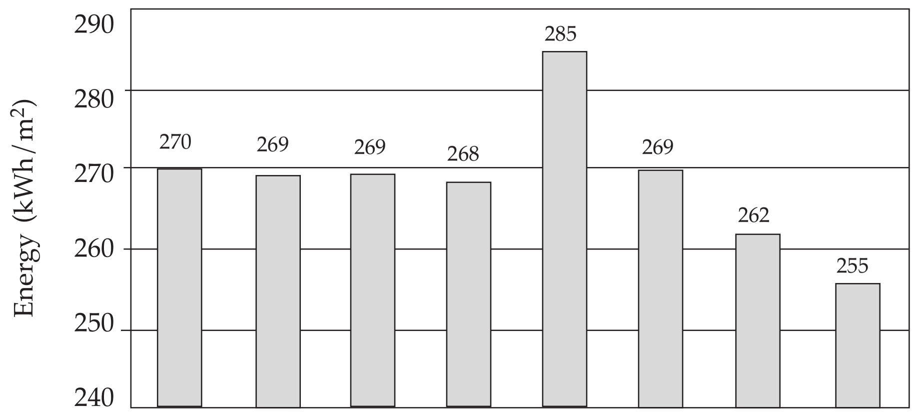
pared to a typical office building (21.52 W/m^2). A glazing type with higher visible transmittance was chosen for the best enclosure case for better visual quality in the space. This resulted in a glazing type with higher shading coefficient, and hence the increase in the total annual energy consumption (from 268 kWh/m^2 to 285 kWh/m^2). We then used the GenOpt (GenOpt 2002) program to improve the enclosure further. The parameters that were considered are: wall U-value, roof U-value, window height, floor mass, and overhang depth for the east and the west facades. The optimized enclosure reduced the energy consumption to 247 kWh/m^2. Figure 5 shows that it is possible to further reduce the total energy consumption to 211 kWh/m^2 (approximately 21% of the base case) with the use of natural ventilation and photovoltaic systems. Analysis of the BAPP building with typical office building loads (21.52 W/m^2) shows that the total annual energy consumption is about 1/3 (110 kWh/m^2) of a typical US office building (300 kWh/m^2) (EIA 1995).

In Figure 6, we show a schematic of the HVAC and energy cascading system (here the Siemens Westinghouse SOFC is considered). Our preliminary analysis shows that using SOFC for power generation is approximately 70% efficient, compared to the electric utility, which is about 30% efficient. The higher efficiency is because of three reasons: 1) the SOFC's power generation efficiency is 45%, 2) there are no distribution and transmission losses, and 3) the thermal energy is utilized on site for heating/cooling purposes.

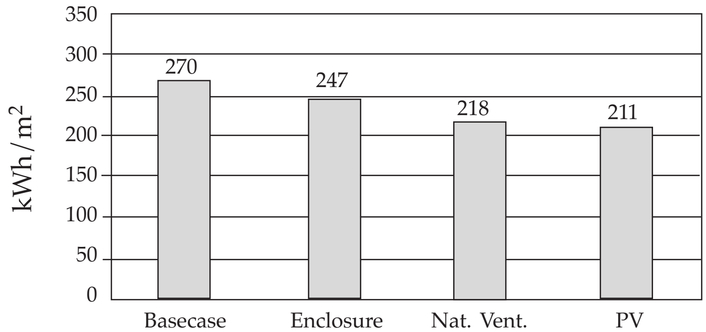
CONCLUSIONS

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 that 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



Basecase	•	•	•	•	•	•	•	•	BASE	BEST
Wall-R		•	•	•	•	•	•	•	143	11
Roof-R			•	•	•	•	•	•	20	35
Floor Mass (cm)				•	•	•	•	•	10	15
Glazing					•	•	•	•	G-2447	G-2665
Interior shade						•	•	•	NO	YES
Overhang							•	•	NO	YES
Daylighting								•	NO	YES
Energy (kWh/m2)	269.9	269.4	269.2	268.3	284.8	269.3	261.8	255.3		
% Base case	100.0	99.8	9.7	99.4	105.5	99.8	97.0	94.6		

Figure 4. Effect of Better Enclosure Options on the Building Energy Consumption



Basecase	•	•	•	•
Enclosure design		•	•	•
Natural ventilation			•	•
Photovoltaics (PV)				•
Energy (kWh)	269.9	247.2	218.2	210.7
% of Basecase	100.0	91.59	80.83	78.08

Figure 5. Effect of Passive and Renewable Strategies on Energy Consumption

analysis of multi-modal conditioning systems and the cascading energy strategies. 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.

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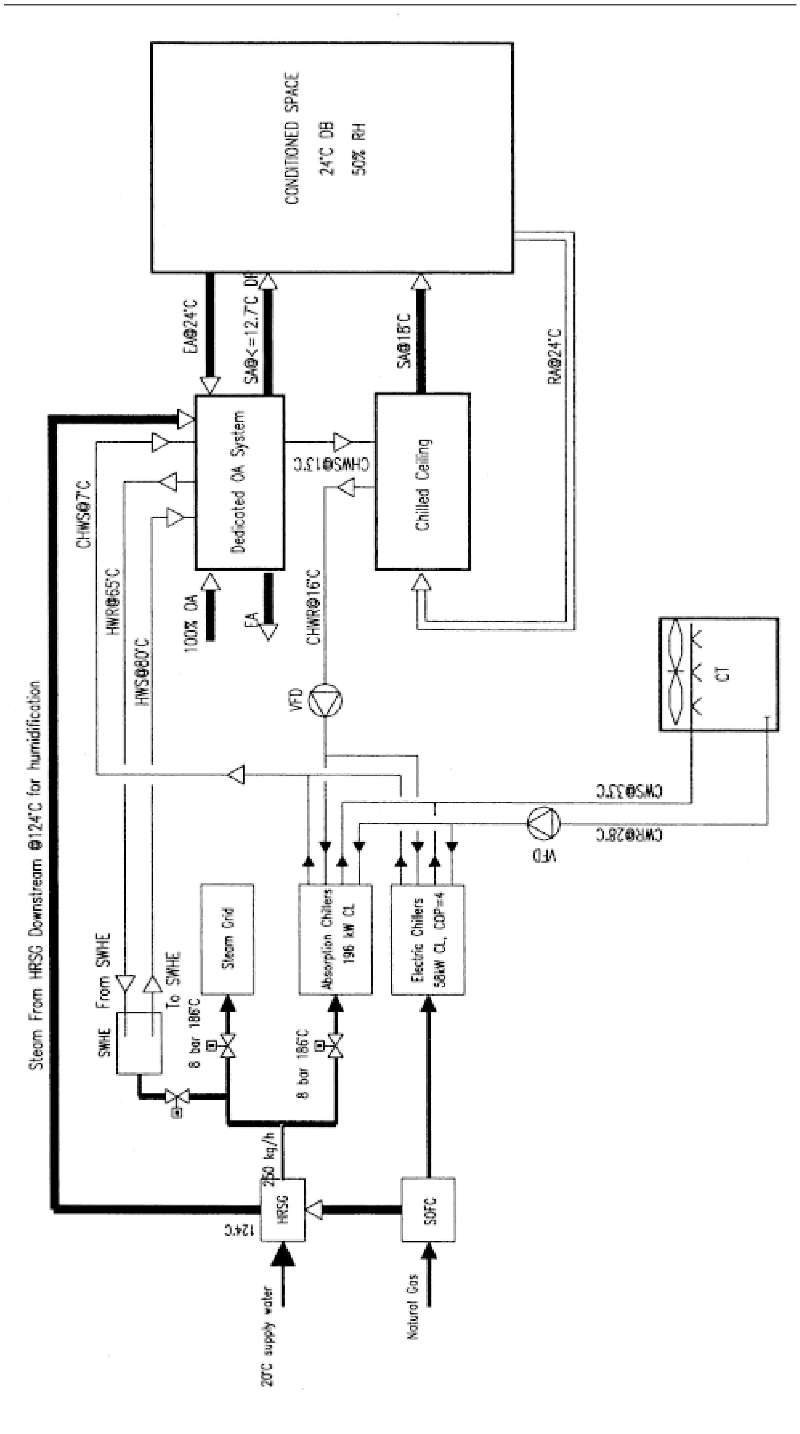

Figure 6. HVAC and Fuel Cell Schematic

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