Professional and Educational Implications of Innovations in Building and Construction

(Demonstrated by the Robert L. Preger Intelligent Workplace (IW) and Expected from the Building as Power Plant (BAPP) / Invention Works Projects at Carnegie Mellon University)

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ABSTRACT: The Center for Building Performance and Diagnostics (CBPD) at Carnegie Mellon University (CMU) in Pittsburgh with the support of the Advanced Building Systems Integration Consortium (ABSIC) has realized the Robert L. Preger Intelligent Workplace (IW), a living (always adapted) and lived-in laboratory occupied by faculty, staff and students. The IW represents a major breakthrough realizing advanced requirements for occupant's comfort and productivity, organizational flexibility and effectiveness, technological adaptability, and energy and environmental effectiveness, throughout the lifecycles of all materials, components and systems.

Building on the experience and success of the Robert L. Preger Intelligent Workplace, CMU, CBPD and the ABSIC are committed to realize the Building as Power Plant (BAPP)/Invention Works project on the CMU campus. In addition to advanced energy-effective enclosure, heating, ventilation, and air-conditioning and lighting technologies, the BAPP will integrate innovative distributed energy generation systems. This will enable that all of the building's energy needs for heating, cooling, ventilating, lighting and equipment are met on-site, maximizing the use of renewable energies. Thereby the BAPP addresses significant international needs in terms of energy effectiveness, energy quality, reliability and security, as well as environmental performances. Consequently, the U.S. Congress has designated the BAPP as the National Test-bed for Energy Efficient Building Technology.

The IW is being visited by about 1000 visitors from all over the world annually, many of them governmental representatives, clients, architects and engineers. Consequently, CBPD faculty and staff were asked to apply major concepts of the IW in buildings in Korea, China, France, Germany and North America. The School of Architecture at CMU has introduced a new course and design-studio sequence in building performance and systems integration. The Graduate Program in Building Performance and Diagnostics currently has 13 doctoral and 6 master students.

1 INTRODUCTION

KEY QUESTION: Taken as a whole, the built environment represents neither any company's core business, nor does it fall under the purview of a single governmental agency's core mission. It is instead the result of many actions, and influenced by numerous actors, while no one takes final responsibility. Should the universities assume this duty to set examples?

CHALLENGES:

- Worldwide growth of nonrenewable resource consumption and waste
- Finite reserves of nonrenewable resources (2009 world-wide peak of oil production)
- Finite carrying capacity of Earth
- 50% of world population living on less than $2/day and mostly on solar income
- The United States of America – the leader in fashion; instant gratification

When focusing on the built environment in the US, we realize that it:

- creates 40% of land-fill waste by weight, and 30% by volume
- consumes almost 40% of the US's primary energy for operation and an additional 10%-20% (estimated) for building materials production

– contributes in the US, over 500 million tons of CO_2 into the atmosphere per year from the generation of the electricity that is used for building operations (67% of total electricity - source: Energy Information Administration, Annual Energy Review 2001)
– produces 18% of the US's total annual CO_2 emissions by cement production

also offers potential for health and productivity savings in the range of $20-200 billion annually through improved practices and systems integration.

2 THE ROBERT L. PREGER INTELLIGENT WORKPLACE:THE LIVING AND LIVED-IN 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, the first National Science Foundation Industry/University Cooperative Research Center in the building industry, 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.

Occupied in December 1997 and continuously being adapted, 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;
– innovations in information technology;
– innovative enclosure, HVAC, power, voice, data networking, and interior systems;
– products for thermal, air, visual, acoustic, connectivity, and spatial quality;
– demonstrations of products' performance in an integrated setting;
– training in material, component, and systems choices and their integration for performance; and hands-on learning in instrumentation and metrics for evaluating performance and occupancy comfort, and in development of CAD packages for design, simulation and management.

The IW enables the interchangeability and side-by-side demonstrations of innovations in HVAC, enclosure, interior, and telecommunication components and assemblies. Most importantly, 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 (*see Figure 2*).

Figure 1. The Intelligent Workplace™, a rooftop extension of Margaret Morrison Hall at Carnegie Mellon University

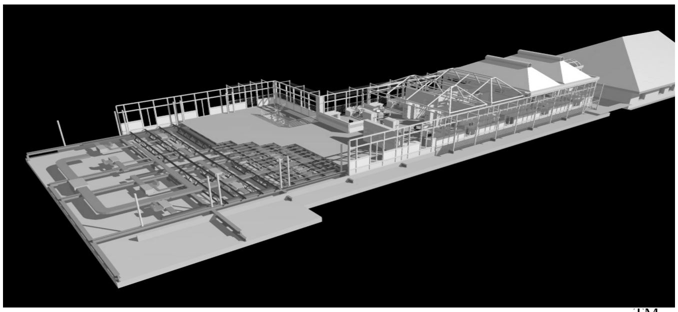


Figure 2. Peel -away view of the Intelligent Workplace™ illustrating the floor-based integration

2.1 *Goals of the Robert L. Preger Intelligent Workplace™*

– *Individual Productivity and Comfort:* The demonstration of advances in individual comfort and productivity requires that 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 for comfort, health, and corresponding productivity.
– *Organizational Flexibility:* The demonstration of advances in organizational flexibility requires that 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.
– *Technological Adaptability:* The demonstration of advances in technological adaptability requires that vertical and horizontal pathways for connectivity are accessible and open and that both interior systems and engineering infrastructures support changing technological demands for horizontal and vertical work surface, lighting, acoustics, thermal conditioning, and ergonomics.
– *Environmental Sustainability:* The demonstration of advances in environmental sustainability requires that both energy and materials are used effectively over a building's and its components' life cycles. Concepts, such as system efficacy, user controls, micro-zoning for flex-time, just-in-time delivery of infrastructures, environmentally sustainable and healthy materials, natural condi-

tioning, should all be demonstrated and comparably measured to standard practice.

2.2 Systems Integration for Performance

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. The IW also provides the platform to explore broad environmental and ecological issues such as recycleability of building products and assemblies, and long -term resource management. As a test-bed of new ideas, and a demonstration center for successful innovations, combined with innovative office 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, allowing the organization and the employees to decide and constructively adjust the location and density of people and equipment, as well as their enclosures for physical, visual and acoustic privacy.

2.3 New Design Approaches to Absorb Change and Avoid Obsolescence: Flexible Grid - Flexible Density – Flexible Closure Systems

To avoid frequent environmental quality failures, or median and long term obsolescence, it is critical to invest in user-based infrastructures that are modular, reconfigurable, and expandable for all key services - ventilation air, thermal conditioning, lighting, data/voice and power networks. The dynamic reconfigurations of space and technology typical in buildings today cannot be accommodated through the existing service infrastructures - either the "blanket systems" for uniform open-plan configurations or the idiosyncratic systems for unique configurations. Instead, flexible infrastructures are required, capable of changing both location and density of services:

> *Flexible Grid - Flexible Density - Flexible Closure Systems 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 requirements and the central system responds with the appropriate ambient conditions, or fully re-locatable, expandable task/ ambient systems.

Advanced buildings today demonstrate that floor-based servicing may more effectively support the dynamic workplace (*Figure 3*). Since networking, ventilation and thermal conditioning need 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. Today, a number of industry partnerships are forming to offer collabora-

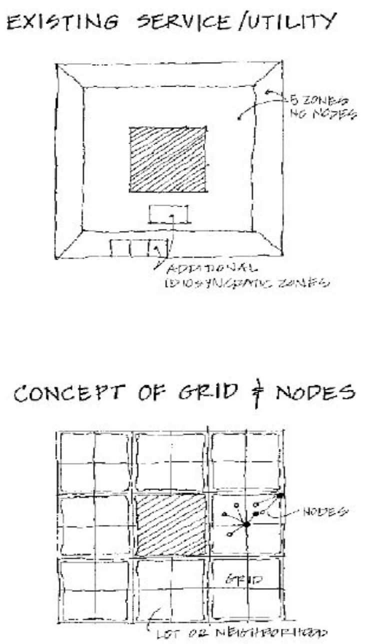
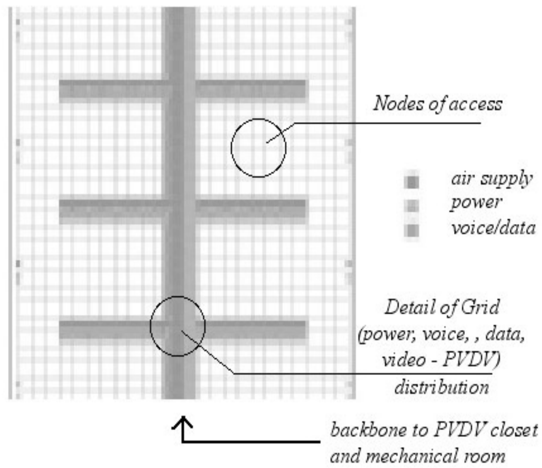


Figure 3. Conventional large zone approaches to thermal conditioning and lighting are incapable of delivering adequate environmental quality to accommodate the dynamics of technology, workstation density and teaming concepts



Nodes of access in the IW

Detail of Grid (power, voice, data, video) distribution in the IW tive solutions to flexible infrastructures - floors, data/ voice, power, thermal conditioning and ventilation. With these modular, floor-based services, the ceiling can become more playful and elegant - as a light and acoustic diffuser - defining working groups, work neighborhoods as well as recreating the ceilings of landmark buildings (Loftness et al, ARTI21-CR, 2003)

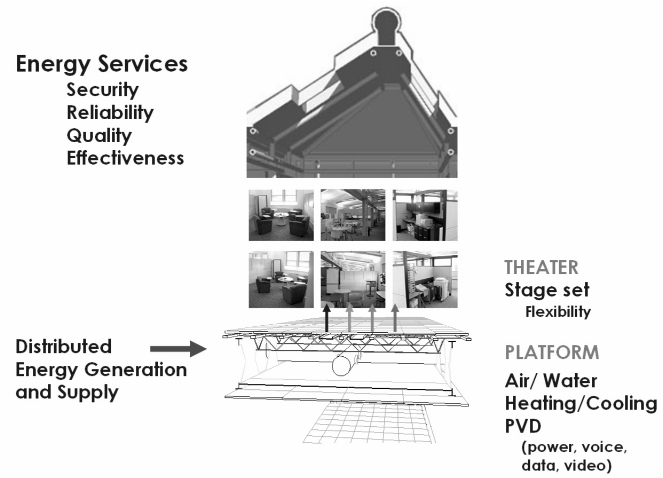


Figure 4. The IW central system integration concept for flexibility, plug and play systems, distributed energy generation and supply, as well as advanced energy services

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.

2.4 Reduced Waste in Construction of the Intelligent Workplace

The IW project exemplifies how the design and engineering, as well as 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. This includes the reduction of NOx by 90%, SO_2 by 70%, and CO_2 by 80%. An analysis of the project also showed dramatic savings potentials when selecting recycled aluminum and steel rather than virgin materials. Here the avoided emissions ranges were similarly pronounced.

In addition, there was no on-site waste during most of the construction phase (steel structure and facade erection as well as interior fit-out), because of the IW's modular design and its off-site fabrication with complete recycling capacity of all by-products. This also resulted in a reduced potential for injury and significant time-savings during construction, which ultimately leads to capital savings by shortening delivery time.

2.5 Reduced Waste in Operation

The IW is conditioned for six or more months through "natural" energies alone during daylight hours (passive and active solar heating, cooling, daylighting and ventilation).

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. 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, as demonstrated in the IW.

This dual concept of just-in-time organizational change and technological change assures that the building is meeting flexibility and adaptability requirements without redundancy or waste. Access in the "open" system and plug-and-play technologies allow for the complete component-by-component, or system-by-system change-out of technology with complete recycleability when and where necessary. These concepts also insure that the building is a renewable asset for its investors and will not become a straightjacket that eventually has to be discarded in whole or in part. These concepts also insure that all changed-out components or systems are fully recyclable, since composite materials are avoided and systems are demountable. For instance, the IW enclosure and structural elements are pinned or bolted and made from recycled aluminum and steel.

Consequently, 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 re-deployable 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. When all fails, at least, the demountable system can be up-cycled completely as either biological or technical nutrient (Michael Braungart, 2002).

In summary, the four waste-management and environmental benefits of the IW are:

- The materials, components and systems during their production and assembly require a fraction of the energies and produce a fraction of the emissions of comparable systems.
- During the construction phase, due to prefabrication and modular design, waste is eliminated.
- During the operational phase, the management of obsolescence supports organizational and tech-

nological changes-on-demand. This is enabled through re-locatable infrastructure: HVAC, lighting, power, communication and interior systems. In addition, the fact that major building components and systems have different life cycles is accounted for through the use of the modular, plug and play systems. This allows for easy change-out and advancement of technology as the need or opportunity arises.

- The design anticipates a complete decommissioning of the building and its constituent parts. The "long life systems", such as structure and envelope, can be redeployed elsewhere. Or, as in all other cases, the materials of non-unified components of subsystems can be completely up-cycled.

2.6 *Intelligent Workplace Energy Systems Analysis*

The energy usage and performance of the Intelligent Workplace and its building control systems are being analyzed. The lessons learned during this study are being used in the design and engineering of integrative demonstration and "laboratory" project, the Building as Power Plant/Invention Works (BAPP) on CMU's campus (see below).

The analysis focuses on: 1) data acquisition system, 2) building control systems, and 3) the next BAPP design.

The IW uses several energy systems to provide heating, cooling, ventilation, dehumidification, and lighting. Heating is provided by the warm water mullions of 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 a 100% outdoor air system with enthalpy wheel for dehumidification. A JCI Metasys system controls most 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 a tool, IW Energy Sentinel (IWES), was developed to: (a) actively capture continuous streams of data from different sources, process and aggregate them into a common format, and provide useful information; (b) create a central repository for storing building system information and sensor information, such as specification and maintenance history, throughout the life cycle of the building; (c) provide visual data displays, reports and alarms that work with multiple building systems; and (d) function successfully without changing the operation of the installed sensor systems. This tool also 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. 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 in 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 when data were missing.

It was found that although energy usage was considerably less in the IW when compared to standard US office buildings (*Figure 7)* there were still areas where the energy consumption could be reduced further. This will be accomplished by the BAPP.

- Several hypotheses 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, due to leakages in the interfaces between the façade and the roof, as well as the floor below.
- The heating set point in the IW was higher than that of a standard office building, which further increased the load.
- The higher then typical amount of glass and exposed surface area caused an increase in cooling energy.
- This cooling load was sometimes increased by inappropriate operations of windows.
- The unconditioned under-floor plenum above several floors below, all of which are not cooled during summers, 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.

Fluorescent fixtures with dimmable ballasts provide artificial lighting. 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^2 (about 1/5th of best US practices), 10.12 kWh/m^2 was caused by transformer losses (the "parasitic" load therefore is a 50% of this reduced load).

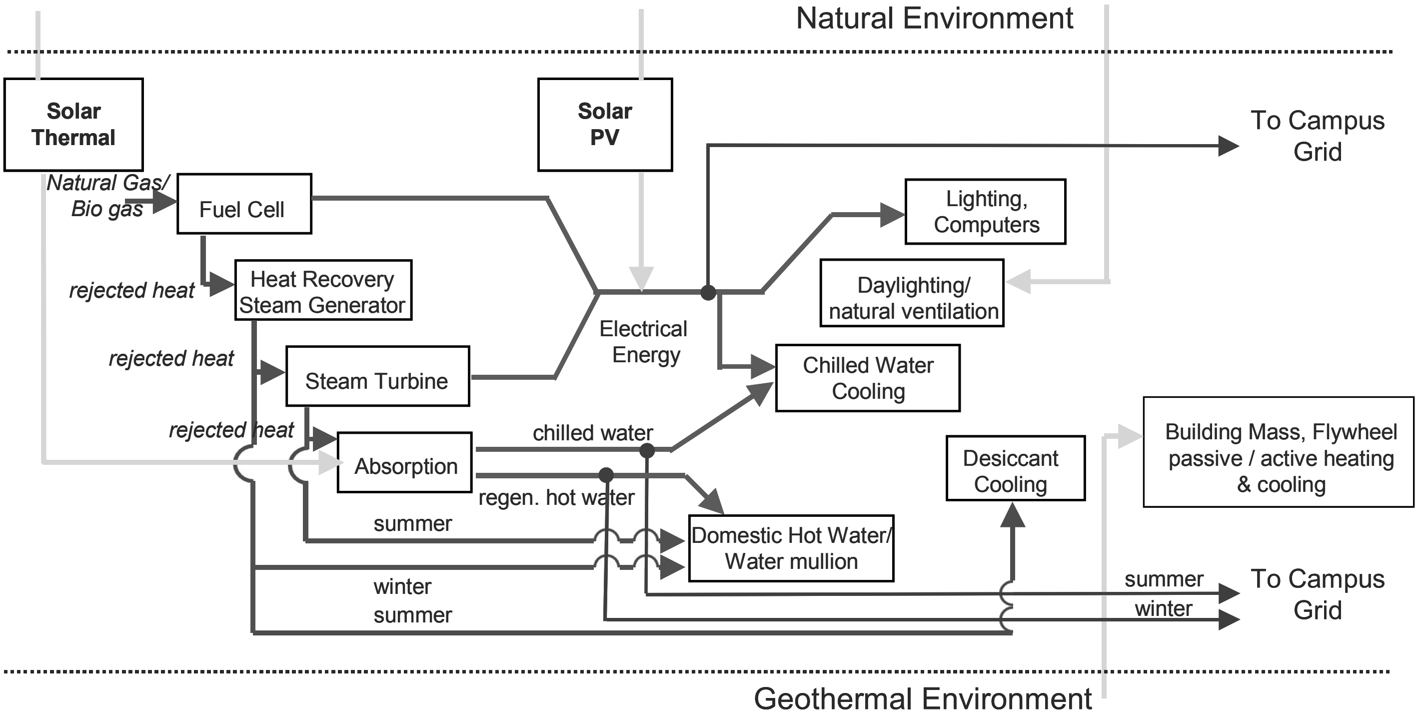


Figure 5. Building as Power Plant conceptual scheme for a building-integrated "ascending-descending" energy system

3 BUILDING AS POWER PLANT/INVENTION WORKS

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 all of the building's energy needs for heating, cooling, ventilating and lighting are met on-site, maximizing the use of renewable energies. (Figure 5 schematically illustrates this idea.)

BAPP is designed as a 6-storey extension of the existing Margaret Morrison Carnegie Hall Building with total area of about 6000 m^2, which houses classrooms, studios, laboratories and administrative offices for the College of Fine Arts. TH BAPP 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.

An "ascending-descending energy scheme" 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

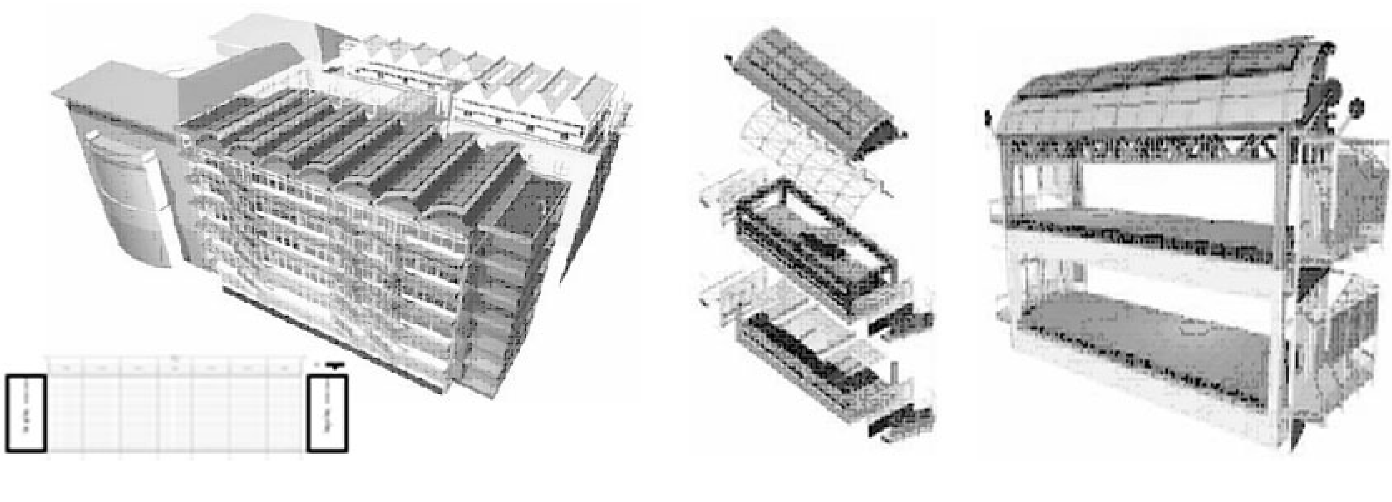


Figure 6. Column-free, flexible floor plan, perspective, modular design, stacked bays and solar-thermal collector arrangements for the new wing of the Building as Power Plant/Invention Works

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 the 'ascending' energy strategy is a 'cascading' energy strategy, designed to make maximum use of limited non-renewable resources. In the building's power generation, reject heat from the fuel cell can be converted into steam, which can be used to drive a steam turbine, and/or in the cascading system, reject heat will be used to drive desiccant, absorption and refrigerant systems; and finally the resulting reject heat can be used for space and domestic hot water heating.

4 CONCLUSION

Figure 7 clearly delineates the vast opportunities of the BAPP project. Increased building performance and energy effectiveness hold for 40% of the primary US energy consumption and 67% of the US electricity demand. In fact, the expected performance of the Building as Power Plant/Invention Works, which will include integrated solar-thermal, ground-source heat pump, as well as fuel cell technologies is expected to function as a significant net energy exporter to the campus at large. This is in addition to providing the environment for occupant productivity, organizational effectiveness and the conservation of material resources.

The mission of the School of Architecture at Carnegie Mellon University is to educate outstanding professionals with design creativity, social responsibility, historical perspective, technical competence, and global environmental consciousness. The School has taken the position that future architects should be accountable for the measurable performance of the buildings they design. This accountability demands that architectural education must provide hands-on knowledge about thermal, air quality, visual, acoustic, and spatial performance, as well as long term building integrity in a fully integrated, occupied setting. To this end, the Intelligent Workplace (IW) serves as a proving ground for the advancement of integrated systems for superior building performance. This innovative office setting begins to establish buildings as renewable assets rather than depreciating investments with liability. At the same time, the IW plays a vital role in the education of our students to provide unprecedented hands-on learning about the performance of integrated building systems, providing settings for individual comfort and productivity, organizational flexibility, technological adaptability, as well as energy and environmental effectiveness (Streitz, et. al., 1999, GSA Office of Real Property, 2004).

The graduate program in building performance is built on the principles of sustainability. The graduate

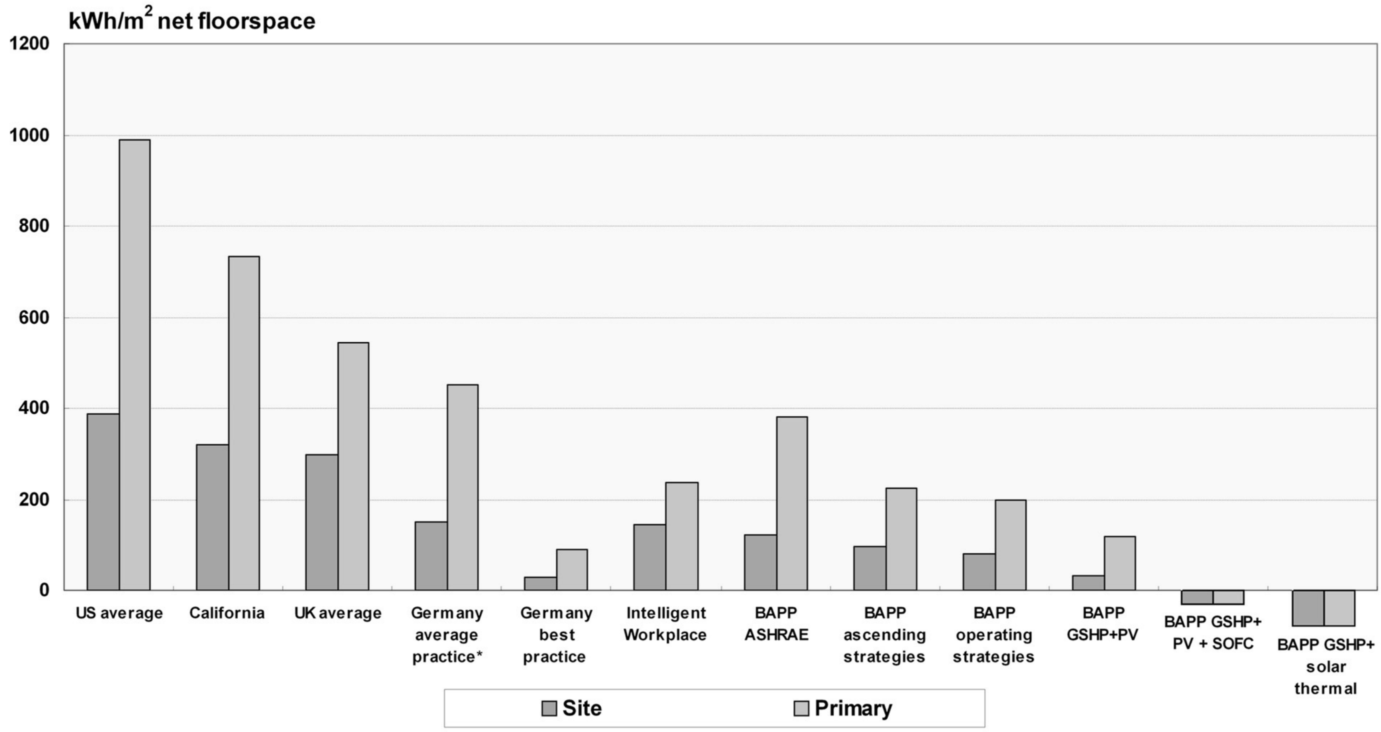


Figure 7. Source (Primary) and Site Energy Comparisons

research focuses on both new science and new engineering developments for environmental sustainability, including simulation tools, design guidelines and decision support tools, innovations in systems and systems integration, as well as demonstration projects and POE towards a more sustainable future for the built environment.

In addition, the CBPD is actively developing strategies for influencing the building delivery process towards improving the performance of buildings. The industry is limited by an overly strong emphasis on first cost decision-making, therefore, the development of a life-cycle tool identifying the cost-benefits of advanced building technologies is central to the commercialization of higher performance building solutions. In a web-based tool called BIDS (Building Investment Decision Support™), the Center is developing life-cycle justifications for high performance building systems with user-customized recalculations of world-wide case studies. BIDS™ is a case-based cost-benefit analysis tool to support investments in advanced and innovative building systems that improve environmental quality, health and productivity in buildings. Through ABSIC support, it continues to identify laboratory and field case studies demonstrating the relationship of high performance components, flexible infrastructures and systems integration to the range of cost-benefit or productivity indices, with over 200 data sets incorporated by July 2005. The team is also expanding the data base relating quality indoor environments to major capital cost and benefit areas, including productivity, health, and operations costs, with baseline data sets to support life cycle decision-making. (http://cbpd.arc.cmu.edu/ebids)

No one discipline owns sustainability. Progressive environmental leadership must draw from ethics, economics, science, technology, and public policy. Progress depends on the sort of cross-campus collaboration – with an eye toward solving real-world problems – that is this Carnegie Mellon's signature strength. Such efforts can lead to policy development. For instance, the US Dept. of Energy (DOE) held the National Lighting Visioning Workshop in the Robert L. Preger Workplace (IW). In 1999 DOE brought 100 Chinese professionals to the IW, amongst them the Vice Minister of Construction. This resulted in the CBPD team to lead the redesign of the Ministry of Science and Technology (MOST) Headquarters for The Agenda 21 Team (Climate Change), jointly with the NRSC and the USDOE. The effort resulted in the 12,000m^2 building to consume 77% less energy than was projected by meeting ASHRAE (American Society of Heating, Refrigeration and Air-conditioning Engineers) standards. The building was recently the centerpiece of the Joint Sino-US Green Building Conference at MOST in Beijing, showing a desirable path of development.

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