Building Technology Research in Architectural Practice: Lessons Learned from Implementations of Energy-Efficient Advanced Building Technologies

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ABSTRACT

This paper discusses relationships between research, architectural design and technology, and provides an overview of lessons learned regarding adoption and implementation of energy-efficient advanced building technologies. The introductory part discusses activities and research program at Perkins+Will Tech Lab. The objectives of the program are to advance the performance of architectural projects, improve decision-making processes, and to inspire innovation through systematic investigations of building performance and emerging building technologies.

Using two specific case studies, we present some of the barriers that are currently present for the wider adoption of advanced, energy-efficiency building technologies. The first case study discusses research on the performance and implementation of double skin facades, while the second case study discusses life-cycle performance and cost analysis of building integrated photovoltaic system. In the conclusion, we offer some recommendations how these barriers can be addressed.

Introduction to Tech Lab

Tech Lab was initiated in 2008 as a research entity within Perkins+Will to enhance project designs through dedicated research. Tech Lab's research agenda focuses on advanced building technologies, materials, sustainability, high-performance buildings, renewable energy sources and computational design. Tech Lab monitors developments in building systems, materials, and information technology; reviews and analyzes emerging building technologies that can have a direct impact on the course of architectural design, and investigates building systems that can significantly improve the value, quality and performance of architectural projects. Examples of Tech Lab's research projects are:

- Performance and life cycle cost analysis for building integrated photovoltaics
- Performance of double skin walls
- Renewable energy systems optimization
- Advanced thermal comfort modeling
- Parametric modeling and design
- Thermal analysis of exterior wall assemblies
- High-performance building envelopes
- Selection of renewable energy sources.

Primary research methods include simulations and computational modeling, which are used to investigate different design scenarios and strategies. Typical research process involves: 1) determination of research objectives and questions based on the needs of specific architectural/design projects; 2) identification of appropriate research methods; 3) identification of the timeline, schedule and research procedures; 4) execution of the study; and 5) dissemination and implementation of research results. Besides implementation of research results on architectural and design projects, sharing and dissemination of findings with the larger architectural and design community is a key aspect of Tech Lab's objectives. Publications of research data and methods, analysis processes and results benefits the entire industry, therefore, research studies and results are shared through Tech Lab Annual Reports (Aksamija 2010a; Aksamija 2011; Aksamija 2012; Aksamija 2013).

The next sections review two specific case studies to illustrate research processes and methods in more detail, as well as lessons learned regarding adoption and implementation of energy-efficient advanced building technologies. The first case study reviews energy performance analysis for a double skin facade, while the second case study discusses life-cycle performance and cost analysis of building integrated photovoltaic system. We also discuss lessons learned and barriers for wider adoption and implementation of energy-efficient advanced building technologies. In the conclusion, we provide recommendations how to address these barriers.

Double Skin Facade: Energy Performance Analysis

Double Skin Facades as an Advanced Building Technology

Double-skin facades consist of distinct exterior and interior glazed wall systems, separated by a ventilated air cavity. The cavity creates a thermal buffer between the interior and exterior environments. The air cavity can be ventilated by natural convection caused by warm air naturally rising, by mechanical devices, or by a hybrid mode that combines the two. In some double-skin facade designs, the air cavity is interrupted vertically or horizontally (or both) by solid or perforated partitions. Selection of the type of the glazing, the width and partitioning of the air cavity, and the ventilation mode depends on climate, building orientation, and design requirements.

Classification of double skin facades can be made according to the geometry and partition (facade) type, ventilation mode and air flow pattern, such as:

- Box window facades have horizontal partitions at each floor level, as well as vertical partitions between windows. Each air cavity is typically ventilated naturally.
- Corridor facades have uninterrupted horizontal air cavities for each floor level, but are physically partitioned at the floor levels. All three ventilation modes are possible.
- Shaft-box facades are similar to corridor facades, but use vertical shafts for natural stack-effect ventilation. Hybrid mode ventilation is often used for this facade type.
- Multi-story facades have uninterrupted air cavities the full height and width of the facade. All three ventilation modes can be used.

The majority of double-skin facades to date have been used for buildings in temperate and cold climates. However, there are buildings in warm, hot, and arid and hot and humid climate types using double-skin facades (Haase, Marques da Silva & Amato 2009; Tanaka et al. 2009). Many of these buildings incorporate natural or hybrid mode ventilation, integrated movable shading devices, hybrid ventilation systems, and different airflow patterns (Badinelli 2009; Blomsteberg 2007).

During the planning and design process, recommendations for the design of double skin walls are to select appropriate control strategy for ventilation air cavity, select glazing properties as well as to plan for provision of shading devices. In analyzing appropriate design strategies that are dependent on the climate and location, comparison of energy consumption for single skin and double skin facade is a viable option. Moreover, selection of design strategies can be improved if design options are investigated based on their effect on energy consumption.

Energy Performance of a Double Skin Facade

There has been substantial research on the performance of double-skin walls in cold and temperate climates (Poirazis 2006; Stec & van Paaseen 2005). Double-skin walls generally perform well in these climates because of their inherent thermal insulation properties. During the winter months, the air cavity provides an effective thermal barrier. During the summer, ventilation of the cavity removes hot air and keeps the interior spaces cooler.

Critical factors for double skin walls in temperate and cold climates are geometry of the air cavity, type of ventilation system and air flow mode. Poizaris claims that the most important parameters in designing the double skin facade in this type of climate are dimensions of the air cavity (width and height), since they have the greatest influence on heat and flow performance (2006). Lee et al. claim that proper ventilation of the cavity is highly dependent on the combination of the glass panes, ventilation mode as well as the size of the air cavity (2002).

In order to illustrate the analysis process, the following case study discussed. Double skin facade along the south side of a bridge was studied as one of the energy-efficient design methods for the Rush University Medical Center, located in Chicago (Abdullah and Aksamija 2012; Aksamija 2009). In order to investigate effects of these design parameters on energy consumption, such as air cavity dimensions, location of double air-insulated glazing as well as difference in operation during winter and summer months, different scenarios were investigated for a multi-story double skin wall shown in Figure 1. In order to study the effects of changing air cavity geometry, location of double skin as well as different air flow types, different design scenarios were investigated using EnergyPlus modeling software.

Static parameters for all facade types are shown in Table 1. Changing properties that were considered are shown in Table 2. Base model included double-glazed single skin facade with low-e glazing. For double skin facade, location of double glazing was varied from the internal to external skin as well as cavity depth from (0.5 m to 1.2 m). Two different types of air flow were investigated—exhaust air during all year as well as combination of exhaust air during summer months and air curtain during winter months. This combined air flow type would allow utilization of warm air during winter to preheat the air cavity. All analyzed double skin scenarios includes shading devices within the air cavity.

Results, showing annual energy consumption for all cases, are presented in Figure 2. Base model (double-glazed single skin facade) has highest overall energy demand; however, looking at the annual energy demand reveals that some cases of double skin wall have higher heating loads during winter months. In particular, air flow type has a major effect, since exhaust air type increases heating demand. Results indicate that trapping air within the air cavity during winter months insulates the double wall, thus significantly lowering heating loads.

Figure 1. Double Skin Wall

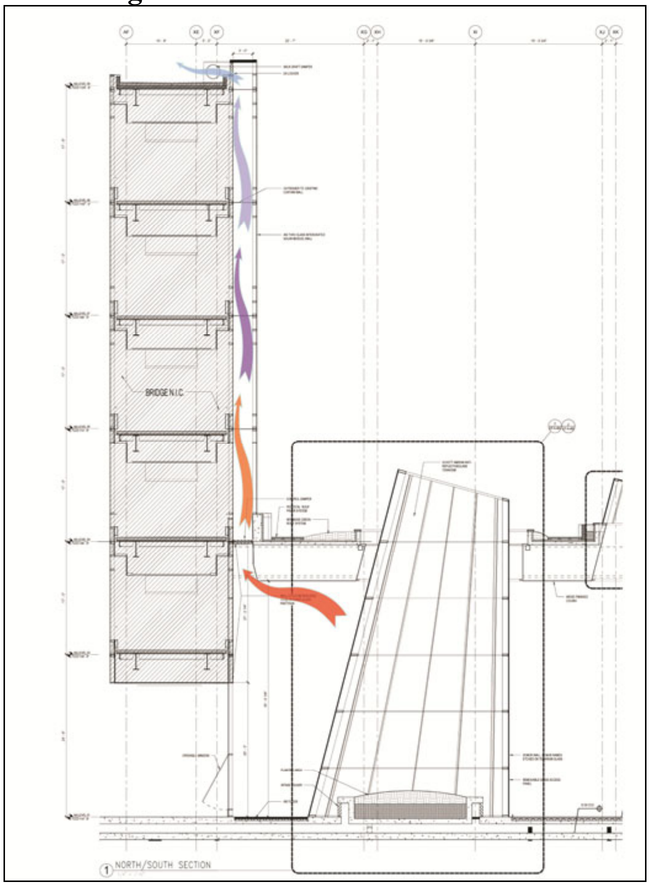


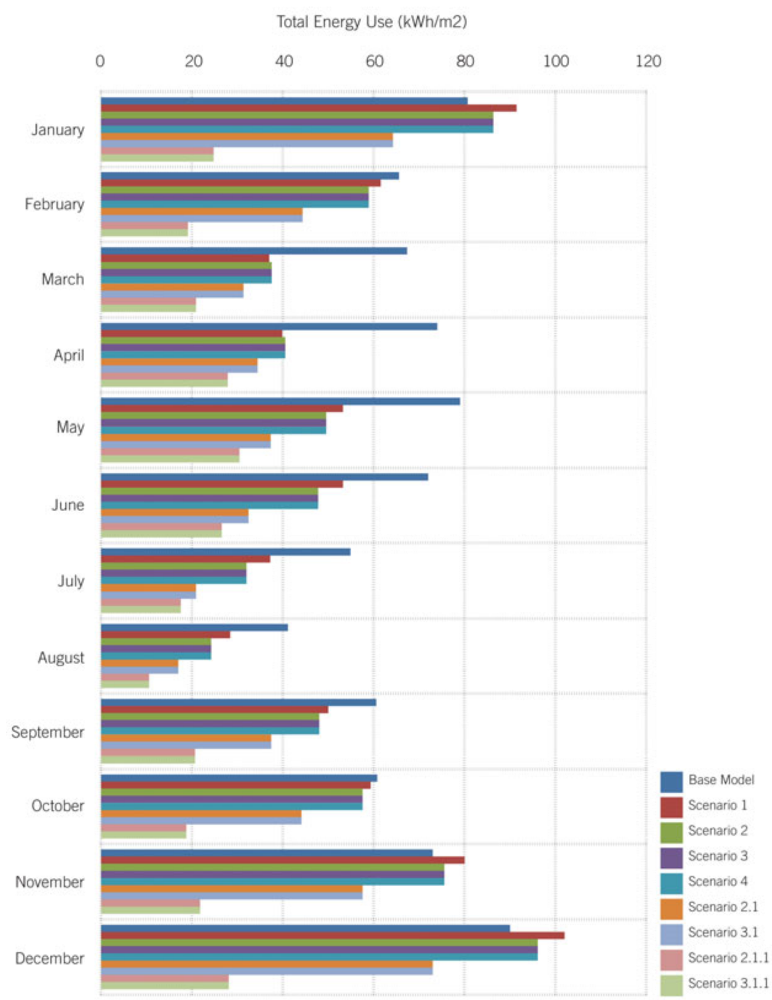
Table 1. Static Variables Used in the Analysis for All Facade Types

All facade types	
Location	Chicago, IL
Orientation	South
Temperature (minimum)	20°C
Temperature (maximum)	26°C
Humidity (maximum)	60%
Occupancy load	0.25 people/m^2
Lighting requirement	200 lux
Equipment load	1.00 W/m^2
Air change rate per occupant	15.0 l/s person
Total air change rate	0.9 roomful per hour
Dimensions	
Depth	5.5 m
Width	21.3 m
Height	18.9 m
Glazing type	low-e
Window area	80%
Double skin facade scenarios	
Type	Multi-story
Ventilation mode	Hybrid (natural, assisted by mechanical)
Flow rate	50 m^3/hr
Shading	Blinds that respond to temperature, located within the air cavity

Table 2. Dynamic Variables for Analyzed Facade Types

Scenario	Location of double glazing	Air flow type	Air cavity depth
Base model	-	-	-
Scenario 1	In	Exhaust air (interior vent supply, exterior vent exhaust)	0.5 m
Scenario 2	In	Exhaust air (interior vent supply, exterior vent exhaust)	0.7 m
Scenario 3	In	Exhaust air (interior vent supply, exterior vent exhaust)	1.0 m
Scenario 4	In	Exhaust air (interior vent supply, exterior vent exhaust)	1.4 m
Scenario 2.1	Out	Exhaust air (interior vent supply, exterior vent exhaust)	0.7 m
Scenario 3.1	Out	Exhaust air (interior vent supply, exterior vent exhaust)	1.0 m
Scenario 2.1.1	Out	Combination (exhaust air summer, air curtain winter)	0.7 m
Scenario 3.1.1	Out	Combination (exhaust air summer, air curtain winter)	1.0 m

Figure 2. Annual Energy Demand for Single Skin and Double Skin Facades



Based on the performed energy analysis for several possible design scenarios, it was concluded that the best possible candidate would contain double glazing on the exterior and single glazing on the interior side, with an air cavity of 1 m, and hybrid airflow mode (exhausted air during summer months assisted with mechanical fans and air curtain during winter months to decrease heating loads). However, the double skin wall was eliminated in the design development stage due to the high initial costs. The final design incorporated a curtain wall facade with fritted glass to limit the solar heat gain and reduce cooling demand.

Barriers for Implementation

Selection of the double-skin ventilation mode (natural, mechanical, or hybrid) should be based on building location (i.e., climate zone). Natural ventilation of the air cavity works best in temperate or cold climates, while mechanical ventilation may be required for hot climates. Hybrid systems will often use natural ventilation during the colder winter months and mechanical ventilation during hot summer months, making this mode applicable for mixed climates. Energy savings are dependent on specific configuration of the facade, climate, environmental aspects and ventilation mechanisms. While there is no energy required for the naturally ventilated air cavity to work in temperate or cold climates, additional energy is required for the mechanically ventilated air cavity to work in hot climates beside energy required to cool the interior space.

Initial costs of double-skin facades are higher than for single-skin facades. However, when designing sustainable facades, life-cycle costs for the life of the building should be taken into consideration. After energy consumption costs are evaluated for the life of the building, higher first-cost designs may result in lower overall costs. This does not take into account other, more difficult to price advantages of double-skin walls, including improved thermal comfort, reduced glare, and improved acoustic performance. Another barrier is that recommendations for building envelope designs that are included in currently adopted energy codes are not stringent enough to require implementations of these advanced building technologies. For example, requirements for U-values in ASHRAE 90.1-2010 are achievable through a simple brick cavity wall with insulation (ASHRAE 2010).

Life-Cycle Performance and Cost Analysis of Building Integrated PV System

BIPV and Renewable Energy Generation

Photovoltaics are commonly used for active energy generation systems in buildings. There are two basic types of PV modules: thin films and solid cells. The first consists of thin films of interconnected solar cells, which convert visible light into electricity. Thin film cells can be integrated into almost any surface, such as shading devices, spandrels, and vision glass. Solid solar cell modules can be integrated with spandrel areas or shading devices. The performance and aesthetic appearance of the PVs depend on their type, their size, available solar radiation on the site and their position relative to the sun’s path.

Performance and Life Cycle Cost Analysis

The objective of this study was to investigate cost associated with including building integrated photovoltaic (BIPV) system for a Sports and Recreation Center, located in hot arid climate (Riyadh, Saudi Arabia). Performance and cost analysis for incorporating roof-integrated photovoltaic system was performed (Aksamija 2010b). The roof construction for this facility utilized metal roof system, and a specialized product is commercially available which incorporates thin-film solar modules, permanently laminated to roofing aluminum profiled sheets. Advantages for using this system include:

- Flexible film amorphous silicon solar cells are used, having smaller manufacturing costs than crystalline silicon modules
- Films are already incorporated within the roof system, additional mounting and installation is not needed
- The total cost includes solar modules, all hardware, and installation
- Location has high yearly solar radiation
- Renewable energy is produced on site, and can provide a significant portion of the energy demand, depending on the system size.

Life-cycle performance and cost analysis was performed in order to analyze life-cycle cost associated with different system sizes, as well as the fraction of renewable energy in comparison to the actual energy demand for this facility. Integrated Environmental Solutions (IES VE) software was first utilized to model the projected energy consumption for the facility. Table 3 presents results for the annual energy demand, as well as scaled hourly demand.

Hybrid Optimization Micropower Energy Renewable (HOMER) model, developed by the National Renewable Energy Laboratory, was utilized to simulate the availability of resources, economic factors, system sizes, as well as the life-cycle cost. The inputs included energy demand of the facility (scaled hourly demand presented in Table 3), solar resources, installation costs, as well as possible system sizes. The inputs to the model were as follows:

- Scaled annual average solar radiation for Riyadh: 5.94 kWh/m^2/d
- Scaled annual average demand: 3,883 kWh/d
- Annual average demand range: 2,000 kWh/d to 4,200 kWh/d
- Lifetime: 20 years (assumed interest rate 6%)
- PV system size range: 17 kW to 600 kW
- PV system price per module: $1,836 (module, hardware, installation)
- Electricity grid rate: $0.1/kWh

Available area for the installation of roof-integrated PV system was 8,336 m^2. Energy balance calculations were performed for each hour in a year, where the energy demand was compared to the renewable energy system supply. Results indicate cost associated with initial installation, annualized cost, cost of electricity, and the renewable energy fraction.

Table 3. Annual Energy Demand for the Analyzed Building

Month	Heating (MWh)	Cooling (MWh)	Equipment (MWh)	Lighting (MWh)	Total (MWh)	Scaled hourly demand (kWh/day)
January	17.1	18.7	30.6	16.3	82.7	114.8
February	14.9	16.4	27.4	14.7	73.4	101.9
March	3.5	31.2	35.8	16.3	86.8	120.6
April	0	46.7	41.4	15.7	103.8	144.2
May	0	74.9	53.8	16.3	145.0	201.4
June	0	84.9	57.2	15.7	157.8	219.2
July	0	90.0	60.0	16.3	166.3	231.0
August	0	91.0	60.4	16.3	166.3	231.0
September	0	74.8	53.0	15.7	157.8	219.2
October	0	65.8	50.0	16.3	132.1	183.5
November	1.1	33.6	36.0	15.7	86.4	120.0
December	11.9	17.4	30.1	16.3	75.7	105.1
Total	48.5	645.4	535.8	191.6	1421.3	
Energy demand per area					365 kWh/m^2	

Results are shown for the several system sizes in Table 4. For example, the smallest PV system (14 kW) has a relatively low initial cost and the associated cost of energy; however, only 3% of the energy demand would be provided by the photovoltaic system. Annualized capital cost is calculated by relating initial capital cost, lifetime, and projected interest rate. Cost of energy is average cost per kWh of the electrical energy produced by the system.

Net present cost (NPC) represents the life-cycle cost of the system. The calculation assesses all costs occurring within the project lifetime, including initial costs, replacements within the project lifetime, and maintenance. NPC is calculated by equation [1], where TAC is total annualized cost, and CRF is capital recovery, given in equation [2]. N is the number of project years, and i is the annual interest rate.

$$NPC = \frac{TAC}{CRF} \quad [1]$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad [2]$$

Net present cost of smaller systems (14 kW and 25 kW) is comparable to the grid only cost, but the energy output is also relatively small. If the assumed lifetime is decreased, the projected net present value would also decrease.

In selecting the right system size, balance between initial cost, overall cost of energy, and renewable fraction is desirable. For example, 136 kW system would provide 23% of the total energy demand, as seen in Figure 3, and would consist of 1,000 modules (approximately one quarter of the roof area). Average daily output of this system is 824 kWh/d, and annual calculated annual electricity production is 300,853 kWh/yr. Annual hours of operation are 4,744 hr/yr. Figure 4 shows daily energy output based on the hours of operation. System of this size would only require 2,160 m^2 of roof area.

Table 4. Life-Cycle Cost for Different Sizes of Roof-Integrated PV Systems

Max power output (kW)	Annual PV output (kWh)	Initial cost ($)	Annualized capital cost ($/year)	Total annualized cost ($/year)	Overall cost of energy PV and grid ($/kWh)	Renewable fraction	Net present cost ($)
0 (Grid only)	0	0	0	109,500	0.100	0	1,399,777
17	30,085	183,700	14,370	106,642	0.111	0.03	1,546,942
25	55,304	337,684	26,416	131,494	0.120	0.05	1,680,930
40	88,486	540,294	42,265	146,611	0.134	0.08	1,874,182
68	150,427	918,500	71,851	175,657	0.160	0.13	2,245,486
136	300,853	1,837,000	143,702	247,003	0.226	0.23	3,157,915
150	331,823	2,026,103	158,495	261,781	0.239	0.24	3,346,443
175	387,126	2,363,787	184,491	288,138	0.263	0.27	3,638,369
190	420,310	2,566,397	200,761	303,962	0.278	0.29	3,885,654

Figure 3. Annual PV Output for 136kw System in Relation to Purchased Energy and Annual Demand

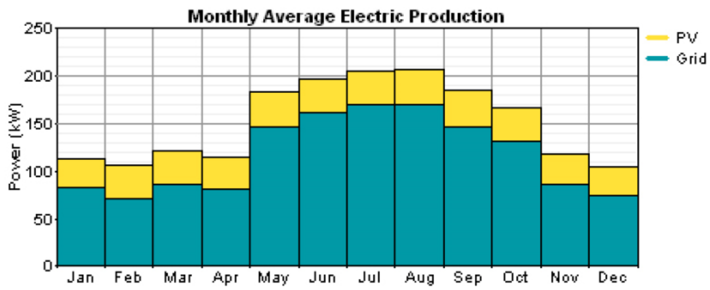
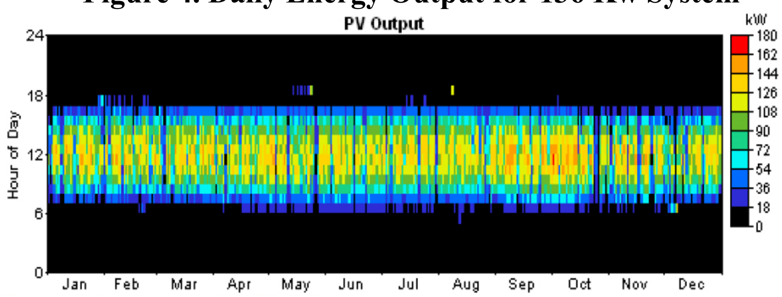


Figure 4. Daily Energy Output for 136 Kw System



Barriers for Implementation

Manufacturing costs for monocrystalline silicon cells are relatively high and their efficiency is typically no more than 20% under the best conditions (measured as a percentage of solar energy converted into electric energy). Polycrystalline cells generally have lower costs and lower efficiencies than monocrystalline cells. Manufacturing costs for amorphous cells are relatively low, but their efficiencies are also low, typically no more than 7%.

The cost and payback period of a photovoltaic system are relatively high. As the lifetime of solar cell is approximately 25 years, the payback period must be less than the lifetime of the solar cell to make the BIPV strategy viable. Also, the electricity grid rates have a significant impact on the decision-making and implementation of renewable energy systems. Lower utility rates for grid-purchased electricity result in higher payback periods.

Recommendations and Conclusion

The major barriers for the implementation of energy-efficient advanced building technologies are:

- **Cost:** Initial costs for the implementation of energy-efficient advanced building technologies are relatively higher compared to conventional building technologies. However, when considering energy-efficient advanced building technologies, life-cycle costs for the life of the building should be taken into consideration.
- **Energy code requirements not stringent enough:** Energy codes are typically the basis for selecting energy-efficient systems. Current recommendations are not stringent enough for the implementation and encouragement of advanced building technologies.
- **Uncertainty about performance of specific technologies:** This is due to the absence of expertise to perform the necessary studies and analyses to investigate specific design strategies and their effect on building performance. The integration of design analysis especially for the advanced building technologies is important to ensure their design performance.
- **Climate specific design approach:** As there are certain strategies that would apply to certain types of climate, considerations of climate-responsive advanced building technologies are also important.

To overcome these barriers, the following recommendations can be considered:

- **Use of performance analysis, energy modeling and simulations during the design process to understand and quantify performance of different design strategies, and inform design:** The study of advanced building technologies, materials, high-performance buildings, renewable energy sources and computational design is very important to ensure the true performance of the energy-efficient advanced building technologies.
- **Development of guidelines for adoption of advanced building technologies:** The development of climate and building-type specific guideline would be a great help for the design industry, especially for firms and organizations that do not have specialized research departments. For example, ASHRAE has started developing such guidelines almost ten years ago to achieve 30% energy reductions (ASHRAE 2004; 2006; ASHRAE 2008). Also, new sets of guidelines for 50% energy reductions have been developed (ASHRAE 2011a; ASHRAE 2011b; ASHRAE 2012). But ASHRAE guidelines are limited to hospitals, commercial building types and schools. More design guidelines need to be developed addressing all climate and building types.

Final conclusions are that implementations of advanced building technologies requires dedicated research and investigations during the design process in order to assess their performance, initial and life-cycle costs, effects on overall energy-efficiency and performance of buildings. Having quantifiable data that evaluate these aspects allows design teams and building owners to make informed decisions regarding implementation of advanced and emerging building technologies. Therefore, practice-based research centers that focus on advanced building technologies and their implementations in architectural projects, improvement of decision-making processes, and systematic investigations of building performance can aid the adoption of advanced, energy-efficient advanced technologies in buildings.

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