# Greater Philadelphia Innovation Cluster: CIMMS[1] Building Integrated Technology Research Roadmap

Task 3: Integrated Technologies
Budget Period One Year-End Deliverable
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[1] Commercial, Institutional, Multifamily, Medium and Small

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## Disclaimer

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# Greater Philadelphia Innovation Cluster: CIMMS Building Integrated Technology Research Roadmap

## The GPIC

Buildings consume approximately 40 percent of all prime energy utilized in the U.S. and 70 percent of all electricity generated. On February 1, 2011 the Greater Philadelphia Innovation Cluster (GPIC) for Energy Efficient Buildings was established as an Energy Regional Innovation Cluster (E-RIC), with funding from four federal agencies and the Commonwealth of Pennsylvania. The E-RIC concept demonstrates a departure from the silo approach of federal agencies in favor of a coordinated intergovernmental attack on the nation's energy and economic problems. The GPIC focuses on developing systems-based approaches to designing, renovating, and operating commercial and institutional buildings. The GPIC integrates its work into a broader regional economic development initiative by linking results with complementary federal, state, local and private sector investments in business development and support, public infrastructure, workforce development, and education focusing on a ten county region surrounding Philadelphia, Pennsylvania.

The strategic focus of the GPIC is on full-spectrum[2] retrofit of existing average size commercial, institutional and multi-family buildings. The goals of the GPIC are to:

1. Demonstrate transformative integrated building retrofit solutions and methods;
2. Improve design tools, building systems, public policies, market incentives, and workforce skills needed to achieve a 50% reduction of energy use in buildings;
3. Improve indoor air quality; and
4. Stimulate private investment and quality job creation in greater Philadelphia and beyond.

The headquarters location for the GPIC is the Navy Yard in Philadelphia, one of the nation's largest and most dynamic redevelopment opportunities. The 1,200 acre Navy Yard includes 270 existing and new buildings that can be utilized as test beds, and an independent unregulated micro-grid being developed as a resource for development and demonstration of smart-grid technologies. The GPIC comprises 24 members including eleven prestigious universities, two DOE laboratories, six global corporations, economic development agencies, and community and technical colleges.

According to President Obama, "*Making our buildings more energy-efficient is one of the fastest, easiest and cheapest ways to save money, combat pollution and create jobs right here in the United States of America.*[3]"

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[2] The National Academy of Science, National Academy of Engineering and National Research Council report Real Prospects for Energy Efficiency in the United States, projected that a 5.9 Quad energy savings (from reduced electricity and natural gas use) could be achieved by 2020, and 9.5 Quads by 2030, from a full spectrum of retrofits (a 30% and 50% reduction, respectively, from current levels) to the existing commercial building stock.

[3] These remarks were made on February 3, 2011 when the President and Secretary Chu announced DOE's Greater Philadelphia Innovation Cluster for Building Energy Efficiency (GPIC) located at the Philadelphia Navy Yard.

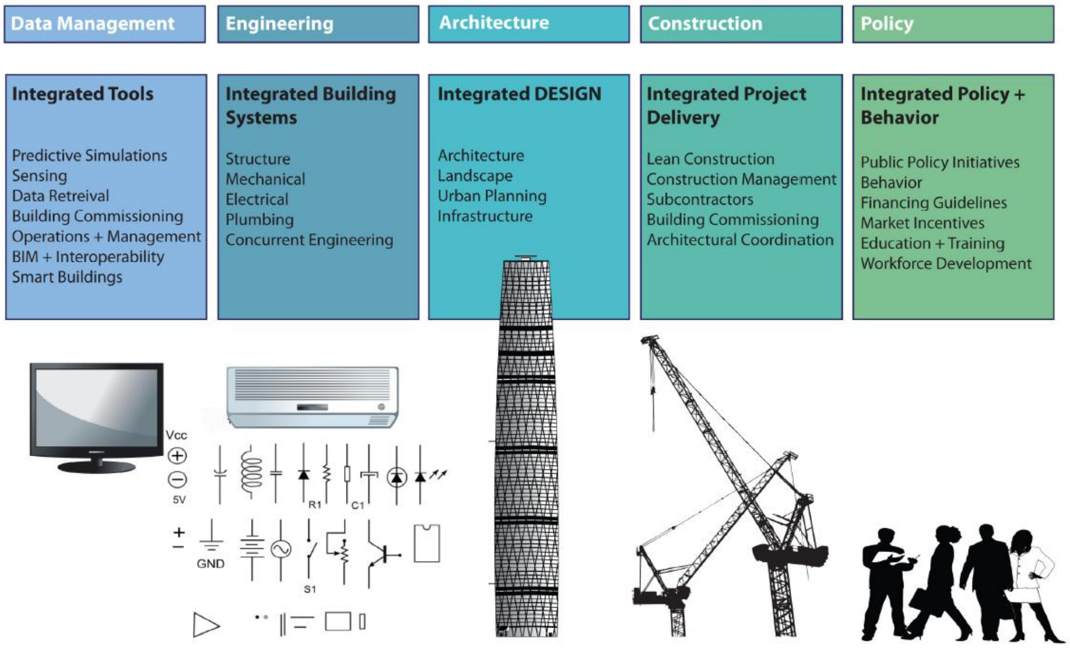

**Figure 1 Integrated Practice**[4]

Figure 1 was developed by the GPIC Policy, Markets and Behavior task team to conceptualize the integrated design process applied to retrofit buildings in the GPIC region. The degree of applicability of the process to a specific energy retrofit task at hand will depend on building and project specifics. The GPIC is developing solutions to the problem facing adoption of full spectrum energy retrofits, the multi-faceted plan of attack to transform a fragmented market, ineffective modeling tools and approaches, and discrete technology offerings into an integrated design approach to deliver results. Applying integrated systems methods to building energy retrofits requires:

1. finding new cost effective means of assessing buildings
2. applying state-of-the-art building components and systems differently
3. changing public policies to eliminate barriers and stimulate business
4. educating the industry, building owners and policy makers to eliminate market barriers and to value energy efficiency
5. training the next generation of energy workers
6. unleashing market mechanisms to deliver energy efficiency value propositions

This research roadmap is focused on conducting research using existing and state-of-the-art building components and systems in an integrated fashion whose results will support Figure 1 Integrated Practice Data Management and Engineering and specifically items 1 and 2 listed above, while understanding and collaborating with the other GPIC efforts[5] focusing on elements 3-6 above. The focus on ten counties, integrated technology solutions and holistic approach to the market distinguishes the GPIC from any prior effort in the commercial, institutional and multi-family building sector.

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[4] Preliminary Roadmap for the successful deployment of Integrated Design Practices tailored for the Retrofit of Buildings in the GPIC 10 County Region, Subtask 4.1 Budget Period 1 Preliminary Report

[5] GPIC Task Groups focus: 1) management, 2) tools for integrated design, 3) integrated technologies and systems, 4) policy, markets, and behavior, 5) education and workforce development, 6) commercialization and deployment, 7) collaborative demonstrations.

To best understand the scope of this Roadmap it is necessary to understand the nature of the research contemplated over the ensuing four years. The research can be classified in two broad areas:

1. building energy modeling algorithm validation and in-the-loop feedback mechanisms
2. test and validation of economics and performance of integrated building technology scenarios by strategic vertical building market segments

The technology research (focusing on existing building stock under 100,000 ft$^2$) can commence immediately and independently of any integrated delivery process as the primary issue in the early years is simply a lack of reliable building-level data and integrated technology performance data. This research can be defined as a function of existing building archetypes, building energy models to be verified (improved), and current and state-of-the-art building components to be developed within integrated technologies scenarios for testing. Furthermore, the nature of the GPIC is such that in-the-loop feedback to all the Task Groups[5] is a continuous process.

## Purpose

The purpose of this Integrated Technology Research Roadmap is to support the transformation of commercial / institutional / multi-family building energy efficiency retrofits by providing robust field-verified models and scalable, tested, integrated technology solutions to existing GPIC building stock. Furthermore, the goal of this Roadmap is to demonstrate, in the Philadelphia region, operational energy savings of 50 percent in the 2013-2020 timeframe in a scalable manner across a broad range of building types, while providing good indoor environment.

This Roadmap reflects research and analysis results from the first six months of GPIC effort and was constructed from the perspective of the Integrated Technologies Task Group recognizing that successful building component, sub-system and whole building system retrofits require technology integration, economic payback, ease of assessment, an educated workforce and consumers, and supportive public policies and an integrated design approach to building retrofits.

Integrated technology concepts and methodologies will be developed, tested and demonstrated based on actual building scenarios in consultation with the design community. This measurement and verification work will be integrated with computer design developments to create a mobile assessment platform to provide cost effective and reliable retrofit evaluations for medium sized buildings. Small footprint buildings will likely require the development of prescriptive solutions developed by application type.

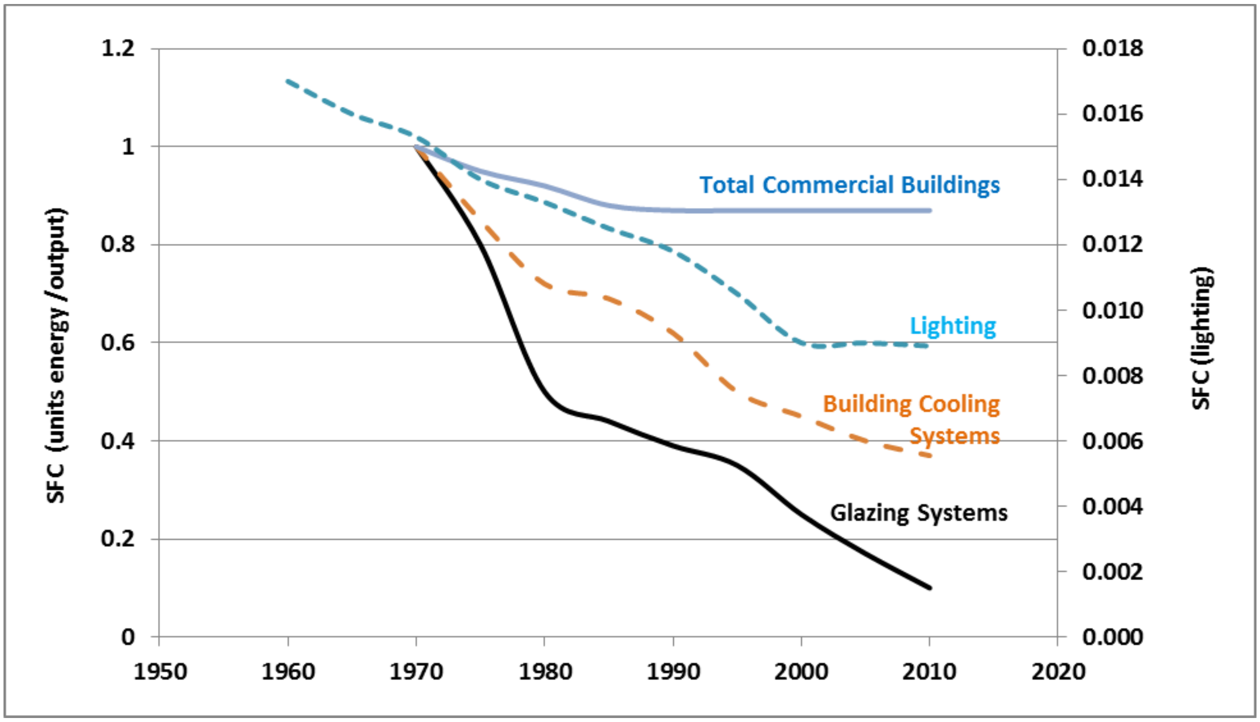

**Figure 2 Specific Fuel Consumption "SFC" of Building Component vs. System Performance Evolution over Time**

State-of-the-art building technologies are all driven by performance standards, public policy incentives and, of course, money. HVAC equipment standards are promulgated by the federal government and require performance of discrete components to be optimized independently at a cost. Likewise, windows, insulation, air and vapor barriers, manual/automatic facades, etc. are all optimized to provide performance to meet component level standards at a cost. Furthermore, building supervisory control systems generally are independently developed from the components they are designed to manage. Currently there are no market drivers that focus building component, subsystem and control manufacturers to optimize their discrete products with respect to integrated building-level design requirements.

Figure 2 represents the core of the technological question this Roadmap seeks to answer. Over the course of the past three decades, specific fuel consumption of building level components and their discrete performance capabilities have significantly improved. Yet, the building stock continues to show minimal energy efficiency improvement. The hypothesis forming the core of this research roadmap focuses on this divergence in component versus integrated system results. The hypothesis this research roadmap specifically addresses is:

> *Medium and small institutional / commercial and multi-family building owners / operators / occupants lack sufficient, reliable and cost-effective information to make optimal energy efficiency decisions leading to full-spectrum energy retrofits over time. Current building retrofit models:*
>
> 1. *do not contain field verified performance algorithms that provide repeatable and reliable results that financial decision makers can use;*

2. *cannot use utility data and spacial information that could be readily available with respect to "as built" designs allowing for fast, accurate and cost-effective assessment; and*
3. *do not have any measured and verified integrated systems approaches to develop into full-spectrum energy efficiency offerings; and re not simple and usable by all practitioners.*

> *If the path defined by this Roadmap provides performance algorithms for models, resolves the issue of building spacial and energy modeling data exchange, measures and verifies the right integrated systems and simplifies the assessment procedures, the adoption of full-spectrum energy retrofits will increase and ultimately become market scalable*[6]*.*

## The Roadmap

The Integrated Technology Research Roadmap is organized around a series of identified technology, verification and operating issues facing the building energy efficiency retrofit industry. The problem statements and matching actions are organized under seven swim lanes, each representing a major issue facing small and medium commercial/institutional building energy use. For each area, performance and economic targets must be established. The problem and action descriptions are concise but also attempt to retain sufficient detail to convey an understanding of their essential intent. Individual actions do not necessarily have the potential to achieve the targets by themselves. In some cases they may build upon each other to achieve the target.

The pictorial overview of the roadmap depicted in Figure 3 provides a limited understanding of the process because it does not convey the extent of system integration that is required. After extensive discussion about the inadequacies of the swim lane visual, it was determined the best way to basically describe the tasks at hand is to couple it with a disclaimer.

> *DISCLAIMER: The diagram in Figure 3 depicts seven swim lanes which are highly interrelated and interactive areas of effort. The overarching emphasis of the technical research depicted in Figure 3 can be summed up in the Integrated Technology swim lane which emphasizes the overall approach touching all the efforts. Furthermore, research results from the seven swim lanes are designed to provide critical performance, economic, and analytical input to the retrofit design process for the Integrated Practice Data Management and Engineering elements contained within* Figure 1*.*

It is very difficult to separate out the integrated technology research required to support the building retrofit market from the policy, market, human behavior, education, workforce training, marketing, commercialization, etc. elements that contribute to market transformation. Also, we have discovered it is impossible to graphically show what we defined in the proposal as "spherical integration."

> *"A radically new form of cooperation and innovation is required to break down institutional, cultural and financial barriers. In particular, to achieve a high level of HUB success, system-driven design and delivery processes (and tools) supported by intellectual property platform that promotes HUB innovation, and industry, policy and*

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[6] This hypothesis assumes successful implementation by the GPIC of the other elements identified on page 5 herein.

> *workforce transformations, are required. "Spherical integration" is the term used to reflect this supreme level of immersion where diverse entities work seamlessly." GPIC HUB Proposal*

The swim lane construct is used to graphically describe the Research Roadmap[7]. The flowchart divides the roadmap into seven strategic issues that are grouped visually by placing them in swim lanes. Each of these issue areas within the roadmap begins with a problem statement which must be solved in order to deliver the energy efficiency goals within the GPIC region. Collectively, solving these strategic problems will deliver the technical solutions to meet the energy efficiency and indoor air quality goals of the GPIC. <u>It should be noted that integrated technology solutions are an important piece of a greater puzzle being solved by the GPIC which also includes improving public policy, market information, education and workforce training, business models and even human behavior.</u>

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[7] Note that considerable discussion surrounded how best to graphically show the research plan and the swim lane graphic was augmented based on the Workshop and retained.

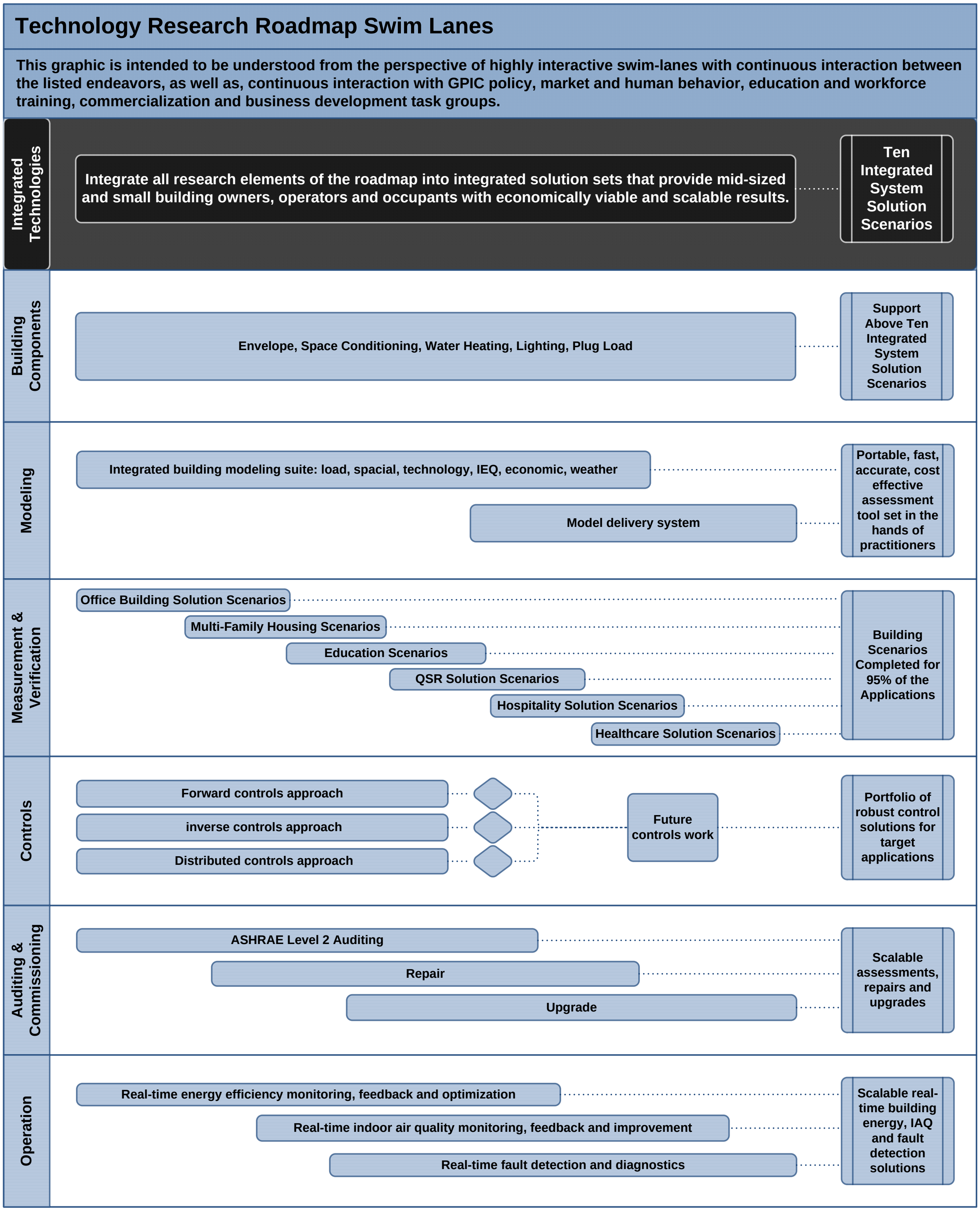

**Figure 3 Technology Roadmap Swim Lane Overview**

## Integrated Technologies

**Problem:** Today, building energy components (walls, roofs, windows, HVAC equipment, sensors, controls, etc.) are generally viewed as discrete elements within a retrofit. This may be influenced by differing useful life cycles, retrofit timing strategies, discretely developed component standards, analysis tools, and a whole host of other influencers. Approaching existing building retrofits holistically, similar to airplane design engineering approaches, focuses on the impact that one component or subsystem upgrade has on the whole system performance. A second and equally important issue is that a discrete change today strategically impacts future energy retrofit design choices. The U.S. Department of Energy (DOE) has invested and continues to invest heavily in development of technologies for improved building energy efficiency. The emphasis of this Roadmap is not on additional technology development but on the delivery of integrated system solutions for buildings by building type. The system performance driven approach to building renovation requires developing subsystem architectures and coordinated, dynamic and adaptive controls to meet internal and envelope loads and producing measurable improvement in the indoor environment, all within a market-acceptable economic model. The systems performance approach requires a radical change in equipment selection wherein selection is based on whole building performance metrics rather than component efficiencies. Achieving significant energy efficiency improvements in existing buildings will require a fundamentally new approach to retrofit design.

**Action 1: Approach existing building retrofits holistically**, similar to airplane design engineering approaches, focused on the impact that one component or subsystem upgrade has on the whole system performance. For example, individual solutions for envelope, lighting, and HVAC systems have not yielded the full results. This action seeks to develop new models, component approach strategies, verified results and tools need to be developed to support this approach.

A near-term effort will provide documentation of innovative materials, components, processes and systems and their performance metrics, from energy to cost-benefits, for high performance renovation projects; both in support of the GPIC Headquarters renovation project known as “Building 661” and for broader applicability in retrofit and new construction in the GPIC region.

**Action 2: Evaluate existing space conditioning and building envelope technologies based on prioritized scalable building scenarios[8].** Evaluate performance and installed cost of integrating existing technologies[9] based on modeled scenarios for pre-existing equipment infrastructure and the prioritized building scenarios. This action seeks to develop successful performance/cost scenario demonstration

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[8] Appendix B includes GPIC assessment of the building stock in the 10-countyregion and the Measurement & Verification swim lane prioritizes building market verticals by potential energy impact.

[9] Based on commercially viable solutions from a variety of existing technologies from the DOE HVAC multiyear plan and major manufacturers in this evaluation effort based on their near-term commercial viability.

reports that will form the basis for case studies, integrated design modeling, retrofit design practices and other market transforming efforts.

A near-term research activity will develop guidelines for highly integrated envelope and HVAC retrofit solutions that are cost effective and can achieve 20-50 percent reductions in energy use for building types that are relevant for the GPIC region. The initial focus for the coming year will be to perform case studies for two office building types: block and curtain wall. This process will be repeated in subsequent years for leveraged building applications as identified by the Policy, Markets and Behavior task group.

A second near-term activity will test the performance of active and passive façade technologies and investigate their integration with lighting, ventilation and thermal systems for retrofit applications.

**Action 3: Develop a long-term "opportunistic" energy planning approach to reach energy savings goals.** The holistic building retrofit approach will focus on component, subsystem whole building interoperability. Many building owners are capital constrained and cannot afford a holistic energy retrofit. Focusing on a strategic planning approach to building energy retrofits recognizing economic life cycles of building components can lead to an "opportunistic" approach to energy retrofits, and may lead to bundled solutions. For example, replacing an aging 10-ton rooftop unit (RTU) with a more efficient 10-ton RTU today may provide a near-term energy efficiency improvement. If new roof insulation is added two years later (coinciding with the roof's useful life) and it drives the building load down to requiring 7 tons of cooling by the new RTU, the HVAC system is now oversized, providing a potential opportunity to upgrade the RTU at the same time and show a strong return on investment. This action seeks to develop a series of opportunistic retrofit plans for targeted prioritized scalable building scenarios.

**Action 4: Work with industry, NGOs and national laboratories that develop component based building energy efficiency solutions for integration as GPIC retrofits.** There are technology roadmaps that exist for many aspects of building technology, like building envelopes, windows, HVAC, solid state lighting, controls and others. This action will develop interactions, complementary strategies and GPIC integrated retrofit demonstrations with organizations focused on improving building components.[10]

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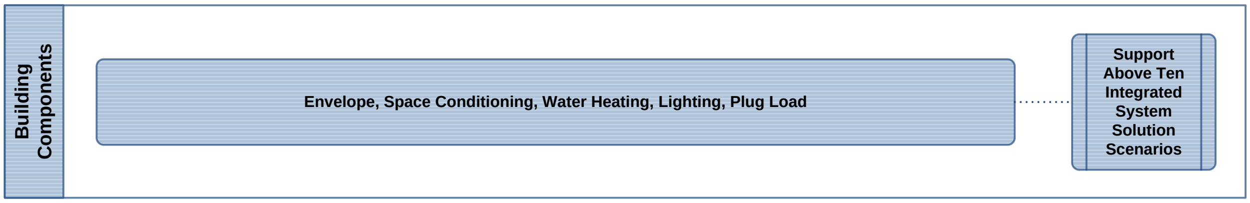
[10] National Labs, ASHRAE, National Institute of Building Sciences, manufacturers etc.

## Building Components



**Problem:** Off-the-shelf component technologies are designed and applied as individual solutions for an integrated building problem. These building components (walls, roofing, glazing, heating, cooling, ventilation, humidity control, air cleaning, lighting, plug loads, etc.) are seldom integrated or system optimized. All GPIC component-level research must focus on integrated solutions that can be applicable within the GPIC region. The actions listed below are to serve as guidance for future research.

**Action 1: Examine passive and active envelope strategies by building construction type and use**. This action evaluates more radical building envelope solutions as enablers to reduce spending on other technologies and increase comfort levels.

Near-term efforts will focus on:
1. Exploring the cost-benefits of value-added roof replacements and quantifying the value of increased R values, reflective surfaces, skylights for day lighting, and rooftop HVAC upgrades, and other performance gains with viable life cycle cost-benefits.
2. Monitoring, evaluating and modeling the thermal properties of various flat roof scenarios to determine the most suitable roofing materials.
3. Developing active elements for a smart insulation system that will reduce HVAC energy consumption through control of wall and attic thermal properties.

**Action 2: Use or create norms for workplace lighting levels to develop of guidelines for fixture replacement economics.** The integrated design aspects of this action are:
- Control systems as enablers, such as timers and occupancy and vacancy sensors;
- Thermal heat load changes that affect the HVAC loading; and
- Lighting system designs may be altered to new norms based on less area lighting.

This is a rapidly evolving field with the economics[11] changing as new technologies achieve greater commercial scale and better price points. This action seeks to develop a series of retrofit design guides incorporating this holistic economic assessment of integrated lighting retrofits.

**Action 3: Evaluate day-lighting, artificial lighting, control systems and window designs; develop retrofit design relationships and demonstration designs for the targeted building population.** Integrated design relationships will be studied and guidelines that optimize the capturing of daylight and the minimizing of both thermal losses and artificial lighting energy use will be developed. Critical performance/economic evaluations by specific cases will be the outcome to determine the retrofit integration efficacy of each element. This action seeks to create retrofit design guidance documents and case studies based on the prioritized scalable building scenarios.

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[11] There are considerable public policy incentives to be incorporated in lighting retrofits which requires considerable interaction to the Policy, Markets and Behavior GPIC Task Group.

A near-term effort will focus on demonstrating a prototype sensor integrated glass unit platform capable of integrating a low-cost, flexible sensor patch with a building-energy-management system. A readout device that is based in the glass unit and that can interface through flexible coupling to the sensor will be developed Wireless communication to BAS may make this viable for existing buildings.

**Action 4: Evaluate high efficiency lighting solutions for integration with DC power buses.** DC power electronic lighting systems are emerging in the market and may play a role in the energy retrofit space. This action seeks to assess energy efficiency and economic viability of lighting integrated with DC power electronics through developing a whitepaper and ultimately through demonstration if warranted.

**Action 5: Study plug load control and sub-metering strategies by building type and energy use.** This action seeks to develop a plug load study to identify actual plug load usage patterns and develop a white paper regarding potential load control strategies. Use of relocatable, open protocol, wireless technology receptacles, including occupancy sensing, may be of use in this study.

**Action 6: Improve indoor air quality (IAQ).**

Indoor air quality (IAQ) plays an important role in the overall quality of building environments. This action seeks to assess[12] technologies that improve IAQ while maintaining or reducing energy consumption.

A near-term effort will develop in-duct ultraviolet germicidal irradiation (UVGI) applications that can improve air quality and reduce HVAC energy use. Design guidance will be developed for selecting and applying integrated indoor air quality management systems that meet or exceed minimum acceptable air quality standards while cost effectively reducing building energy use in retrofit applications. This guidance will be tailored to the building types present in the greater Philadelphia region.

There are some interactions and considerations between alternative IAQ systems and HVAC energy consumption that should be addressed during the retrofit design stage, as they ‘lock in’ fan energy consumption over the subsequent lifetime of the HVAC system. For example, the upfront capital cost of adding space for 6” or 12” air filters rather than standard 2” air filter tracks is dwarfed by the fan energy cost to push air through the thinner (higher resistance) filters over the lifetime of the RTU or AHU as well as the lifecycle cost of the disposable air filters. Similarly, building in a track for gas-phase (odor) filters is cheapest when done during initial design and installation of the RTU or AHU

**Action 7: Incorporate energy scenario strategies into Commercial building domestic hot water (DHW) based planning and testing, where appropriate.** DHW requirements vary widely by end use. DHW energy system approaches will depend on the specific application and end-use. For example, commercial DHW circulating pumps often run continuously to provide “instant” hot water at the faucet. Control schemes or even distributed heating solutions can save a considerable amount of energy. For example, control schemes to optimize system performance based on historical usage patterns and thermal storage to take advantage of Time of Day power pricing. This action seeks to assess DHW systems within the prioritized scalable building scenarios.

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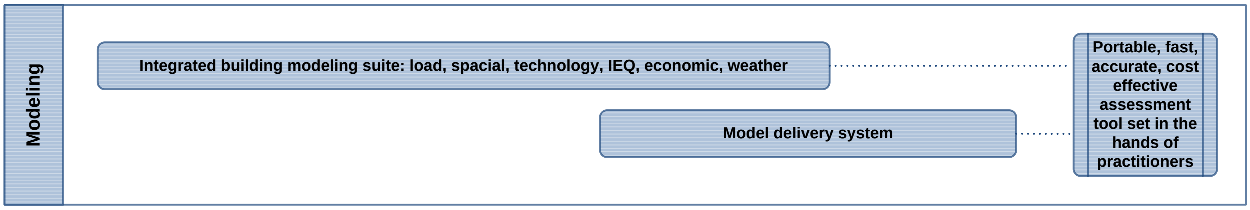
[12] Study, test, measure and verify integrated performance and cost

## Modeling



**Problem:**
There are no publicly available financial-decision-grade modeling programs that can input utility data to calibrate the design model and confirm load profiles. Most building models today are manually iterated to match utility data by changing ventilation air rates, occupancy schedules or similar variables as a curve fitting technique. Furthermore, achieving high performance in building energy retrofits through integrated design means new approaches for which energy data does not exist from individual component manufacturers. If energy data does not exist for these new approaches, then modeling must be used to predict the energy results. Systematic measurement and verification of models on demonstration buildings are needed and envisioned to reduce risk by developing models that are field verified and can link utility data with key spacial information. Of course, models cannot be a substitute for good engineering, but can be designed to reduce variables and risk.

Even when modeling results are available, an interoperability problem exists. Most currently available building load models, design programs, building component specialty models, and building information models are not designed to work with other programs, therefore additional time and money are required for analysis and the chance for error is increased.

Modeling is frequently important in the early stages of assessment of retrofit opportunities and also in the design process. The effectiveness of the current generation of software tools is limited not only by the previously noted lack of interoperability, but also by inability to simulate many emerging energy efficient technologies and by a lack of user-friendliness that discourages their use for reasons of cost. Improvements in all of these areas are needed in order to realize the potential of simulation in design and, ultimately, the goals of low energy use that are at the core of the GPIC mission.

Developing an integrated information exchange among different analytic tools to support rapid analysis of alternatives could increase accuracy of results and reduce assessment time. Making use of new technology like cloud computing could allow for rapid parallel processing, when required, and house up-to-date performance, economic and policy information. One can envision a future where a handheld computer application easily downloads from the cloud a building's “as built” configuration, current operating data, and all current applicable regulations. This new application then guides the engineer or technician through performing the essential building Indoor Environmental Quality (IEQ) assessments. Trustworthy approaches can also be delivered from a maintained centralized database leveraging mobile computing.

**Action 1: Model ideal retrofit practices in energy efficient building design** by defining and describing the discrete stages of the process and determining how various building simulation, design, control, and optimization tools intersect with the design process stages along with the information needed at each stage. This action seeks to formalize the practices of the integrated energy efficient retrofit design and delivery process in a manner that is transferrable from organization to organization.

Near-term efforts will:

1. Develop the information architecture and framework for implementing intelligent workspaces in a high quality digital media environment to facilitate rich interactions with building information models, simulation and analysis tools for integrated teams.
2. Develop the methodology, data and information requirements, and tools to facilitate audits of building energy use and to rapidly estimate energy savings and economic impact of conventional and deep retrofits at the system, individual building and portfolio levels. This will involve the development of an integrated information flow from the energy audit process through the feasibility, energy economic analysis and BIM (Building Information Management) enabled design process for energy retrofits.

**Action 2: Assess, recommend upgrades, and validate existing simulation, design, control, and optimization tools** such as EnergyPlus, CONTAM, Radiance, Modelica, and others at the component, subsystem, and system levels to support decision making throughout the energy efficient building retrofit design process.

Near-term efforts will:

1. Create a series of advanced modules that incorporate the Radiance software operating in a parallel processing mode for the analysis of day lighting and photo sensor-controlled lighting systems, permitting users to analyze annual daylight delivery system performance with complex fenestration systems and shading devices, to determine hourly lighting power levels, energy savings, and photo sensor control system daylight tracking ability for a multitude of system configurations, and to assess occupant visual comfort in these spaces.
2. Enable building simulation programs, such as CONTAMW, TRNSYS, DAYSIM or EnergyPlus, to use higher fidelity airflow and heat transfer models for the design of advanced ventilation systems for building retrofits, such as under floor air distribution, displacement ventilation, hybrid ventilation, and natural ventilation systems.
3. Develop a simplified multizone modeling environment that integrates expert knowledge into the user interface with the goal of producing high-quality models that may be validated and/or calibrated.

**Action 3: Define scalable strategies for hosting validated high performance computational simulation, design, control, and optimization tools** in an open computing environment which is readily and seamlessly accessible by architects, engineers, and other energy efficient retrofit integrated design process participants.

A near-term effort will design a holistic database as opposed to fragmented databases with a common set of desirable data management services to minimize fragmentation and improve interoperability among design, analysis and simulation tools used within and across different phases of the building lifecycle by sharing standardized common data through a platform-mediated loose coupling mechanism.

**Action 4: Develop open standards for the exchange of information** between the simulation, design, control and optimization tools.

A near-term effort will develop an Enterprise Architecture for integrating Building Information Modeling and integrated practice into the building lifecycle process for energy efficient buildings. It will enhance the Integrated Building Lifecycle Process Model (IBLPM) defined within Year One, along with the clear definition of the important information exchanges between key processes. This will provide a foundation for defining the necessary information exchange points, and provide a structure for integrating computational tools and simulations used for design, construction and operations of energy efficient buildings into the IBLPM.

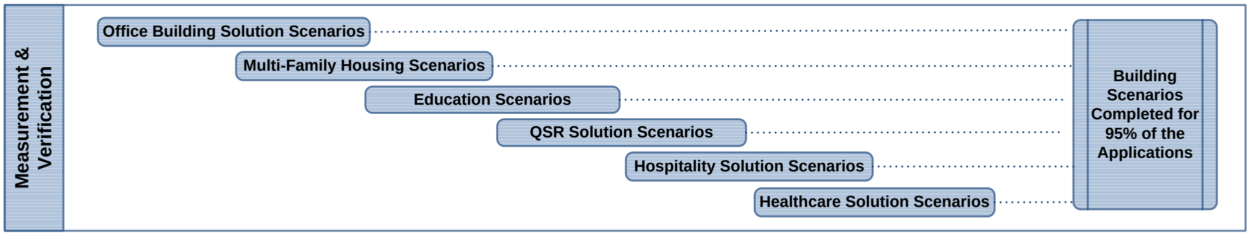
**Action 5: Promote use of upgraded, validated, affordable, and available simulation, design, control, and optimization tools** by architects, engineers, and other energy efficient retrofit integrated design process participants.

Near-term efforts will:

1. Synthesize tools for adaptive HVAC sizing and optimization-based predictive energy management controls, in particular for buildings in urban settings impacted by restricted solar access. Some examples are critical ventilation reset, duct static pressure reset, and dynamic water differential pressure reset. This work will demonstrate the importance of shading and measured irradiance data in reducing building energy usage and provide guidelines as to how to collect and utilize this data in a cost-effective manner.
2. Develop and demonstrate a library of diagnostics decision support tools that can enable cost effective diagnostics solutions for existing buildings. The project teams will initially focus on two select building types: 1) buildings that employ packaged rooftop air conditioners (RTU) and 2) buildings that utilize built-up air-handling units (AHU) with variable-air-volume (VAV). These building types were selected to be representative of the 10-county GPIC region.
3. Prototype and evaluate the use of a methodology and tools for performing rapid uncertainty quantification, sensitivity analysis, and parameter investigations during deep retrofit design, leveraging accessible and affordable high performance computing and cloud infrastructure. Whole building simulation and energy performance models contain thousands of uncertain parameters, many of which have large variability in energy performance estimates.

**Action 6: Create hand held and/or PC-based applications for building energy and IAQ assessment.** This will occur later in the technology roadmap process and would be a multiyear effort with the outcome to be a functioning device in the later years of the project to provide a cost effective means of collecting and assessing relevant building energy retrofit information.

## Measurement and Verification



**Problem:** The existing building stock exists to support its occupants and not serve as a research platform to study building technology integration, verify building energy models, experiment with control schemes or be a test platform for new building component, subsystem and system cost and performance results. Therefore, there is little field data of sufficient fidelity to improve the accuracy of energy models, validate integrated technology performance scenarios, or validate actual costs. Furthermore; integrated design requirements for varying building construction types, uses, age and other factors make some buildings more likely candidates for retrofits. With limited resources, focus must be on the building population that makes up the majority of the building stock. Some applications and building owners may be more ready to change than others and may have stronger economic drivers than others.

**Action 1: Measure and verify performance of full spectrum retrofit scenarios illustrating integrated technology concepts by building construction types and uses.** "The Market for Commercial Property Energy Retrofits in the Philadelphia Region" baseline report[13] conducted by Econsult Corporation and meetings with the Policy, Markets and Behavior Task Group was used as the source of building information to create a set of target building scenarios for integrated retrofit demonstration and validation projects. This action seeks to test, demonstrate, measure and verify repeatable building solutions.

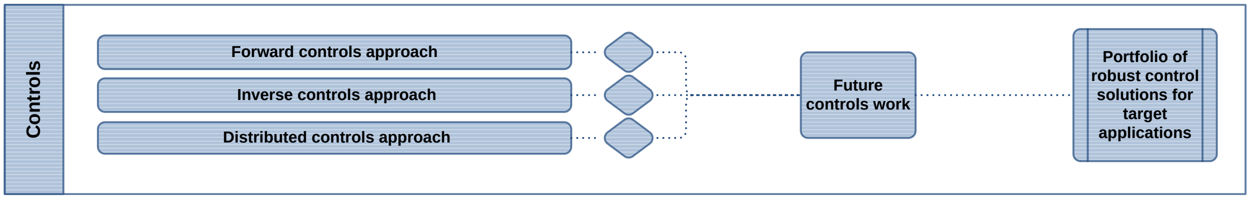
A near-term effort will develop and deploy a database for components, sub-systems, integrated building systems, controls, performance and diagnostic systems including performance, cost, installation, commissioning and operational data to support the research effort of GPIC. The database will provide a single source for public access to retrofit technology and database support for development of new technology, control systems, performance monitoring and diagnostics.

**Action 2: Instrument buildings to validate energy load model.** Three Navy Yard buildings (Buildings 14 101, and 661) are being instrumented as research platforms (office buildings) for purposes of energy and spacial load modeling validation. Further work will be needed to expand to other building design types (e.g. curtain wall structures), as well as, other applications (e.g. medical/surgical – Building 489).

**Action 3: Instrument buildings to validate energy retrofit strategies.** Buildings 101, 489 and eventually 661 are also being instrumented to test cost and performance of energy efficient control system improvements and strategies. Further work will be needed to expand to other building design types (e.g. curtain wall structures), as well as, other applications (e.g. medical/surgical – Building 489).

**Action 4: Instrument buildings to validate operational strategies.** Building 101 will be instrumented to test cost and performance of energy efficient monitoring. Further work will be needed to expand to other building design types (e.g. curtain wall structures), as well as, other applications (e.g. medical/surgical – Building 489).

## Controls



**Problem**: Often, commercial buildings have legacy control systems that do not offer supervisory capability. The building control system may itself be functionally outdated or the building may have been repurposed without upgrading the control system to reflect the changes. A performance gain is possible by updating control systems to enable supervisory capability, intelligent control and compatibility with fault diagnostics. One example would be an overlay of an existing system with a web-based solution with low cost offsite supervisory capability.

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[13] GPIC final report dated November 2011

**Action 1: Evaluate advanced control methodologies and verification strategies**. Assess the deployment of advanced control algorithms for optimal whole-building operation. This includes development of control algorithms based on occupancy, weather, usage profiles, etc. Periodic verification of the control strategies are also required to calibrate their operational efficiencies in the context of varying building conditions. This action seeks to demonstrate performance improvement by deploying advanced control algorithms for optimal whole-building operation. An example would be a continuous, automated verification application utilizing predefined and flexible conditional declarations.

A near-term effort will develop and demonstrate a process, tool and algorithms that will significantly reduce the development and commissioning time/cost to implement advanced building control algorithms for retrofits by automating model and control law generation.

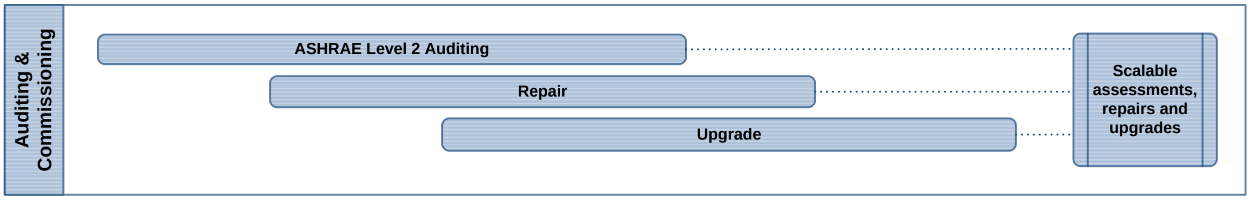
**Action 2: Evaluate open protocol, energy harvesting, wireless sensor systems for integrated remote signals to a central location for control.** Study existing products for capabilities and develop application guidelines for low cost open protocol, energy harvesting, wireless sensor systems. This action will deliver a state-of-the-art report.

**Action 3: Ensure that affordable, open systems with verifiable, robust fault diagnostics are the outcome of demonstration solutions from GPIC.** Test bed will be developed to allow manufacturers to measure and verify prototype solutions that will be specific to medium and small sized commercial buildings. This action seeks to deliver measurement and verification reports.

A near-term effort will develop and demonstrate a library of diagnostics decision support tools that can enable cost effective diagnostics solutions for existing buildings. Whole building diagnostic and decision support tools should robustly maintain building energy performance at an optimal level following commissioning of retrofitted buildings.

**Action 4: Create measured, verified and optimized control strategies by building type/use.** These solutions would be technology specific and range from sophisticated to simplistic based on the need and scope of a building. The emphasis would be on what is the minimum affordable control system that provides a robust solution that can be repeated by building category. Medium sized buildings of various uses would be one class of study topic, but small (<20,000 ft$^2$ for example) buildings should be evaluated for solutions that are more simplistic and affordable. This action contemplates specific controls design guides and approaches. One example would be with a variable speed (built-up) system, real time measurements of airflow and pressure drop across the air filter bank(s) can be used to create a control algorithm to recommend dirty filter change-out that minimize operating fan power consumption and filter life-cycle cost. Annual savings can be on the order of ~15 percent of fan kWh, amounting to a few $100s of dollars per standard 2000 cfm filter opening.

## Auditing and Commissioning



**Problem**: The tendency of many paying the operating bills for commercial buildings is to use custodial or other untrained help wherever possible until a failure occurs that impacts tenants (HVAC system not functioning, etc.). Furthermore there are often split incentives where building owners are not motivated by energy efficiency improvements that cost them capital and only reduce their tenants' operating costs. Consequently, most existing commercial buildings have no-cost, low-cost retro-commissioning opportunities that would save energy and pay for them, however there is no motivation to invest in auditing, retro-commissioning or upgrading.

**Action 1: Develop guidelines by building type and use for conducting retro-commissioning.** Working with local practitioners focusing on ASHRAE Level I, Level II, and Level III analytical methods, this action will identify potential improvements to deliver more accurate, cost effective and/or quicker results.

A near-term effort will develop and demonstrate methods for enabling the implementation of building control systems that can commission and audit themselves via predefined conditional declarations. It will also adapt to varying environmental conditions and changing occupant factors, optimize energy performance, and accommodate the integration of multiple subsystems including on-site power generation, renewables and energy storage.

**Action 2: Develop whole building performance label for the GPIC region.** EPA's Portfolio Manager, DOE's Commercial Building Asset Rating Program, and ASHRAE's Building Energy Quotient labeling program are all focused on developing a clear and consistent means of rating existing building performance. This action will test these approaches and assess each with respect to their efficacy and scalability in the GPIC region.

**Action 3: Create benchmarking references for air leakage rates on existing buildings by construction type and building use.** Poor performers are hard to detect and undermine energy performance. The study will determine what is required to:

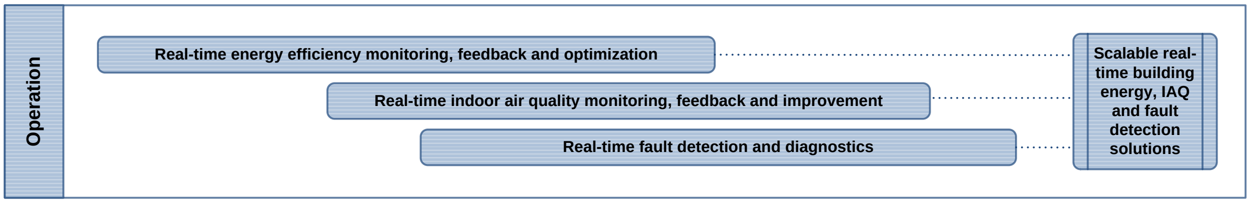
- evaluate and/or develop leakage testing protocols;
- profile target building population for leakage rates;
- set targets for building retrofits by construction type and building use; and
- develop methods for identifying causes and solutions.

This action seeks to identify leak rates and pathways and develop suggested methods for remediating common leak pathways.

**Action 4: Develop tools for field Indoor Environmental Quality assessment** to deliver clear and accurate assessment of the indoor environment and the direct linkage to occupant acceptability.

A near-term effort will refine an existing building evaluation tool (NEAT: National Environmental Assessment Toolkit) to capture building IEQ (Indoor Environmental Quality), and its technical attributes (TABS: Technical Attributes of Building Systems), especially those that may contribute to energy consumption and user satisfaction.

## Operations



**Problem**: Commercial buildings' legacy control systems are known to not maintain performance over time. This can be due to maintenance practices, hysteresis, component failure and lack of diagnostic capability.

**Action 1: Develop a building energy management system** utilizing predefined conditional declarations for optimization based prediction, machine learning, and embedded design and verification techniques to automate fault diagnostics.

**Action 2: Develop GUI and APP interfaces for building operation and occupant feedback utilizing flexible programming declarations perhaps even over a web based browser.** Most small and medium sized buildings do not have trained building energy and/or operations personnel. Deploy a building operation/energy GUI interface to determine its energy reduction potential on a cost per point basis. Develop and deploy a personal APP to influence/measure occupant energy efficiency behavior and garner occupant satisfaction feedback.

**Action 3: Evaluate sub-metering strategies for consistent operation of building systems and provide troubleshooting capability.** Develop practical scenario based solutions to facilitate building operations personnel to systematically trouble shoot excessive loads in a facility. There may be options for retrofits that enable handheld device use or have monitoring installed. Guidelines by building scenarios should be examined.

# APPENDIX A - Documents Referenced in Preparing This Report

1. Advanced Energy Retrofit Guides – Office Buildings, Pacific Northwest National Laboratory and PECI, PNNL-20761, September 2011
2. Advanced Energy Retrofit Guides – Retail Buildings, Pacific Northwest National Laboratory and PECI, September 2011
3. Advanced Sensors and Controls for Building Applications: Market Assessment and Potential R&D Pathways, Brambley, M.R., Haves, P., McDonald, S.C., Tocellini, P., Hansen, D., Holmberg, D.R., Roth, K.W., PNNL-15149, April 2005
4. Building Envelope Technology Roadmap, DOE, May 2001
5. Building Technologies Program Multi-Year Work Plan 2011-2015, U.S. Department of Energy
6. DOE Building Technologies Program Advanced HVAC RD&D Roadmap (DRAFT), 2011
7. Energy Efficiency Guide for Existing Buildings: Technical Implementation, Landsberg, D.R. ASHRAE, 2011
8. Energy Efficiency in Buildings – Heating and Cooling DRAFT, International Energy Agency, 28 January 2011
9. The Energy Impact of Commercial Building Controls and Performance Diagnostics: Market Characterization, Energy Impact of Building Faults and Energy Savings Potential, Roth, K.W., Westphalen, D., Feng, M.Y., Llana, P., Quartararo, L., prepared by TIAX LLC for DOE, November 2005
10. GPIC Expert Workshop Report, Loftness, V., Aziz, A., Lam, K.P., Lee, S., Cochran, E., Leininger, C., Park, J., prepared for DOE, December 2011
11. High-Performance Commercial Buildings – A Technology Roadmap, DOE/GO-102001-1323, June 2001
12. Light Commercial Buildings Roadmap Workshop, co-sponsored by The Department of Energy Building Technologies Program and Oak Ridge National Laboratory, University of California Davis, August 4, 2011
13. The Market for Commercial Property Energy Retrofits in the Philadelphia Region, GPIC Hub Task 4 Report, November 2011
14. Preliminary Roadmap for the Successful Deployment of Integrated Design Practices Tailored for the Retrofit of Buildings in the GPIC 10 County Region, Subtask 4.1 Budget Period 1 Preliminary Report, Trubiana, F., 2011
15. Solid-State Lighting Research and Development: Multi Year Program Plan, DOE, May 2011

## APPENDIX B - Background

The GPIC has identified 9,058 commercial and institutional buildings of interest in the ten county region that are below 100,000 ft$^2$

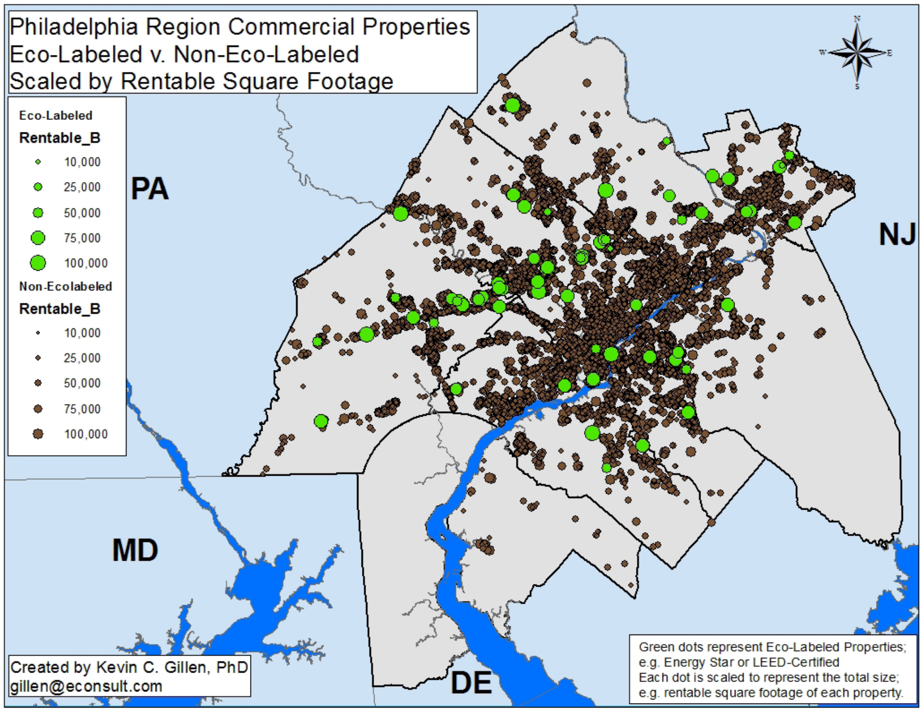


**Figure 4 Ten County Building Data**

Six property-level metrics are being used to as individual building screen to determine likelihood to benefit from an energy retrofit:

- **Age Index:** Older buildings are likelier candidates for improvements.
- **Property Type Index:** Different property types have different levels of energy consumption.
- **Enclosure Index:** Shorter buildings are more cost-effective candidates for improved energy efficiency via improvements to their envelope or enclosure.
- **Materials Index:** Buildings with masonry exteriors, rather than steel and/or glass, are likelier to have more gaps in their envelope and hence benefit from improvements to their exterior.
- **Internal Load Index:** Buildings in which daylight is unable to penetrate to interior spaces must use greater amounts of synthetic light, which increases their energy consumption.
- **Owner-Concentration Index:** Multiple buildings which are owned by a single entity are easier to retrofit for the purely practical reason that it is logistically and legally easier to deal with one owner rather than several.

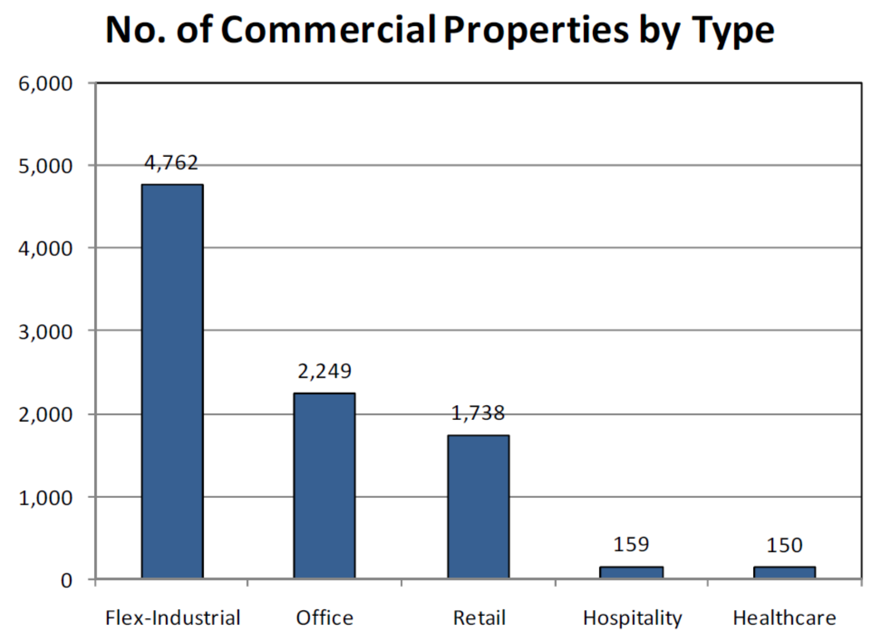


**Figure 5 Ten County Region "Top-5" Building Applications**

A Composite Index was computed as the cross-tabulation of all the previous indices, and hence identifies those properties which qualify as a retrofit candidate in *all* of the indices. Because it is the most stringent of the indices, it is best thought of as index that identifies not just properties that could be considered for a retrofit, but one that identifies the top candidates for a retrofit, since a property must simultaneously meet all of the component criteria for consideration.

The following table summarizes the quantity of properties and square footage in all of the indices, including the Composite Index:

| **Index** | **Pct. Candidates** | **No. of Properties** | **Total Square Footage (000,000)** |
|---|---|---|---|
| Age Index | 77% | 6,962 | 304.0 |
| Property Type Index | 22% | 1,976 | 86.3 |
| Retrofit Index | 79% | 7,138 | 311.6 |
| Owner-Concentration Index | 10% | 877 | 44.9 |
| Composite Index | 3% | 232 | 49.1 |

The Composite Index indicates that three percent of the commercial stock, which includes 877 properties covering nearly 46 million square feet, meets the most rigorous threshold to be considered for a retrofit. They are more than twenty years old, have above-average energy bills, are less than six stories in height, have an envelope that is not steel-and-glass, have below average daylight penetration and are owned by one of the top 25 largest commercial landlords in the region. In addition, it can be inferred that the individual properties are, on average, relatively large in size because even though these properties account for only three percent of the number of total properties in the stock, their area accounts for 12.5 percent of the total square footage in that same stock. Since there are presumably some economies of scale in energy retrofits, this is an additional attribute that makes these properties well-positioned to not only accrue the greatest benefits from a retrofit, but to do so in a relatively cost-effective manner. To gain some further insights on these top candidates, the following map shows their location in the region.

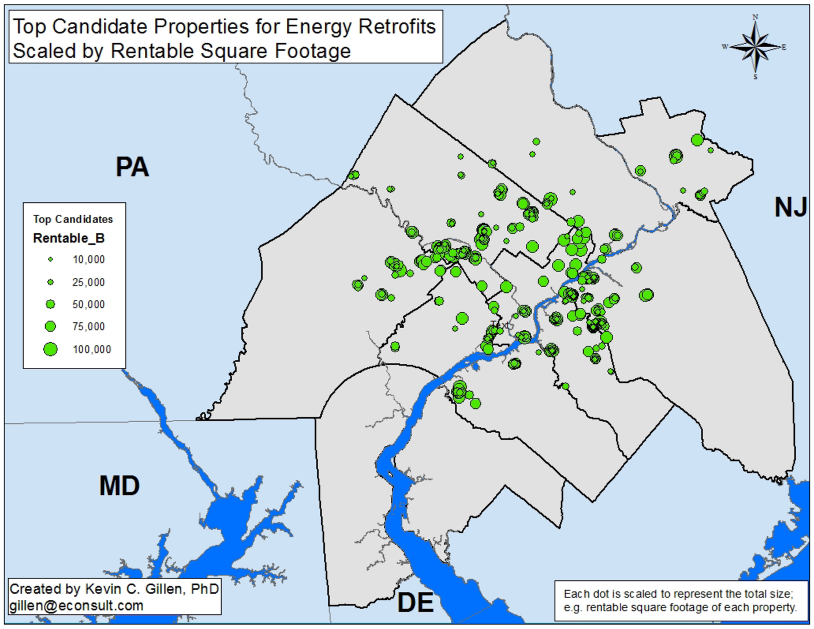


**Figure 6 232 Top Candidate Buildings for Energy Retrofits**

The map indicates that most of these properties are located in the commercial corridors of older, inner-ring suburbs, such as Pennsauken, Valley Forge, Plymouth Meeting, Mount Laurel and Malvern. Some are located in industrial corridors or near transportation hubs such as Thorofare, Bridgeport, Hamilton, Bristol, Northeast Philadelphia, the Navy Yard (appropriately!) and around the Philadelphia International Airport.

## APPENDIX C – Research Roadmap Reviewers

A high-energy and productive process using the research-based techniques[14] of CPSB (Creative Problem Solving Group of Buffalo) formed the basis for the CIMMS (Commercial, Institutional, Multifamily, Medium and Small buildings) Integrated Technology Research Roadmap Workshop sponsored by GPIC on October 18 and 19, 2011. The overall purpose of the CIMMS Integrated Technology Roadmap Workshop was to bring together key technology experts, GPIC area retrofit service delivery experts, policy makers, and national laboratory representatives to examine GPIC's early draft CIMMS Integrated Technology Research Roadmap and help chart GPIC's path forward to realize energy savings for the targeted buildings in the 10-county region of Philadelphia.

The CIMMS Integrated Technology Roadmap Workshop had multiple objectives. The first goal was to identify specific technological solutions, tools, and methodologies to help achieve GPIC's target to demonstrate scalable solutions to improve energy efficiency by 50 percent in existing buildings in the 2015 to 2020 timeframe. A second goal was to identify barriers to achieving the GPIC target, especially those that can be addressed by technology. Third, we reviewed and provided input to refine the CIMMS Integrated Technology Research Roadmap. Fourth, we began the process of having key stakeholders endorse the plan articulated by the integrated technology roadmap. Finally, the workshop helped us to understand ways to keep key stakeholders engaged after the workshop.

The engagement and excellent work of all participants over the course of the 2-day CIMMS Integrated Technology Research Roadmap Workshop provided a substantial start to accelerate GPIC's path forward in pursuit of improving energy efficiency of targeted buildings in the 10-county Philadelphia.

Workshop participants are listed in Table 1.

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[14] Creative Problem Solving by Donald J. Treffinger, Scott G. Isaksen, and K. Brian Dorval

**Table 1 CIMMS Integrated Technology Research Roadmap Workshop Participants**

| Name | Affiliation | Role | email |
|---|---|---|---|
| **Abi Kallushi** | Alliance to Save Energy | Buildings Program Associate | akallushi@ase.org |
| **Aldo Zambetti** | Sheet Metal Workers Local 19 | Training Center Coordinator | azambetti@lu19.com |
| **Andrew Cronin** | KieranTimberlake | Project Architect | acronin@kierantimberlake.com |
| **Anthony Wigglesworth** | Phila Area Labor Mgmt Comm | President | awiggles@palmnet.org |
| **Billie Faircloth** | KieranTimberlake | Research Director | bfaircloth@kierantimberlake.com |
| **Daniel Tisak** | Bala Consulting Engineers, Inc. | Engineering | djt@bala.com |
| **Doug McCleery** | MaGrann Associates | VP of Technical Services | DougMcCleery@magrann.com |
| **Ernest Menold** | Ernest D. Menold Inc. | President | ejmenold@menold.com |
| **Hugh Henderson** | CDH Energy | President | hugh.i.henderson@gmail.com |
| **Janet Milkman** | DVGBC | Exec Director | jmilkman@dvgbc.org |
| **Juliet Whelan** | Jibe Design | CEO | juliet@jibedesign.net |
| **Jeffrey Harris** | Alliance to Save Energy | Senior VP Programs | JHarris@ase.org |
| **Jeremy Leman** | KieranTimberlake | Architectural Designer | jleman@kierantimberlake.com |
| **Jim Yorgey** | Lutron | Technical Applications Manager | jyorgey@lutron.com |
| **Ken Strump** | IAQ Inc | President | iaqinc@comcast.net |
| **Liz Robinson** | Energy Coordinating Agency | Exec Director | lizr@ecasavesenergy.org |
| **Matt Dugan** | DVL Automation | Energy/IEQ  systems design | mdugan@dvla.com |
| **Michael Brambley** | PNNL | Staff Scientist | michael.brambley@pnnl.gov |
| **Patrick Hughes** | ORNL | Director | hughespj1@ornl.gov |
| **Prathib Skandakumaran** | Bayer Material Science | Innovation Manager | Prathib.skandakumarn@bayer.com |
| **Raymond Morris** | Dome Tech | RetroComissioning | r_morris@dome-tech.com |
| **Ray Yourd** | Bayer Material Science | Director Innovation & Characterization | raymond.yourd@bayer.com |
| **Rich Sweetser** | GPIC | T&O Office | rsweetser@exergypartners.com |
| **Rick Baxendell** | GPIC | Roadmap PI | Richard.Baxendell@bayer.com |
| **Scott Lawson** | PHY | Vice President | slawson@phyinc.com |
| **Srinivas Katipamula** | PNNL | | Srinivas.Katipamula@pnl.gov |
| **Stephanie Carlisle** | KieranTimberlake | Researcher | scarlisle@kierantimberlake.com |
| **Thomas Butcher** | BNNL | | butcher@bnl.gov |
| **Tim Wagner** | GPIC | Integrated Technologies PI | wagnertc@utrc.utc.com |
| **Val Patrick** | Bayer Corporation | Sustainability Coordinator | Valerie.patrick@bayer.com |

The CIMMS Integrated Technology Roadmap Workshop assessment teams (Red, Blue and Green) provided sound guidance. Many of the suggestions have been incorporated in the Research Roadmap.

The following summary insights from Identified Advantages and Limitations are included below.

Insights from the Red Team's advantages and limitations were as follows:

- GPIC is an opportunity for job creation and education in the building industry as well as a way to tackle a real part of the GHG emissions challenge (existing buildings which account for 40 percent of GHG emissions in the U.S.).
- It gives credibility to GPIC to take a science-based and integrated approach utilizing existing technology and experience as much as possible and keeping cost-effectiveness in the forefront.
- It also gives credibility to GPIC to identify current technology challenges that need to be addressed such as the need for information exchange between different software packages for energy modeling, the need for easily accessible and actionable information, and the need for affordable instrumentation to understand your buildings' energy performance.
- The primary themes of the limitations identified were how to get building owners to engage, how to provide actionable guidance on how to really do integration, and how to present a credible risk/benefit analysis that included both hard and soft costs and could address the wide variety of building types.

Insights from the Blue Team's advantages and limitations were as follows:

- GPIC's approach is credible because the goal is ambitious, the swim lanes cover most aspects of the building industry transformation that will be needed to achieve the ambitious goal, and the breadth of the target market is both large and accessible.
- GPIC's efforts to make complex modeling tools and systems audits/commissioning accessible to lower the cost of pursuing and achieving the ambitious goal is laudable.
- The primary themes of the limitations identified were that the swim lanes were not adequately depicting the building industry transformation needed; a new modeling paradigm is needed to support this industry transformation, specific triggers for renovation/retrofit/rebuild need to be identified, and need to focus on and supply more specifics on the most critical few system integration goals.

Insights from the Green Team's advantages and limitations were as follows:

- It is good that GPIC has acknowledged the central role that modeling and controls have to play in providing guidance to the best integrated path forward to optimize energy performance. Also appreciate GPIC's recognition of the need for information exchange between modeling tools as well as handheld solutions for modeling.
- GPIC also acknowledges that measurement & verification is critical to building owners developing confidence in modeling and controls.
- Agree with GPIC that integrated systems provide new opportunities for energy savings in buildings.
- The primary themes of the limitations were how to get building owners to take action on improving energy efficiency and how to have viable modeling options available to optimize energy efficiency that is theoretically attainable.

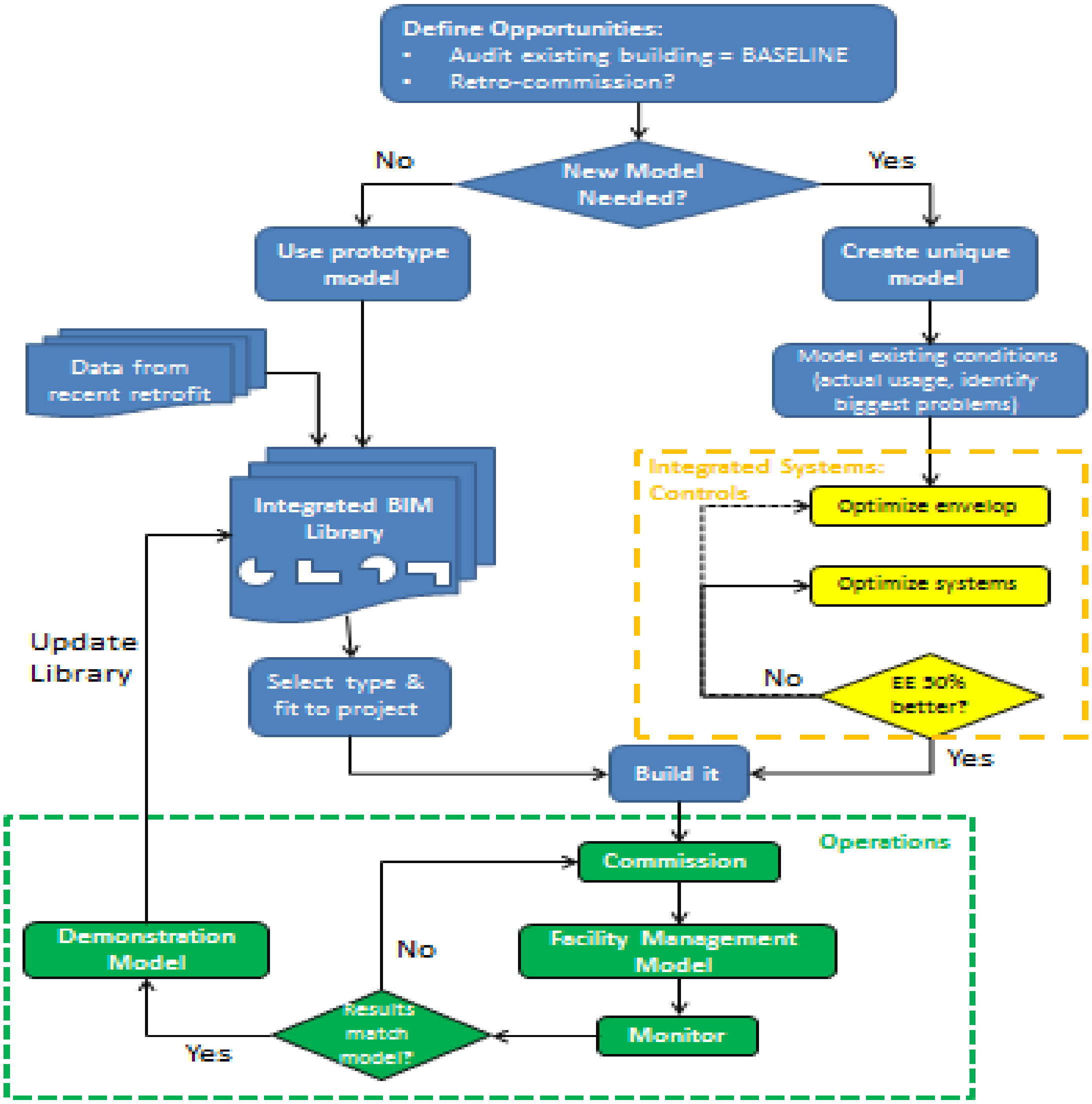

**Figure 7 Building Model Process Flow Diagram**

Figure 7 was recommended by the Blue Team to pictorially represent a forward modeling approach with in-the-loop feedback providing continuous improvement. This graphic is indicative of the forward modeling approach that contained in this Roadmap.

## APPENDIX D – Task 3 Integrated Technology FY2011 Research Projects

This is a list of the GPIC Fiscal Year 2011 study topics. It is arranged by Topic, Research Institution and DOE Deliverable. These can be referenced in the GPIC share point system with 1 page summary reports and full project deliverable reports.

### Subtask 3.1 Integrated Systems

| | Research Project | Institution | DOE Deliverable |
|---|---|---|---|
| **3.1.1** | **Develop innovative user-based controls for energy, IEQ, and robustness** | **Carnegie Mellon University** | **Building 661 Report** |
| **3.1.2** | **Support Charette Building 661** | **Carnegie Mellon University** | **Building 661 Report** |
| **3.1.3** | **Existing energy efficient retrofit solutions, envelopes, lighting and materials.** | **Bayer Material Science** | **Building 661 Report** |
| **3.1.4** | **Evaluation of lighting systems & equipment for Bldg. 661** | **Pennsylvania State University** | **Building 661 Report** |
| **3.1.5** | **On-site power/energy generation and use** | **University of Pittsburgh** | **Building 661 Report** |
| **3.1.6** | **Integration of reconfigurable façade technologies and controllable building subsystems for commercial perimeter zones** | **Purdue University** | **Technology Roadmap** |
| **3.1.7** | **Solid-State (LED/OLED) Lighting for Energy Efficient Buildings** | **Purdue University** | **Technology Roadmap** |
| **3.1.8** | **Hydronic Heating Systems** | **Rutgers University** | **Building 661 Report** |
| **3.1.9** | **Process and tools for exploring and selecting system configurations** | **UTRC** | **Technology Database** |

# Subtask 3.2 Integrated Systems

| | Research Project | Institution | DOE Deliverable |
|---|---|---|---|
| 3.2.1 | Identify performance gaps: envelopes, lighting, and materials having an impact on indoor air quality. | Bayer Material Science | Technology Roadmap |
| 3.2.2 | State of the Art Report for Indoor Environmental Quality (IEQ) Sensors and Sensor Networks | Drexel University | Building 661 Report |
| 3.2.3 | Prototype of hybrid ventilation components to Building 661 | Morgan State Univ.) | Building 661 Report |
| 3.2.4 | Design and performance demonstration of BIPV Systems for Bldg. 661 | Pennsylvania State Univ. | Building 661 Report |
| 3.2.5 | Comparative Study of Glazing Systems Employing Transparent Insulation with those Using BIPV Glazing | Pennsylvania State Univ. | Technology Roadmap |
| 3.2.6 | UV germicidal lamps and demand control ventilation strategies in an air handling system for Bldg. 661. | Pennsylvania State Univ. | Technology Roadmap |
| 3.2.7 | Humidity Management in Buildings Using Microwave Energy | Pennsylvania State Univ. | Technology Roadmap |
| 3.2.8 | Adaptive Insulation for Dynamic Facades | University of Pittsburgh | Technology Roadmap |
| 3.2.9 | Low solar heat gain performance glazings and coatings, dynamic window shading, etc | PPG Industries | Building 661 Report |
| 3.2.10 | Highly sensitive low cost thin-film transistor temperature sensor | Princeton University, | Technology Roadmap |
| 3.2.11 | Analysis and performance evaluation of active building envelope components and dynamic façade elements | Purdue University | Technology Roadmap |
| 3.2.12 | Sensor specifications for T, RH, u, CO2, CO, and smoke sensors (RENAMED) | Rutgers University | Technology Roadmap |
| 3.2.13 | Extended Functionality Adaptive Building Envelope Retro-Fit Solution Development | Rutgers University | Building 661 Report |
| 3.2.14 | Adaptive and Reconfigurable Combined PV and PT systems assessment | Rutgers University | Technology Roadmap |
| 3.2.15 | System and component level design of energy inputs and outputs and recycled energy | Rutgers University | Technology Roadmap |

# Subtask 3.3 Robust Control Systems

| | Research Project | Institution | DOE Deliverable |
|---|---|---|---|
| 3.3.1 | Develop innovative control systems for lighting, thermal conditioning and ventilation as well as plug load management | Carnegie Mellon University | Technology Database |
| 3.3.2 | Develop sensor and data processing framework | Drexel University | Technology Roadmap |
| 3.3.3 | Monitoring and sub-system control through power line | Morgan State University | Technology Roadmap |
| 3.3.4 | Control system requirements, modeling and infrastructure development for Bldg. 661 | Pennsylvania State University | Building 661 Report |
| 3.3.5 | Dynamic control methods | University of Pittsburgh | Technology Roadmap |
| 3.3.6 | Develop an initial framework for evaluating agent-based controls. | Purdue University | Technology Roadmap |
| 3.3.7 | Adaptive/Automated demand response and energy supply chain | Rutgers | Technology Roadmap |
| 3.3.8 | Control requirements and Specification, MATLAB/Simulink Simplified Control Models, MATLAB Tollobox for high fidelity MATLAB/ENERGY+ co-simulation | University of Pennsylvania | Building 661 Report |
| 3.3.9 | Verification requirements for Simulink/STATEFLOW models, verification toolboxes for control design | University of Pennsylvania | Technology Roadmap |
| 3.3.10 | Interfaces for sensors and actuators to the instrumentation network, MATLAB Toolbox for embedded code generation from Simulink control models | University of Pennsylvania | Technology Roadmap |
| 3.3.11 | Deliver control algorithms and simulation-based performance analysis results | UTRC | Building 661 Report |
| 3.3.12 | Reduced-order model-based sensor and actuator placement techniques | Virginia Tech | Building 661 Report |

## Subtask 3.4 Performance Monitoring and Diagnostic Systems

| | Research Project | Institution | DOE Deliverable |
|---|---|---|---|
| 3.4.1 | Develop innovative user-based controls for energy, IEQ, and robustness | CMU | Technology Roadmap |
| 3.4.2 | Initial M&V sensor system design and uncertainty protocol design | Drexel University | Building 661 Report |
| 3.4.3 | Design of the information infrastructure | Rutgers University | Building 661 Report |
| 3.4.4 | Data model for building characteristics, sensors, meters, BMS, energy performance, loads, weather, GHG emission, and other performance metrics | IBM Corporation | Technology Database |
| 3.4.5 | Data warehouse for building characteristics, sensors, meters, BMS, energy performance, loads, weather, GHG emission, and other performance metrics | IBM Corporation | Technology Database |
| 3.4.6 | Dashboard for reporting, visualization, simulation and optimization of building energy performance. | IBM Corporation | Technology Database |
| 3.4.7 | Develop statistical model based tool for anomaly detection and diagnosis | IBM Corporation | Technology Roadmap |
| 3.4.8 | Machine learning algorithms, data mining algorithms and physics based inversion models | IBM Corporation | Technology Roadmap |
| 3.4.9 | Distributed Embedded Diagnostics Techniques & Algorithms for Building Systems. | Morgan State University | Technology Roadmap |
| 3.4.10 | Green roof designs to ascertain energy savings and provide data for decision support. | Morgan State University | Technology Roadmap |
| 3.4.11 | Occupant pattern recognition via integrated sensor network | Morgan State University | Technology Roadmap |
| 3.4.12 | Power for wireless sensors | University of Pittsburgh | Technology Roadmap |
| 3.4.13 | Definition of requirements for flexible large area sensor system retrofit integration | Princeton University | Technology Roadmap |
| 3.4.14 | Develop inverse modeling approaches to enable enhanced monitoring, fault detection, and controls | Purdue University | Technology Roadmap |
| 3.4.15 | Integrated Virtual Sensing and Decision Support for HVAC Equipment | Purdue University | Technology Roadmap |
| 3.4.16 | Building performance metrics and monitoring and diagnostic specification | UTC | Technology Roadmap |