Appendix/Attachments

[According to the FOA, the following material does not count towards page limit]

1-page Resumes attached for the following Team Members:

Letter of Commitment from Cost-Sharing Provider

1-page Letters of Commitment [Partners/End-Users]

Full Appendix F: Technical Potential and Payback Calculation [pp. 15-18]

Leslie K. Norford
Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA 02139
lnorford@mit.edu

Professional preparation

Cornell University, Ithaca, NY	B.S. Engineering Science	1973
Princeton University, Princeton, NJ	M.A.	1982
Princeton University	Ph.D. Mechanical and Aerospace Engineering	1984
Princeton University	Lecturer, postdoctoral associate & research staff	1984-1988

National service

U.S. Navy/ U.S. Department of Energy	Nuclear power engineer	1974-1979

Appointments

George Macomber (1948) Professor in Construction Management	2014-
Professor of Building Technology, Department of Architecture, MIT	2003-
Associate Professor of Building Technology with tenure, Dept. of Arch., MIT	1996-2003
Thomas D. and Virginia W. Cabot Career Development Professorship	1995-1998
Associate Professor of Building Technology without tenure, Dept. of Arch., MIT	1993-1996
Assistant Professor of Building Technology, Dept. of Architecture, MIT	1988-1993
Nuclear power engineer, U.S. Navy/U.S. Department of Energy	1974-1979

Patents

Leeb, S.B., L.K. Norford, J.J. Cooley and A.-T. Avestruz. Fluorescent lamp with integral proximity sensor for building energy management U.S. patent 7,923,936. April 12, 2011

Selected relevant publications

1. Kim, Y.-J., D.H. Blum, N. Xu, L. Su and L.K. Norford. Technologies and magnitude of ancillary services provided by commercial buildings. *Proceedings of the IEEE.* 104(4) April 2016 758-779.
2. Blum, D.H., N. Xu and L.K. Norford. A novel multi-market optimization problem for commercial HVAC systems providing ancillary services using multi-zone inverse comprehensive room transfer functions. *Science and Technology for the Built Environment* Vol 22 2016, Issue 6 783-797
3. Zakula, T., L. Norford and P. Armstrong. Advanced cooling technology with thermally activated building surfaces and model predictive control. *Energy and Buildings* 86 (2015) 640-650
4. Gayeski, N.T., P.R. Armstrong and L.K. Norford. 2012. Predictive cooling of thermo-active building systems with low-lift chillers. *HVAC&R Research* 18(5):858-873.
5. Zakula, T., P.R. Armstrong and L.K. Norford. 2012. Optimal coordination of heat pump compressor and fan speed and subcooling over a wide range of loads and conditions. *HVAC&R Research* 18(6):1153-1167

Research interests

Field studies of energy use in buildings; control of space-conditioning equipment; energy conservation strategies; advanced electric metering; energy and lighting simulation; building ventilation, interactions of buildings with the urban environment and with electricity distribution systems.

Michael C. Caramanis
Professor of Mechanical and Systems Engineering, Boston University, College of Engineering
mcaraman@bu.edu

Education, Teaching and Research: Education *BS* (1971), Chemical Engineering, Stanford University; *MS* (1972), *PhD* (1976), Engineering, Harvard University; Courses Stochastic Dynamic Control, Sustainable Power Systems; Research Decomposition approaches to the planning and scheduling of complex stochastic systems; Decentralized control under distributed decision making and centrally supervised horizontal and vertical coordination. Power market design. Spatiotemporal marginal costing of network distributed commodities.
Employment History: 1983-today Boston University; 2004-2008 (while on leave from Boston University) President, Greek Regulatory Authority for Energy, and Chair, Investment Group, Energy Charter (Brussels); 1979-1982 Deputy Manager Utility Systems Program, M.I.T. Energy Laboratory; 1976-79 National Energy Council, Ministry of Coordination and Planning, Athens, Greece, Deputy Director of Scientific Secretariat; Industrial Collaboration/ Consulting: Pratt and Whitney, UTC; Tyco Electronics, MA/COM corp.; Solectron Inc.; G.E.; Analog Devices; Lucent Technologies, National Grid Company U.K., Day Ahead Power market design; Endessa Power Company, Madrid Spain, 1998, evaluation of real time market impact; Consolidated Edison of NY, 1993-2000, Real time Pricing Experiment design; Excelergy Inc., Italian Independent System Operators (GME and GRTN), 2001-2003.
Research Awards: EPRI, $1.2M development of the EGEAS software. 1979-82; US DoE and NY State ERDA $200K on Marginal Wheeling Costs. 1985-89; NSF $400K Manufacturing Systems Design 1987-1989; NSF $600K Strategic Manufacturing Initiative I 1989-1992; $600K Strategic Manufacturing Initiative II 1993-1997; NSF $1.16M KDI 1998-2002, NSF $350K Planning, Coordination, and Control of Supply Chains 2003-2007; NSF EFRI SEED award, $2M. Smart Microgrid Enabled Buildings Interacting with Utility-Side-of-the-Meter Electricity Markets, 2010-2014; ARPA-E award on Topology Control, $3M, 2013-2016. NSF on distribution network reconfiguration, $300K, 2017-2021; SLOAN Foundation, Economics of Distribution Networks, $500K, Sept 2017, August 2019.
Selected Publications
M. Caramanis, R. Bohn and F. Schweppe, "Optimal Spot Pricing: Practice and Theory"; IEEE Tr. on PAS, Vol. PAS-101, No. 9, pp. 3234-3245, September 1982.
J. M. Foster, M. C. Caramanis “Optimal Power Market Participation of Plug-In EVs Pooled by Distribution Feeder” IEEE TPS, Vol. 28, No. 3, pp. 2065-2076, August, 2013
P. A. Ruiz, J. M. Foster, A. Rudkevich and M. C. Caramanis, “Tractable transmission topology control using sensitivity analysis,” IEEE TPS, vol. 27, no. 3, 2012, pp. 1550 – 1559.
E. Bilgin, M. Caramanis, I. Paschalidis, and C. Cassandras, “Provision of Regulation Service by Smart Buildings” IEEE Transactions on Smart Grid, Vol. 7, No. 3, pp. 1683-1693, 2016.
M. Caramanis, E. Ntakou , W. Hogan, A. Chakrabortty and J. Schoene, “Co-Optimization of Power and Reserves in Dynamic T&D Power Markets with Non-Dispatchable Renewable Generation and Distributed Energy Resources” The Proceedings of IEEE, Vol. 104, No. 4, pp. 807-836, April 2016
J. Baillieul, M. Caramanis, M. Ilic “Control Challenges in Microgrids and the Role of Energy-Efficient Buildings” The Proceedings of IEEE, Vol. 104, No. 4, pp. 692-696, April 2016
F. Babonneau, M. Caramanis, Alain Haurie, “A linear programming model for power distribution with demand”, Applied Energy, 181 pp. 83–95, 2016.

Panagiotis Andrianesis
Postdoctoral Associate, Division of Systems Engineering, Boston University
Email: panosa@bu.edu

Education and Training: *Ph.D. in Operations Research*: Department of Mechanical Engineering (Mech. Eng. Dpt.), University of Thessaly (UTh), Volos, Greece (GR); topic: Analysis and Evaluation of Pricing Mechanisms in Markets with Non-Convexities with Reference to Electricity Markets; advisor: Prof. G. Liberopoulos; 2016. *M.Sc. in Production Management*: Mech. Eng. Dpt., UTh, 2011 (GPA: 9.3/10, 1st in class). *Diploma in Electrical and Computer Engineering*: School of Electrical & Computer Engineering, National Technical University of Athens, GR, 2010 (GPA: 9.63/10, 5th in class). *B.Sc. in Economics*: National and Kapodistrian University of Athens, GR, 2004 (GPA: 8.5/10, 1st in class). *Languages*: English (excellent), French (excellent), German (basic), Greek (native). *Software & Tools*: AMPL, GAMS, ILOG/CPLEX, AIMMS, DELPHI, C/C++, Matlab, Mathematica, SPSS, OpenDSS, Gridlab-D.

Employment History: *Boston University*, Division of Systems Engineering (2017-present): Postdoctoral Associate; Principal researcher SLOAN Foundation Grant “Electricity Distribution Network Economics”; affiliated with Information Data Science (IDS) Research Group, ECE. *University of Thessaly*, Department of Mech. Engineering, Production Management Lab (2007-2017): Researcher, Research Associate, TA; Projects: Greek Regulatory Authority for Energy (RAE) (2007-2008) “Investigation of the Interaction between the Energy and Reserves Markets”; Electricity Authority of Cyprus (2012-2017), “Development of a mathematical optimization model and a decision support system for solving the problem of unit commitment and dispatch”; Computer Data Intl. Co. (2012-2016) & AIMS IT Services (2016-2017), “Development of operations research tools for the optimization of commercial airlines' operational procedures”. *ECCO Intl. Inc.* (2012-2017): Consultant & Research Associate. *RAE*, GR (2011): External Collaborator in Project “Mobile Energy Resources in Grids of Electricity”.

Awards and Honors: State Scholarship Foundation, 2003-2004; Next-to-Best Paper Award, MMET*10 Conf.; 2010 IEEE Antennas & Propagation Society Pre-Doctoral Research Award.

List of Selected Publications:

G. Liberopoulos, P. Andrianesis, "Critical Review of Pricing in Markets with Non-Convex Costs," *Operations Research*, 64 (1), 2016, 17-31.

A. Papalexopoulos, P. Andrianesis, "Performance-based pricing of frequency regulation in electricity markets," *IEEE Trans. Power Systems*, 29 (1), 2014, 441-449.

P. Andrianesis, P. Biskas, G. Liberopoulos,"An overview of Greece's wholesale electricity market with emphasis on ancillary services", *Electric Power Syst. Res*., 81 (8), 2011, 1631-1642.

P. Andrianesis, G. Liberopoulos, G. Kozanidis, A. Papalexopoulos, "Recovery mechanisms in day-ahead electricity markets with non-convexities – Part I: Design and evaluation methodology," *IEEE Trans. Power Systems*, 28 (2), 2013, 960-968; ____ – Part II: Implementation and numerical evaluation," *IEEE Trans. Power Systems*, 28 (2), 2013, 969-977.

P. Andrianesis, G. Liberopoulos, "The "hidden cost" of renewable energy sources in electricity pool markets," *Proc. EEM '12*, Florence, Italy, 2012.

P. Andrianesis, G. Liberopoulos, C. Varnavas, "The impact of wind generation on isolated power systems: The case of Cyprus," *Proc. IEEE PowerTech 2013*, Grenoble, France.

P. Andrianesis, A. Papalexopoulos, S. Papathanassiou, "Energy Control Centers and Electricity Markets in the Greek Non Interconnected Islands," *Proc. MEDPOWER 2014*, Athens, Greece.

P. Andrianesis, M. Caramanis, “Optimal Grid Operation and DER Dispatch in Active Electricity Distribution Networks,” *23rd ISMP*, Bordeaux, France, 1-6 July 2018.

Brian C. Beauregard

Superintendent – Electric Division City of Holyoke Gas & Electric Department

Education and Training

- M.B.A., September 1999, Western New England University, Springfield MA
- M.S. Electrical Engineering (Power Systems), May 1996, Worcester Polytechnic Institute, Worcester MA
- B.S. Electrical Engineering, May 1992, Worcester Polytechnic Institute, Worcester, MA

Employment History

Electric Division Superintendent –Holyoke Gas & Electric, Holyoke, MA ▪ May 1999 – Present

Manage overall electric areas including production, transmission, distribution, metering, power supply and operations.

Electric Division Assistant Superintendent –Holyoke Gas & Electric, Holyoke, MA ▪ July 1996 – April 1999

Direct charge of Electric Production and Electric Distribution divisions, backup to Superintendent for the Electric Operation division, and founder/head of a new Telecommunications division.

Senior Electrical Engineer/Electrical Distribution Engineer –Holyoke Gas & Electric, Holyoke, MA ▪ January 1995 – June 1996

Plans, designs and supervises the installation of all types of electric utility distribution (primary, secondary, lighting) and sub-transmission systems.

Junior Electrical Engineer –Holyoke Gas & Electric, Holyoke, MA ▪ May 1992 – December 1994

Responsible for overseeing automated mapping facilities management system, updating standard operating procedures and rules & regulations, and developing switching orders. Plans and designs the installation of all types of electric utility distribution systems at the direction of the Senior Electrical Engineer.

Cadet Engineer –Holyoke Gas & Electric, Holyoke, MA ▪ May 1989 – April 1992

Recorded foreman’s reports, updated blueprints, digitized maps, performed dig safe markings and conducted projects for both Gas & Electric Divisions.

Sarah LaRose
Project Engineer
City of Holyoke Gas & Electric Department
slarose@hged.com

Education and Training
- B.S. Environmental Engineering, May 2011, Rensselaer Polytechnic Institute, Troy, NY
- MBA, May 2018, University of Massachusetts, Amherst, MA

Employment History
Holyoke Gas & Electric ▪ Holyoke, MA ▪ June 2007 – Present
Project Engineer ▪ July 2011 – Present
- Involved in various renewable energy development and compliance projects
- Oversaw permitting and construction of a communications tower
- Ensure hydro system compliance to FERC License requirements
- Involved in the design and permitting activities for a fish exclusion rack at hydro facility
- Permitted and oversaw a hydrokinetic demonstration in Holyoke Canal System
- Oversaw the FERC relicensing process of three small hydro units
- Managed the design and construction of an indoor switchgear enclosure
- Conducted feasibility analyses of various hydroelectric projects
- Coordinate various clean energy, energy efficiency and smart grid demonstration projects
- Support various project permitting efforts

Cadet Engineer ▪ June 2007 – January 2011
- Involved in pre-permitting and planning activities for a wind energy development project
- Developed permit applications for various utility scale solar facilities
- Supported the analysis of LED roadway light retrofits
- Experience with Microsoft Office Suites: Word, Excel, Power Point &Access

Commissioners:
Francis J. Hoey, III
Robert H. Griffin
James A. Sutter
Manager:
James M. Lavelle

August 14, 2018

Michael C. Caramanis, Professor
Boston University, College of Engineering
Mechanical and Systems Engineering
110 Cummington Mall
Boston, MA 02215

REF: MIT-BU proposal titled: Adaptation of Building Demand Response to Spatiotemporal Marginal Costs on Distribution Networks. Control number: 1825-1781. In Response to Department of Energy DE-FOA-0001825, Building Energy Efficiency Frontiers & Innovation Technologies BENEFIT) -2018, Research Performance Period: April 1, 2019 to March 31, 2022.

Dear Professor Caramanis,

The City of Holyoke Gas & Electric Department (HG&E) would like to express its support for your proposal in collaboration with MIT Professor Leslie Norford to the Department of Energy on Advanced Building demand response guided by dynamic distribution network marginal costs.

HG&E is a municipal utility serving electric, gas and telecom services to over 18,000 customers. Our mission is to provide competitive rates, reliable service and excellent customer service. Our retail electricity sales are on average 95% carbon free, with about 70% coming entirely from renewable sources of generation located directly within Holyoke, MA. HG&E remains vertically integrated and as such offers the capability of analyzing effects to Distribution, Transmission, Generation and the end users within the interconnected electric system.

Given our high penetration of intermittent renewable generators in the City and our strong commitment to a carbon free future with no compromise on the reliability of supply, we are particularly interested in your proposed residential and commercial space conditioning demand response framework that takes into consideration actual distribution network marginal costs. We are also keenly interested in understanding the costs and benefits associated with optimal operational response of Distributed Energy Resources (DERs) in general and smart thermostats/space condition management systems in particular. We share your opinion that modern efficient heat-pump-based space conditioning technology has storage-like capabilities and degrees of freedom, which, while complex to control in the absence of detailed HVAC modeling, are capable of internalizing and optimizing social distribution-system-wide costs and benefits. Given the importance of storage in a future where renewable generation will dominate, HG&E is interested in exploring storage-like time shifting demand response offered by options that promise more economically efficient and environmentally friendlier contributions compared to batteries and other competitive explicit storage technologies.

City of Holyoke Gas & Electric Department
99 Suffolk Street • Holyoke, MA 01040-5082
Tel: 413.536.9300 • Fax: 413.536.9315
Web: www.hged.com, www.hge.net

To this end, should your proposal be funded, HG&E will be happy to assist by assigning Sarah LaRose, Project Engineer, as the lead contact person who will be invited to your meetings and have access to your reports and publications. Through Ms. LaRose, the HG&E project team will follow up on your findings, evaluate your results, share them with our staff and provide advice that reflects salient practical issues from a technical, regulatory and business point of view. We will also be happy to provide data representing HG&E distribution feeder electrical properties and actual load data which we monitor on a short interval basis. Additionally, I would be happy to make myself personally available to assist in the above mentioned collaboration.

As HG&E envisions this work, Ms. LaRose and a team of HG&E engineers would be available for at least two days in aggregate each month (twenty-four days per year) and I would be available to provide oversight on HG&E's end for at least four days each year over the three year period that the project is expected to run. Based on rates inclusive of fringe benefits and overhead of $750 per day for Ms. LaRose and HG&E engineers, and $1,200 per day for myself, we estimate the value of support to this project to be $22,800 per year, or $68,400 over the three year performance period. Additionally, we will consider a proposal by your research team to provide our customers connected on selected feeders with advanced HVAC control software and communication tools. We of course understand that data confidentiality will be protected by two way non-disclosure agreements as needed.

If you have any questions, please contact me at (413) 536-9352 or by email at bbeauregard@hged.com.

Sincerely,

Brian C Beauregard

Brian C. Beauregard
Superintendent – Electric Division

KGS BUILDINGS

Control Number: 1825-1781

66 Union Square, Suite 300
Somerville, MA 02143

August 8th, 2018

Prof. Leslie K. Norford
Department of Architecture
Massachusetts Institute of Technology

Dear Prof. Norford:

KGS Buildings (KGS) is very interested in your proposal, "Adaptation of Building Demand Response to Spatiotemporal Marginal Costs on Distribution Networks," to the DOE BENEFIT-2018 program and enthusiastically accepts your invitation to participate in the project monitoring committee if the proposal is selected for funding.

KGS is a cloud-based building performance analytics company providing automated intelligence for smarter facility management. KGS offers its flagship software, Clockworks™, to building managers, operators and service providers to deliver energy and cost savings while improving comfort and operations by combining actionable building information and building technologies. KGS has deployed its technology on everything from 60+ building university portfolios to retail stores with five rooftop units. Currently, Clockworks™ provides performance analytics on approximately 140,000 equipment connected in 1,300 buildings in 15 countries.

We believe that the work proposed by MIT and Boston University could have a significant impact. We are familiar with and value MIT's previous laboratory and simulation studies of model-predictive control. To enable cooling equipment to return the most economic value to building occupants, its control must respond to accurate information about utility costs at the distribution grid, which BU's research will identify. This research will provide KGS with information to assess applicability and scalability of such solutions into our existing and potential future client base.

KSG is pleased to commit to membership in the project monitoring committee and understands that this will involve at least two face-to-face meetings each year at MIT, which is a neighbor in Cambridge, MA.

Sincerely,

Nicholas Gayeski, PhD
CEO, KGS Buildings
nick@kgsbuildings.com

Control Number: 1825-1781

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Tel. 617.621.7500 www.merl.com. Fax 617.621.7550

for a greener tomorrow eco Changes

8 August 2018

Prof. Leslie K. Norford
Department of Architecture
Massachusetts Institute of Technology

Dear Prof. Norford:

Mitsubishi Electric Research Laboratories (MERL) is very interested in your DOE BENEFIT-2018 program proposal, titled "Adaptation of Building Demand Response to Spatiotemporal Marginal Costs on Distribution Networks," and enthusiastically accepts your invitation to participate in the project monitoring committee if the proposal is selected for funding.

MERL is Mitsubishi Electric Corporation's North American research and development subsidiary. Its research into multi-physical systems and devices includes modeling and control of Mitsubishi Electric ductless heat pumps, which are known for their energy efficiency and significant market share in the U.S. There is a wealth of opportunity in using the dynamic control of cooling equipment to reduce energy consumption and its associated carbon emissions and, more broadly, to enable smart buildings to more effectively interact with smart grids.

We believe that the work proposed by MIT and Boston University could have a significant impact. We are familiar with and value MIT's previous laboratory and simulation studies of model predictive control, which made use of our cooling equipment. To enable this equipment to return the most economic value to building occupants, its control must respond to accurate information about utility costs at the distribution grid, which BU's research will identify. This work will also provide MERL researchers with the information needed to further develop and assess the benefits of enhanced embedded controls relating to both the equipment operation and the interactions between the equipment and the information from grid operators.

MERL is pleased to commit to membership in the project monitoring committee and understands that this will involve at least two face-to-face meetings each year at MIT, which is a neighbor in Cambridge, MA. We particularly note opportunities to guide your team in state-of-the-art approaches to modeling the dynamics of cooling equipment and buildings using the Modelica Buildings Library, developed at Lawrence Berkeley National Laboratory, which is designed to produce simulation models that can be widely adopted by others.

Sincerely,

Christopher Laughman

Senior Principal Research Staff
Multiphysical Systems & Devices Group
Mitsubishi Electric Research Laboratories
laughman@merl.com

Life Is On | Schneider Electric

August 16, 2018

Prof. Leslie K. Norford
Department of Architecture
Massachusetts Institute of Technology

Dear Prof. Norford:

Schneider Electric is very interested in your proposal, "Adaptation of Building Demand Response to Spatiotemporal Marginal Costs on Distribution Networks," to the DOE BENEFIT-2018 program and enthusiastically accepts your invitation to participate in the project monitoring committee if the proposal is selected for funding.

Schneider Electric is a global corporation that develops hardware, software and services to meet customer needs in energy management and automation. It employs 144,000 employees in about 100 countries. The company is actively developing products and services to support the interaction of smart buildings with a smart electricity grid. Its Wiser Air program has produced a smart thermostat that acts as a home energy management system.

We believe that the work proposed by MIT and Boston University could have a significant impact. To enable cooling equipment to return the most economic value to building occupants, its control must respond to accurate information about utility costs at the distribution grid, which BU's research will identify. MIT's model predictive control algorithms will enable near-optimal customer response to price signals. This research will provide Schneider Electric researchers with the information needed to further develop and assess the benefits of enhanced embedded controls in its products.

Schneider Electric is pleased to commit to membership in the project monitoring committee and understands that this will involve at least two meetings each year at MIT.

Sincerely,

Gary Pollard
Engineering Director
Analytics and Artificial Intelligence
Schneider Electric
gary.pollard@schneider-electric.com

Schneider Electric
8001 Knightdale Blvd
Knightdale, NC 27545
Phone: 919-266-3671

schneider-electric.com

Appendix F. Technical Potential and Payback Calculation

Technical potential

The technical potential for model-predictive control of residential cooling systems as described in this proposal can be estimated with Equation F1 in the FOA:

$$\begin{bmatrix}\text{Primary Energy Savings}\\ \text{Technical Potential}\\ \text{(TBtu)}\end{bmatrix} = \begin{bmatrix}\text{\% Energy Savings}\\ \text{Over Typical New}\\ \text{Technology}\end{bmatrix} x \begin{bmatrix}\text{2030 Energy Market}\\ \text{Size}\\ \text{(TBtu)}\end{bmatrix}$$

Energy savings over typical new technology

The proposed research will use simulations and field measurements to quantify savings of model predictive control in occupied houses under marginal electricity prices that are resolved spatially and temporally for one utility. We can predict savings on the basis of previously performed test-cell measurements and simulations for a related control methodology applied to thermal zones subject to a commercial-building schedule.

The essence of this control methodology is to schedule the operation of cooling equipment to minimize operating cost. The optimal schedule accounts for indoor and outdoor temperatures, cooling load (both of which influence equipment efficiency) and the time-varying electricity cost to the consumer.

Model-predictive control experiments[1] were previously conducted in a single-zone test cell subject to daytime occupancy and controlled to minimize energy consumption and not cost (the electricity rate was assumed to be time-invariant). The tested cooling system adapted a commercial high-efficiency, variable-speed split-system air conditioner to produce chilled water for a concrete-core radiant floor thermos-active building system TABS). Experiments showed savings relative to normal operation of split system (cool air produced by evaporating refrigerant in the indoor unit, scheduled to respond to cooling loads without forecast) of 25% and 19% over a typical summer week in climates associated with Atlanta, GA, and Phoenix, AZ, respectively.

Further simulations[2] extended the comparison to commercial TABS in multiple U.S. climate zones. Relative to a commercial building VAV system operated to maintain indoor temperatures only during occupied periods (i.e., no forecast), savings for five cities (Chicago, Houston, Las Vegas, Miami and Phoenix) over a 22-week summer period (May 1 through September 30) were 44-50%. Relative to the VAV system with pre-cooling, the savings were 15-24%. The difference

[1] Gayeski, N.T., P.R. Armstrong and L.K. Norford. Predictive pre-cooling of thermos-active building systems with low-lift chillers. *HVAC&R Research* 18(5):858-873, 2012.
[2] Zakula, T., L. Norford and P. Armstrong. Advanced cooling technology with thermally activated building surfaces and model predictive control. *Energy and Buildings* 86 (2015) 640-650

suggests that pre-cooling control of the VAV system could produce savings on the order of 25%, without relying on embedding radiant cooling in the floor slab.

Further, MPC control of split-systems was simulated under conditions that matched the experiments conducted in the test cell[3]. MPC applied to the split system was found to achieve higher savings that MPC applied to the TABS system, when measured for sensible cooling only over a summer week: 19% savings (Atlanta) and 11% savings (Phoenix). The same simulation methodology compared MPC for TABS with convention control for the split system, to mimic the experimental work in the test cell reported above; these simulations showed savings of 9% for Atlanta and 10% for Phoenix. As summarized in Table F1, simulations therefore predicted savings of 28% (Atlanta) and 21% (Phoenix) for MPC of a split system relative to conventional control of the same system.

Mapping achieved and simulated energy savings to occupied houses involves considerable uncertainty, which motivates the proposed research. Occupant schedules and control of cooling equipment vary, the equipment itself varies in part-load control and models of the thermal response of occupied houses and of the equipment will likely fall short of lab-grade efforts. According, we estimate savings of 50% of those shown in Table F1, or ~ 12%.

Table F1. Estimated percentage savings for model predictive control of split system air conditioners relative to conventional control, for a simulated summer week in Atlanta and Phoenix

	Energy savings, %	
control	Atlanta	Phoenix
MPC of split system relative to MPC of TABS	19	11
MPC of TABS relative to conventional control of split system	9	10
MPC of split system relative to conventional control of split system	28	21

Energy market size

The following inputs were used in the EERE Baseline Energy Calculator:

1. Projection year — 2030
2. Climate zone — All
3. Building type — All residential
4. End-use — Cooling
5. Fuel type — Electricity
6. Technology — Air source heat pump (electric), central A/C and ground source heat pump

The Baseline Energy Calculator returned a market size of 2.2 Quads primary energy, or 2200 TBtu. Note that the room/window A/C units were excluded as being less compatible with smart thermostats and building-grid interaction, due to their use of an internal thermostat and very low cost. This exclusion reduced the energy market by 0.2 Quads primary energy, from 2.4 to 2.2

[3] Zakula, T. Model predictive control for energy efficient cooling and dehumidification. Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA, June 2013.

Quads. Table F2 expands this calculation to identify energy market by climate zone and type of cooling system.

Table F2. Energy market for residential cooling systems in 2030

	Technology			
Climate zone	Air-source heat pump	Central A/C	Ground-source heat pump	All
1	7	95	2	104
2	20	222	4	247
3	104	360	8	472
4	135	314	7	457
5	176	695	11	881
All	441	1700	33	2173

Primary energy savings

Applying an estimated savings potential of 12% relative to baseline operation and an energy market of 2173 TBtu produces an estimated savings of 261 TBtu or 0.26 Quad of primary energy.

Simple payback

The simple payback calculation is based on an incremental cost of $100 for a smart thermostat, to support sensors and communication needed for price-based control. Following the FOA, the payback calculation is

$$\begin{bmatrix}\text{Simple}\\\text{Payback}\\\text{(Yr)}\end{bmatrix} = \frac{\begin{bmatrix}\text{Unit Cost of}\\\text{Proposed Technology}\\\text{at Scale (\$)}\end{bmatrix} - \begin{bmatrix}\text{Unit Cost of}\\\text{Typical New}\\\text{Technology}\end{bmatrix}}{\begin{bmatrix}\text{Unit Energy Consumed by}\\\text{Typical New Technology}\\\text{Per Year (kWh/Yr)}\end{bmatrix}\begin{bmatrix}\text{Energy cost}\\\text{(\$/kWh)}\end{bmatrix}\begin{bmatrix}\text{\% Energy Savings}\\\text{Over Typical New}\\\text{Technology}\end{bmatrix}}$$

$$= \frac{\begin{bmatrix}\text{Unit Cost of}\\\text{Proposed Smart Thermostat}\\\text{at Scale (\$)}\end{bmatrix} - \begin{bmatrix}\text{Unit Cost of}\\\text{Typical Smart Thermostat}\end{bmatrix}}{\begin{bmatrix}\text{Unit Energy Consumed by}\\\text{Typical Residential A/C}\\\text{Per Year (kWh/Yr)}\end{bmatrix}\begin{bmatrix}\text{Energy cost}\\\text{(\$/kWh)}\end{bmatrix}\begin{bmatrix}\text{\% Energy Savings}\\\text{Over Typical New}\\\text{Technology}\end{bmatrix}}$$

$$= \frac{[\$300] - [\$200]}{\begin{bmatrix}\text{Unit Energy Consumed by} \\ \text{Typical Residential A/C} \\ \text{Per Year (kWh/Yr)}\end{bmatrix}\begin{bmatrix}0.1264 \\ (\$/\text{kWh})\end{bmatrix}[0.12]}$$

The U.S. average house consumed 11,320 kWh of electricity in 2009, with 6.2% devoted to cooling.[4] Using these data,

$$\begin{bmatrix}\text{Simple} \\ \text{Payback} \\ \text{(Yr)}\end{bmatrix} = \frac{[\$300] - [\$200]}{\begin{bmatrix}11{,}320{*}0.062 \\ (\text{kWh/Yr})\end{bmatrix}\begin{bmatrix}0.1264 \\ (\$/\text{kWh})\end{bmatrix}[0.12]} = 9.4 \text{ Years}$$

Houses in Florida Spend $2,000 annually on energy, 90% of which is for electricity.[5] Twenty-seven percent of site energy is used for cooling, four times the national average. Applying that percentage to electricity cost (a reasonable approximation, given the predominance of electricity) yields

$$\begin{bmatrix}\text{Simple} \\ \text{Payback} \\ \text{(Yr)}\end{bmatrix} = \frac{[\$300] - [\$200]}{\begin{bmatrix}2{,}000 \\ (\$/\text{Yr})\end{bmatrix}\begin{bmatrix}0.9 \\ \text{fraction electricity}\end{bmatrix}\begin{bmatrix}0.27 \\ \text{fraction cooling}\end{bmatrix}[0.12]} = 1.7 \text{ Years}$$

These calculations show a shorter payback in houses that use more air conditioning. The payback in Florida is sufficiently short that a larger incremental cost for the proposed technology could remain financially attractive in that state and others with large residential cooling loads.

[4] U.S. Energy Information Agency Today in Energy March 7, 2013
https://www.eia.gov/todayinenergy/detail.php?id=10271
[5] U.S. Energy Information Agency Household Energy Use in Florida
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