

# Energy Efficiency Demonstration

2012 TECHNICAL REPORT



# Energy Efficiency Demonstration

1025437

Final Report, September 2012

EPRI Project Manager  
T. Geist

## **DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES**

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

**EPRI**

## **NOTE**

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail [askepri@epri.com](mailto:askepri@epri.com).

Electric Power Research Institute, EPRI, and TOGETHER...SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

Copyright © 2012 Electric Power Research Institute, Inc. All rights reserved.

# ACKNOWLEDGMENTS

---

The following organization prepared this report:

Electric Power Research Institute (EPRI)  
942 Corridor Park Blvd.  
Knoxville, TN 37932

Principal Investigators

Ammi Amarnath  
Glen Bailey  
John Bush  
Scott Bunton  
Ron Domitrovic  
Ben Ealey  
Wes Forbes  
Brian Fortenbery  
Tom Geist  
Karen George  
Krish Gomatom  
Chris Holmes  
Ellen Petrill  
Dennis Symanski  
Chuck Thomas  
Sheila Tian  
Chris Trueblood

This report describes research sponsored by EPRI.

---

This publication is a corporate document that should be cited in the literature in the following manner:

*Energy Efficiency Demonstration*. EPRI, Palo Alto, CA: 2012. 1025437.



# ABSTRACT

---

The Energy Efficiency Demonstration was a field-performance assessment of emerging, efficient end-use technologies, deployed with extensive measurement instrumentation at multiple sites throughout the United States. EPRI collaborated with fourteen utilities spread throughout the United States. The selected technologies were known to have the potential to significantly reduce energy consumption in residential and commercial applications. The technologies demonstrated were: light emitting diode (LED) for use in street and area lighting (LEDSAL), ductless heat pumps (DHPs), variable refrigerant flow (VRF), advanced clothes washers and dryers, advanced refrigerators, heat pump water heaters (HPWH), and technologies for reducing energy consumption in data centers, including airflow management, efficient power supplies, and DC power distribution. The Demonstration began in the spring of 2009 and completed data collection in March of 2012. For each of the technologies, this report provides an industry and technology overview, documents potential savings, discusses applicable standards and provides results and analysis of the laboratory work and the field demonstrations—particularly energy savings, reliability, performance, and customer satisfaction.

## **Keywords**

Energy Efficiency  
Heat Pump Water Heater  
Light-Emitting Diode (LED)  
Refrigerator  
Clothes Washer  
Clothes Dryer  
Variable Refrigerant Flow (VRF)  
Ductless Heat Pump (DHP)  
Data Center



# CONTENTS

---

<b>1 INTRODUCTION .....</b>	<b>1-1</b>
<b>2 HEAT PUMP WATER HEATERS .....</b>	<b>2-1</b>
Introduction .....	2-1
Industry Overview.....	2-1
Research Objectives .....	2-2
Research Methodology.....	2-4
Design and Assemble Instrumentation Packages .....	2-4
Procure and Test HPWHs in the Laboratory .....	2-8
Prepare and Test Instruments in the Laboratory .....	2-8
Conduct Site-Selection Surveys.....	2-8
Procure and Ship HPWHs and Instruments for Field Testing .....	2-8
Install HPWHs and Instruments in the Field .....	2-8
Collect and Analyze Data.....	2-9
Conduct Customer-Satisfaction Surveys.....	2-9
Laboratory Investigation .....	2-9
Twenty-Four-Hour Tests .....	2-9
Draw Tests.....	2-10
Collection and Analysis of Field Data .....	2-11
Field Test Results .....	2-12
Data Description.....	2-12
Demand Impact Analysis.....	2-22
Consumer Surveys .....	2-27
Special Case: Utility D Opt-Out Respondents .....	2-30
Satisfaction.....	2-30
Seasonal Performance .....	2-31
Noise .....	2-31
Savings .....	2-31

Survey Summary.....	2-31
Summary.....	2-32
Readiness for Program.....	2-33
<b>3 DATA CENTERS.....</b>	<b>3-1</b>
Introduction .....	3-1
Industry Overview.....	3-1
Server Power Supply Retrofits.....	3-2
Airflow Management with Adaptive Controls.....	3-3
DC Power Distribution.....	3-3
A Timeline for Technology Advances.....	3-4
Research Objective .....	3-5
Research Method.....	3-7
Power Supply Retrofits .....	3-7
Airflow Management.....	3-10
DC Power Distribution.....	3-11
Instrumentation.....	3-12
Power Supply Retrofits.....	3-12
Airflow Management .....	3-14
DC Power Distribution.....	3-15
Data Collection and Analysis .....	3-15
Power Supply Retrofits.....	3-15
Airflow Management .....	3-16
DC Power Distribution.....	3-17
DC Network Efficiency.....	3-17
AC Network Efficiency.....	3-18
Laboratory Investigation .....	3-19
Power Supply Retrofits .....	3-19
Test Description .....	3-19
DC Power Distribution.....	3-21
Field Data and Analysis.....	3-22
Field Data .....	3-22
Power Supply Retrofits.....	3-22
Airflow Management .....	3-23
DC Power Distribution.....	3-24

Data Analysis.....	3-24
Power Supply Retrofits.....	3-24
Airflow Management .....	3-25
DC Power Distribution.....	3-25
Research Questions Applicable to All Three Technologies .....	3-26
Summary.....	3-27
Power Supply Retrofits .....	3-27
Airflow Management .....	3-27
DC Power Distribution.....	3-28
Readiness for Program.....	3-29
<b>4 VARIABLE REFRIGERANT FLOW.....</b>	<b>4-1</b>
Introduction .....	4-1
Industry Overview.....	4-1
Technology Summary.....	4-2
VRF-Heat Pump and VRF-Heat Recovery .....	4-3
Air-Source and Water-Source .....	4-3
Zoning and Control .....	4-5
Thermodynamics .....	4-6
Outdoor Units.....	4-9
Indoor Units.....	4-10
Refrigerant Piping Network .....	4-11
Field Evaluation.....	4-15
Research Objectives .....	4-15
Research Method .....	4-19
Laboratory Investigation .....	4-20
Field Data.....	4-20
Site B.....	4-20
Site C.....	4-24
Site A.....	4-31
Site D.....	4-38
Survey Results .....	4-42
Satisfaction .....	4-42
Summer .....	4-43
Winter .....	4-43

Comfort.....	4-43
Technical Performance.....	4-44
Survey Summary.....	4-45
Summary.....	4-45
Readiness for Program.....	4-46
<b>5 DUCTLESS HEAT PUMPS .....</b>	<b>5-1</b>
Introduction .....	5-1
Industry Overview.....	5-1
Related Studies .....	5-2
Research Objective .....	5-4
Research Method .....	5-4
Host Site and Equipment Summaries .....	5-4
Utility A .....	5-5
Utility B .....	5-7
Utility C .....	5-9
Installed Equipment .....	5-11
Field Monitoring .....	5-11
Instrumentation.....	5-12
Survey .....	5-13
Laboratory Investigation .....	5-13
Field Data.....	5-13
Utility A Sites .....	5-13
Utility B Sites .....	5-19
Utility C Sites .....	5-26
Survey Results .....	5-29
Satisfaction .....	5-29
Comfort.....	5-30
Savings.....	5-31
Summary.....	5-32
Readiness for Program.....	5-32
<b>6 LIGHT-EMITTING DIODES FOR STREET AND AREA LIGHTING.....</b>	<b>6-1</b>
Introduction .....	6-1
Industry Overview.....	6-1

Savings Potential .....	6-1
Technology .....	6-2
DOE Municipal Solid-State Street Lighting Consortium .....	6-3
MSSLC Retrofit Financial Analysis Tool .....	6-4
IES LM-80-2008, Approved Method for Measuring Lumen Depreciation of LED Light Sources .....	6-4
Research Objective .....	6-4
Research Method .....	6-5
Laboratory Measurements .....	6-5
Field Measurements .....	6-6
Installation of Monitors .....	6-7
Scotty .....	6-9
Laboratory Investigation .....	6-11
Physical Construction .....	6-11
Thermal Inspection .....	6-11
Power Draw (Compared to Data Sheet).....	6-12
Thermal Chamber Test .....	6-14
Distribution Pattern .....	6-15
Drivers .....	6-16
Field Data .....	6-18
Projected and Actual Savings .....	6-18
Lighting Control.....	6-22
Defined Area Efficacy .....	6-26
Reliability .....	6-28
Temperature .....	6-30
Power Factor .....	6-33
Radio Interference .....	6-34
Labeling .....	6-34
Survey .....	6-35
Overall Satisfaction .....	6-35
Installation .....	6-36
Technical Performance .....	6-36
Bill Savings .....	6-36
Safety .....	6-37
Future Implementation .....	6-37

Summary.....	6-37
Readiness for Program.....	6-40
<b>7 HYPER-EFFICIENT APPLIANCES .....</b>	<b>7-1</b>
Introduction .....	7-1
Industry Overview.....	7-1
Refrigerators.....	7-1
Overview.....	7-1
Timeline .....	7-3
Market Statistics.....	7-3
Refrigerator Options and Advances.....	7-4
Clothes Washers .....	7-5
Overview.....	7-5
Timeline .....	7-6
Options and Advances .....	7-6
Clothes Dryer.....	7-8
Overview.....	7-8
Options and Advances .....	7-8
Standards .....	7-9
Refrigerator.....	7-10
Clothes Washer.....	7-13
Clothes Dryer .....	7-14
Potential Savings.....	7-15
Refrigerator.....	7-15
Clothes Washer .....	7-17
Clothes Dryer.....	7-19
Key Research Questions.....	7-21
Clothes Washers and Dryers .....	7-21
Refrigerator/Freezers.....	7-21
Laboratory Testing .....	7-21
Washer and Dryer Operating Times.....	7-21
Data Collection.....	7-25
Overview.....	7-25
Data Collection Methods and Sites .....	7-26
Instrumentation.....	7-26

Installed Appliances .....	7-28
Customer Surveys .....	7-29
Survey Results: Refrigerators .....	7-29
Survey Results: Clothes Washers and Dryers .....	7-30
Field Test Results .....	7-30
Clothes Washer and Dryer .....	7-30
Data Description .....	7-30
System Impact .....	7-31
Energy .....	7-31
Load Shapes .....	7-34
Technology Assessment .....	7-35
Energy per Laundry Cycle .....	7-36
Power Profiles .....	7-40
Refrigerators .....	7-44
Data Description .....	7-44
System Impact .....	7-45
Energy .....	7-45
Load Shapes .....	7-47
Technology Assessment .....	7-48
Summary .....	7-50
Washer/Dryers .....	7-50
Refrigerators .....	7-50
Readiness for Program .....	7-51
<b>8 SUMMARY .....</b>	<b>8-1</b>
Light Emitting Diode for Street and Area Lighting .....	8-1
Efficient Data Centers .....	8-1
Variable Flow Refrigerant .....	8-2
Ductless Heat Pump .....	8-2
Hyper-Efficient Appliances .....	8-2
Washer/Dryer .....	8-2
Refrigerator .....	8-3
Heat Pump Water Heater .....	8-3
<b>9 REFERENCES .....</b>	<b>9-1</b>

**10 GLOSSARY.....10-1**

**A HEAT PUMP WATER HEATER.....A-1**

**B WORKSHEET FOR SCOTTY SITE VISIT.....B-1**

**C INDUCTION LIGHT LEVELS.....C-1**

**D U.S. FEDERAL STANDARDS STATUS AND SCHEDULE FOR RESIDENTIAL  
APPLIANCES.....D-1**

# LIST OF FIGURES

---

Figure 1-1 The Energy Efficiency Demonstration Is an Outgrowth of the Prism-MERGE Analyses That Identified the Steps Needed to Reduce Global Emission of CO <sub>2</sub> .....	1-1
Figure 1-2 The Six Energy Efficiency Demonstration Technologies Offer Potential for Significant Energy Savings.....	1-2
Figure 1-3 Map of the U.S. Showing Collaborators and Scope of Geographic Diversity .....	1-3
Figure 2-1 HPWH Full Instrumentation Package .....	2-5
Figure 2-2 HPWH Lite Instrumentation Package .....	2-6
Figure 2-3 Overall COP and Recovery Power During a 24-Hour Test .....	2-10
Figure 2-4 The Effect of Inlet Water Temperature on COP and Energy Consumption.....	2-11
Figure 2-5 Instrumentation Used to Measure Field Variables .....	2-12
Figure 2-6 Number of Installations over Time.....	2-14
Figure 2-7 Average Daily Water Draw and HPWH Energy for Models A and B, by Month, All Sites .....	2-15
Figure 2-8 Average Daily Energy for Control and Treatment Water Heaters .....	2-15
Figure 2-9 Average Daily COP for Each Model, by Season, for Mixed Humid Climate .....	2-16
Figure 2-10 Effect of Ambient Air Temperature on COP for All Climates .....	2-17
Figure 2-11 Frequency of Ambient Temperature Bins and COP for Cold Climate, All Models .....	2-18
Figure 2-12 Effect of Daily Water Draw on COP for All Climates .....	2-19
Figure 2-13 Effect of Installation Location, All Climates.....	2-20
Figure 2-14 COP for Each Model for Similar Ambient Air and Draw Volume, with Different Entering Water Temperature .....	2-21
Figure 2-15 Comparison of COP for the 60- and 80-Gallon Tank Sizes .....	2-21
Figure 2-16 COP vs. Daily Water Draw for 60-Gallon and 80-Gallon HPWHs, with Data Screened for Ambient Air and Entering and Supply Water Temperature .....	2-22
Figure 2-17 Load Shape for Mixed-Humid Climate, Winter 2010–2011 .....	2-24
Figure 2-18 Load Shape for Mixed-Humid Climate, Spring and Fall 2011 .....	2-25
Figure 2-19 Load Shape for Mixed-Humid Climate, Summer 2011.....	2-25
Figure 2-20 Load Shape for Mixed-Humid Climate, Winter 2011–2012.....	2-26
Figure 2-21 Load Shape for Cold Climate, Winter 2010–2011 .....	2-27
Figure 2-22 Load Shape for Cold Climate, Winter 2011–2012 .....	2-27
Figure 3-1 Data Center Energy Use by Equipment Type (From LBNL) .....	3-2
Figure 3-2 A Blade Enclosure for Six Power Supplies .....	3-7

Figure 3-3 A Server With Hot-Swappable Power Supplies .....	3-8
Figure 3-4 A Rack of Blade Enclosures.....	3-8
Figure 3-5 EPRI Data-Collection Plan for Utility A Data Center EE Demonstration Site .....	3-10
Figure 3-6 Test Setup .....	3-11
Figure 3-7 Power Supply Unit (PSU) Configuration for All Servers in Racks 1 – 3 .....	3-11
Figure 3-8 Meter Locations Including Formulas Used to Characterize System Performance.....	3-12
Figure 3-9 Meter Layout.....	3-13
Figure 3-10 Circuit Configuration for All Blade Enclosures and Racks .....	3-14
Figure 3-11 Equipment Used to Monitor 22 Three-Phase Circuits.....	3-14
Figure 3-12 Meter and Data-Acquisition Network Configuration .....	3-15
Figure 3-13 Test Configurations (With and Without 80 PLUS PSU and With and Without Dynamic Power Management Turned OFF and ON) .....	3-16
Figure 3-14 Graphical Representation of All Metered and Sensor Data Points Used in the Evaluation .....	3-17
Figure 3-15 Setup for Testing Internal Desktop Computer Power Supplies .....	3-20
Figure 3-16 Results of Comparison Tests Between Standard AC Power Supplies and 80 PLUS Platinum Power Supplies .....	3-21
Figure 3-17 Results of Comparison Tests Between AC and DC Power Supplies .....	3-21
Figure 3-18 Results of Single Test on a Blade Enclosure.....	3-22
Figure 3-19 Average Power (kW) per CRAC .....	3-23
Figure 4-1 Single-Mode VRF Operation—Heating Shown in Red and Cooling in Blue .....	4-4
Figure 4-2 VRF-HR Simultaneous Heating and Cooling Operation .....	4-4
Figure 4-3 Water-Source VRF Heat-Recovery System with Refrigerant-Side and Water- Side Heat Recovery .....	4-5
Figure 4-4 Example Cooling Capacity and Load Characteristics for a Single-Speed Air Conditioner .....	4-6
Figure 4-5 Example Cooling Capacity and Load Characteristics for a Variable-Speed Air Conditioner .....	4-7
Figure 4-6 General Schematic of a Multi-Zone Variable-Capacity DX System .....	4-8
Figure 4-7 General Schematic of a Single-Speed DX Air Conditioner .....	4-8
Figure 4-8 Three Paralleled Outdoor Units Comprising a Single VRF Outdoor System.....	4-9
Figure 4-9 VRF Outdoor Units Coupled to a Low Ambient Module.....	4-10
Figure 4-10 Four-Way Ceiling Cassette Indoor Unit .....	4-10
Figure 4-11 Encased Floor Standing Indoor Unit.....	4-11
Figure 4-12 Horizontal Ducted Indoor Unit .....	4-11
Figure 4-13 Single Heat-Recovery Control Unit with Home-Run Piping from Indoor Units .....	4-12
Figure 4-14 Heat-Recovery Control Unit for Each Indoor Zone .....	4-12
Figure 4-15 Multiple Heat-Recovery Units Each Serving Multiple Indoor Zones .....	4-13
Figure 4-16 Sixteen-Circuit Branch Controller for a Two-Pipe VRF Heat-Recovery System .....	4-13

Figure 4-17 Rendering of a Six-Circuit Branch Controller .....	4-14
Figure 4-18 Installed Four-Circuit Heat-Recovery Unit Made by Manufacturer C .....	4-15
Figure 4-19 VRF Systems Installed at Site C .....	4-17
Figure 4-20 Ceiling Cassette-Type Indoor Unit at Site B .....	4-18
Figure 4-21 VRF System Installed at Site B .....	4-19
Figure 4-22 Cumulative Energy Consumption at VRF Site B.....	4-21
Figure 4-23 Power Consumption and Temperature at Site B VRF Sites for a Cold Winter Weekday .....	4-23
Figure 4-24 Power Consumption and Temperature at Site B VRF Sites for a Warm Weekday .....	4-24
Figure 4-25 Monthly Energy Consumption for Modeled Baseline, Modeled VRF, and Field VRF Site C.....	4-25
Figure 4-26 Monthly Peak Power for Modeled Baseline and VRF and Field VRF Site C.....	4-27
Figure 4-27 VRF Site C Power and Temperature for August 4, 2011 .....	4-29
Figure 4-28 VRF Site C Power and Temperature for December 5, 2011.....	4-30
Figure 4-29 VRF Site C One-Week Winter Data .....	4-31
Figure 4-30 Site A VRF Energy Consumption .....	4-32
Figure 4-31 VRF Site A Power and Temperature for January 14, 2011.....	4-33
Figure 4-32 VRF Site A Power and Temperature for August 2, 2011 .....	4-36
Figure 4-33 CO2 Concentration and DOAS Power for Site A .....	4-37
Figure 4-34 Power and Temperature for One Winter Week at VRF Site A .....	4-38
Figure 4-35 VRF Site D Cumulative Energy Consumption .....	4-39
Figure 4-36 VRF Site D Power and Temperature for August 25, 2011 .....	4-40
Figure 4-37 VRF Site D Power and Temperature for January 18, 2012 .....	4-41
Figure 4-38 VRF Site D Power for One Winter Week (Dashed Line Indicates Weekend Days).....	4-42
Figure 5-1 Climate Zones of DHP Installations.....	5-5
Figure 5-2 Utility A Residential Site .....	5-6
Figure 5-3 Two Variable-Capacity Heat Pumps at a Utility A Site.....	5-6
Figure 5-4 Non-Ducted Wall-Mount Terminal Unit.....	5-7
Figure 5-5 Utility B Residential Site .....	5-8
Figure 5-6 Two Zones in a Utility B Site Being Served by Separate Wall-Mount Terminal Units.....	5-8
Figure 5-7 Outdoor Unit at the Utility B Site (Refrigerant Lines Hidden by the Gutter Line- Hide) .....	5-9
Figure 5-8 Enlisted Barracks Treatment (DHP) Building.....	5-10
Figure 5-9 Junior Officer Barracks Baseline Building.....	5-10
Figure 5-10 Low Static Air Handler.....	5-11
Figure 5-11 Instrumentation of a DHP Installation .....	5-12
Figure 5-12 DHP Data-Acquisition Panel .....	5-12

Figure 5-13 Location of DHP and Instrumentation.....	5-13
Figure 5-14 Total Energy Consumption, Cumulative, March 2011 – March 2012 for Utility A Sites.....	5-16
Figure 5-15 Total Energy Consumption Normalized by Square Footage, Cumulative, March 2011 – March 2012 for Utility A Sites.....	5-17
Figure 5-16 July 2011 Utility A Sites Selected Data (5-Minute Interval).....	5-18
Figure 5-17 December 2011 Utility A Sites Selected Data 5-Minute Intervals .....	5-19
Figure 5-18 Utility B Cumulative Energy for Each Site, 2011.....	5-20
Figure 5-19 Utility B Cumulative Energy per Square Foot for Each Site, 2011 .....	5-21
Figure 5-20 Utility B Monthly Energy for Each Site, 2011 .....	5-22
Figure 5-21 Utility B Monthly Energy per Square Foot for Each Site, 2011.....	5-23
Figure 5-22 February, 2011 5-Minute Power and Temperature for Selected Representative Utility B Sites .....	5-25
Figure 5-23 July, 2011 5-minute Power and Temperature Data for Selected Representative Utility B Sites .....	5-26
Figure 5-24 Utility C Sites 36 and 37 Cumulative Energy .....	5-27
Figure 5-25 Utility C Sites 38 and 39 Cumulative Energy .....	5-28
Figure 5-26 Utility C Sites 40 and 41 Cumulative Energy .....	5-29
Figure 6-1 EPRI’s Workflow Diagram for Laboratory Assessment of LED Street and Area Lighting Fixtures.....	6-6
Figure 6-2 EPRI’s Energy Monitor on a Light Pole .....	6-8
Figure 6-3 An Energy Monitor Installed in a UL 508A Enclosure .....	6-8
Figure 6-4 The Scotty, a Mobile Light-Measurement Platform.....	6-9
Figure 6-5 The Various Subsystems That Comprise the Scotty .....	6-10
Figure 6-6 A Wide Variety of Form Factors for LED Fixtures.....	6-11
Figure 6-7 Thermal Images Showing Differences in Thermal Management for Four LED Fixtures .....	6-12
Figure 6-8 Variation in Power Consumption After Warm-Up of Twelve Identical Fixtures.....	6-13
Figure 6-9 Maximum and Average Variation in Input Power for Three Leading Manufacturers of LED Fixtures .....	6-14
Figure 6-10 Relative Change in Input Power as a Function of Temperature for Two Fixtures from Two Different Manufacturers.....	6-15
Figure 6-11 Variations in Distribution Pattern for Four Different Models of LED Fixtures.....	6-16
Figure 6-12 Plot of Driver Efficiency (AC In/DC Out) for Four Different LED Drivers .....	6-17
Figure 6-13 A Failed LED Driver .....	6-18
Figure 6-14 Plot of Projected and Actual Savings for Eight LED Demonstration Sites.....	6-19
Figure 6-15 Before (Left) and After Photographs Demonstrating Less Up-Light, More Even Distribution, and Higher Color Temperature Afforded by LED Fixtures .....	6-19
Figure 6-16 Daily Energy Consumption over One Year at Site 16.....	6-20
Figure 6-17 Daily Energy Consumption over One Year at Site 23.....	6-21
Figure 6-18 Daily Energy Consumption over One Year at Site 11 .....	6-22

Figure 6-19 Poor Placement of a Photocell at a Demonstration Site .....	6-23
Figure 6-20 A Plot of Darkness Hours and the Amount of Time That the Lights Were Energized Over Several Years for Site 12 .....	6-23
Figure 6-21 A Plot of Darkness Hours and the Amount of Time That the Lights Were Energized Over Several Years for Site 19 .....	6-24
Figure 6-22 A Plot of Darkness Hours and the Amount of Time That the Lights Were Energized Over Several Years for Site 16 .....	6-25
Figure 6-23 Over-Lighting Among Sites, Indicating the Potential for Energy Savings If the Location of the Control Sensor Is Improved .....	6-26
Figure 6-24 Under-Lighting Among Sites, Indicating the Potential for Liability Issues and Artificial Energy Savings .....	6-26
Figure 6-25 Light Levels Produced by an HID Control Fixture .....	6-27
Figure 6-26 Light Levels Produced by an LED Treatment Fixture (Same Location as Control). .....	6-28
Figure 6-27 LED Failures, Both Out of the Box (Blue) and in the Field for the LED Energy Efficiency Demonstration.....	6-29
Figure 6-28 Input Power to a Demonstration Circuit Over Several Months.....	6-30
Figure 6-29 Average Power per Month for a Demonstration Site in the Midwest Showing Temperature Dependence of Power .....	6-31
Figure 6-30 Laboratory Data Showing Warm-Up Time for a Fixture .....	6-32
Figure 6-31 The Potential Savings Possible Through Use of a Temperature-Compensation Circuit .....	6-33
Figure 6-32 Power Factor for Ten Sites (Control and Treatment).....	6-34
Figure 6-33 A Traditional Cobrahead Showing Location of Identifying Label .....	6-35
Figure 7-1 Representative Configuration of a Refrigerator with Top-Mounted Freezer .....	7-2
Figure 7-2 Operation of Inverter-Driven Variable-Speed Compressor Versus Single-Speed Compressor .....	7-5
Figure 7-3 Energy Consumption of Refrigerator-Freezers .....	7-12
Figure 7-4 Date of Manufacture of Residential Refrigerators as of 2009 .....	7-16
Figure 7-5 The Potential Savings of Hyper-Efficient Refrigerators Compared to 2008 Usage Statistics.....	7-17
Figure 7-6 Age of Clothes Washers in Homes as Reported by the 2009 EIA RECS .....	7-18
Figure 7-7 The Temperature of Wash Cycles Used in Homes.....	7-19
Figure 7-8 Market Share of Appliances by Type of Fuel.....	7-20
Figure 7-9 Age Estimate of Clothes Dryer in Service.....	7-20
Figure 7-10 Trend Line of Washer Operating Time by Setting.....	7-22
Figure 7-11 Maximum and Minimum Washer Operating Times by Setting .....	7-23
Figure 7-12 Trend Line of Dryer Operating Time by Setting .....	7-24
Figure 7-13 Maximum and Minimum Dryer Operating Times by Setting.....	7-25
Figure 7-14 Instrumentation Mounted on the Back of a Refrigerator .....	7-27
Figure 7-15 Instrumentation on the Back of the Clothes Dryer .....	7-28

Figure 7-16 Instrumentation Mounted on the Back of the Clothes Washer to Measure Hot/Cold Water Temperature and Flow .....	7-28
Figure 7-17 Energy Savings of Treatment Washer and Dryer Pairs with a Calculated Cost of Hot Water Energy Using Water Heaters with Resistive Heating Elements.....	7-33
Figure 7-18 Energy Savings of Treatment Washer and Dryer Pairs with Calculated Hot Water Energy Cost Using Heat Pump Water Heaters by Type of Day (Weekday, Weekend Day, Average Day) Compared to Both the Control Installations and the ENERGY STAR Rating .....	7-34
Figure 7-19 Average Load Shape for a Weekday of a Washer and Dryer Pair for Both Control and Treatment Installations .....	7-35
Figure 7-20 Average Load Shape for a Weekend Day of a Washer and Dryer Pair for Both Control and Treatment Installations.....	7-35
Figure 7-21 Average Water Usage per Laundry Cycle for Fifteen Sites with Pre/Post Control Configuration.....	7-38
Figure 7-22 Average Energy per Laundry Cycle Excluding Energy Content of the Hot Water for Fifteen Installations with Pre/Post Configuration .....	7-39
Figure 7-23 Average Operating Time per Laundry Cycle for Fifteen Installations with Pre/Post Configuration .....	7-40
Figure 7-24 Representative Power Profile for a Control Clothes Washer .....	7-41
Figure 7-25 Representative Power Profile for a Treatment Clothes Washer.....	7-41
Figure 7-26 Representative Power Profile for a Treatment Washing Machine Configured for Steam Cycle.....	7-42
Figure 7-27 Representative Power Profile for a Treatment Washing Machine Configured for Sanitize and Steam Cycle .....	7-42
Figure 7-28 Representative Power Profile for a Control Dryer.....	7-43
Figure 7-29 Representative Power Profile for a Treatment Dryer .....	7-43
Figure 7-30 Representative Power Profile for a Treatment Washing Machine Using the Refresh Setting.....	7-44
Figure 7-31 Energy of Treatment Refrigerators by Type of Day (Weekday, Weekend, Average) Compared to Both the Control Installations and the ENERGY STAR Rating.....	7-46
Figure 7-32 Average Daily Energy for Each Installation by Control and Treatment (Models 1 – 3) .....	7-46
Figure 7-33 Average Daily Energy of Treatment Refrigerators for Pre/Post Control Configuration.....	7-47
Figure 7-34 Average Load Shape for a Weekday for Both Control and Treatment Refrigerators .....	7-47
Figure 7-35 Average Load Shape for a Weekend Day for Both Control and Treatment Refrigerators .....	7-48
Figure 7-36 Power Use of Model 3 for One 24-Hour Period on a Day with Low Energy Use.....	7-49
Figure 7-37 Power Use of Model 3 for One 24-Hour Period on a Day with Medium Energy Use .....	7-49

Figure 7-38 Power Use of Model 3 for One 24-Hour Period on a Day with High Energy  
Use.....7-49



# LIST OF TABLES

---

Table 2-1 Comparison of Lite and Full Instrumentation Packages.....	2-7
Table 2-2 Number of HPWH Installations by Characteristic .....	2-13
Table 2-3 Number of HPWH Installations for Each Host Utility by Climate Zone .....	2-13
Table 2-4 Number of HPWH Installations for Each Utility by Type of Conditioned Space.....	2-14
Table 2-5 Energy Consumption by Manufacturer and by Region .....	2-16
Table 2-6 Coincident Demand Reduction for Utility Peak Days .....	2-23
Table 2-7 HPWH Satisfaction Ratings by Utility .....	2-29
Table 2-8 HPWH Purchase Consideration by Utility .....	2-29
Table 2-9 HPWH Participant Recommendation by Utility .....	2-30
Table 3-1 Comparison of a Typical-Efficiency Power-Distribution System to a High-Efficiency AC System and a DC System for a Compute Load of 100 kW.....	3-4
Table 3-2 Variables Associated With the Test Setup and Configuration.....	3-9
Table 3-3 DC Network Efficiencies.....	3-18
Table 3-4 AC Distribution Efficiencies .....	3-18
Table 3-5 80 PLUS Levels of Compliance for 230-Volt Internal Redundant Efficiencies.....	3-19
Table 3-6 Results of Single Test on a Blade Enclosure.....	3-22
Table 3-7 Energy Use of Existing AC Power System and New DC Power System.....	3-24
Table 4-1 Monthly Breakdown of Energy Consumption.....	4-22
Table 4-2 Monthly Energy Consumption for Model Baseline, Modeled VRF, and Field VRF Site C .....	4-26
Table 4-3 Site C Measured VRF Energy, Normalized by Square Footage .....	4-27
Table 4-4 Monthly Peak Power for Model Baseline and VRF and Field VRF Site C.....	4-28
Table 4-5 Site A, Three-Year Average Utility Data and Measured VRF System Energy.....	4-34
Table 4-6 Calculated Cost of Electricity for Office Space Plus Natural Gas and VRF Energy Cost .....	4-35
Table 4-7 VRF Site D Energy Consumption and Consumption per Square Foot.....	4-40
Table 5-1 Energy Savings for DHP from the BPA Study .....	5-3
Table 5-2 Number of Control and Treatment Sites .....	5-4
Table 5-3 Utility A Monthly Site Overview, March 2011 – August 2011 .....	5-15
Table 5-4 Utility A Monthly Site Overview, September 2011 – February 2012.....	5-15
Table 5-5 Utility A Site Square Footages.....	5-16
Table 5-6 Home Area of Utility B Sites .....	5-21
Table 5-7 Utility B Summary Monthly Data for January-June, 2011.....	5-23

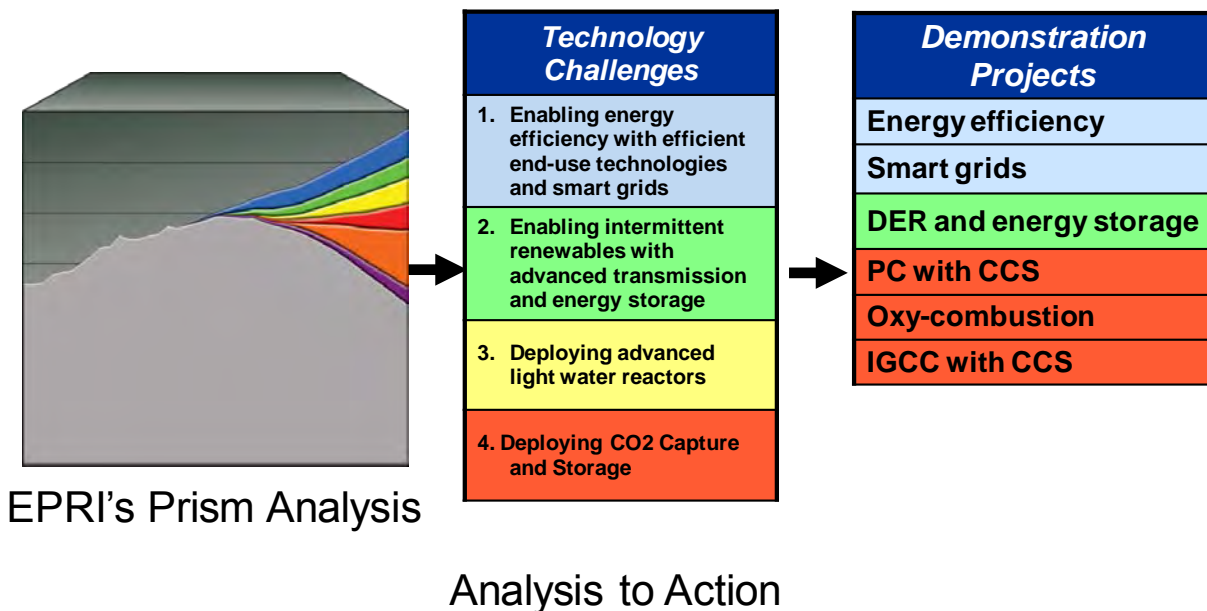
Table 5-8 Utility B Summary Monthly Data for July-December, 2011 .....	5-24
Table 6-1 Efficiency as a Function of Lamp Size for High-Pressure Sodium Fixtures.....	6-3
Table 7-1 U.S. Energy-Efficiency Standards for Common Refrigerator/Freezer Types.....	7-11
Table 7-2 Refrigerator ENERGY STAR and CEE Ratings.....	7-13
Table 7-3 Clothes Washer ENERGY STAR and CEE Ratings .....	7-14
Table 7-4 Existing Federal Standard for Clothes Dryers.....	7-14
Table 7-5 Upcoming Revision to the Federal Standard for Clothes Dryers.....	7-15
Table 7-6 The Annual Energy Consumption for Different Types of Refrigerators in 2008.....	7-17
Table 7-7 The Potential Savings If All Clothes Washers Were Converted to Hyper- Efficient Models .....	7-19
Table 7-8 Appliances Tested in the Energy Efficiency Demonstration.....	7-29
Table 7-9 Total Installations for Appliances Demonstration .....	7-31
Table 7-10 Average Energy per Laundry Cycle for All Installations .....	7-36
Table 7-11 Average Energy per Laundry Cycle for Pre/Post Installations.....	7-37
Table 7-12 Average Time per Laundry Cycle of a Washer and Dryer Pair for Both Control and Treatment Installations .....	7-40
Table 7-13 Number of Refrigerator Installations by Manufacturer and Utility .....	7-45
Table 7-14 Table Showing the Minimum, Maximum, and Average Values of the Average Load Shape for Both the Refrigerator Week Day and Weekend Day.....	7-48
Table A-1 Detailed Data for Comparing Performance of 60-Gallon and 80-Gallon Systems .....	A-1
Table A-2 Detailed Data for Comparing Performance vs. Ambient Temperature.....	A-2
Table A-3 Detailed Data for Comparing Performance vs. Daily Water Use .....	A-3

# 1

## INTRODUCTION

In 2007, EPRI released its first Prism and MERGE analyses, providing a technically and economically feasible roadmap for the electricity sector as it seeks to reduce greenhouse gas emissions over the next few decades. The Prism analysis provided a comprehensive assessment of potential CO<sub>2</sub> reductions in seven key technology areas of the electricity sector. The MERGE analysis identified the economically optimal technology portfolio in response to a given CO<sub>2</sub> emissions constraint.

The Prism-MERGE analyses showed that by deploying a full portfolio of technologies, meaningful CO<sub>2</sub> emissions reductions can be achieved in a cost-effective way. Although analysis is important, action is even more critical in order to address the challenges of deploying the full portfolio. EPRI took action and launched a number of industry demonstration projects addressing the key technology challenges, as shown in Figure 1-1. One of the demonstration projects focused on energy efficiency.

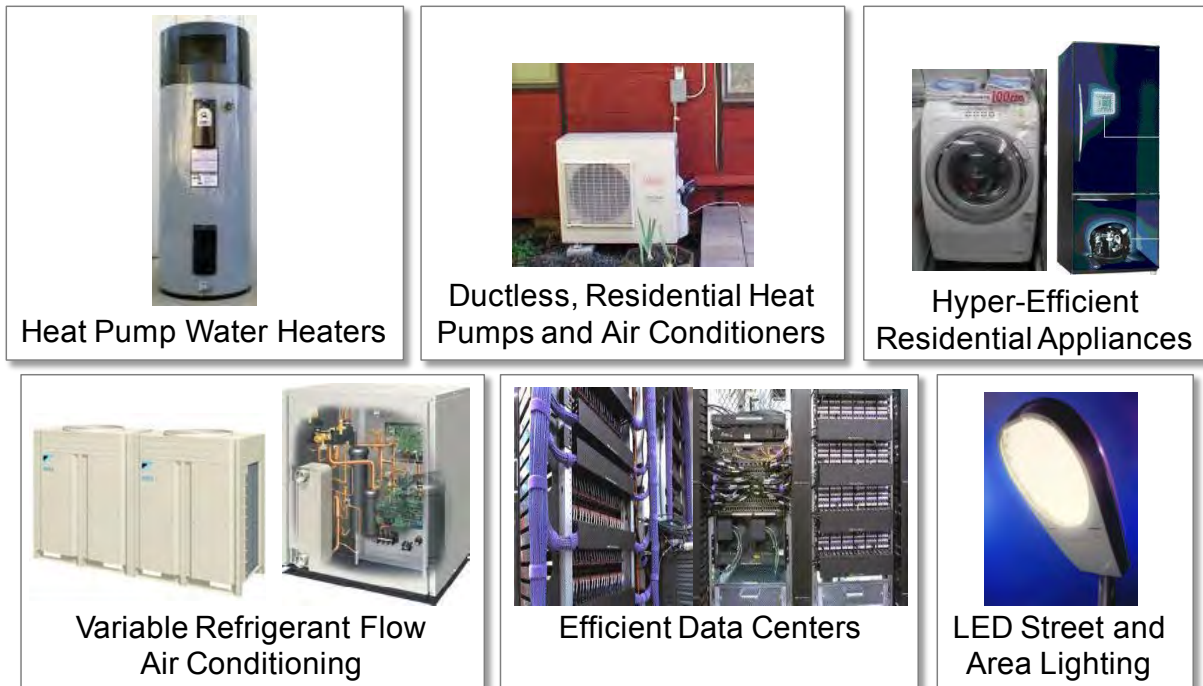


**Figure 1-1**  
**The Energy Efficiency Demonstration Is an Outgrowth of the Prism-MERGE Analyses That Identified the Steps Needed to Reduce Global Emission of CO<sub>2</sub>**

The EPRI Energy Efficiency Demonstration, which started in 2008, project focused on end-use electric utilization, specifically on “hyper-efficient” examples of technologies that use electricity to heat, cool, and light. What is meant by *hyper-efficient*? EPRI defined hyper-efficient technologies as those that go beyond incremental efficiency improvements and have the potential

for up to 40% energy savings. Such technologies represent a substantial opportunity to meet consumer demand for electricity and make a significant impact on reduction of CO<sub>2</sub> emissions.

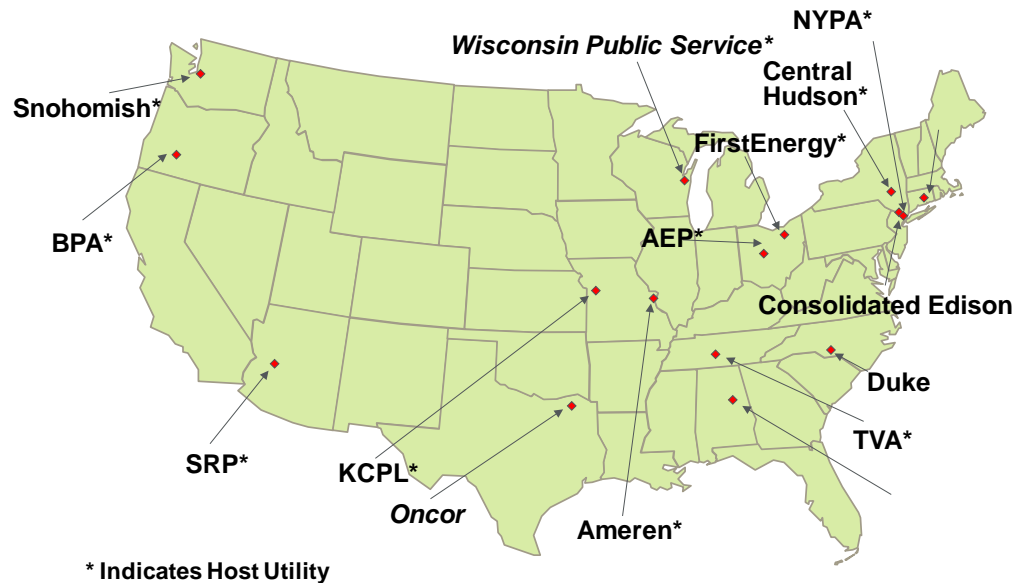
EPRI identified six categories of energy-efficient technologies with the potential to significantly reduce energy usage in U. S. buildings and homes (see Figure 1-2). These technologies were commercially available, but each had limited penetration in the U.S. market. The Demonstration was launched to gain experience with these technologies and to gather data on their energy savings and performance in the field. The Demonstration also focused on validating applicability in North America.



**Figure 1-2**  
**The Six Energy Efficiency Demonstration Technologies Offer Potential for Significant Energy Savings**

The research was designed to answer research questions related to performance in the field, level of energy savings, compatibility with building designs and various codes and standards, and differences in quality and other effects compared to traditional technologies. Because the products did not have significant market share in the U.S., research also addressed what could be done to accelerate adoption.

The technologies were demonstrated with several utilities using different selection criteria—such as climate, population density, and regulatory restrictions—to assess their performance when deployed in diverse environments. Figure 1-3 lists the collaborators and provides an indication of the geographic diversity. Most of the collaborators hosted one technology demonstration and in some cases, more than one.



**Figure 1-3**  
**Map of the U.S. Showing Collaborators and Scope of Geographic Diversity**

This project demonstrated and evaluated the performance of six hyper-efficient technologies at multiple utility sites with the following objectives:

Examine the efficiency and performance of the technologies.

Assess energy savings for different climatic regions, different building designs and constructions, and even different consumer demographics.

Identify and quantify different qualities of products within the technology category and effects when compared with traditional technology.

Understand technical obstacles such as the possible impact that the technologies may have on the performance of the electric grid.

EPRI designed the overall scope and managed the Demonstration. Within the scope of the project, EPRI identified and qualified the products within the technology categories for demonstration, worked with manufacturers to secure their availability, created the demonstration protocol, ran and executed tests, performed an evaluation of the data, and documented the results.

The project included two types of participants:

A *collaborator* to provide funding into the project, help guide the project, review and discuss the preliminary findings, and request to perform additional analysis or propose additional research questions.

A *host utility* that has the additional responsibility associated with actively demonstrating the selected energy-efficient technologies on their grids.

Host utilities secured customer commitments and aided with the coordination and scheduling of access to the customer locations. Host utilities were responsible for the installation of the equipment, customer support, and removal of the equipment if necessary. Utilities also installed

monitoring equipment and supported data collection. In the LED Street and Area Lighting Demonstration, utilities installed fixtures provided by EPRI.

With support of participants and engagement with manufacturers and industry groups, EPRI worked to understand the obstacles that impede the adoption of energy-efficient technologies. Clearly, the energy savings achieved during the demonstrations were largely due to the energy-efficient technologies themselves. However, in some cases, consumer behavior modulated these savings – both up and down. Because consumer behavior can be an important factor of actual energy savings, EPRI conducted several of the technology demonstrations in consumer premises.

For a number of utilities, energy efficiency is now and will increasingly be one of the key strategies to enable them to meet consumer demand. Collectively, the six technologies in the Energy Efficiency Demonstration have the technical potential to reduce the consumption of electricity by between 10% and 20%.

# 2

## HEAT PUMP WATER HEATERS

---

### Introduction

Although they have been around since the 1980s, heat pump water heaters (HPWHs) are just now receiving attention from the electric utility industry because of involvement by major manufacturers, exciting efficiency claims from manufacturers, and approval by the DOE to designate the ENERGY STAR rating. Robust research reveals that it is simply more efficient to transfer heat from the air and into a water tank (via a heat pump) than it is to heat water with an electrical heating element. The efficiencies are expected to be higher in Southern and Western portions of the United States, especially in areas where ambient temperatures are relatively high.

According to manufacturers' literature, efficiencies of HPWHs may double the efficiencies of traditional electric water heaters. Whereas traditional electric water heaters have an energy factor (EF, or annual efficiency) of less than 1.0, the EF of available HPWHs is typically higher than 2.0, resulting in an annual savings of \$250 or more for a typical household, according to the U.S. Department of Energy (DOE).

The EF of an HPWH depends upon usage patterns, climate, and location of installation. Manufacturers claim that such water heaters have the potential to operate efficiently in the southern and western climatic regions; their operability in northern and northwestern regions is unknown. The EPRI Energy Efficiency Demonstration is designed to test the efficiency and reliability of HPWHs in most climatic conditions in the U.S., for a period of two years.

### Industry Overview

Storage water heaters have been around since the turn of the 19th century. Since that time, the most widely used methods of heating water for household use have been ordinary fire and running electricity through an electrical heater immersed in a water tank. Since the introduction of gas pipelines to American homes, gas-combustion water heaters have become as popular as electric water heaters. Today, water heating is the second largest energy end use in homes (after space heating and cooling) and accounts for about 17% of consumed energy.

There has been progress in water-heating technology, especially as related to materials of construction, insulation, and gas burners. However, in the 1980s, manufacturers of the heat pump applied the technology to household water heating in the hopes that the mature technology could allay the efficiency woes of traditional electric and combustion water heaters. Heat pumps are more efficient than electrical immersion heaters because they use energy from the surrounding air to heat water—instead of running electricity directly through resistive elements. Like refrigerators and air conditioners, the heat pump water heater contains refrigerant in a sealed loop. As the refrigerant undergoes expansion, evaporation, compression, and condensation, it extracts heat from the surrounding air and releases it to the water tank.

Most HPWHs are hybrids, containing a heat pump and two electrical immersion heaters, all of which can operate independently or in combination. The heat pump can be either integrated with the water heater—as is the case with most models—or separate from it, in which case the heat pump is mounted next to the water heater or even outside the residence.

The typical control strategy is that when the tank water is drawn down (meaning temperature at one or more measurement points drops below a set point), the heat pump operates. When a more substantial draw causes the measured temperature to go below a second set point, the electric resistance elements will turn on as well to provide a speedy recovery. For each unit, the set points and their differentials are tuned differently in different operating modes. Operating modes include one that prioritizes energy savings and another that prioritizes hot water supply.

The ENERGY STAR rating has recently been applied to HPWH technology, with the most recent generation of water heater ENERGY STAR criteria effective as of January, 2009. In order for an electric water heater to qualify for the ENERGY STAR label, it must have an energy factor of 2.0 or greater (effectively mandating HPWHs for ENERGY STAR electric water heaters), with a first-hour rating of at least 50 gallons per hour. This means that many or most residential heat pump water heaters qualify as ENERGY STAR appliances.

Despite their higher energy efficiency, HPWHs have yet to penetrate the U.S. market, largely because of previous reliability issues and higher first costs. The most common HPWHs in the United States typically cost around three to five times the price of conventional electric water heaters, with prices in the range of \$1,200 to \$2,000. The systems are often advertised with ten-year warranties. Because the products are new, longevity is uncertain. Manufacturers expect a lifespan somewhere between 10 and 15 years. In the last decade, sales of HPWHs may account for only around 0.1% of all residential water heaters sold. It is expected that the costs of HPWHs will decrease as the market accepts the product. Therefore, federal credits and utility programs will become critical to the adoption and sustainability of HPWHs in the market.

Location of the installation may also pose a challenge. To draw energy from the ambient air, the heat pump of an HPWH has to have adequate air circulation, so that the colder air exiting the unit is easily vented. Therefore, the most appropriate locations for an HPWH may be unconditioned spaces like a garage or basement. However, if an HPWH is to be installed in a conditioned space, such as a closet, the unit must have adequate surrounding space or ductwork for the exhaust air, and the byproduct effect of air cooling may or may not be desirable.

Other consumer apprehensions may include reliability of the heat pump and noise during operation of the heat pump. As of now, unbiased field data on the reliability, efficiency, operational quality, and customer acceptance of HPWHs is not available in this country. Therefore, stakeholders in the entire country are looking to the EPRI Energy Efficiency Demonstration for such unbiased data.

## **Research Objectives**

Because heat pump water heaters have been deployed only in small numbers, the technology still needs to be proven. Although the technology itself is fairly well understood, the actual performance of HPWH systems had not been quantified in sufficient numbers. This Demonstration aimed to provide that quantification. The variation of system efficiency with climate, water usage, and installation location was examined. Using this information, insights

can be made regarding the viability of HPWHs for larger-scale deployment as an energy-efficiency measure.

The areas of research for the field portion of the HPWH Demonstration were the following:

1. Efficiency
2. Reliability
3. Customer Satisfaction

The efficiency is determined by observing the load-shape impacts and performance of these units in real-world settings. Doing so enables utilities to design customer programs that create utility and customer value.

Typically, a field comparison requires the development of a baseline, from which the efficient units can be compared. Utilities are most interested in three components: 1) Reliability of this new technology; 2) the impact on energy consumption as measured by the difference in the average load shapes; and 3) the coincident demand impact by assessing the impacts at the time of their system peak. The second component reduces the customer electric bills and utility cost savings, which ultimately are passed back to customers. The third reduces peak demand or coincident demand, which may result in deferring constructions of future power plants. These deferred costs are also passed back to customers.

To determine the effects of climate, ambient temperature, and temperature of the incoming water, the demonstration monitored the temperatures of the incoming and outgoing water flow and the air surrounding the HPWHs. The results of this monitoring will help to quantify the impact of climate and point toward conclusions about which climate zones are best suited for HPWH installations.

Previous laboratory work performed by EPRI has examined HPWH system performance in a laboratory setting. In 2009, EPRI conducted laboratory tests of several heat pump water heaters to assess their performance and energy efficiency. EPRI test three brands of HPWHs. These units are designed to be integral, drop-in replacements for standard electric water heaters. Additionally, EPRI tested a Japanese-manufactured heat pump water heater, which is a split unit with an outdoor heat pump utilizing CO<sub>2</sub> as the refrigerant and an indoor hot-water tank.

In its Knoxville laboratory, EPRI conducted a series of “draw tests” and “24-hour tests” under conditions that were not held within the prescribed bounds articulated in the federal water-heating test protocol, titled “Uniform Test Method for Measuring the Energy Consumption of Water Heaters,” from the U.S. Federal Code of Regulations, although this protocol was used as a guiding reference. EPRI’s laboratory tests were conducted using each water heater’s default operating mode, a 120°F (49°C)<sup>1</sup> water temperature setting, and other targeted testing conditions (maintained within EPRI’s lab-testing capabilities). The Demonstration sought to affirm the findings from the laboratory testing across a spectrum of conditions in the field, accounting for conditions that cannot be captured in laboratory testing.

In addition to performance goals, the Demonstration aimed to develop an understanding of the reliability and customer satisfaction with these products. Because the active deployment of

---

<sup>1</sup> (°F – 32) x 5/9 = °C

HPWHs is very low nationally, the Demonstration was among the first to see how HPWHs operate over an extended period and receive feedback from users on their experiences.

The research of the Heat Pump Water Heater Demonstration attempted to answer the following questions:

How does the efficiency and performance of HPWHs compare to the efficiencies of electrical immersion water heaters?

What is the coefficient of performance (COP) of HPWHs?

How is the reliability of the HPWHs? How do the performance and efficiency of HPWHs vary according to model?

How does climate affect HPWH efficiency and performance?

How does the location of installation affect HPWH efficiency and performance?

How does the location of installation affect the consumer?

How well do HPWHs reduce coincident demand during the winter and summer peak days?

How do the load shapes of HPWHs compare to the load shapes of traditional technologies? How does the size of the tank (55 gallons versus 80 gallons) affect the coincident demand reduction? Assuming the same draw pattern, larger tanks generally reduce the usage of electric resistance heaters, meaning reduced peak power.

What is the average mean time between failures (MTBF) of HPWHs?

What are the perceptions of consumers regarding the efficiency, performance, and aesthetic appeal of HPWHs?

What is the effect of inlet water temperature on efficiency?

## **Research Methodology**

The research methodology consisted of the following sub-tasks:

Design, test, and assemble instrumentation packages for treatment and control units.

Test commercially available HPWHs from each of the major manufacturers that were available at the inception of the Demonstration.

Conduct site-selection surveys to identify appropriate locations for treatment and control sites.

Install HPWHs and instruments in the field.

Collect and analyze data.

Conduct customer-satisfaction surveys.

## ***Design and Assemble Instrumentation Packages***

The HPWH systems installed in the field were instrumented to measure the quantity of hot water provided and the power/energy used in operation, among other significant variables. The “full” instrumentation package at each site included:

A power meter to measure the consumption of electricity by both the whole house and the water heater electricity (included two CTs for the whole house and one for the water heater).

A water-flow totalizer with sufficient resolution to capture small and large draws.

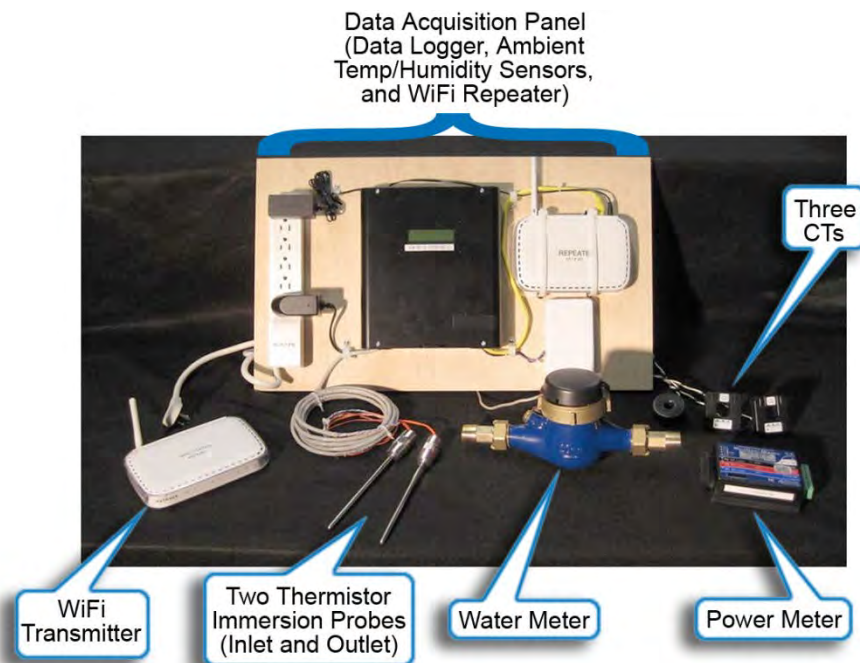
Two immersion thermistor probes for water inlet and outlet temperature.

An ambient temperature/humidity sensor for the air conditions surrounding the water heater.

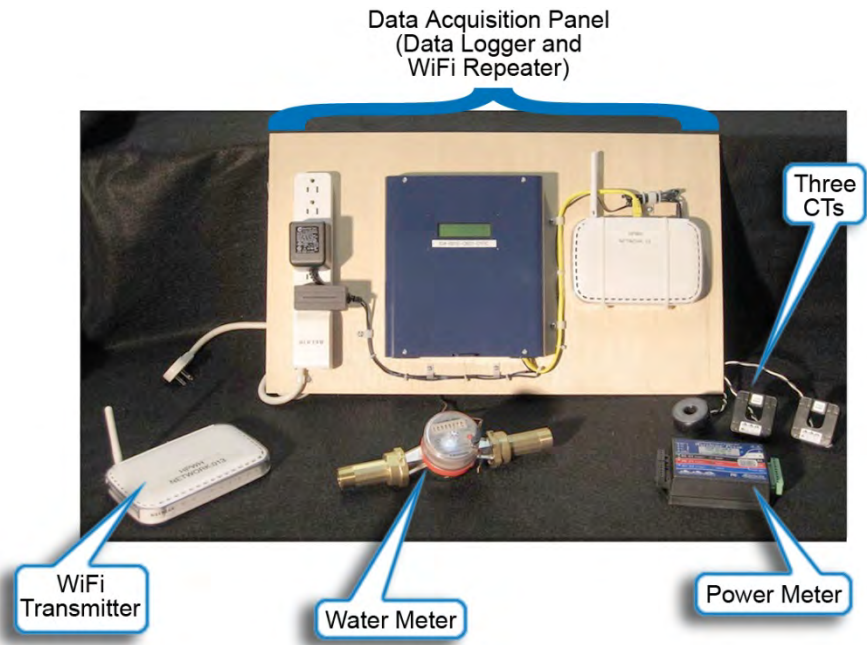
A data-acquisition device with wireless transmitter (WiFi) that plugs into the home router.

Some control sites were given a “lite” instrumentation package, which included a flow totalizer and energy measurements for the water heater and whole house. Figure 2-1 and Figure 2-2 show the full and lite packages, and Table 2-1 compares their characteristics.

Lite packages were initially specified for the control water heater sites as a cost-saving measure. The lite packages had the disadvantages of not including water temperature sensors and delivering a slightly different data file to EPRI, requiring additional data-processing steps. As the project progressed, the benefits of having a full package on control sites as well as treatment sites became clear, and some control sites installed later in the project received full instrumentation packages.



**Figure 2-1**  
**HPWH Full Instrumentation Package**



**Figure 2-2**  
**HPWH Lite Instrumentation Package**

**Table 2-1**  
**Comparison of Lite and Full Instrumentation Packages**

	<i>Units</i>	<b>Full</b>	<b>Lite</b>
<b>Data Logger</b>			
Recording interval	<i>minutes</i>	<b>1</b>	<b>5</b>
Memory capacity	<i>days</i>	<b>30</b>	<b>5</b>
Time (UTC)		✓	✓
Time (local to site)		✓	✓
<b>Whole House</b>			
Energy used (cumulative)	<i>Wh</i>	✓	✓
Power demand	<i>W</i>	✓	✓
Power	<i>W</i>	✓	
Voltages (L1-N, L2-N, L1-L2)	<i>V</i>	✓	
Currents (L1, L2)	<i>A</i>	✓	
Frequency	<i>Hz</i>	✓	
Reactive energy	<i>VARh</i>	✓	
Reactive power demand	<i>VAR</i>	✓	
Reactive power	<i>VAR</i>	✓	
<b>Water Heater</b>			
Energy used (cumulative)	<i>Wh</i>	✓	✓
Power demand	<i>W</i>	✓	✓
Power	<i>W</i>	✓	
Current	<i>A</i>	✓	
Reactive energy	<i>VARh</i>	✓	
Reactive power demand	<i>VAR</i>	✓	
Reactive power	<i>VAR</i>	✓	
Water volume used (cumulative)	<i>gal</i>	✓	✓
Water flow rate (avg)	<i>gpm</i>	✓	✓
Water inlet temperature (avg, min, max)	<i>°F</i>	✓	
Water outlet temperature (avg, min, max)	<i>°F</i>	✓	
Ambient temperature (avg)	<i>°F</i>	✓	
Ambient relative humidity (avg)	<i>%</i>	✓	
Natural gas volume used (cumulative)	<i>cu-ft</i>	*	*
<b>Additional Calculated Values</b>			
Energy content of hot water used	<i>Btu</i>	✓	
Efficiency (average COP over 1+ days)		✓	

\* *Optional, if control site utilizes a gas water heater.*

### ***Procure and Test HPWHs in the Laboratory***

EPRI procured HPWHs from three manufacturers. These were pre-production units provided for testing and evaluation purposes, substantively similar but not identical to the final production units produced by the manufacturers. EPRI performed laboratory testing on three brands of residential heat pump water heaters. Each was subjected to draw tests and 24-hour simulated use tests. The testing was performed using the systems' automatic "hybrid" modes, where the operation of the heat pump and resistance elements is controlled by the system.

### ***Prepare and Test Instruments in the Laboratory***

As the instrumentation was prepared by EPRI and a contractor, the system functionality for some packages was tested. Before packaging, each component was plugged into the data-acquisition system, and data from the data-acquisition system was transmitted to EPRI's data servers. This was done without tank connection, meaning that temperatures would be ambient air temperatures, and there was no water flow. Because the programming of a data-acquisition system can be saved and exported to all remaining data-acquisition systems, it was not necessary to confirm operation of all data-acquisition systems.

### ***Conduct Site-Selection Surveys***

Collaborating utilities selected potential sites for installation of HPWHs. Surveys were sent to the consumers at these sites. A site was approved if it satisfied several requirements. It was required that installation of both the water heater and the data-acquisition system could be performed without requiring additional engineering or parts. Requirements included having sufficient space for the water heater to be installed, having convenient access to power for the data acquisition, and having access to the customer's Internet connection for data transmission. Also, a site was rejected if it had any unusual loading or configurations, such as households with only one resident or where an instantaneous water heater was in use to boost temperature at one or more taps.

### ***Procure and Ship HPWHs and Instruments for Field Testing***

EPRI established standing accounts with the major vendors used for the Demonstration, with units available to be shipped to utility sites or installers on demand. The data-acquisition system was developed in partnership with a local contractor.

Several models of HPWHs from vendors were made available to EPRI for testing. Three models were predominantly used. They will be referred to in this report as Model A, Model B, and Model C.

### ***Install HPWHs and Instruments in the Field***

Water heaters and instruments were installed by local contractors, who were selected by the host utility. The process was outlined in instructions provided by EPRI. The two configurations—control and treatment—varied slightly, with most control sites receiving "Lite" packages (described above). Some control sites were installed with, or upgraded to, "Full" packages later in the project as "Full" packages became available. After installation, the installer was instructed to contact EPRI to confirm proper installation and data transmission.

In addition to the treatment HPWH systems, a number of baseline electric emersion water heaters were instrumented. These systems were already installed at the customer houses, varying greatly in age, size, and manufacturer. As of March, 2012, there were 159 HPWH and 38 control units in the field.

### ***Collect and Analyze Data***

Data was sent to EPRI approximately every 8 hours, automatically, by the data-acquisition system. Although the number of sites is too large for continuous site-by-site analysis, a checking methodology was added to monitor selected information from each site in order to catch errors or anomalies.

### ***Conduct Customer-Satisfaction Surveys***

The purpose of the HPWH customer surveys is to gauge customer satisfaction levels with the installation and operation of the equipment, as well as opinions regarding equipment appearance, noise levels, the existence of condensate leakage, and others.

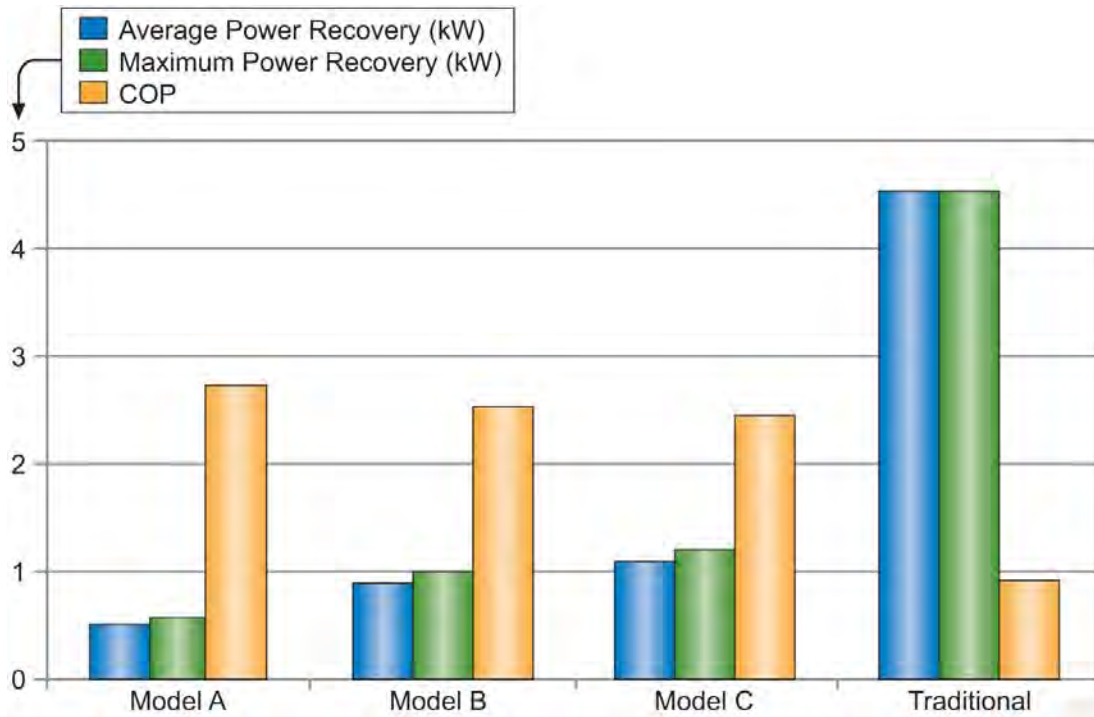
### **Laboratory Investigation**

In 2009, EPRI performed laboratory testing on residential heat pump water heaters under a complementary project [2-1]. The effort included testing of systems manufactured by three major manufacturers. Each was subjected to draw tests and 24-hour simulated use tests. The testing was performed using the systems' automatic "hybrid" modes, where the operation of the heat pump and resistance elements is controlled by the system. Each U.S. HPWH engaged a resistive element during a portion of the recovery period. The draw tests suggest that the tested HPWHs are more than twice as efficient as standard electric water heaters. During the draw tests, the three different models achieved an overall COP of 2.0 or higher. The recovery period differed for each water heater, ranging from 1.4 hours to 3.4 hours.

#### **Twenty-Four-Hour Tests**

During the 24-hour tests, which subjected water heaters to a simulated water-usage pattern, each HPWH engaged only the heat pump system and achieved an overall COP of 2.4 or higher. Figure 2-3 shows the results of a 24-hour test for three HPWH models and a traditional resistance water heater. Additionally, the water heaters drew less than 25% of the average power drawn by a standard electric water heater during their periodic recovery cycles.

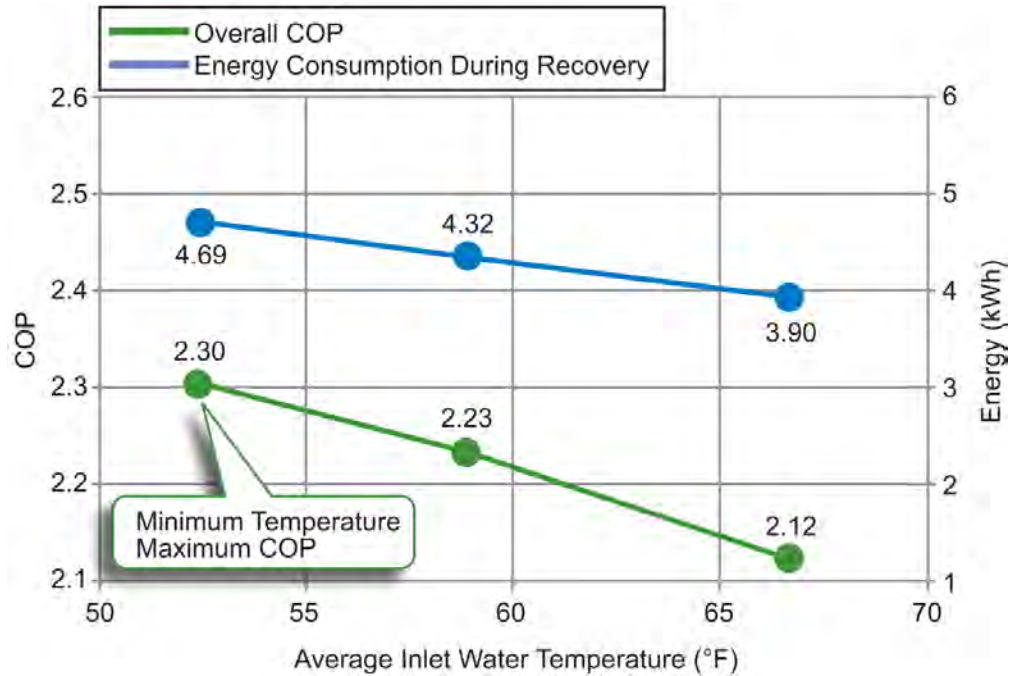
In addition to the three U.S. HPWHs, a Japanese system, which uses CO<sub>2</sub> as the refrigerant, was tested. The design of this system differs from the U.S. models in that it does not incorporate electric resistance elements. It should be noted that there are currently no commercially available CO<sub>2</sub> systems in the United States. During the draw testing, the CO<sub>2</sub> system operated with a COP of 3.8. However, because the unit did not have a resistance element, the duration of reheating was longer than the conventional systems. The results of this work can be found in [2-1].



**Figure 2-3**  
**Overall COP and Recovery Power During a 24-Hour Test**

### Draw Tests

To characterize the effect of inlet water temperature on efficiency and energy consumption during recovery, three draw tests were performed at 52, 59, and 67°F (11, 15, and 19°C). Each test had a draw rate of 3 gallons/minute for a duration of 3.7, 3.4, and 3.1 hours, respectively. Figure 2-4 shows a typical pattern for HPWHs. Generally, the colder the supply of water, the higher the efficiency but the greater the energy required to recover the consumed hot water during the draw test. The efficiency is higher at colder inlet temperatures because it is easier for the heat pump to move heat to cold water than to warm water.

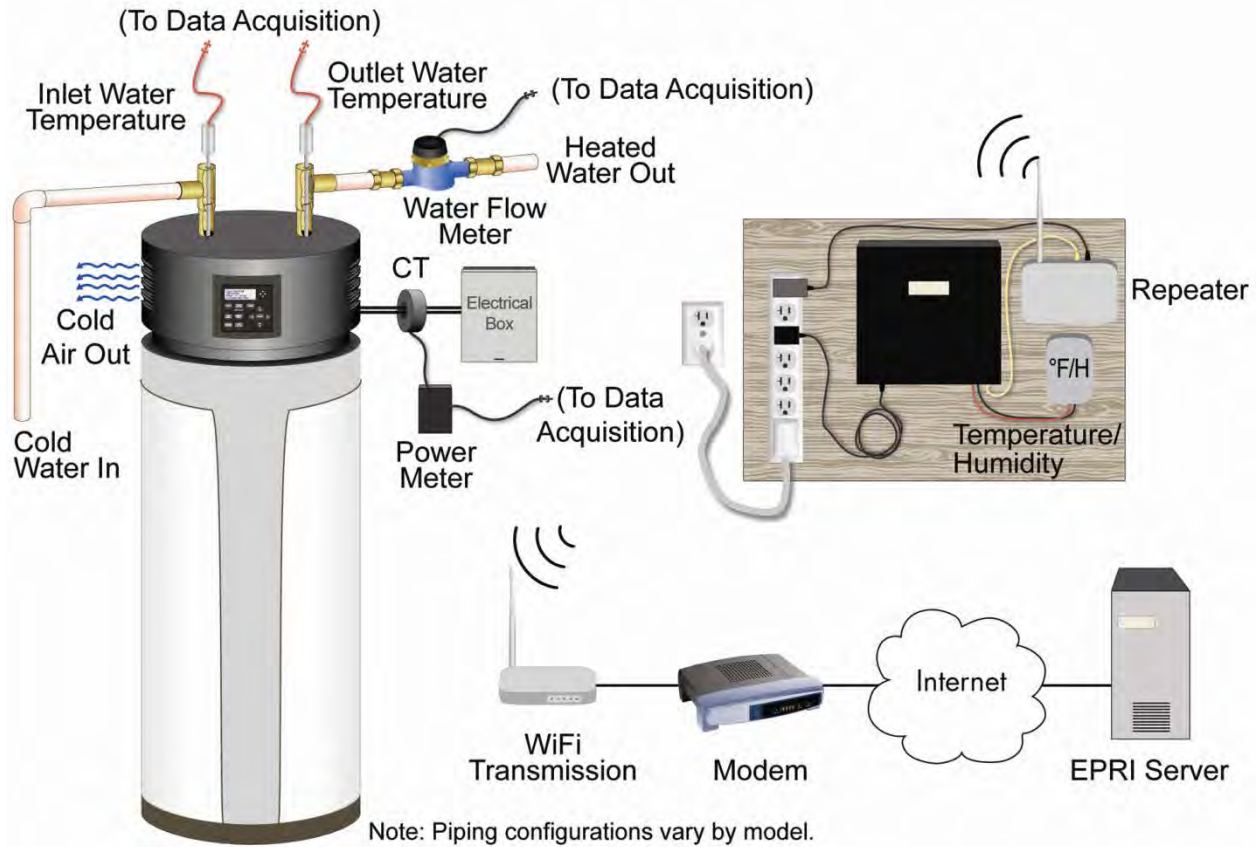


**Figure 2-4**  
**The Effect of Inlet Water Temperature on COP and Energy Consumption**

### Collection and Analysis of Field Data

The host utilities attempted to select treatment and control sites from the larger list of customers willing to be subjected to testing. However, some installation sites were not randomly selected and do not constitute a statistically valid sample.

Data was collected using the data-acquisition package shown in Figure 2-5 and described above. The schematic below shows how the data acquisition might look on a typical HPWH installation. The data collected from the water-flow and temperature sensors and the power meter were collected locally on the data-acquisition box, then sent via the Internet to EPRI's servers. The data was stored in a database, from which it can be recalled and analyzed by the EPRI Analytics department and EPRI's thermal and HVAC engineers. Note that temperature/humidity sensors were mounted on a board with the data-acquisition device, and installers were instructed to mount the board out of the direct path of airflow from the heat pump. Measurements were made automatically on a one-minute basis.



**Figure 2-5**  
**Instrumentation Used to Measure Field Variables**

### **Field Test Results**

#### **Data Description**

The distribution of control and treatment sites by climate zone, and the distribution within each climate zone for each type of water heater, is shown in Table 2-2. The sites listed in this table represent only sites for which the data, after initial screening, was used in analysis. Some sites were removed if the data set had substantial gaps. As can be seen, the largest distribution of water heaters was in the mixed-humid climate. For that reason, much of the “overview” data focuses primarily on the mixed-humid climate. Figure 2-6 shows the number of installations over time. The data in Table 2-3 shows the number of sites in each climate zone, under each utility.

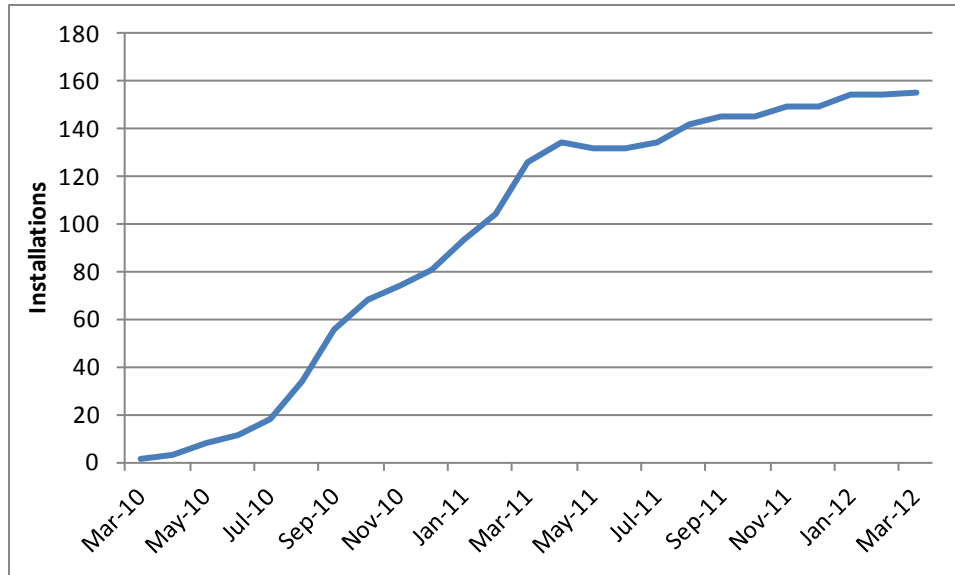
**Table 2-2**  
**Number of HPWH Installations by Characteristic**

	Control			Treatment				Total*
	Electricity	Natural Gas	Control Total	Mfg. 1	Mfg. 2	Mfg. 3	Treatment Total	
<b>Cold</b>	3	N/A	3	8	N/A	3	11	14
<b>Hot-Humid</b>	1	1	2	6	3	3	12	14
<b>Marine</b>	4	N/A	4	11	3	3	17	21
<b>Mixed-Humid</b>	15	2	17	32	30	12	74	91
<b>Total</b>	23	3	26	57	36	21	114	140

\* Some installations experienced interruptions in data.

**Table 2-3**  
**Number of HPWH Installations for Each Host Utility by Climate Zone**

	Cold	Hot-Humid	Marine	Mixed-Humid	Total
<b>Utility A</b>	N/A	12	N/A	15	27
<b>Utility B</b>	N/A	N/A	N/A	35	35
<b>Utility C</b>	N/A	N/A	N/A	22	22
<b>Utility D</b>	11	N/A	17	2	30
<b>Total</b>	11	12	17	74	114



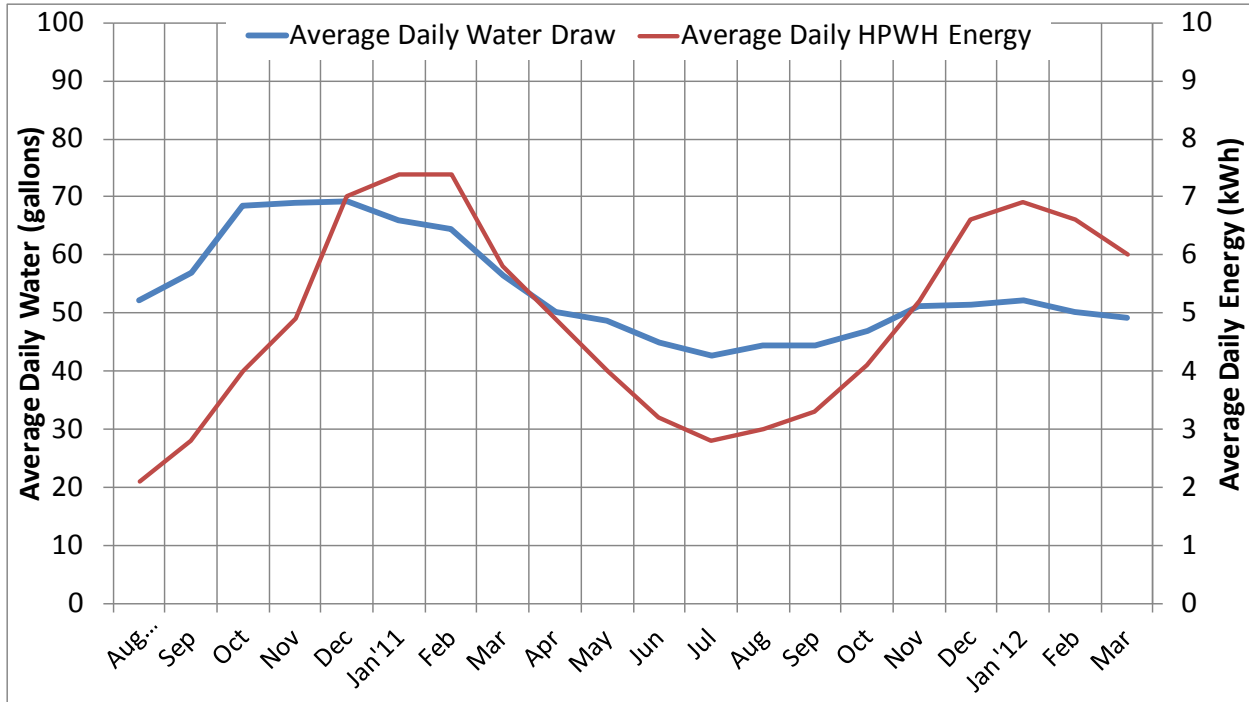
**Figure 2-6**  
Number of Installations over Time

Table 2-4 shows the number of heat pump water heaters installed in conditioned or unconditioned space for each utility. In general, “unconditioned” refers to a space that is not directly in an HVAC-controlled zone. Examples include garages and unfinished basements. As can be seen, the installation location trend varied significantly by utility: In three of the four utilities, a large majority of the water heaters were in unconditioned spaces; however, Utility C had more water heaters in conditioned spaces than in unconditioned spaces. It should be noted that not all sites had an identified installation location; for some sites, the installation location was inferred based on data for ambient air temperature.

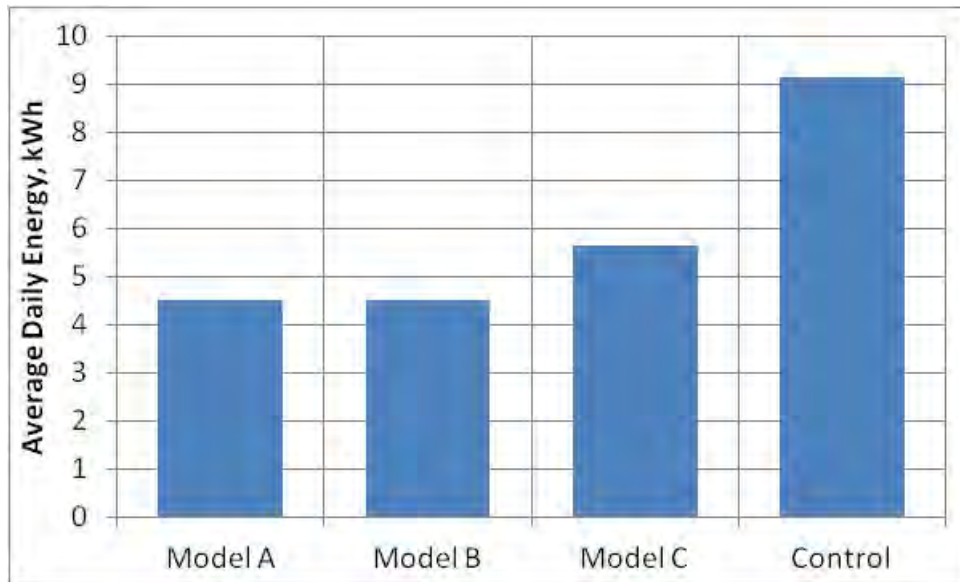
**Table 2-4**  
Number of HPWH Installations for Each Utility by Type of Conditioned Space

	Unconditioned Space*	Conditioned Space**	Total
Utility A	24	3	27
Utility B	28	7	35
Utility C	10	12	22
Utility D	24	6	30
<b>Total</b>	<b>86</b>	<b>28</b>	<b>114</b>
*Example: Garage			
**Space heating or cooling regulated by a thermostat. Example: indoor closet.			

Figure 2-7 shows the average daily water draw for all sites during the demonstration. One interesting observation from this data is that significantly more water was used in the winter of 2010–11 than winter 2011–2012. This may be related to the relatively colder winter in 2010–11 for much of the country. This trend was observed even controlling for the changing number of sites, by comparing those sites that were installed in both winters.



**Figure 2-7**  
Average Daily Water Draw and HPWH Energy for Models A and B, by Month, All Sites



**Figure 2-8**  
Average Daily Energy for Control and Treatment Water Heaters

The average daily energy consumption of the control water heaters was 9.43 kWh per day. The average consumption for all heat pump water heaters in the mixed humid climate was 4.69 kWh per day, a reduction of 50%. Model C had a specific design that caused more use of the electric resistance elements in many installations. If Model C is excluded, the average energy consumption was 4.53 kWh per day or 52% less than the control sites. The average energy consumption is also shown by region, and by model, in Table 2-5. It is important to recognize

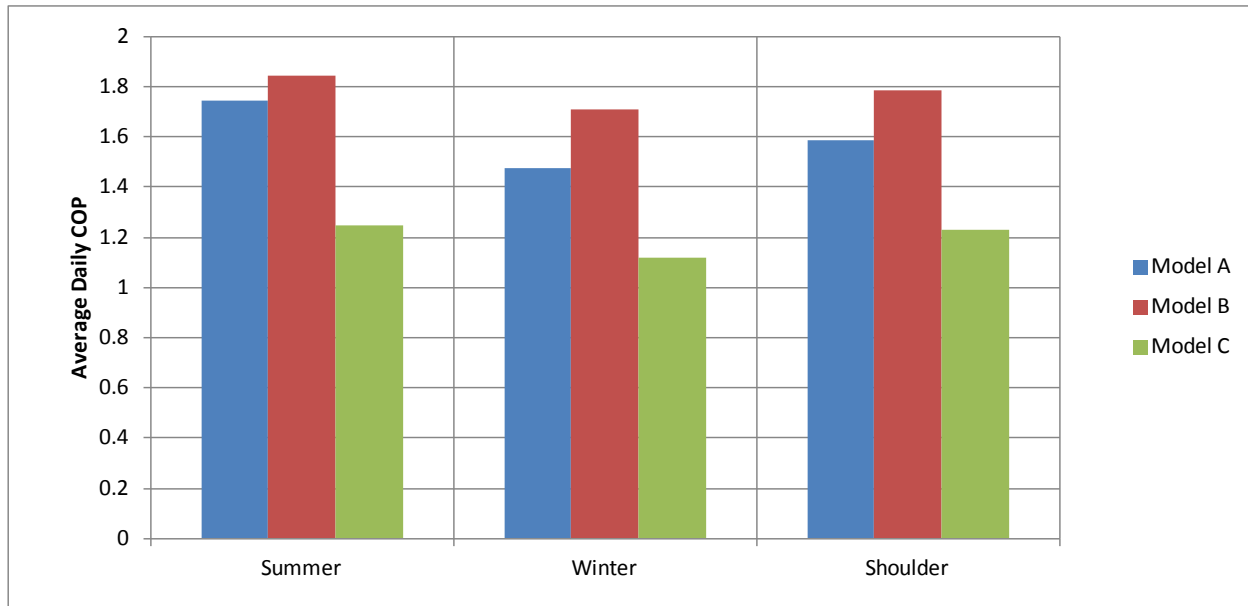
that the comparison of energy alone is not sufficient to distinguish the units: This number is not adjusted for the amount or temperature of hot water, and in some regions, few units of a particular model may be installed.

**Table 2-5  
Energy Consumption by Manufacturer and by Region**

Energy Consumption per Day (kWh)	Model A	Model B	Model C
Cold	6.1	(insufficient data)	8.2
Mixed Humid	4.5	4.5	5.7
Marine	5.8	5.6	6.7
Hot Humid	4.7	3.2	4.4

The average COP for each model is shown for the mixed humid climate in Figure 2-9. Average COP is a more reliable number than energy, because it incorporates the amount of delivered water and amount of heat added to the water, as well as energy consumption. As can be seen in Figure 2-9, the Model C system had the lowest COP in all seasons. The COP was 1.25 in summer, 1.12 in winter, and 1.23 in the shoulder seasons. Model A had a higher COP: 1.74 in summer, 1.48 in winter, and 1.59 in the shoulder seasons. Model B had the highest COP. Model B’s COP was 1.84 in the summer, 1.71 in the winter, and 1.79 in the shoulder seasons.

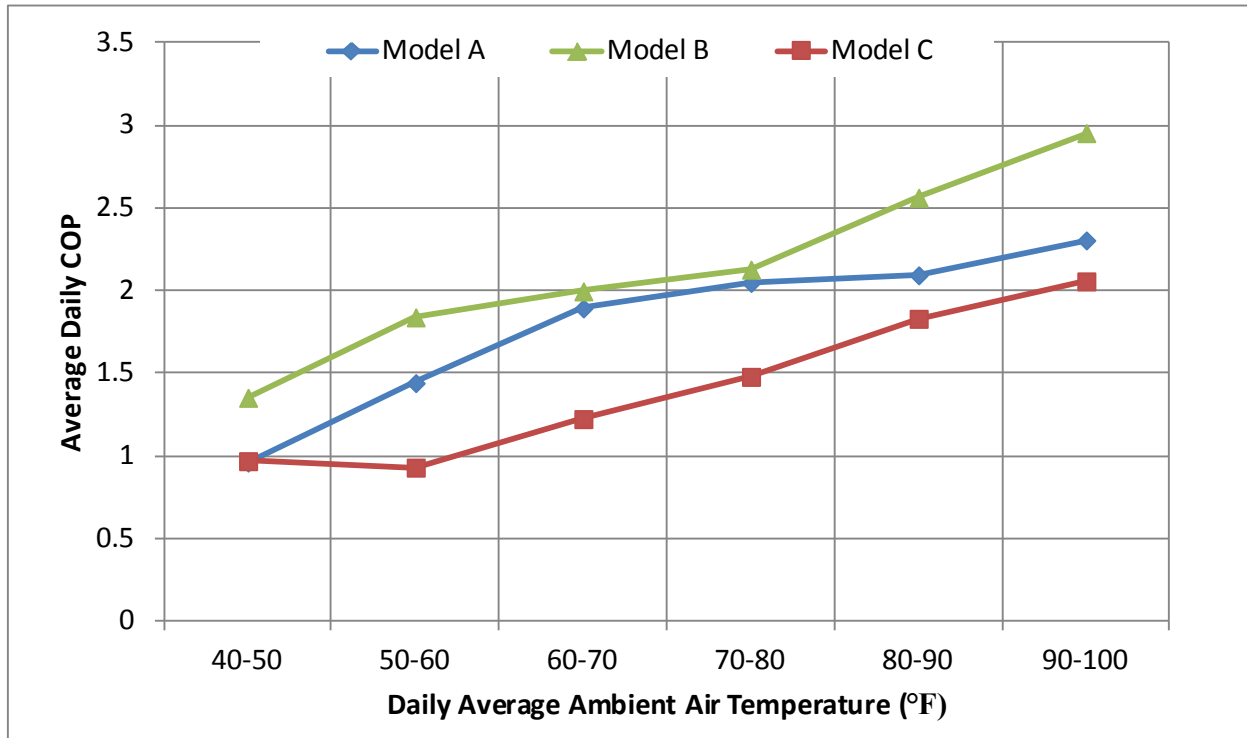
The average COP for the electric resistance water heaters, nation-wide, was 0.83.



**Figure 2-9  
Average Daily COP for Each Model, by Season, for Mixed Humid Climate**

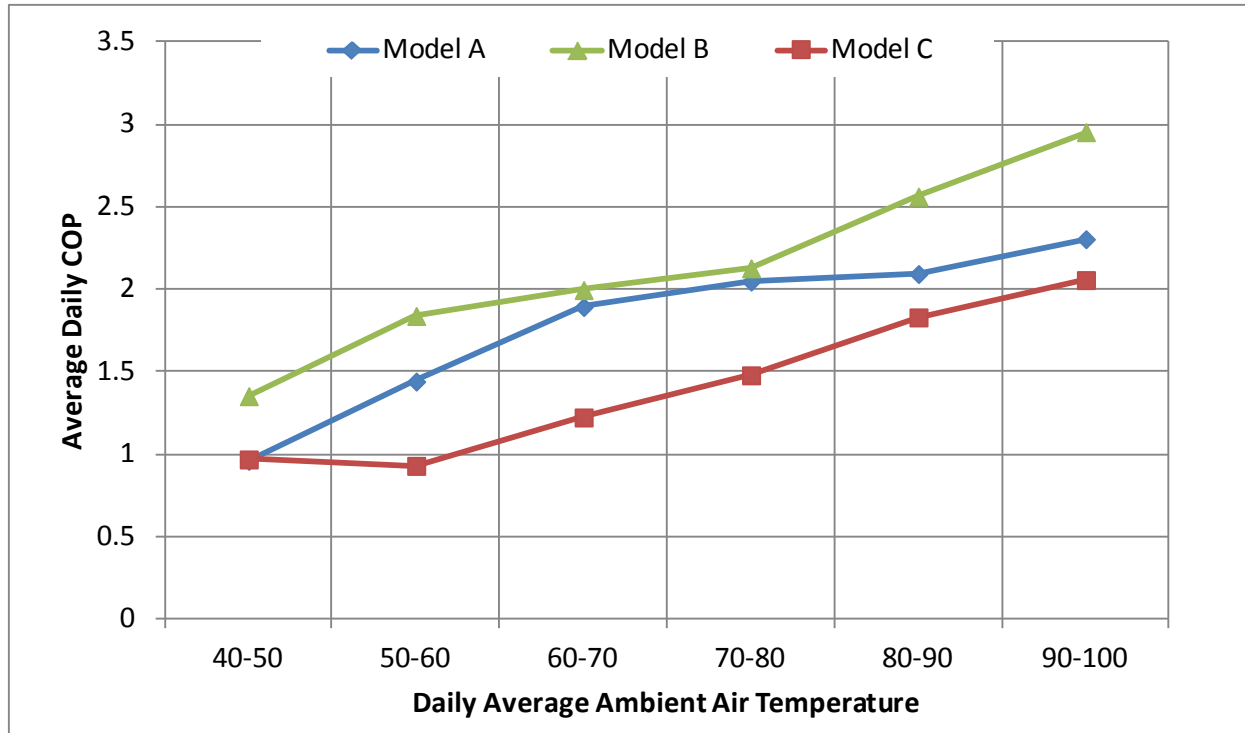
The effect of ambient temperature on COP is examined in Figure 2-10, which shows the COP for each model of HPWH. The data was screened to include water draw ranging from 40–60 gallons per day and to have maximum supply temperatures (approximate set-point temperatures)

between 117°F (47°C) and 130°F (54°C), to try to isolate the effects of ambient temperature. The trend is generally as expected, with COPs lowest when the ambient temperature was very low (the models tested generally only allow electric resistance operation in temperatures starting around 45°F [7°C]), and high COPs when ambient temperature was high. Table A-2 in Appendix A summarizes the relevant data in more detail.



**Figure 2-10**  
Effect of Ambient Air Temperature on COP for All Climates

It is of interest to understand the performance heat pump water heaters in northern climates and in winter. The HPWHs in the “cold” climate zone used on average 6.18 kWh per day in 2011, 34% less than the electric resistance water heaters. Looking in further depth, Figure 2-11 shows the frequency in site-days for each average ambient air temperature bin for November, 2011 through March, 2012. The number of site-days represents the total number of days, for all sites, in that bin. For example, if one site was within the 40°F (4.4°C) to 50°F (10°C) bin for two days, and one more site was in that bin for one day, the total number of site-days would be three. As can be seen, there are infrequent times even in the cold climate in which the ambient temperature was below approximately 50°F (10°C) in the winter. Among these sites for winter 2011–2012, the average COP for unconditioned spaces for winter was 1.01; in conditioned spaces, it was 1.47.



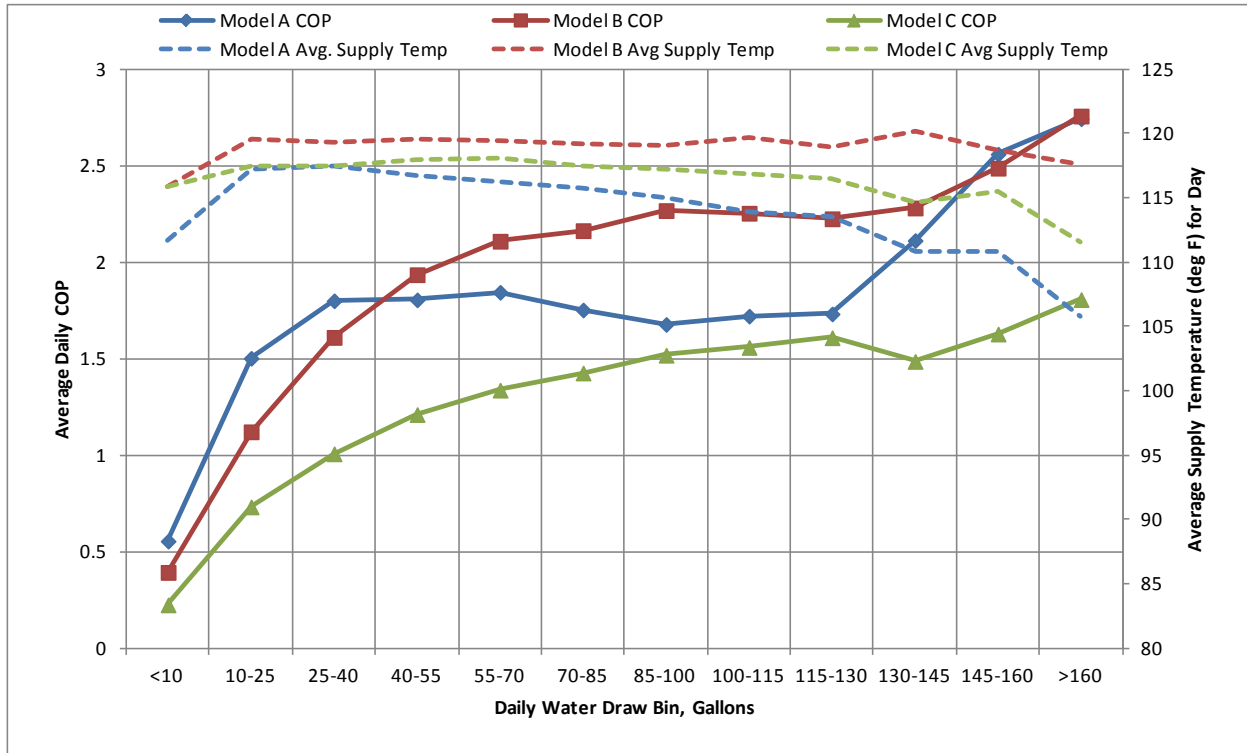
**Figure 2-11**  
**Frequency of Ambient Temperature Bins and COP for Cold Climate, All Models**

The effect of daily water draw is shown in Figure 2-12, showing both the values for each model. Table A-1 in Appendix A shows more detailed data. As shown, at low daily usage, the COP was low, and the average supply temperature was low. In these cases, the supply temperature shown was likely low because of standby losses into the pipe: Generally water-temperature data is only used in calculations when water is being delivered, in effect removing pipe losses from system performance; however, when very little water is delivered, the standby temperature represents a much larger proportion of delivered water. The COP was also low in these cases, because most energy goes to recovering standby losses rather than heating delivered water. The recovery was not included in calculation of COP.

At the high end of the water-draw spectrum, temperature of the delivered water can be seen to drop off, suggesting that some large draws or series of draw events were depleting the HPWH storage such that delivery temperature declined. In these cases, the COP was also relatively high, which highlights an important consideration: High COP does not necessarily mean all demands are met. High efficiency is not useful if the user does not receive enough hot water.

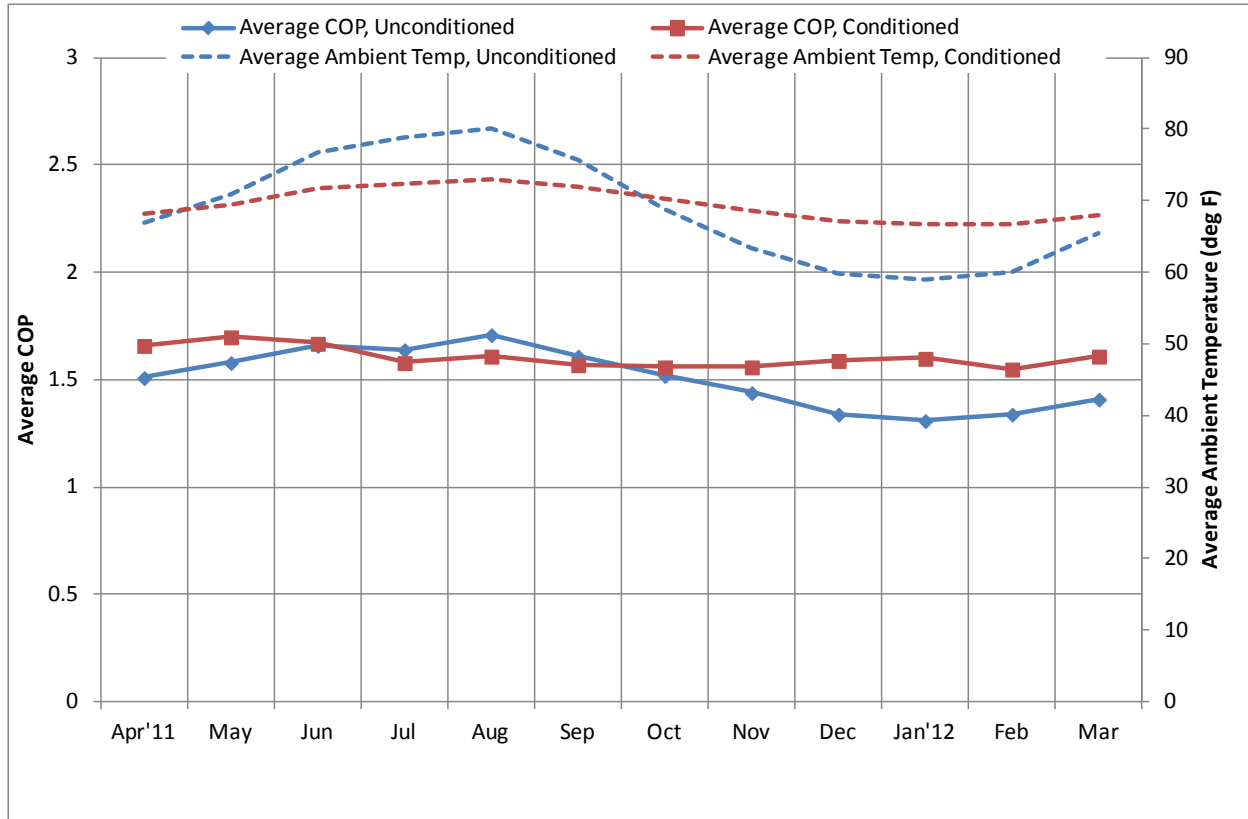
Looking at the more moderate daily water demands, some distinction between the systems can be seen. Model A had the highest COP at low-load conditions, up to approximately 40 gallons. Model A also had a slightly decreased COP for moderate-to-high demands, suggesting some increased dependence upon electric resistance heat. The average delivered water temperature for the Model A systems can be seen to decrease consistently, which may suggest that some loads were not met at higher draw rates. Model B had the highest COP, starting at 40 gallons per day, and the average delivered temperature did not reduce much with increased flow until very high flow rates. This improvement was likely related to the higher volume of the tank storage of the

Model B systems. Model C had the lowest COP consistently and also saw reduction in average supply temperature with higher water draws.



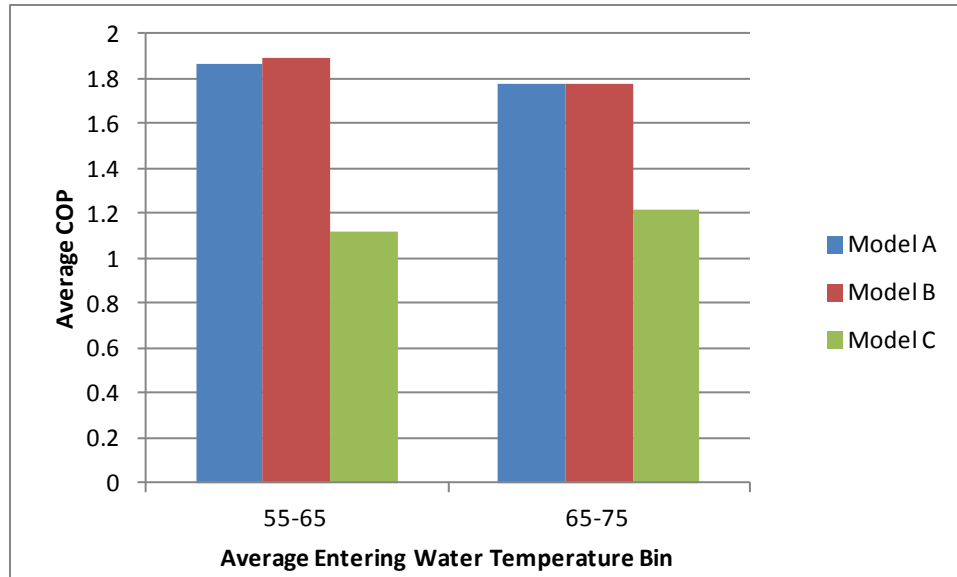
**Figure 2-12**  
Effect of Daily Water Draw on COP for All Climates

The effect of installation location (conditioned or unconditioned) is examined in Figure 2-13 for all water heater models and locations. The average ambient temperature is shown with dotted lines for conditioned and unconditioned installation, with the average COP shown by solid lines. It should be noted that the number of unconditioned installations is substantially higher than the number of conditioned installations. The results shown in this figure align with expectations: the COP was relatively level in the conditioned space where ambient temperature was steadier, and the COP fluctuated seasonally in the unconditioned space where exposure to outdoor conditions was higher. The most striking difference here is in the winter, when COP was approximately 15 to 20% lower in the unconditioned space than in the conditioned space.



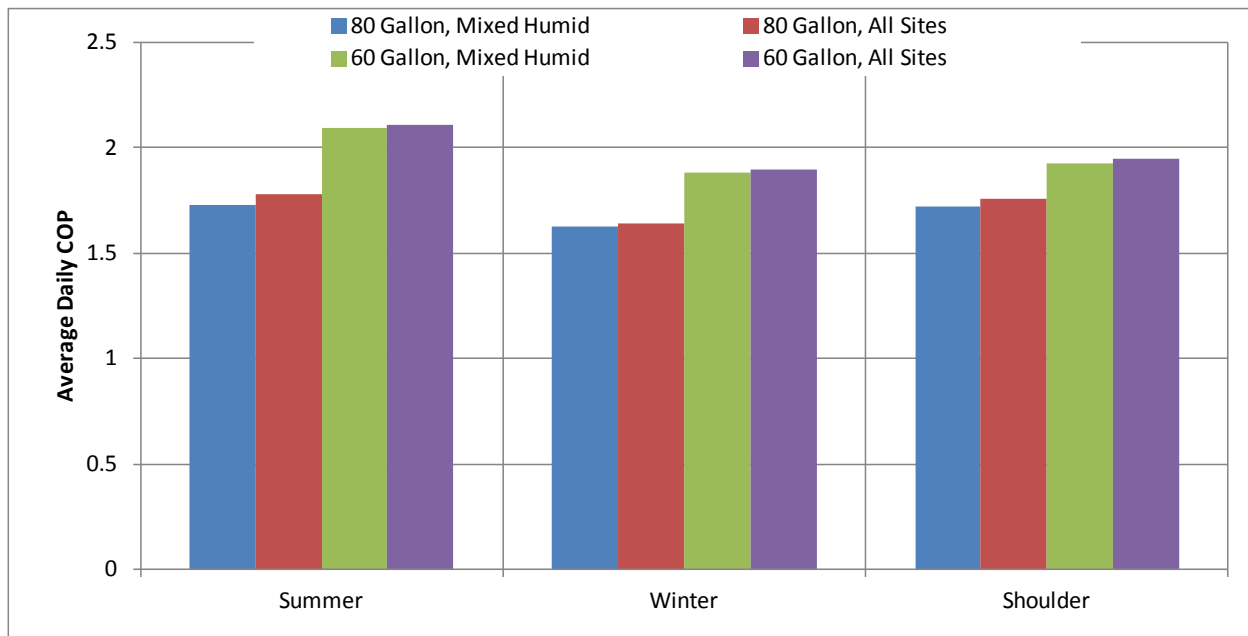
**Figure 2-13**  
**Effect of Installation Location, All Climates**

The effect of inlet water temperature is difficult to extract from the data because it is intimately related to climatic effects—region and season—which in turn impact ambient temperature. Figure 2-14 shows a reasonably fair comparison. Sites were screened to have water draw between 40 and 55 gallons per day and ambient air temperatures from 60 to 70°F (16 to 21°C) per day. The figure compares days for which the average inlet temperature was 55 to 65°F (13 to 18°C) and those where water was 65 to 75°F (18 to 24°C). This average reflects the water entering the tank, not necessarily the temperature of the local supply water. The average temperature for each of the three models was approximately 2°F (9°C) higher for the cases where the average temperature of the entering water was higher. Controlling for other variables as discussed, the COP was approximately 5% higher for Models A and B, with entering water temperature approximately 10°F (6°C) lower. For Model C, a slight increase in COP was seen, suggesting that additional factors that are not addressed by the data screening are at play.



**Figure 2-14**  
**COP for Each Model for Similar Ambient Air and Draw Volume, with Different Entering Water Temperature**

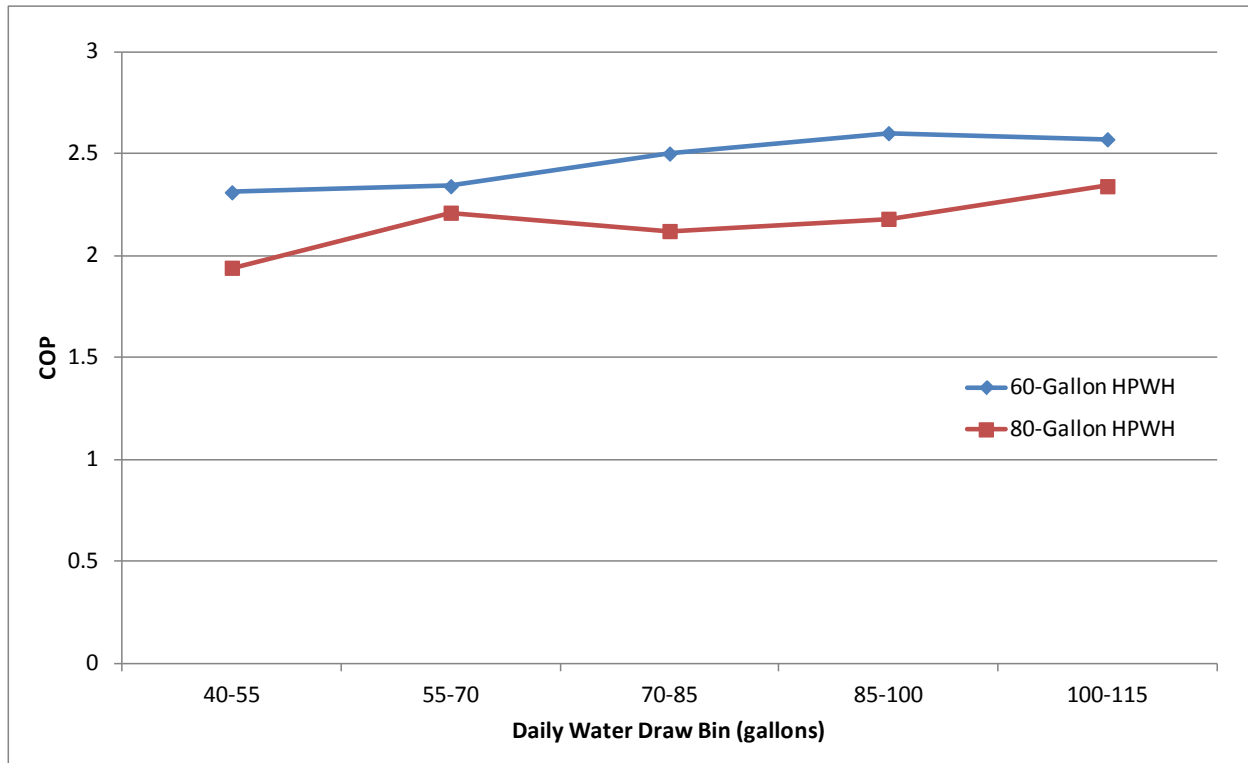
It is also of interest to compare the effect of tank size. Model B was the only model tested that was available with two different tank sizes. Figure 2-15 shows the average COP for the mixed humid climate, as well as for all sites, for the Model B 60- and 80-gallon systems. There was a slight improvement in COP for the 60-gallon HPWH as compared with the 80-gallon model.



**Figure 2-15**  
**Comparison of COP for the 60- and 80-Gallon Tank Sizes**

The average daily water consumption for 80-gallon units was 53.1 gallons; for 60-gallon units, the average was 50.6. A closer analysis of the tank size was also performed, a summary of which is shown in Figure 2-16. The data collected is also summarized in Table A-1 in Appendix A,

which shows other considerations such as ambient temperature and supply temperature. Sites were selected from the Mixed-Humid climate, with ambient air temperature between 60°F (16°C) and 80°F (27°C), average entering water temperature between 60°F (16°C) and 65°F (18°C), and average supply water temperature between 118 and 122°F (50°C). As Figure 2-16 shows, the average COP was higher for the 60-gallon units across all daily draw bins. It should be noted that while the average supply temperature is accounted for, no metric is shown for the frequency of delivery below the desired outlet temperature. This result suggests that further analysis and laboratory testing may prove useful in identifying the appropriate application for the larger storage tank.



**Figure 2-16**  
**COP vs. Daily Water Draw for 60-Gallon and 80-Gallon HPWHs, with Data Screened for Ambient Air and Entering and Supply Water Temperature**

### Demand Impact Analysis

Most HPWHs have an electric resistance element that can cause them to operate in exactly the same manner as a conventional electric water heater under some conditions, and it is possible that they contribute to utility peaks. This is of particular concern in the winter, when water usage tends to be high and ambient air temperature may be low.

Table 2-6 shows the coincident demand reduction for HPWHs during the peak periods reported to EPRI by the utility hosts. For the winter, the peak hours are defined as hour-ending 6:00 AM to hour-ending 8:00 AM, and for summer they are hour-ending 4:00 PM to hour-ending 6:00 PM. As can be seen, the winter 2011 and winter 2012 findings are consistent with past findings from the Demonstration: The peak demand reduction is low on worst-case winter days. In

summer, the coincident demand reduction was considerably higher, ranging from 231 W to 369 W.

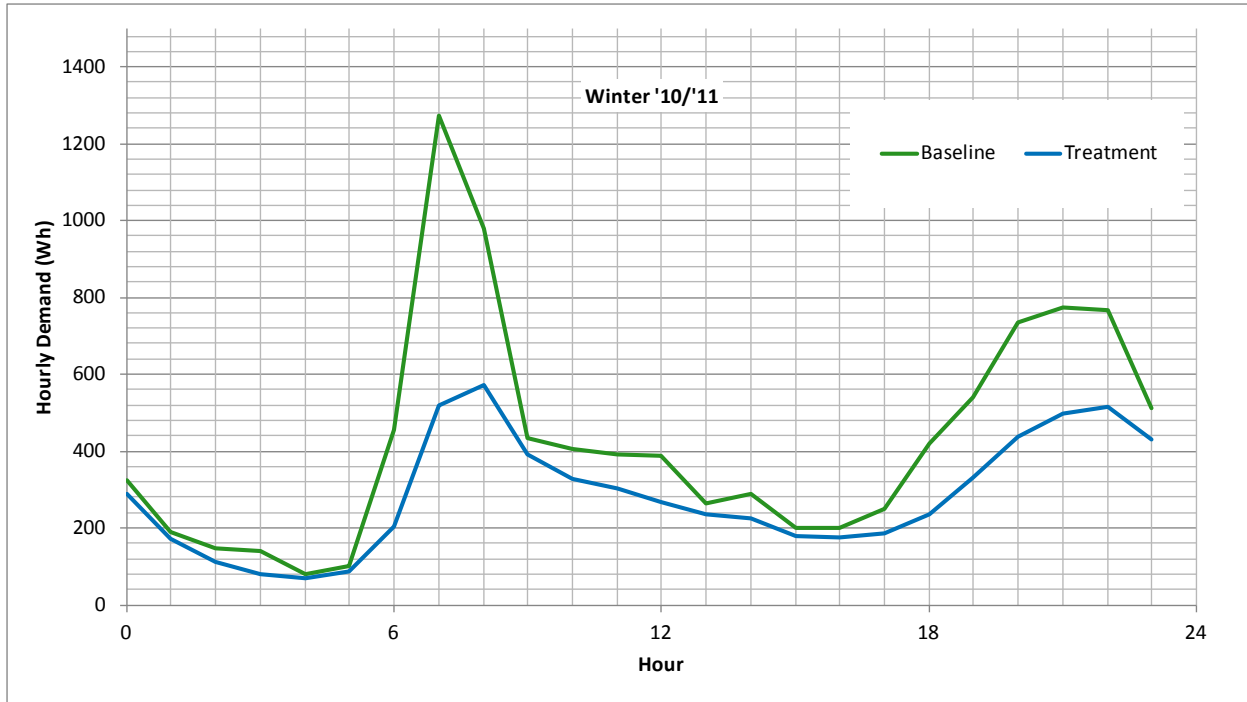
**Table 2-6**  
**Coincident Demand Reduction for Utility Peak Days**

Season	Coincident Demand Reduction (W) (Percent Reduction in Parentheses)				System Peak Days (by Host)
	Cold	Hot-Humid	Marine	Mixed-Humid	
Winter 2011	102 W (3.31%)	120 W (6.56%)	97 W (2.23%)	136 W (7.32%)	03 Jan 2011 14 Jan 2011 08 Feb 2011
Summer 2011	298 W (10.23%)	268 W (19.53%)	231 W (12.35%)	369 W ( 23.38%)	01 Aug 2011 03 Aug 2011 25 Aug 2011
Winter 2012	193 W (7.38%)	186 W (9.84%)	168 W (8.18%)	246 W (11.39%)	13 Dec 2011 04 Jan 2012 12 Jan 2012 13 Feb 2012

The utility winter peak typically represents conditions least favorable to heat pump water heaters. It is also of interest to look at more typical load profiles, which are shown below. Because it has by far the largest sample size, the Mixed-Humid climate is used.

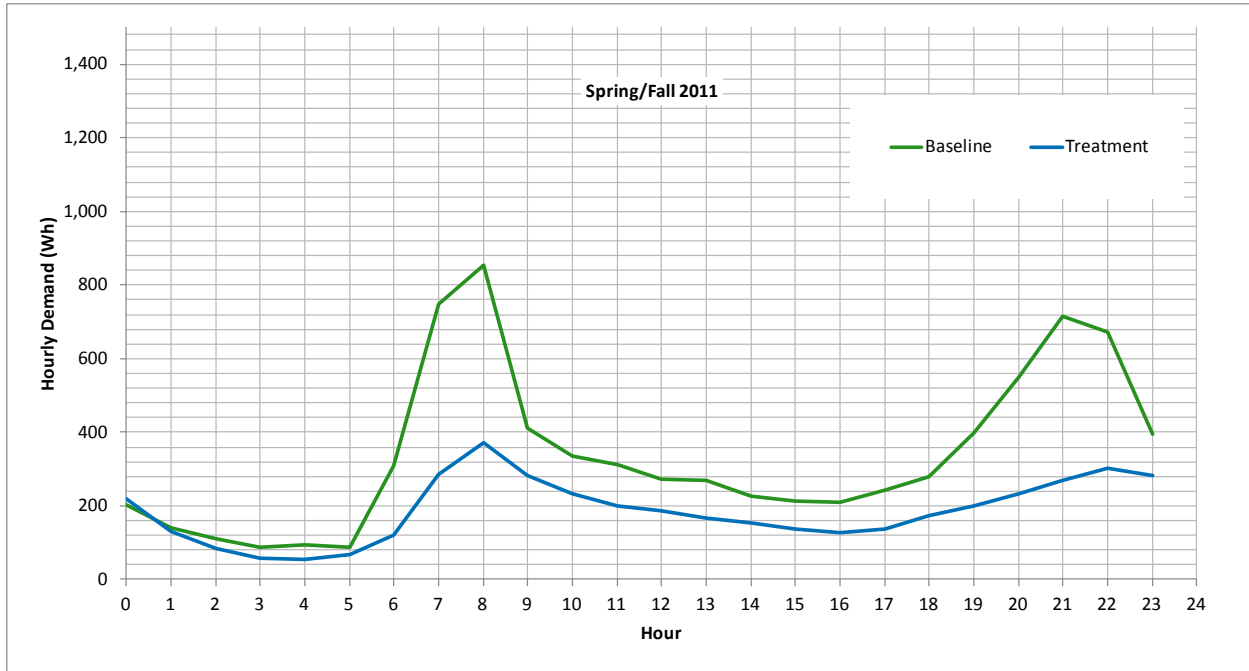
Figure 2-17 through Figure 2-22 show the average load shapes for winter 2010–11 (defined as December through March), spring and fall of 2011 (April, May, October, and November), Summer 2011 (June, July, August, and September), and Winter of 2011–12 (December through March). The average daily energy consumption for each season for the Mixed-Humid climate is shown in Figure 2-17. For both control and HPWH, the consumption is highest in winter and lowest in summer, with the largest percent savings occurring in the summertime.

The load shapes shown below show both the relative performance of heat pump water heaters compared with electric resistance units, as well as the seasonal variation. It may be noted that winter 2011–12 was milder than winter of 2010–11, which may in part explain the apparent lower water-heating demand seen in winter 2011–12 than 2010–11. Also, although the sites span several time-zones, the averages shown below are calculated with the local time of each site.

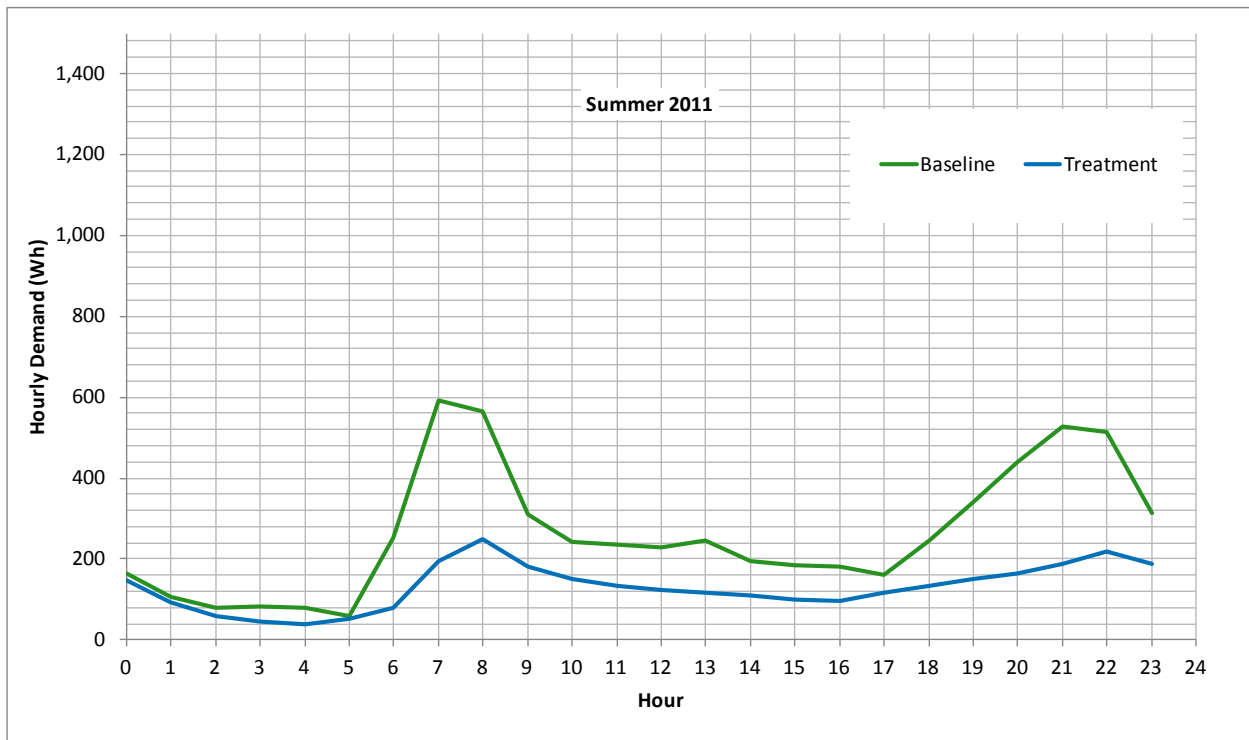


**Figure 2-17**  
**Load Shape for Mixed-Humid Climate, Winter 2010–2011**

Figure 2-17 shows the demand for all Mixed-Humid sites for Winter 2011–12. The peak hourly demand for control sites was 1.27 kW for the hour ending 7:00 AM (note: further discussion of hours will refer to “hour ending”). For the HPWH sites, the peak hourly demand was 570 watts at 8:00 AM, and the demand at 7:00 AM was 519 watts, 59% lower than that of the baseline systems. Figure 2-18 shows demand for the spring and fall of 2011. The peak hourly demand of each group was at 8:00 AM, with the baseline sites using 853 watts and the HPWHs using 372 watts, a 56% demand reduction.



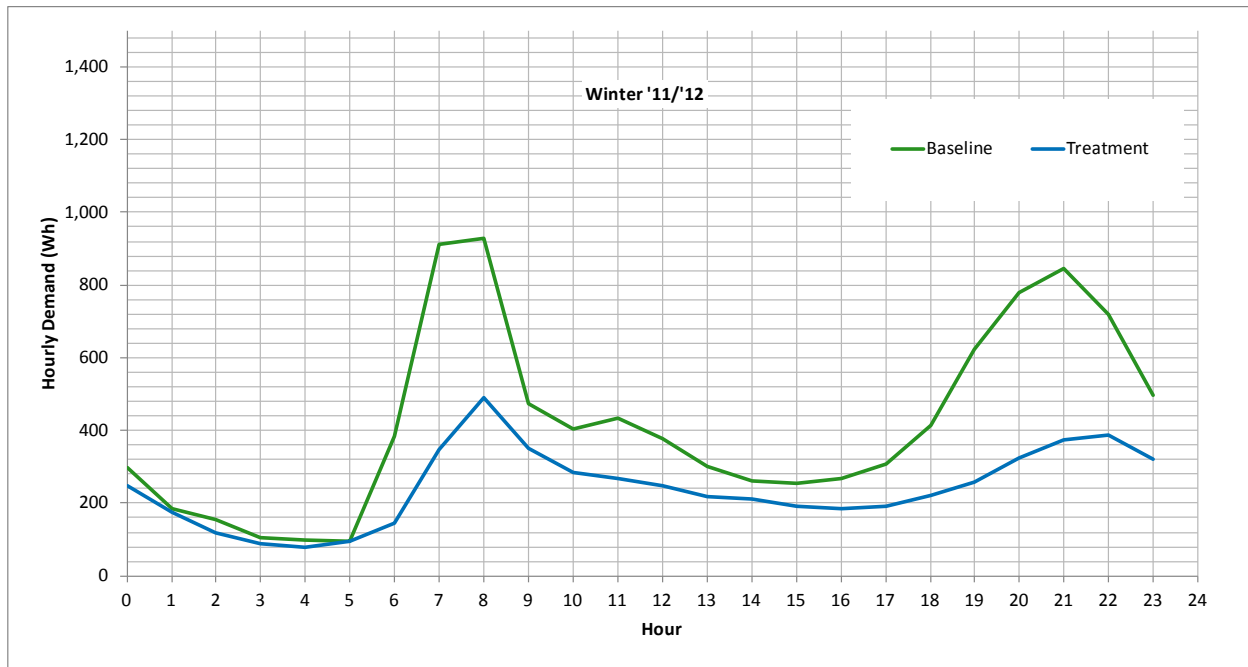
**Figure 2-18**  
Load Shape for Mixed-Humid Climate, Spring and Fall 2011



**Figure 2-19**  
Load Shape for Mixed-Humid Climate, Summer 2011

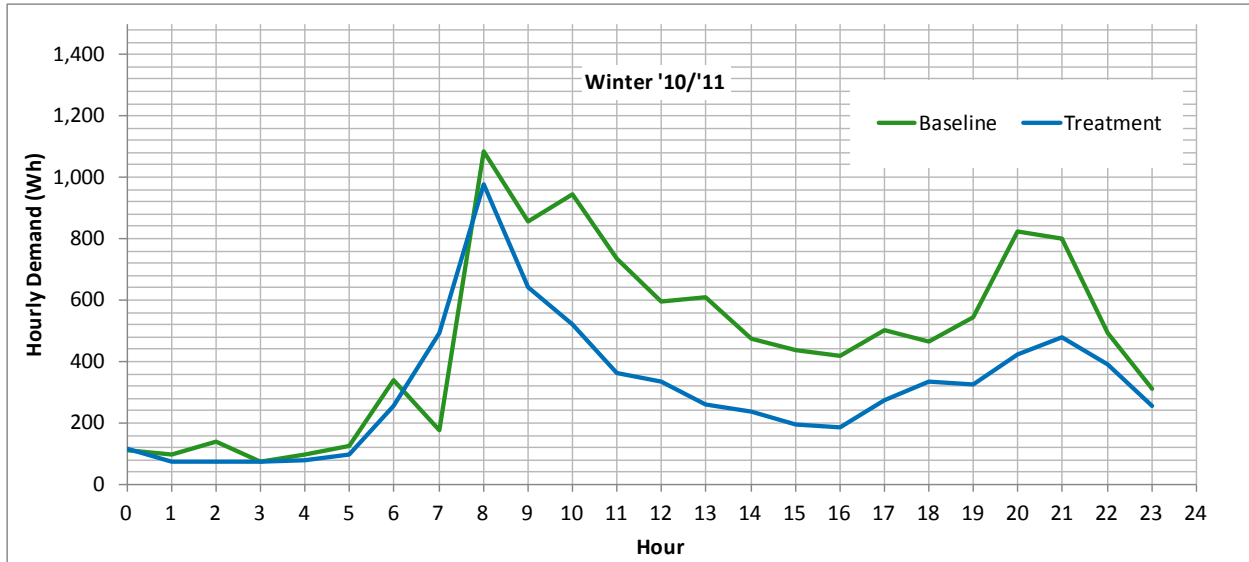
Figure 2-19 shows the load shape for the Mixed-Humid climate for the summer of 2011. The maximum power demand for the baseline sites was 592 watts, at 7:00 AM. The HPWH units had a maximum demand of 251 watts at 8:00 AM. The HPWH demand at 7:00 AM was 195 watts,

67% lower than the baseline. Figure 2-20 shows the demand for the winter of 2011–12. The maximum demand for the baseline sites was 928 watts, at 8:00 AM. The maximum HPWH demand was 490 watts, also at 8:00 AM. This is a reduction of 47%.

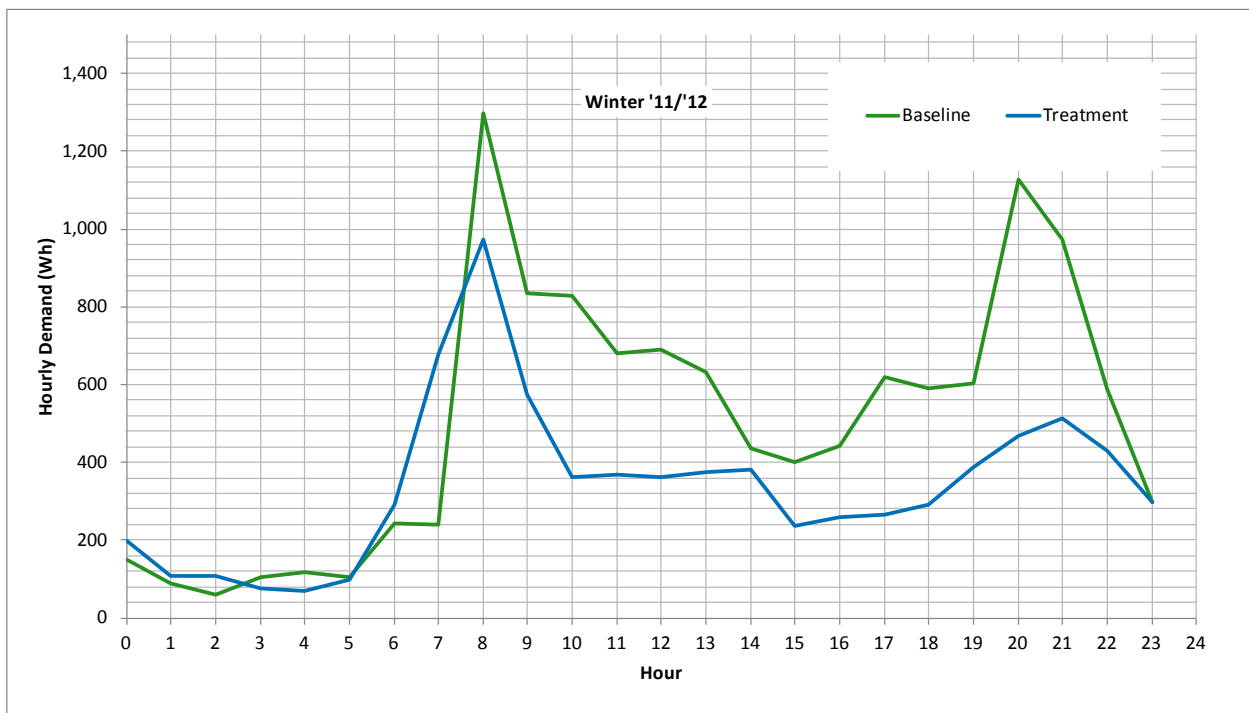


**Figure 2-20**  
**Load Shape for Mixed-Humid Climate, Winter 2011–2012**

Although the number of sites is substantially smaller, the relative performance in cold climates is of particular interest. Figure 2-21 shows the winter 2010–11 load shape for the sites in the cold region. The baseline sites had a peak demand of 1083 watts, compared with the HPWH demand of 979 watts, both at 8:00 AM. In Figure 2-22, the winter 2011-12 demand is shown, with the peak demand again at 8:00 AM for both baseline and HPWH systems. The baseline peak was 1297 watts, and the HPWH was 974 watts. The high HPWH demand during morning peak loads was likely related to low ambient temperatures causing the system to rely more on electric resistance heat than in warmer climates. Although for both winters the average daily energy consumption was lower (by 34% and 33%), the peak reductions were much less significant: 10% in 2010–11 and 25% in 2011–12.



**Figure 2-21**  
Load Shape for Cold Climate, Winter 2010–2011



**Figure 2-22**  
Load Shape for Cold Climate, Winter 2011–2012

### Consumer Surveys

In September of 2011, EPRI published a technical update concerning the Energy Efficiency Demonstration (1024605), detailing the results of the post-installation consumer satisfaction surveys for heat pump water heaters. This initial set of post-installation surveys was administered to 65 participants by two participating utilities, Utility A (28) and Utility D (37 participants).

This survey was intended to glean anecdotal insights into the issues and overall satisfaction regarding consumers' heat pump water heaters during their first month of use.

To recap that survey's findings: Most consumers were satisfied with their heat pump water heaters, particularly at the Utility A demonstrations, where only one participant expressed any dissatisfaction with their unit. The Utility D demonstration survey received six responses indicating some level of dissatisfaction, citing issues with the temperature and/or duration of hot water, slow recovery of the water heater, lower water pressure, and a longer time for hot water to reach the faucets. Running out of hot water during the winter months seemed to be a common problem, and three Utility D customers indicated condensation or moisture on the floor around the heat pump water heater. Most Utility A and Utility D respondents indicated that the heat pump water heaters produced a noticeable difference in the noise level compared to their previous water heaters; four customers from Utility D and two from Utility A indicated that the increase in noise was bothersome. Cool air expelled by the heat pump water heater was seen as both a benefit and nuisance, depending on location of the tank, time of year, and overall climate at the demonstration site. Customers also commented on the appearance of their units, with some indicating that the heat pump water heater was unattractive, displayed excessive amounts of plumbing, or took up too much space. Location of the unit seemed to have some impact on overall customer satisfaction, because the cool air, increased noise, and large size could be problematic in occupied areas.

In its continued effort to understand consumers' reactions to heat pump water heaters, EPRI developed two additional post-installation field evaluation surveys, which were fielded to end customers via the participating utilities. The following represents findings from the final post-installation survey, which was fielded after the units had been in place for up to approximately two years (depending on the utility). EPRI collected 67 total responses: 30 from Utility D, 19 from Utility C, and 18 from Utility B. Furthermore, Utility A collected 29 responses through an additional survey that it fielded independently (although question structure was identical to the EPRI survey), for a total of 96 survey responses.

Overall reactions seemed to echo what was found previously, although special cases were observed with some Utility D customers. These are examined in more detail below, along with the overall results.

### ***Overall Satisfaction***

Overall, most customers expressed satisfaction with their heat pump water heaters. Forty-eight of all respondents indicated that they were "highly satisfied," and 31 were "satisfied" with the performance of their units. These respondents cited sources of satisfaction including persistent delivery and adequate supply of hot water, attractive appearance, dehumidification and cooling of the surrounding air, energy and bill savings, ease of operation, and reliable performance. Thirteen indicated that they were "neither satisfied nor dissatisfied," citing reasons that included inadequate winter performance, slower recovery, uncertainty of savings, inadequate supply of hot water, noise, loss of water pressure, and maintenance issues. Three respondents stated that they were "dissatisfied," and one was "highly dissatisfied" with the performance of the units. Perceived increases in electric bill, undesired cooling of surrounding air, reduced water pressure, and poor winter performance were provided as reasons for customer dissatisfaction.

When asked if they would consider purchasing a similar unit, 53 customers indicated that they would, and 24 that they might. Those who provided reasons for this mentioned bill savings, energy savings, acceptable performance, and “green appeal.” Fourteen indicated that they would not consider purchasing a heat pump water heater in the future due to unsatisfactory performance during the winter or colder ambient conditions, poor service from technical repair staff, noise, and cost.

When asked if participants would recommend heat pump water heaters to their friends or family, 56 customers responded that they would, citing the same reasons that they would consider purchasing one themselves. Twenty indicated that they might recommend the units, but their recommendation would depend on the savings provided by the unit, the initial cost, and their need for hot water. Similarly, those who would not recommend the units, 15 responses in total, cited the same reasons as they did for not purchasing one for themselves.

Table 2-7, Table 2-8, and Table 2-9 list results to the survey questions, broken out by utility.

**Table 2-7**  
**HPWH Satisfaction Ratings by Utility**

Utility	N	Response				
		Highly Satisfied	Satisfied	Neither Satisfied Nor Dissatisfied	Dissatisfied	Highly Dissatisfied
D	30	7	14	6	2	1
C	19	14	3	2	0	0
A	29	20	6	2	1	0
B	18	7	8	3	0	0

**Table 2-8**  
**HPWH Purchase Consideration by Utility**

Utility	N	Response			
		Yes	Maybe	No	No Response
D	30	9	9	10	2
C	19	14	3	1	1
A	29	23	3	3	0
B	18	7	9	0	2

**Table 2-9  
HPWH Participant Recommendation by Utility**

Utility	N	Response			
		Yes	Maybe	No	No Response
D	30	8	9	11	2
C	19	14	3	1	1
A	29	24	3	2	0
B	18	10	5	1	2

### Special Case: Utility D Opt-Out Respondents

At the end of the Utility D demonstration, participating customers were given the opportunity to have their heat pump water heaters removed and trade them in for a standard resistance water heater. Utility D notified EPRI that a total of 10 customers chose to have their heat pump water heaters removed. Of these participants, seven completed the final consumer satisfaction survey. Because these results provide insight regarding the potential barriers to customer adoption and satisfaction, EPRI examined the responses provided by these “opt-out respondents” in detail. Closer examination of the survey results did not reveal any obvious difference in satisfaction based on the model of heat pump that the customer had. The removed units were not distributed heavily towards one model over any other.

### Satisfaction

In general, opt-out responses indicated that consumer satisfaction was varied, with only three participants expressing satisfaction with their heat pump water heater. These respondents mentioned the excess noise and a lack of observed savings as primary reasons for their level of satisfaction.

Two participants indicated that they were “neither satisfied nor dissatisfied,” while one participant stated that they were “dissatisfied,” and another, “highly dissatisfied.” When asked to provide reasons for these ratings, respondents included the excessive noise (which was also mentioned by “satisfied” customers), but they also identified poor winter performance and failure to meet functional expectations for water heating. One participant also mentioned that the unit actually increased their home’s electricity use and “sucked any heat from the crawl space” where it was located.

Only one customer indicated that they would consider purchasing this type of water heater in the future. Others stated that the unit was too large, noisy, was not an improvement to standard water heaters, or did not perform satisfactorily in the winter or in a cooler climate. Additionally, only one respondent indicated that they might recommend this type of water heater to friends or relatives, but stipulated that they would provide them with the same reactions expressed in the survey. All other respondents felt that they would not recommend heat pump water heaters, for the same reasons mentioned previously.

When told that the cost of a purchasing and installing a heat pump water heater was between \$1800 and \$2400, no customers indicated that they would have installed one on their own. Most cited reasons including the noise, comfort level, high upfront costs, or unapparent savings.

### *Seasonal Performance*

Two respondents identified changes to their water heating during the winter months. One customer indicated that hot water did not reach the faucet as quickly as it did with their previous water heater, which was somewhat bothersome to the respondent. The other response mentioned that despite being located in a “finished basement,” the hot water temperature decreased and the “compressor ran a lot,” which was identified as a bothersome change by the respondent. Both of these participants noticed decreases in the amount of hot water available during winter months. One customer indicated that they “had to keep adjusting the faucet to hotter [temperatures] during showers,” and the other noted that their hot water “would not sustain two consecutive showers.” The respondents indicated that these changes were “somewhat bothersome” and “bothersome,” respectively. Four respondents noticed changes around the area surrounding the unit, with half indicating that the decrease in temperature was bothersome and the others stating that it was at least somewhat bothersome.

### *Noise*

All customers indicated that they noticed a change in the level of noise produced by their water heaters, and over half indicated that this noise was bothersome. Those who did not find the noise bothersome stipulated that, when the unit was working properly, the increased noise was “only noticeable but not annoying.” Others found the noise level to be bothersome, indicating that it was “very noisy,” “noticeable,” and sounded like “a jet plane with bad bearings.” One other respondent mentioned that heat pump water heater’s operation created noise and vibrations at a high enough level to vibrate the screws out of their unit. One customer even indicated that the noise level was so severe that they changed the water heater’s mode of operation to “electric only,” commenting that in their opinion, the unit would “never be marketable.”

### *Savings*

When asked if they had noticed any changes in their electric bill, less than half of the opt-out respondents stated that they had observed any change. Of these, only one respondent observed energy savings, but also mentioned that they were unsure of the heat pump water heater’s impact because they had installed another energy efficient product within the same month. The other two customers seemed to observe an increase in their electricity bills, with one stating that “it has definitely increased my [electricity] usage.”

### *Survey Summary*

When implemented properly, heat pump water heaters can maintain satisfactory performance and even some additional benefits to customers in warmer climates. However, responses from dissatisfied participants indicate that heat pump water heaters may not be able to perform satisfactorily in cooler climatic conditions. Additionally, increased noise and a potential for space cooling highlight design considerations that should be addressed prior to the unit’s installation. The location of the heat pump water heater also seems to be tied to overall

satisfaction, and proper unit placement may help minimize issues that could negatively impact customer acceptance.

## **Summary**

A field deployment of heat pump water heaters was performed, with over 150 total water heaters monitored nationally. The results show substantial energy savings. Compared with the energy consumption calculated for baseline electric resistance water heaters, the heat pump water heaters in this study used on average 50% less energy. One of the models tested showed lower performance and used 20% more energy on average than the other two models. With that model excluded, the reduction of energy consumption was approximately 52%.

The COP of these units varied seasonally. The average COP for the two well-performing models ranged from 1.74 to 1.84 during summer and ranged from 1.45 to 1.71 during winter. The average daily COP of the electric resistance water heaters was calculated to be 0.83. Some variables of interest in water heater performance include the ambient air temperature and total water draw. Increasing ambient air temperature was shown to result in increasing COP. The average daily COP was also shown to generally increase with increasing water draw. The calculated COP was high for higher daily draw rates. However, the average delivered temperature decreased for two of the three models at higher daily draws, suggesting that for these cases, there were times when demand for hot water was not met. The daily draw for which all loads were met varied with the timing and frequency of draw and the particular model of water heater.

Inlet water temperature was also observed to have an impact on COP: With all other conditions controlled, a lower entering water temperature led to a higher COP. The effect of tank size on energy use and COP was evaluated for the 60 and 80 gallon tanks made by the same manufacturer. The 60-gallon tanks were shown to use less energy and have a higher COP. This result was counterintuitive. It suggests that further laboratory testing is beneficial to identify the circumstances in which the larger tank volume provides higher efficiency.

The HPWHs performed well and consumed substantially less energy than the electric resistance water heaters in all climates. In cold climates, HPWHs installed in unconditioned spaces may be exposed to ambient temperatures for the coldest portion of the year, which causes electric resistance elements to operate more frequently. In the winter of 2011–2012, the COP of HPWHs in unconditioned spaces was 1.01; in conditioned spaces, it was 1.47. Performance was better during the warmer months.

The HPWHs were observed to provide minimal reduction to utility peak-day, on-peak demands. The winter peak periods were reported to EPRI by the host utilities. In the winter of 2010–11 and winter 2011–12, the on-peak demand reduction provided by HPWHs was 2.2 to 11.4%. This result is not unexpected because cold ambient conditions combined with large water draws will tend to cause HPWHs to operate in electric resistance mode. The summer peak reduction was higher, although HPWHs are less a contributor to summer peaks than winter peaks because water heater usage is generally low during the mid- to late afternoon.

The average load shapes for electric resistance water heaters and heat pump water heaters were also evaluated with a particular focus on the Mixed-Humid climate, which provided the best sample size. The average daily load shapes showed significant reductions in power during the

morning and evening peaks, with reductions at the peak hour ranging from 47 to 56%, even in winter, which is substantially better than the utility peak day. However, analysis of the small sample of cold-climate water heaters showed that in winter, those units provided only minimal reduction in peak power (10 to 25%) on average, although full-day energy consumption was 33 to 34% lower. This finding points to a larger continuing issue for heat pump water heaters: When faced with large loads and low ambient temperatures, the devices will operate similarly to electric resistance water heaters and contribute to winter peaks in the same manner.

Customer satisfaction and HPWH reliability were generally high. The majority of customers for all utility hosts reported being “highly satisfied” or “satisfied.” Customers reported adequate hot water supply, as well as energy and cost savings as benefits. Some customers reported noticing a performance drop-off during winter, and some reported not liking the cooling provided by the devices. Many customers reported that they would consider purchasing a HPWH on their own, although all customers expressed reservations at the HPWH prices (based on prices at the beginning of the Demonstration).

### ***Readiness for Program***

This Demonstration has shown strong results for HPWHs in terms of energy savings, reliability, and performance. Customer satisfaction was good. The technology has been used in several utility energy efficiency programs already. However, the penetration has not been as high as desired, indicating a need to address market barriers to adoption. EPRI recommends further work prior to utility full program rollout of HPWHs. Toward this end, EPRI and eight utility collaborators are addressing HPWH market barriers in the Coordinated Early Deployments stage of the technology-development pipeline. Deployment of HPWHs are planned with three of the utility collaborators in late 2012 and 2013 with the specific objective of better understanding the market barriers and develop strategies to overcome them. The goal of the coordinated early deployment is to help utilities plan their full program rollout for HPWHs.



# 3

## DATA CENTERS

---

### Introduction

The data center industry is experiencing tremendous growth, and with that growth comes increasing power consumption. The 2007 EPA report to Congress estimated that the power consumption in the industry had doubled from 2001 to 2006 and would double again by 2011 if allowed to continue unabated. Researchers around the world have recently engaged in efforts to identify and develop methods to measure and improve power consumption in the data center industry. These improvements, along with the 2008 financial crisis, have resulted in less power per server and a lower installed base than predicted by 2010. As a result, new estimates of the growth of electricity use in data centers show about a 36% increase, instead of doubling. Even so, new applications and economic recovery will likely cause the growth trend to continue, such that the electricity consumed by data centers will increase in the coming years.

All utilities have data center customers who are experiencing increasing energy consumption. These data centers often use more than twice as much power as needed by the servers themselves. In addition, this increase eventually leads to problems with heat removal, because the servers and electrical equipment generate heat that must be removed by the HVAC systems. The rapid growth often results in cooling systems that have reached their maximum capacity, so that no more server load can be added.

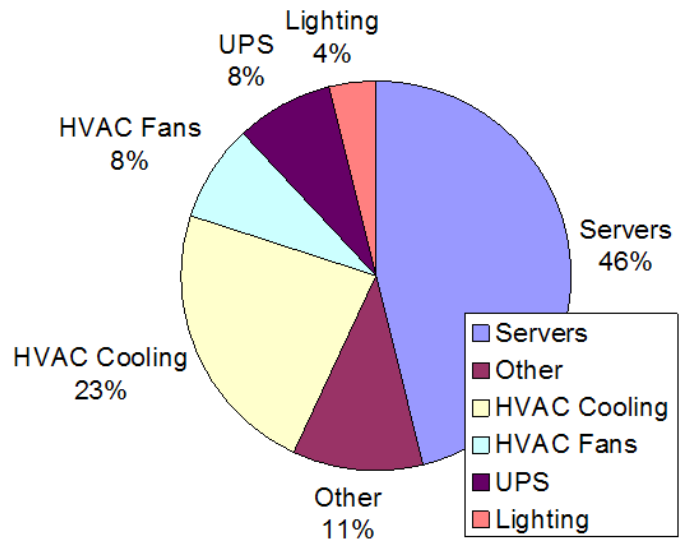
Any new developments in efficiency for both data centers and commercial office space can bring about substantial energy savings. In fact, at the present pace, over one-third of every dollar spent for computing power is used for heat removal, so any improvements in efficiency at any point between the service transformer and the peripheral support equipment provide a magnified saving potential due to reduction of heat load. EPRI is positioned to help electric service providers develop practical plans to assist their customers with information and support in this area. Because the computing environment is so diverse—ranging from home offices to large data centers—there is no single best efficiency option. However, EPRI is working in each of the application areas where more efficient technologies can benefit the overall computing industry.

### Industry Overview

Between 2000 and 2006, the number of servers being installed in the United States increased from 5.5 million per year to 10.9 million per year. Energy use in data centers was estimated to be 1.5% of the U.S. total electricity use in 2006 [3-1] and was expected to double in five years. Power failures and limitations on space, power, and cooling capacity were expected to affect almost all data centers in that time period [3-2].

Coupled with inefficient air conditioning and other components, the data center operates with the IT loads using only about a third to a half of the input power [3-3]. Over half of the power consumption of power and cooling systems is fixed and does not vary with the IT load. Power

and cooling systems that can operate at or near capacity and can also adjust capacity to meet loads will reduce the effects of fixed losses and transients and increase efficiency [3-4]. A benchmarking study of 22 data centers by LBNL revealed that energy was used as shown in Figure 3-1 [3-5].



**Figure 3-1**  
**Data Center Energy Use by Equipment Type (From LBNL)**

The EPRI Energy Efficiency (EE) Demonstration on data centers involves the demonstration of three basic technologies. Utility members were informed of around a dozen possibilities and narrowed the field to three. The selected technologies were:

- Server power supply retrofits with 80 PLUS power supplies
- Airflow management with adaptive control
- DC power distribution

### **Server Power Supply Retrofits**

The 80 PLUS program has proffered a specification for power supplies to be operated at 80% efficiency over most of their load range. While much research has been undertaken to alleviate the inefficiencies in cooling systems and the many conversions, the biggest impact can be realized by improving the efficiency of the server power supply. This is true because every watt used at the server causes losses (and heat) in the upstream conversion devices. Likewise, every watt saved at the server results in a reduction in losses for every device upstream, as well as lowering the cooling load. Previous tests of power supply retrofits with 80 PLUS power supplies in commercial buildings have shown energy savings on the order of 17 to 20%. These savings include a significant reduction in computer energy consumption as well as reduction in the wiring losses that would normally be incurred as a result of low power factor. The fact that 80 PLUS power supplies have power-factor correction removes those losses.

The refresh rates of typical IT equipment are 3 to 5 years, although most equipment lasts longer, and can be used for other purposes. 80 PLUS power supplies will exhibit the same lifespan as the

original equipment. During the test reported here, the power supply retrofits cost about \$350 each.

### ***Airflow Management with Adaptive Controls***

Airflow management allows for a solution to improve cooling, IT reliability, security, and energy efficiency for data centers. One vendor provides a supervisory control system running adaptive control algorithms. Most data centers' air conditioning systems provide more cooling than necessary. The approach is to control the computer room air conditioners (CRACs) based on measured temperature values throughout the facility to balance the cooling with the heat load. Variable-frequency drives (VFDs) are used to vary fan speed in the CRACs, thus affording a significant savings in energy consumption.

Wireless temperature sensors should have lifetimes of greater than 5 years. Adjustable speed drives will last more than 10 years. The server used to implement the supervisory control algorithms will have a lifetime similar to other IT equipment, 3 to 5 years or longer. Airflow management can save over 20% of data center energy use. Airflow management with automatic fan control costs approximately \$23 per square foot of raised floor as a retrofit.

### ***DC Power Distribution***

Typical data center power delivery designs use AC power, distributed to the facility at 480 V<sub>AC</sub>. This AC power is then stepped down to 208 V<sub>AC</sub> or 120 V<sub>AC</sub> for distribution to racks for use by servers and other information technology (IT) equipment. An uninterruptible power supply (UPS) isolates equipment from power interruptions or other disturbances. This technology generally involves converting incoming AC power to DC for energy storage. The DC power is then converted back to AC for the facility distribution grid and routed to power distribution units (PDUs) and remote power panels (RPPs) for distribution to equipment in racks.

Inside the servers and other IT equipment such as storage or networking units, power supplies convert AC (at 208/120 V<sub>AC</sub>) to DC voltage needed for the digital electronics. Power supplies usually provide power-factor correction as well as load isolation from the incoming power line for these sensitive electronic components. Thus, there can be up to six or more power-conversion stages between facility power entry and the microprocessor or other data-processing circuits.

The power losses due to inefficiencies in power-conversion devices from both outside and within equipment result in a large loss of useful electrical power, as well as direct increases in the energy required to remove the heat produced. While estimates and actual measurements vary, the actual power utilization by IT loads can sometimes be as low as 50% of the total input power consumption, or worse.

A detailed study by Intel and other industry leaders of the power distribution system performed a comparison of three systems. The first one was a baseline 480-V<sub>AC</sub> system, the second one was a 480-V<sub>AC</sub> system with the best efficiency available in the market, and the third was a 400-V<sub>DC</sub> system. Table 3-1 shows the efficiency of each system and how these values impact the input power for a compute load of 100 kW. While the high-efficiency AC system can effect a 25% improvement, going to DC can be even better. In addition, the high-efficiency AC system assumes that cost is not a barrier, when in fact the DC system can be less costly than the original system.

**Table 3-1  
Comparison of a Typical-Efficiency Power-Distribution System to a High-Efficiency AC System and a DC System for a Compute Load of 100 kW**

System Type	Total System Efficiency	Input Power (kW)	Difference
Typical Efficiency	51.17%	195.5	--
High-Efficiency AC	67.87%	147.4	24.61%
DC	72.04%	138.8	28.97%
		DC vs. High-Eff. AC	5.79%

In a field experiment with LBNL, similar values were measured. The overall improvement over the high-efficiency system was measured at about a 7% reduction in power use. All components used in the distribution system are well-known in the industry, and should exhibit 30-year lifetimes. DC distribution costs approximately \$2.50 per watt of IT load.

### ***A Timeline for Technology Advances***

Power supply research has continued since 2002, when early efforts began with external power supplies (such as phone chargers) and evolved into internal power supplies for personal computers and then servers. The 80 PLUS program<sup>2</sup> began as a utility buy-down program for the computer and then the server market to incent the sales of power supplies with greater than 80% efficiency. The 80 PLUS specification was adopted by the ENERGY STAR program in 2007. The Climate Savers Computing Initiative followed, using similar metrics and standards.

Airflow management has been used in data centers for many years, although accomplished in a manual fashion (moving perforated tiles and filling gaps with blanking panels). In recent years, as energy use has become more of a concern, automated airflow-management systems have emerged and hold much promise as an important emerging technology for retrofits.

The effort to develop DC power-distribution systems in data centers started around 2004, with some very small demonstrations by EPRI and others. In those early demonstrations, technical and market barriers were identified, and over the past seven years, most of those have been overcome. As the barriers continue to fall, market adoption slowly grows.

Efficient power supplies and DC power distribution both solve the problem of electrical/electronic power converters generating heat. The power losses in those conversions are compounded by the requirement to remove the heat, thus requiring more energy to be used for cooling. Both technologies offer the possibility to save more than 20% of the energy normally used in the data center.

Airflow management overcomes the problem that most data centers are over-provisioned for cooling, resulting in mixing of hot and cold air, a very inefficient process. Managing the airflow helps prevent the mixing, as well as controlling fan speeds to minimum required levels.

<sup>2</sup> [www.plugloadsolutions.com/80PlusPowerSupplies.aspx](http://www.plugloadsolutions.com/80PlusPowerSupplies.aspx)

## Research Objective

The specific questions asked during this research were:

What are the actual measured energy savings for each technology?

- Defining baseline
- Controlling baseline

What are the issues with implementation of efficient power supplies?

- Availability
  - 80PLUS
  - Other
- Installation: Are they hot swappable?
- Reliability: Must last as long as originals.
- Performance: Must perform as well as originals.

What are the issues with implementation of DC power distribution systems?

What are the issues with airflow management?

Is the installation simple and fast?

Is the equipment compatible?

Will end users be willing to commit sufficient time to product support?

What are the issues related to wide adoption of 380-VDC systems in data centers?

- Component availability: There is concern but UL listed components can be obtained, if customers ask for them:
  - Rectifiers
  - Circuit breakers
  - Ground fault circuit interrupters
  - Arc flash
  - Extinguishing-arcs connectors UL listed at 380-V
  - Power supplies designed to take 380 VDC
- Safety is a concern in the industry (are electricians trained to handle 380 VDC?)
- Installation: Retrofit or greenfield
- Reliability: Last as long as AC systems?
- Performance: Perform the same or better than AC systems?
- Cost: Capex, greenfield, retrofits
- Will fear of the unknown require market education?

What metrics and specifications can be developed to inform utility incentive programs? CEE is working to understand the industry but has just begun. Data center industry has used only Power Usage Effectiveness (PUE) and Data Center Infrastructure Efficiency (DCiE) sparingly, although PUE is gaining acceptance from end users. Incentives are offered for virtualization based on number of servers unplugged. This has no energy-measurement component. Metrics and specs are needed to inform utility incentives. The work in this Demonstration should provide knowledge and understanding that will allow some metric and spec definition and development.

What measurement and verification procedures can be developed to support those programs? Just as the metrics need to be developed, some standardized procedures for measuring them will be needed. This work will provide the opportunity to develop those procedures for each technology chosen.

What are the issues with implementation of power-management software? There are several vendors in the market, but it is not clear how different server functions will be affected by their power-management approaches. The Demonstration will allow study of these approaches both before and during implementation.

Field measurements will provide hard data on energy efficiency. As for the rest of the questions, measurements may not answer these questions directly, but the process of installing and operating the equipment, collecting the data and analyzing it will contribute to the resolution of the issues raised by the questions.

These questions form the basis for the “unknowns” that can act as market barriers to technology adoption. If the questions are answered satisfactorily, with rigor, the demonstrations can accelerate market adoption and provide utilities with more tools to use in their programs.

The 80 PLUS program includes a long-term laboratory measurement program at EPRI whereby positive power supply efficiency trends can be seen. The shortcomings of this work include the fact that until the devices are installed in the field, it is unclear how effective they might be—issues such as ease of installation and actual performance in a data center are unknown. EPRI completed a study with ConEd showing these kinds of results for personal computers. This demonstration went one step further to show them for servers.

Vendors have shown some early versions of the automated airflow-management technology in the field. LBNL has documented the opportunities possible using various methods of airflow management using hardware at their supercomputer center as well as some field demonstrations. This demonstration will ensure full rigor in data collection and analysis.

DC power distribution has been studied by several entities, including EPRI, Intel, Emerson, EYP, NTT, France Telecom, Net Power (Sweden), and many others. Intel, Emerson, and EYP completed a design study with positive results. Most of the fielded hardware demonstrations also yielded promising results. This demonstration will provide a more rigorous approach, and thus more concrete results.

The 80 PLUS program has a well-defined and internationally accepted test protocol. Test protocols for field work will be developed as a part of this project.

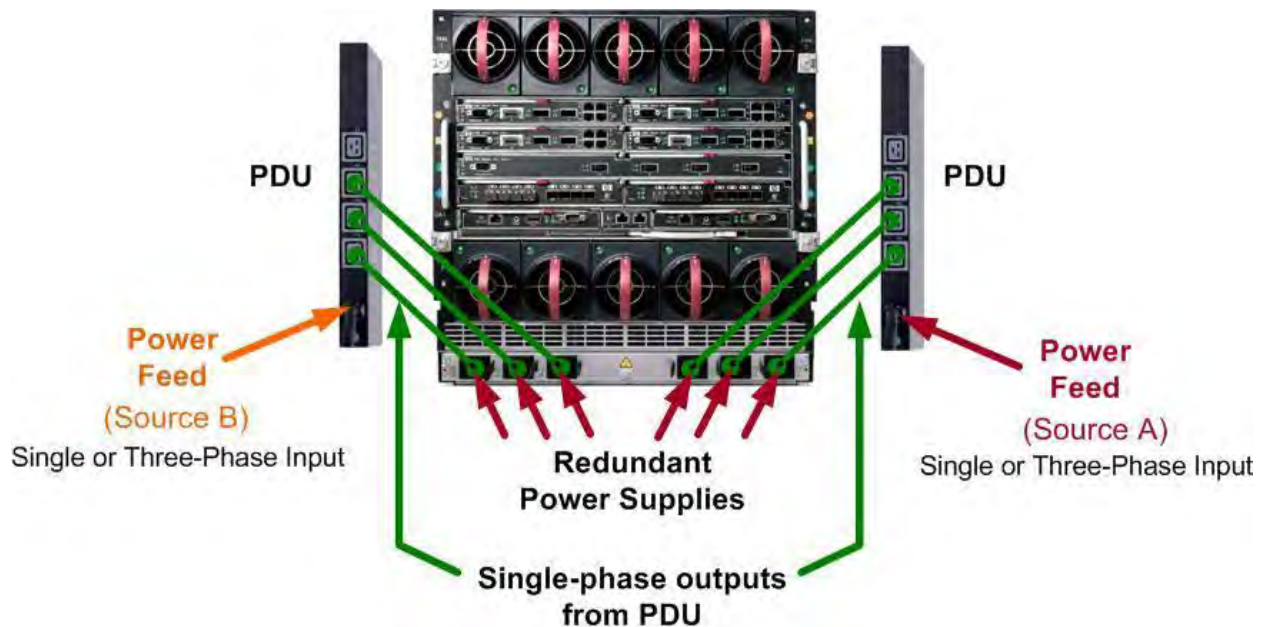
This demonstration is a natural extension of the research previously carried out. Similar approaches might be taken, for example, but with larger samples or better system design.

## Research Method

### Power Supply Retrofits

Utility A signed on as a demonstration host and chose to implement efficient power supplies in their data center. After a review of the servers in use, it was found that they had six blade enclosures that all used the same power supplies, which are compliant with 80 PLUS (see Figure 3-2). This provided an excellent opportunity to implement the retrofit and measure the results.

Power supplies that are compliant with 80 PLUS were ordered to fit the blade enclosures, and after baseline power consumption was measured, power supplies were swapped out for four of the six enclosures. The remaining two were kept running on the old power supplies to provide a control group for comparison.



**Figure 3-2**  
**A Blade Enclosure for Six Power Supplies**

Because the power supplies are hot-swappable, it was a simple matter to remove and replace individual units without affecting the operation of the server. One example of the actual servers is shown in Figure 3-3.



**Figure 3-3**  
**A Server With Hot-Swappable Power Supplies**

The racks that contain the blade enclosures are shown in Figure 3-4.



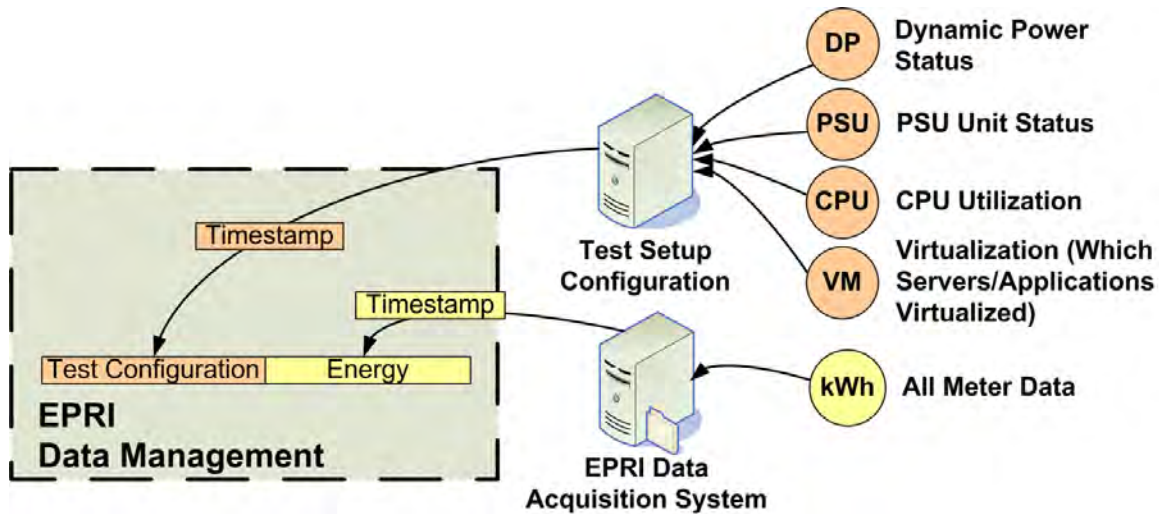
**Figure 3-4**  
**A Rack of Blade Enclosures**

The goal of the EE Demonstration at utility A's data center is to evaluate energy usage of blade servers in a production environment with and without 80-PLUS-certified power supply units. Another technology evaluated during the demonstration was a dynamic power management software tool, which is included from the manufacturer of the Blade enclosure. In order to measure and verify the energy usage before and after the technologies are introduced to the data center, EPRI worked with Utility A to identify all variables, listed in Table 3-2, that impact energy usage and developed a plan to monitor and control these variables to control the test setup.

**Table 3-2**  
**Variables Associated With the Test Setup and Configuration**

Variable	Description	Impact
Blade Server Configuration (Servers) or Virtualization	Blade enclosures are comprised of up to 16 servers.	Servers and their associated applications determine the aggregate load of each enclosure. In order to verify the performance of the technology under evaluation, this variable should remain the same during a test.
Blade Server Configuration (PSU)	Blade enclosures are comprised of six power supply units (PSU).	The project is designed to measure the impact of this variable.
Server CPU Utilization	Server load is directly related to the server's processing load, expressed in percent utilization.	The averaged CPU utilization was monitored to ensure changes in demand could be correlated to changes in utilization.
Dynamic Power Management Application	Designed to manage server power supply efficiency by shifting the load from all PSU to a few.	The project is designed to measure the impact of this variable.
Energy and Demand	Demand and energy measurements of each discrete blade enclosure, each rack (comprised of two enclosures) and all servers.	N/A. Impact is based on all other variables listed above.

In addition to variable identification, EPRI devised a method to collect and save the data for analysis. The variables and associated data, including the methods used to save the data, are illustrated in Figure 3-5.



**Figure 3-5**  
**EPRI Data-Collection Plan for Utility A Data Center EE Demonstration Site**

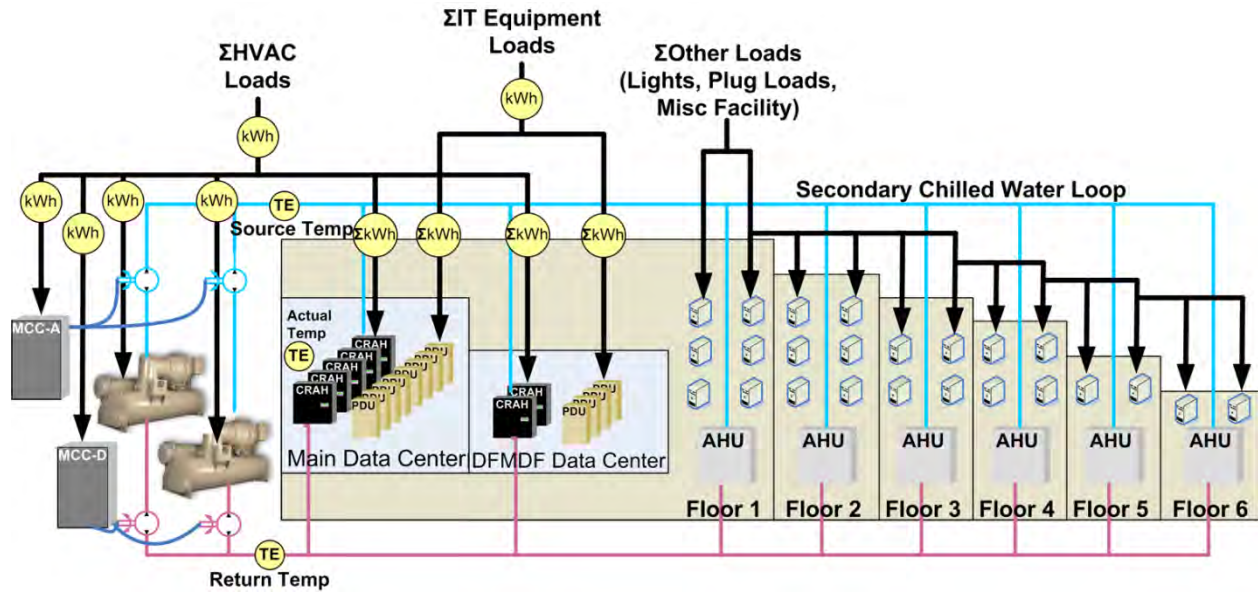
The variables that impact the performance of the technologies being evaluated were collected via manual and automated systems. All data was captured and stored in a central database to enable the correlation of test setup and configuration with energy usage.

### **Airflow Management**

Utility B had planned to replace its computer room air conditioners (CRACs) with models that allowed variable-speed control for their fans. Because the supervisory adaptive control software to be demonstrated by EPRI also provided speed control, these two technologies could work together. This allowed the experiment to demonstrate two different approaches: one, to fully replace CRACs with new models using speed control, and the other to use a retrofit control package with VFDs to accomplish the speed control. In order to align the ongoing improvements with efficiency measures associated with the EPRI demonstration, some timing and coordination were necessary.

Energy meters were installed to capture usage *pre* and *post* treatment for each of the measures above. The new CRACs were run both with and without speed control, and energy use was compared to the baseline. This demonstrated the full replacement approach. The supervisory controls were added and operated, and energy use was compared to the baseline and the full-replacement approach. Finally, raising the operating temperature and temperature of the chilled water was assessed using an energy comparison before and after.

EPRI installed and networked 21 electric power meters on facility and data center equipment in utility B's data center. The meters were installed on systems that impact the performance of the main data center's air-management system. Because the project's objective was to measure the energy usage of a new data center air-management system whose performance is measured by the system's efficiency of removing heat, the meters were logically placed in groups based on the thermal impact on the air-management system. The graphical representation of the test setup is shown in Figure 3-6.

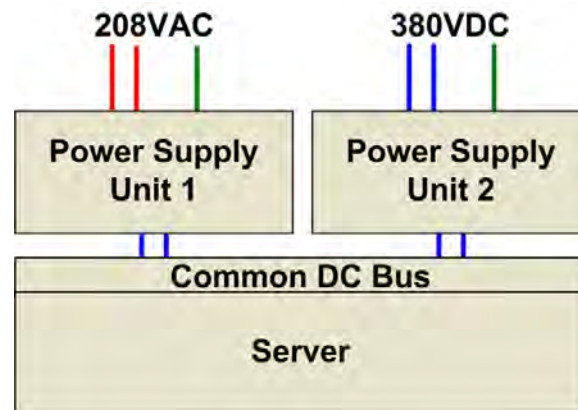


**Figure 3-6**  
**Test Setup**

### **DC Power Distribution**

The goal of the test was to compare the efficiencies (losses) of AC and DC power networks in a typical data center application. Because data center loads are dynamic and efficiencies typically vary with load levels, tests on both systems were conducted to measure the efficiency ranges of equipment over a wide range of load conditions.

The server setup in Figure 3-7 shows that both the AC and DC networks are connected to each rack. Each server is equipped with two power supplies, one configured with a 208-VAC input, and the other with a 380-VDC input, as shown in Figure 3-7.



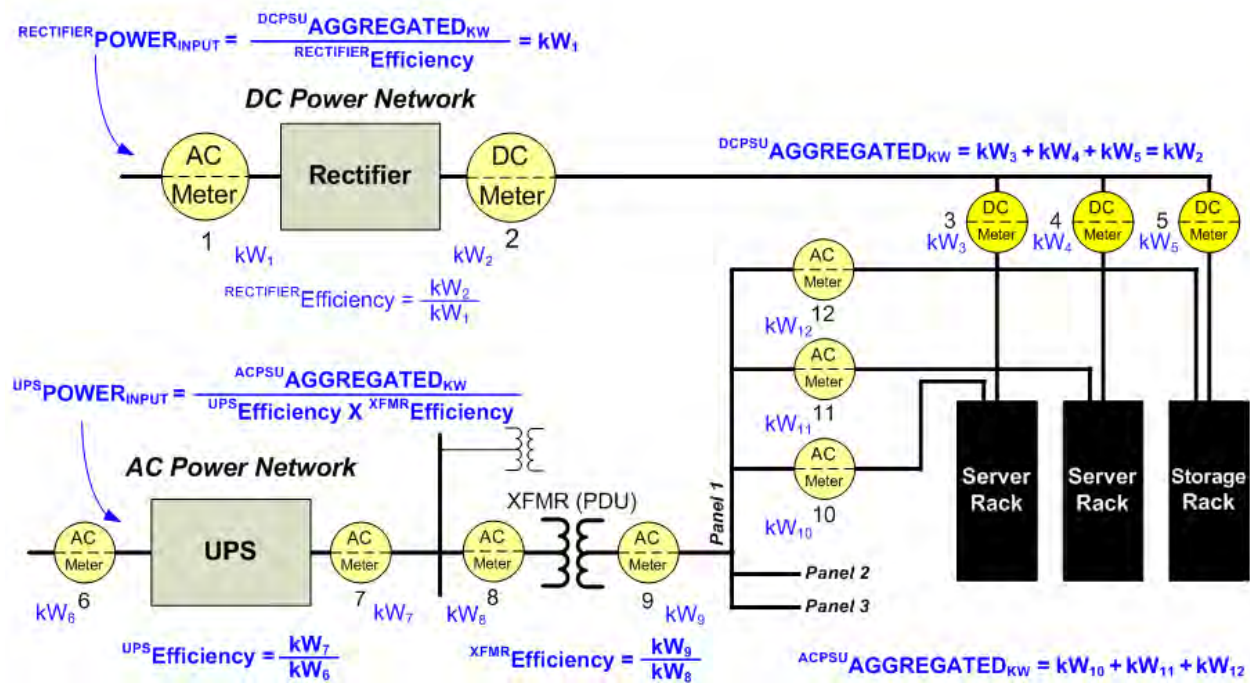
**Figure 3-7**  
**Power Supply Unit (PSU) Configuration for All Servers in Racks 1 – 3**

This configuration enables the server to be powered by both power sources at the same time. This configuration enables data centers to install and test DC power networks while running on AC power to ease the transition for retrofit applications. Even though the servers could be powered by both power sources at the same time, this test is designed to evaluate both systems

individually, which means that power to one of the power supplies is disconnected and measurements are taken, and then the disconnected source is reconnected. The process is repeated for the other source.

The data products of this measurement and verification plan include measured efficiencies and potential savings based on a comparison between AC and DC networks components and end-use loads. Another set of calculations are included using the AC and DC networks as the dependent variable. For example, data center cooling load requirements depend on the efficiencies of AC or DC network system components and end-use loads.

Power measured on the input and output of each device is used to calculate efficiencies of both the AC and DC power networks. The aggregated demand of both the AC and DC power supply units are used to provide insight into the efficiencies of the power supply units. The meters and formulas shown in Figure 3-8 illustrate the location, parameters, and calculations used to evaluate the systems.



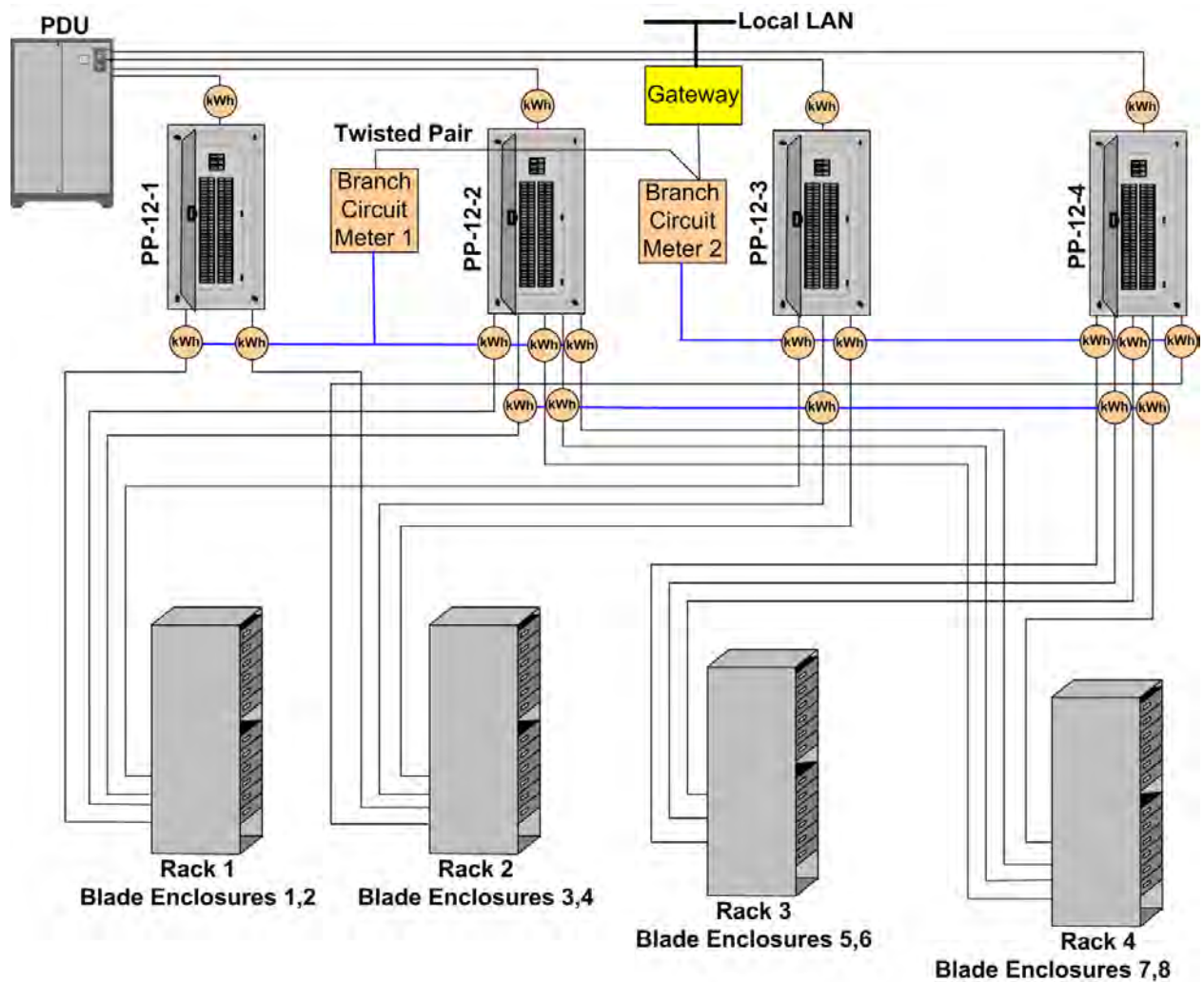
**Figure 3-8**  
**Meter Locations Including Formulas Used to Characterize System Performance**

### Instrumentation

#### Power Supply Retrofits

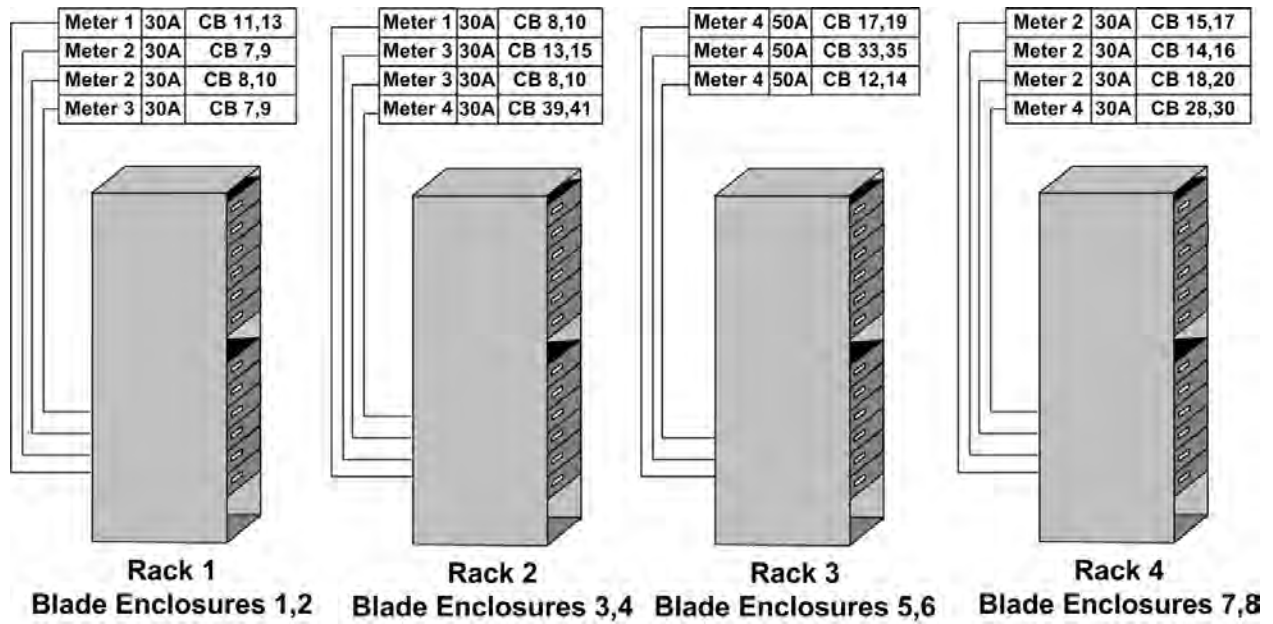
EPRI installed meters to measure demand and energy for each blade enclosure, rack, and aggregate load of all data center IT equipment. All IT equipment in the Utility A data center is powered by one 480-208/120-V power distribution unit (PDU). Blade enclosures under test were powered by two-pole circuits (208 V) located in four branch circuit panels, as shown in Figure

3-9. Branch circuit meters were used to log power and energy for all blade enclosures, racks, panels, and aggregate load of all IT equipment.



**Figure 3-9**  
**Meter Layout**

As shown in Figure 3-10, the power to all blade enclosures was distributed across all three branch circuit panels.



**Figure 3-10**  
**Circuit Configuration for All Blade Enclosures and Racks**

### Airflow Management

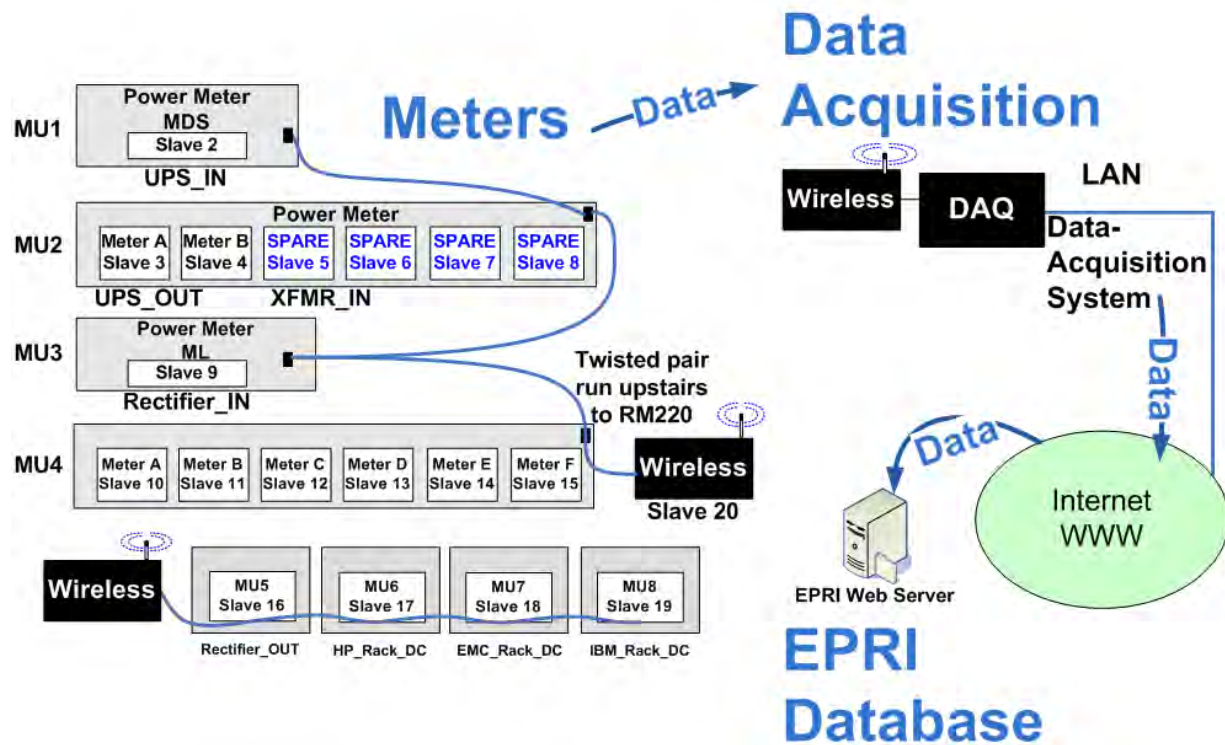
In all, 22 three-phase circuits were monitored for this demonstration, using equipment shown below. The monitors were connected to a data-acquisition system through a wireless mesh network.



**Figure 3-11**  
**Equipment Used to Monitor 22 Three-Phase Circuits**

## DC Power Distribution

All meters were networked together using wireless communications. The metering network architecture is depicted in Figure 3-12.

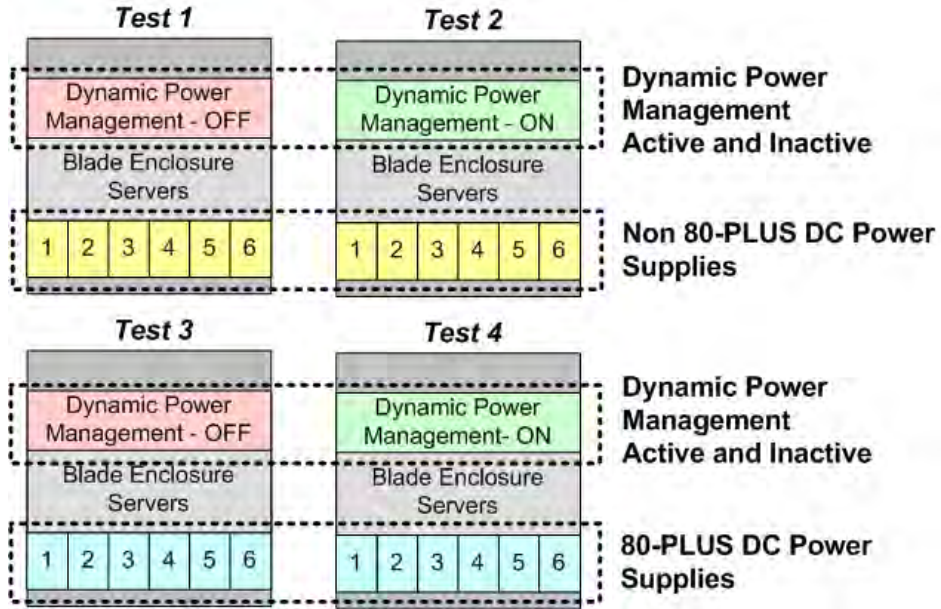


**Figure 3-12**  
Meter and Data-Acquisition Network Configuration

## Data Collection and Analysis

### Power Supply Retrofits

The two technologies evaluated were the blade enclosure power supplies and the Dynamic Power Management. To control the test setup, a total of four different tests were performed, as illustrated in Figure 3-13. While the blade enclosure was in the recommended test configuration, data was collected for at least two weeks. And to ensure that the IT equipment (servers) was loaded the same between all four test setups, Utility A data center employees ensured that no applications or servers were moved either in or out of the blade enclosure under test.



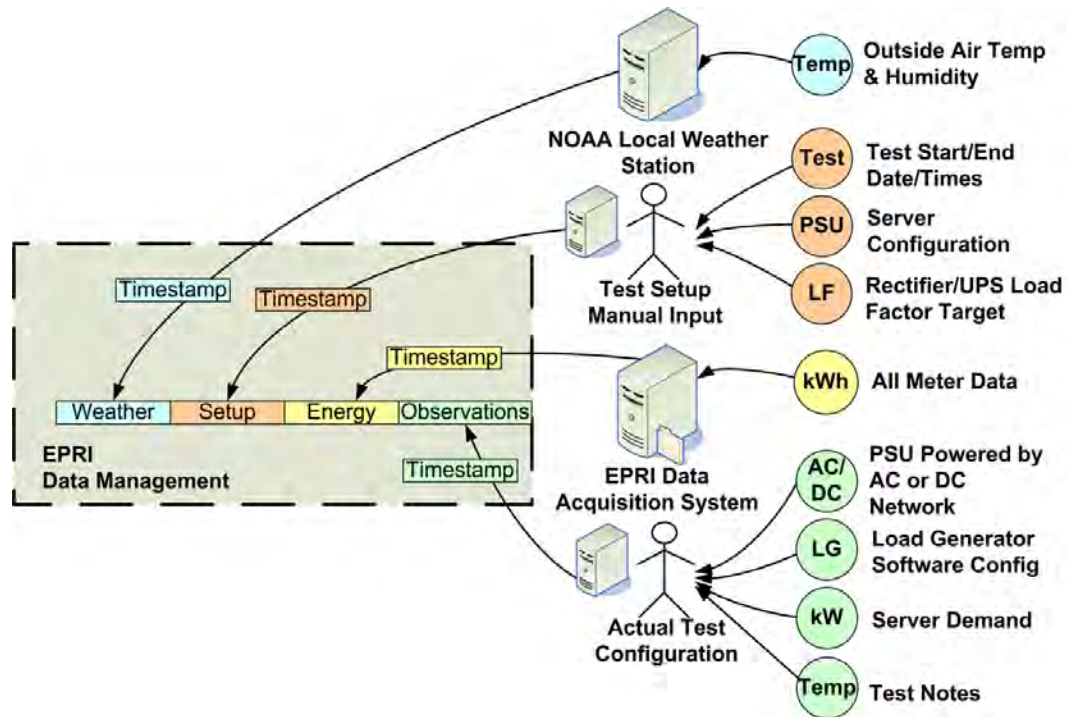
**Figure 3-13**  
**Test Configurations (With and Without 80 PLUS PSU and With and Without Dynamic Power Management Turned OFF and ON)**

### Airflow Management

Ten meters were installed on panels that power IT equipment. Besides weather and solar impacts on the building, IT equipment is a major thermal load on the air-management system.

Eleven meters were installed on HVAC systems related to removing the building’s thermal loads, like the chillers, chilled water loop subsystems and air handling units.

In order to correlate the impacts of thermal loads and the HVAC system to the building’s performance, data points like temperature must also be recorded. A graphical representation of all relevant data required for the analysis is included in Figure 3-14. Sensor measurements were time stamped and recorded.



**Figure 3-14**  
**Graphical Representation of All Metered and Sensor Data Points Used in the Evaluation**

The systems related to adding thermal energy to the data center were grouped and summed or subtracted to differentiate server load to the main and secondary data centers. The systems related to managing the thermal loads were also grouped, subtracted, or summed to differentiate chiller, chiller subsystem, main, and secondary data center power for the computer room air handlers (CRAHs).

In order to correlate data center and building performance, power levels were correlated with internal and external (outside) temperatures.

In order to compare the impacts of the different air-management control technologies and methods, a baseline was generated.

## DC Power Distribution

### *DC Network Efficiency*

The efficiency of the DC network can be characterized by measuring the power into and out of each network component, which in the case of a DC network is simply the rectifier. The data products for the DC network are detailed in Table 3-3.

**Table 3-3  
DC Network Efficiencies**

System	Component	Efficiency	Variable
DC Network	Rectifier	$\frac{\text{RECTIFIER POWER}_{\text{OUT}}}{\text{RECTIFIER POWER}_{\text{IN}}}$	$\text{RECTIFIER Efficiency}$
Total DC Network Efficiency <i>Equation 1</i>	$\text{RECTIFIER Efficiency} = \text{DCNetwork Efficiency}$		

*AC Network Efficiency*

The efficiency of the AC network can be characterized by measuring the power into and out of each system component (UPS and transformer) using the calculations detailed in Table 3-4.

**Table 3-4  
AC Distribution Efficiencies**

System	Component	Efficiency	Variable
AC Network	UPS	$\frac{\text{UPS POWER}_{\text{OUT}}}{\text{UPS POWER}_{\text{IN}}}$	$\text{UPS Efficiency}$
AC Stepdown	Transformer	$\frac{\text{XFMR POWER}_{\text{OUT}}}{\text{XFMR POWER}_{\text{IN}}}$	$\text{XFMR Efficiency}$
Total AC Network Efficiency <i>Equation 2</i>	$\text{UPS Efficiency} \times \text{XFMR Efficiency} = \text{ACNetwork Efficiency}$		

Because the UPS powers loads other than racks 1 through 3, the differences in demand cannot be measured by comparing the actual measured power for each network. To determine the potential savings, the demand at the UPS input can be calculated by summing the power to all racks and then dividing it by the product of the efficiencies for each system between the racks and the UPS input, as shown in Equation 3.

$$\frac{\text{RACK}_{n+1} \sum \text{acPOWER}_{\text{IN}}}{\text{UPS Efficiency} \times \text{XFMR Efficiency}} = \text{UPS Calculated POWER}_{\text{INPUT}} \quad \text{Equation 3}$$

The estimated savings can be determined by comparing the demand of the rectifier to the demand of the UPS, as shown in Equation 4.

$$\Delta \text{POWER} = \text{UPS Calculated POWER}_{\text{INPUT}} - \text{RECTIFIER POWER}_{\text{IN}} \quad \text{Equation 4}$$

## Laboratory Investigation

### Power Supply Retrofits

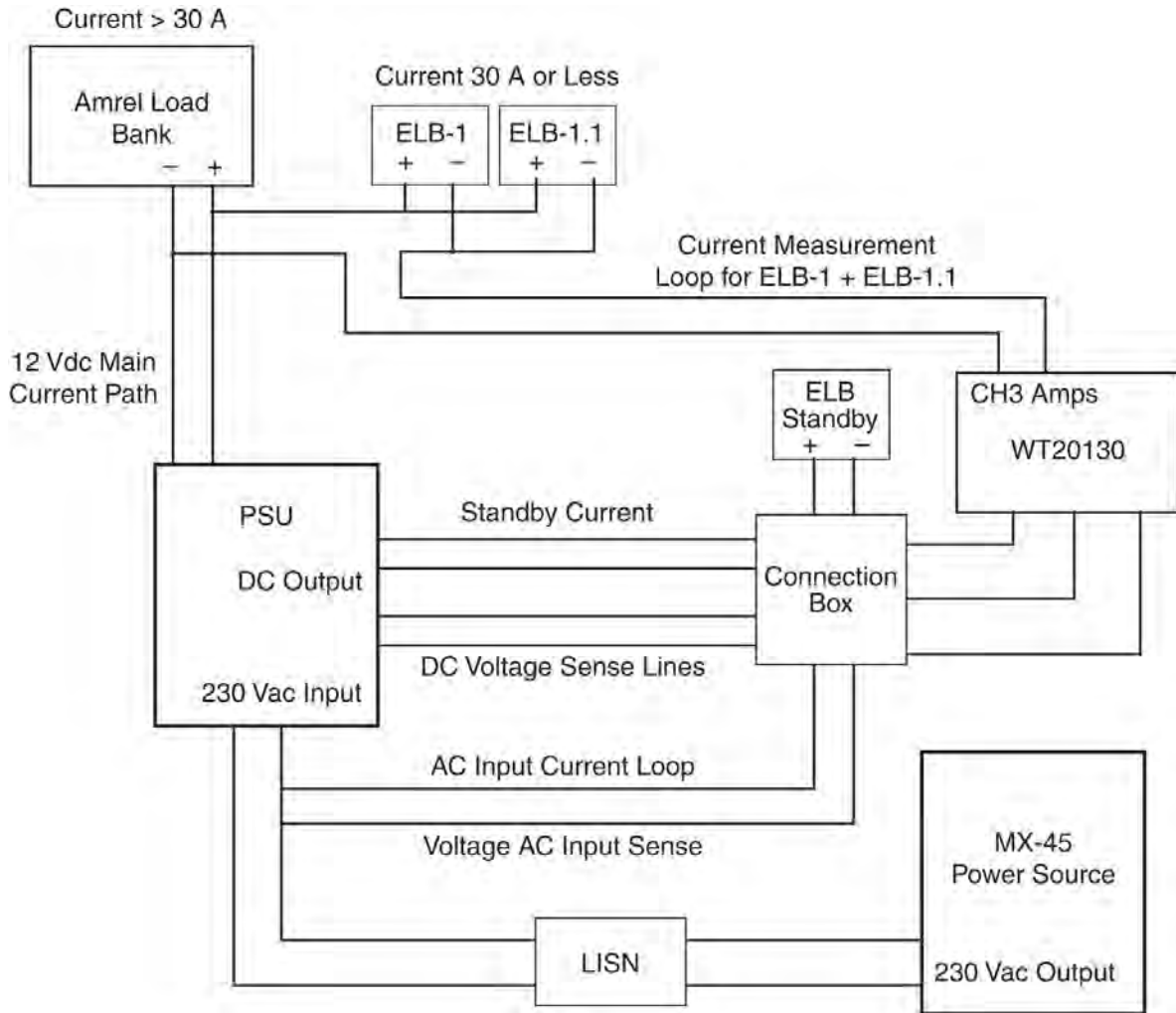
A set of the original power supplies for the blade servers were tested, along with a pair of the 80 PLUS models that were to replace them. The 80 PLUS program has developed four levels of compliance, depending on the level of efficiency.

**Table 3-5**  
**80 PLUS Levels of Compliance for 230-Volt Internal Redundant Efficiencies**

Compliance Level	20% Load	50% Load	100% Load	Power Factor
80 Plus Bronze	81%	85%	81%	0.90 PF @ 50% Load
80 Plus Silver	85%	89%	85%	0.90 PF @ 50% Load
80 Plus Gold	88%	92%	88%	0.90 PF @ 50% Load
80 Plus Platinum	90%	94%	91%	0.95 PF @ 50% Load

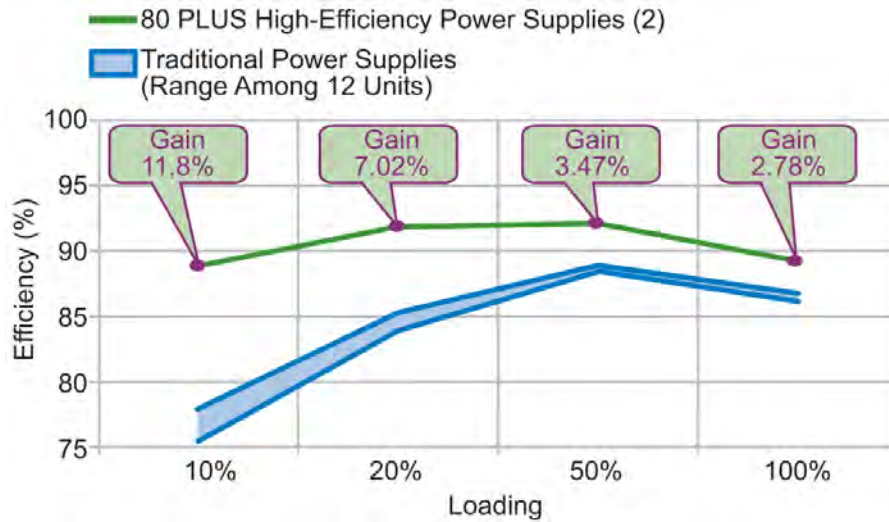
### Test Description

EPRI previously developed a standardized test procedure for testing internal desktop computer power supplies, *Test Protocol for Internal AC-DC Power Supplies, Revision 6.4.3* [3-6]. The test setup is shown in Figure 3-15.



**Figure 3-15**  
**Setup for Testing Internal Desktop Computer Power Supplies**

Figure 3-16 shows the results, where the older models are labeled EE-01 through EE-12, and the new ones are labeled PSU-1 and PSU-2. The new models' efficiency curves can clearly be seen well above the rest.

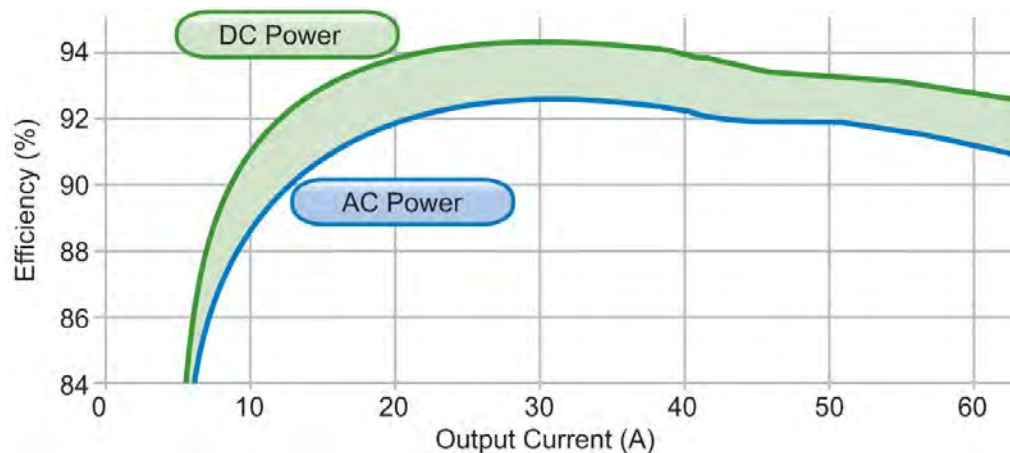


**Figure 3-16**  
**Results of Comparison Tests Between Standard AC Power Supplies and 80 PLUS Platinum Power Supplies**

These results show that the original power supplies were very efficient compared with market averages. However, the new 80PLUS models were Gold level, while the old ones were only bronze.

### DC Power Distribution

For the DC power demonstration, efficiency tests were performed by the manufacturer on the power supplies modified to take 380 V<sub>DC</sub>. These were compared with conventional, very-high-efficiency power supplies operating at 208 V<sub>AC</sub>. The test procedure was identical to the one developed by EPRI and adopted as standard. The results are shown in Figure 3-17.



**Figure 3-17**  
**Results of Comparison Tests Between AC and DC Power Supplies**

## Field Data and Analysis

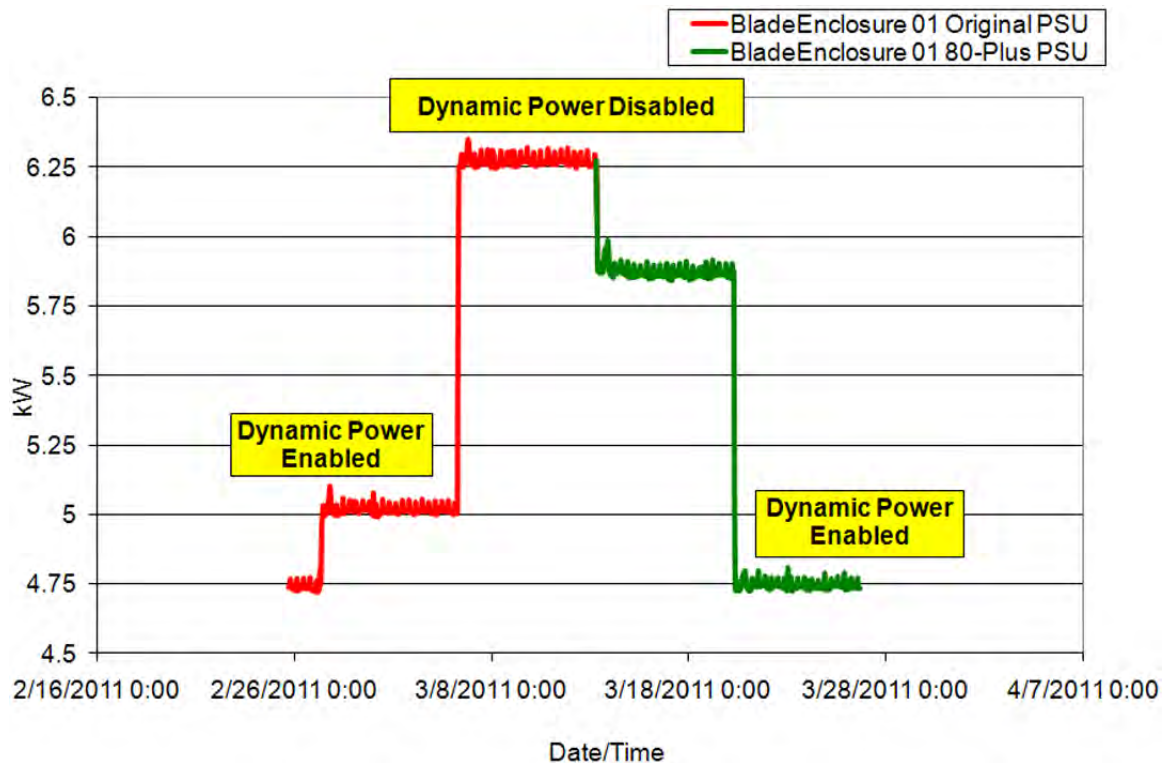
### Field Data

#### Power Supply Retrofits

Tests demonstrated that both technologies improved the utilization of blade enclosures. The results of one test conducted on blade enclosure 1 is tabulated in Table 3-6 and graphically represented in Figure 3-18.

**Table 3-6**  
**Results of Single Test on a Blade Enclosure**

Power Supplies	Dynamic Power Management	kW	$\Delta$ kW	% $\Delta$ kW
Original	On	5	-	-
Original	Off	6.3	1.3	26%
80 PLUS	Off	5.9	-0.4	-6%
80 PLUS	On	4.7	-1.2	-20%



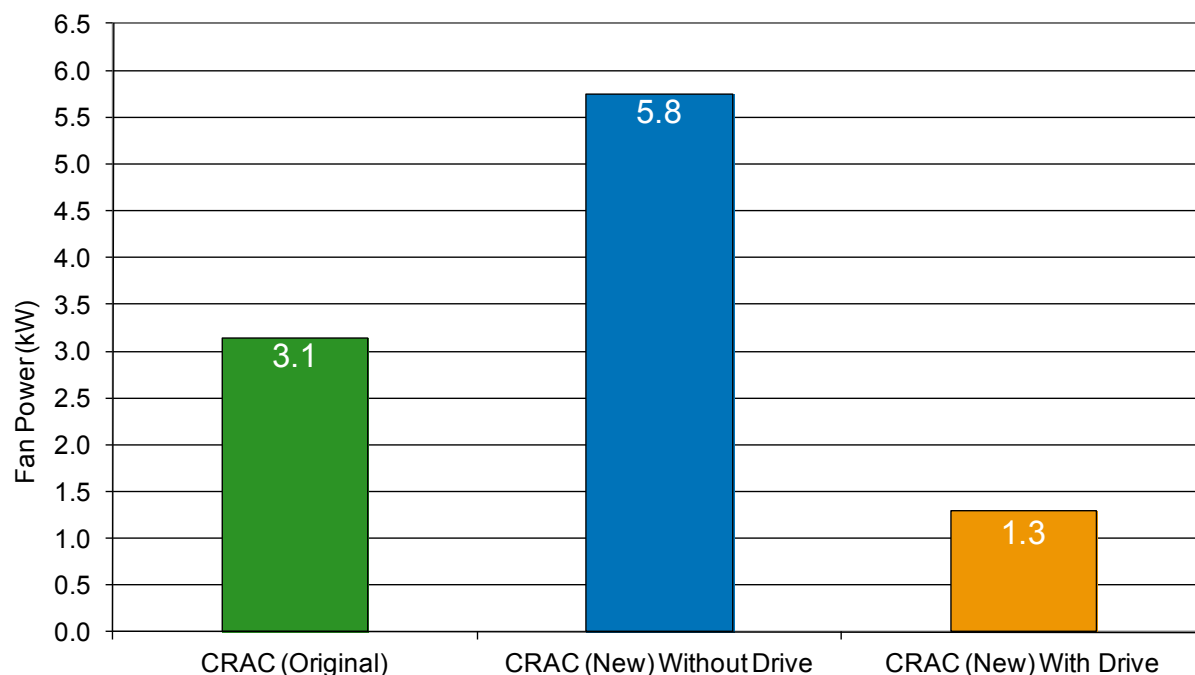
**Figure 3-18**  
**Results of Single Test on a Blade Enclosure**

## Airflow Management

Because the new CRACs can operate with VFDs for control of fan speed, the project was able to compare performance of the replacement system with the retrofit. In doing this, one test was designed using just the new CRACs, and energy use was compared with the old, original CRACs. Another test was to put the new CRACs in a mode that did not control the fan speed and allow the retrofit system to control the fan speed. This allowed the comparison of the retrofit to the replacement approach to airflow management.

Because the retrofit system can slow the fan speed to reduce energy (based on temperature feedback), the inlet temperature at the servers typically increases, to a level that is still safe for the server, but does not overcool them, which is an unnecessary use of energy. As a result of this, the outlet temperature of those servers and the overall room temperature rise. Additional tests were performed by raising the set points for the server inlet temperatures. It is expected that for every degree rise in inlet temperature, there will be a corresponding reduction in energy use by fans as well as chillers. In order to accomplish these tests, the data center operators had to be comfortable with the fact that the overall room temperature would rise. This was done while still remaining within the boundaries for safe operation of the servers. Once the operators were comfortable, testing was carried out.

Results for just the fan power are shown in Figure 3-19 (average kW per CRAC, five total CRACs in the main data center). Because this is the biggest savings area, it is a good indicator that the use of the VFDs would result in significant energy savings.



**Figure 3-19**  
Average Power (kW) per CRAC

## DC Power Distribution

The table below shows the results of the tests comparing energy use of the existing AC power system with that of the new DC power system. Load factors of the UPS and the rectifier were carefully controlled to ensure that they both operated at the same point on their efficiency curve. It can be seen that the load variation is quite small. Therefore, energy use is directly proportional to power consumption, increasing linearly with time. The DC system used 15% less power and energy than the AC system.

**Table 3-7  
Energy Use of Existing AC Power System and New DC Power System**

Parameter	Average	Max	Min	Standard Deviation
UPS Load Factor	29.8%	30.0%	29.7%	0.001
Rectifier Load Factor	30.5%	30.7%	30.4%	0.001
Unconditioned Power Rectifier	9.206	9.278	9.185	0.020
Unconditioned Power Required at UPS Input	10.851	10.888	10.823	0.019
Percentage Difference Less than AC Network	15.2%	14.8%	15.1%	
Average (Standard Deviation)				0.010

## Data Analysis

### Power Supply Retrofits

Several questions were addressed by this research:

What are the actual measured energy savings for each technology?

The energy savings approach 20% using 80 PLUS power supplies; this includes savings due to the lower power consumption of the unit, lower line losses due to the lower power consumption, and lower line losses due to power-factor correction (removal of distorted current).

What are the issues with implementation of efficient power supplies?

- Availability – 80 PLUS power supplies are available for certain old models and most new models of servers. Language was developed for inclusion in the data center operator’s future purchase orders to ensure that new stock includes those power supplies.
- Installation – Installation turned out to be the easiest of all technologies. Each blade server enclosure required the swap-out of six power supplies, but only took about two minutes. The hot-swappable feature was proven by this exercise.
- Reliability – 80 PLUS power supplies are tested and guaranteed by the manufacturer just as the original models were. The project did not experience any problems with operation of the units.

- Performance – All servers operated as expected, without any issues.

What are the issues with implementation of Dynamic Power Management?

There was no impact noted on performance of server activities by the users. The Dynamic Power Management was easy to start and stop, and performance was not an issue. In cases of very intensive computation load, it should be expected that some performance reduction will occur.

## Airflow Management

Several questions were addressed by this research:

What are the efficiency improvements possible with airflow management?

Results show nearly 80% reduction in fan power consumption.

What are the issues with airflow management?

- Installation – For market adoption, it is assumed that technologies that can be installed simply and quickly will succeed. This technology has been reported to require one or two days to install with a relatively non-intrusive procedure. In this project, the installation required only a few days.
- Communications and protocols – In order for the installation and operation to work, the existing controls and communication equipment in the data center must be compatible with those being installed. This project illustrated the problems and delays that can occur when this compatibility does not exist. Many months of testing were lost to issues such as requirements for protocol converters and vendor consent with respect to warranty.
- End-user commitment – The issues above created scenarios that required far more personnel involvement than ever envisioned for this project. It should be noted that while results look very promising, it is quite possible that commissioning this type of technology may be very time-consuming for the end user.
- Lessons learned – End users should carefully plan installations based on which communication protocol is in use, vendor expectations, and local contractors' understanding of those expectations. Communication among all parties was and will be the key to success.

## DC Power Distribution

Several questions were addressed by this research:

What are the efficiency improvements possible using DC?

Project results showed a 15% reduction in power consumption.

What are the issues related to wide adoption of 380-VDC systems in data centers?

- Availability
  - Component availability – UL-listed components can be obtained, if customers ask for them.

- Rectifiers – There are currently two manufacturers.
  - Circuit breakers – Many breakers are available.
  - Ground fault circuit interrupters – This technology needs development.
  - Arc flash – Studies have been completed; testing will be done by a manufacturer to determine the boundary values.
  - Connectors (extinguishing arcs) – UL listed 380-VDC connectors were not yet available at the start of this project. This issue has been resolved - three manufacturers offer these products today.
  - Power supplies – Power supplies designed to take 380 VDC can be specially ordered but are not widely available yet.
- Safety is a concern in the industry – Electricians may not be trained to handle 380 VDC.
  - Installation – Originally, it was assumed that this technology would be suited only for greenfield sites due to its complexity. End users would be hesitant to install this infrastructure if it meant ripping out the old AC power distribution system. However, a refreshing finding was that the DC system could easily be installed as a retrofit, simultaneously powering the load with the original AC equipment. The AC source could be turned off and kept as a backup. This presents an interesting possibility for market penetration.
  - Reliability – DC systems exhibit much higher reliability than AC systems. The telecom industry is an excellent example of this.
  - Performance – Servers performed flawlessly during this project. The power system operated without any issues.
  - Cost – Studies have shown that capital costs are lower for greenfield sites. This project operated as a retrofit, which did not yield any useful cost-comparison information.
  - Fear of the unknown – This project established another safe, reliable installation with high performance, but market education is necessary.

### Research Questions Applicable to All Three Technologies

What metrics and specifications can be developed to inform utility incentive programs?

- The 80 PLUS program is already a well-established incentive program for power supplies.
- Some utilities provide incentives for airflow management, but it is thought that their metrics overestimate the savings. Work within the EPRI research portfolio will develop a more comprehensive procedure.
- The data center industry has only used PUE and DCiE sparingly, although PUE is gaining acceptance from end users.
- Incentives are offered by utilities for virtualization based on number of servers unplugged, although this has no energy measurement component.

- Metrics and specifications are needed to inform utility incentives. The work in this Demonstration provided knowledge and understanding that will allow some metric and specification definition and development.

What measurement and verification procedures can be developed to support those programs?

- EPRI developed a comprehensive measurement and verification procedure for the DC power distribution demonstration. This was vetted by an outside third party and deemed suitable for use in the utility incentive program.
- A measurement plan was developed for the airflow management demonstration, but further enhancements, as mentioned above are forthcoming.

## Summary

### **Power Supply Retrofits**

Servers and cooling account for as much as 90% of the total power consumed by a data center. Test results show that as much as 20% of server energy use can be eliminated through this treatment. Because energy use by cooling systems is commonly close to the amount the servers use, and is driven by the heat load caused by the servers, it is likely that a 20% reduction in cooling will occur also. This equates to nearly a 20% energy reduction for the entire data center.

As utilities look for technologies to include in their portfolio of incentive programs, the 80 PLUS program offers an exceptional opportunity. Utility energy-efficiency incentive programs often focus on the large energy users: HVAC systems, commercial equipment, and lighting. But collectively, electronic loads account for a fast growing portion of business and residential annual energy consumption. Servers in data centers can offer a high concentration of electronic loads that can be addressed very simply using power supply retrofits or ensuring 80 PLUS compliance in the specification stage of hardware refresh.

Installation of retrofit 80 PLUS power supplies turned out to be the easiest of all the technologies to install during the Data Center Demonstration, taking only a few minutes. The Dynamic Power Management software was easy to start and stop, and performance was not an issue. In cases of very intensive computation load, it should be expected that some performance reduction will occur.

*Based on the results of this project, utilities should consider joining the 80 PLUS program, which provides incentives for manufacturers to ship qualified products. In addition, power supply retrofits and power-management software should be considered for inclusion in incentive programs.*

### **Airflow Management**

This technology shows the most promise in terms of inclusion in incentive programs; some utilities already offer incentives to customers for adopting this approach. Care must be taken in design because “airflow management” can be accomplished by several different methods, each of which may provide a different level of savings.

Automated systems are capable of reducing data center power consumption by as much as 25%. Manual approaches can also save energy. For example, rearranging perforated tiles to optimize

airflow, installing blanking panels in racks to prevent mixing of hot and cold air, and closing floor penetrations that allow too much airflow can all be effective in reducing cooling energy, although there is little or no data available on actual savings possible through these actions.

If a data center is set up to control the average room temperature to 72° F, the cooling air entering the servers will be much lower, perhaps 60° F. ASHRAE standards currently allow that temperature to go as high as 86° F. This fact provides a large opportunity for energy savings, but getting buy-off from those who work in a warmer environment may be difficult. During one project, EPRI was able to obtain that buy-off and reduce the anxiety of the workers.

*This is a very important development, because it shows that one of the most difficult barriers was overcome: Operators now can be convinced that operating with raised inlet temperatures (and thus higher room temperatures) can be accomplished without fear of downtime for their servers. Utilities should consider airflow management for their incentive programs. However, because it can come in many forms, they will need to be very specific about how it is accomplished.*

### **DC Power Distribution**

The results showed a 15% energy savings compared to the existing AC power system. Of course, these results will vary depending on the type of system being compared. For example, if an existing AC system has a very-high-efficiency UPS, the improvement by going to DC could be reduced. However, the DC system is inherently more efficient due to the lower number of power-conversion devices, and so will always result in energy savings.

One other key finding was that this technology is suitable for retrofit applications. Existing power systems need not be removed or replaced; rather, the DC system can be installed in parallel with the AC one, and one of the redundant power supplies in each server can be hot-swapped for a DC-powered unit. It was shown in this demonstration that the servers can operate from either the AC or DC source, or from both simultaneously. Operators could do this to achieve immediate savings and retire the AC system later.

One of the drivers for this technology, besides efficiency, is reliability. Because the DC system is inherently more reliable than the AC system (think DC telephone systems), data center operators have the opportunity to bring their system reliability up to telecom levels with a simple retrofit.

EPRI developed a comprehensive measurement and verification plan for this project, which was examined and validated by a third party familiar with regulatory requirements for incentive programs. By using this plan and the retrofit approach, this technology is ready for utility programs, with only a few barriers.

The first barrier is that the rectifier will require UL listing. The vendor used in this project is already engaged in getting that UL listing, so this barrier will soon be removed. The second barrier is safety, specifically concerns about arc flash. The project showed that using proper personal protection equipment (PPE) for 480-V systems and, whenever possible, de-energizing the system before working are effective in preventing any problems. Arc-flash studies have been performed on DC systems, and some of the vendors involved are compiling that research and performing testing at high voltage to verify performance. Mitigation of arc flash requires limiting the duration of the fault. Products are under development for 380-V<sub>DC</sub> breakers, fuses, and GFCIs that will accomplish this limitation.

*Utilities should consider DC power distribution retrofits in their incentive programs for their data center customers. In each case, the new system can parallel the old and the measurement and verification procedure developed during the course of the Demonstration can be used to verify the savings.*

### **Readiness for Program**

Each aspect of the data center energy-reduction strategies tested in the Demonstration resulted in energy savings. Each of the strategies could be considered in utility energy efficiency programs. In addition, EPRI recommends early deployment projects through the Coordinated Early Deployments Project to overcome market adoption barriers and to work with the supply chain to minimize barriers in supply. Conducting early deployments will help ensure success in utility programs at a lower cost and risk than launching programs at full utility rollout scale. Furthermore, through a collaborative process, utilities can learn from each other and potentially build on deployments conducted by others.



# 4

## VARIABLE REFRIGERANT FLOW

---

### Introduction

This chapter provides an overview of variable refrigerant flow (VRF) technology, a description of the four VRF Demonstration field sites and summary data. The emphasis of data collection and analysis is on capturing energy-use profiles for VRF systems because they depend on relevant external variables, such as outdoor and indoor temperature, season, and time of day. Detailed knowledge of VRF operation is essential for utilities to accurately gauge the potential for energy efficiency of incentivized VRF installations.

### Industry Overview

VRF is a family of air-conditioning and heat-pump products that expand the capabilities of the tried-and-true vapor-compression platform with the incorporation of variable capacity and distributed control (VCDC). The vapor-compression system for air conditioning has proliferated around the world since its discovery and invention across the 19<sup>th</sup> century, culminating with Carrier's invention of what became the modern-day vapor-compression air conditioner and heat pump. To a large degree, the unitary stock of American air conditioners and heat pumps are single-speed. The historically wide acceptance of these relatively simple and reliable systems in the United States was in part due to an abundance of available energy and the relative inexpensive cost of operation. In areas of the world with less abundant energy and higher cost, engineers have pushed the envelope of performance for direct expansion (DX), developing systems that, in the U.S. market, were less cost-effective. Newly invigorated drivers in the push for the efficient use of energy, particularly in devices that consume large amounts of it, are changing the American space-conditioning landscape by creating markets for advances in variable-capacity technology that a short time ago would have been considered unnecessary.

Although simple in concept, capacity variation in vapor compression is not simple to implement because of a variety of complicating factors, including components that are not variable and difficulties with refrigerant and oil-flow management. Fixed-capacity systems have the unfortunate behavior that capacity decreases in the direction of increasing load. Cooling capacity of an air conditioner decreases as the outdoor temperature rises (as the demand for cooling increases). Likewise, the heating capacity of a heat pump decreases as outdoor temperature drops. Capacity variation allows nominally sized equipment to operate at excess compressor speeds and fan speeds and at appropriately altered expansion valve states to enable capacity increases upwards of 50% beyond nominal rating.

Advanced and highly efficient new products built on the established vapor-compression base technology can act as effective resources for managing energy consumption while maintaining or improving indoor comfort. The American utility industry is on a constant search for tools to help manage the growth of the electric load and temporal variation. The variable-capacity, distributed-

control platform is seen as a next comprehensive tool for managing both short-term load variations and long-term load growth.

There is a need in the utility industry for greater understanding of the actual benefits of VRF heat pump and VRF heat recovery (HR) systems. These systems, which are relatively new to the United States, are accepted, in large part on the promise of increased energy efficiency, but often without a firm picture of what the true efficiency gains are. Utility companies and the greater HVAC industry have a keen interest in the perceived benefits of VRF, both for energy-efficiency purposes and as energy-management resources. Several key needs that the VRF-specifying professionals as a whole still require are accurate and reliable modeling of system performance, laboratory and field performance data, and standardized testing methods that allow for fair comparison both of comparable VRF systems and VRF with conventional systems. Until recently, VRF systems remained outside the realm of conventional rating standards and are thus difficult to compare to conventional HVAC systems. The recently adopted standard 1230 of the Air Conditioning, Heating, and Refrigeration Institute (AHRI) is a step in the direction of providing the needed tools for comparison.

Early forms of VRF were available in Asia several decades ago, with introduction to the United States 10 to 15 years ago. A main advancement was the introduction of simultaneous heating-and-cooling systems (heat recovery) to the United States over the last 5 to 10 years (progress is ongoing, with new manufacturers offering systems).

VRF as a platform offers a high degree of system design flexibility and scaling on what is at its heart a traditional-vapor compression (split-system) heat-pump arrangement. The ability to make certain key components variable (compressor, expansion valves, and fans), coupled with specific sensors and control algorithms, enables vapor compression to be used in much more flexible arrangements than previously done with single-speed systems.

## Technology Summary

VRF systems transfer heat via two-phase refrigerant piped throughout a building to a network of indoor units. Four attributes that distinguish VRF from other DX system types are: multiple indoor units connected to a common outdoor unit, scalability, variable capacity, and distributed control. The ability to have a distributed network of indoor units allows the space setpoint temperature to be controlled locally. VRF systems are generally applicable for buildings with multiple distinct spaces or zones that would benefit from local thermostat control. Central plant with individual room fan coils and/or variable air volume (VAV) systems offer similar levels of local control and are generally viewed as competing system types to VRF.

There are a variety of system types built on the variable-capacity DX platform as summarized below. This chapter primarily focuses on numbers 5 and 6, which are commonly termed VRF and VRF-HR, respectively, which are the larger commercial systems with a capacity greater than 65,000 Btu/hr.

1. Small ductless single-split systems covering the range of  $\sim 3/4$  tons to 2 tons, commonly called *ductless heat pumps* (DHPs). Some manufacturers offer mini-ducted, or what is termed *low-static ducted air handlers*, in this family of products.
2. Intermediate multi-split heat pumps, where two to eight indoor units pipe directly to the outdoor unit, ranging from 2 to 4 tons total capacity.

3. Unitary variable-speed split systems with a traditional American-style high-static residential air handler ranging from 2 to 5 tons. This type is currently limited to one indoor unit per outdoor unit.
4. Intermediate VRF heat pumps, where up to eight indoor units connect to a common refrigerant line set and a single outdoor unit in the range of 3 to 4 tons.
5. Full-size VRF heat pumps, where tens to hundreds of indoor units connect to a common refrigerant line set and an array of coupled outdoor units under a common control system.
6. Full-size heat-recovery VRF systems, similar to above, but that can perform simultaneous heating and cooling among indoor units, while the outdoor unit operates in net cooling or net heating mode determined by the percentage of demand for each.

All systems share the common platform that the primary transport of heat is via refrigerant. Transfer to or from the conditioned air is through a variety of indoor unit configurations, including wall-mount or floor-mount fan-coil units, ceiling cassettes, low static air handlers, and traditional high static air handlers. The term *ductless heat pump* has become somewhat of a catch-all term for many of the variable-capacity systems, but it is something of a misnomer. Any system can be ductless, and any can be ducted, and the intermediate-size to full-size variable-capacity systems often integrate both ducted and ductless indoor units into a coordinated design.

### ***VRF-Heat Pump and VRF-Heat Recovery***

VRF systems come in two general types: heat pump and heat recovery. Heat-pump systems operate with the total system in either heating mode or cooling mode. HR systems are heat pumps that allow for individual indoor units to operate in heating or cooling mode, while the overall system operates in net cooling or heating as determined by the aggregate demand of the indoor units. In HR operation, heat is transferred from zones requiring cooling to zones requiring heating via the refrigerant piping network. HR is appropriate for buildings that operate with non-concurrent demands for heating and cooling at different zones across the floor plan.

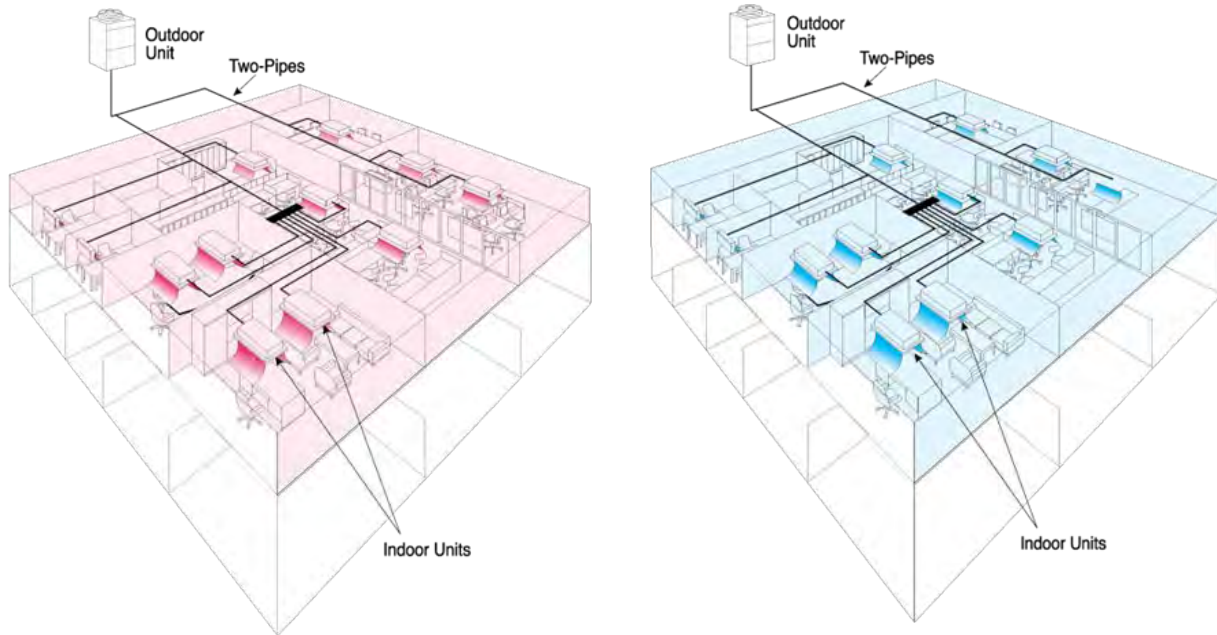
### ***Air-Source and Water-Source***

Being constructed on base DX technology, VRF systems can be air-source or water-source, although the predominance of North American systems are air-source. With water-source equipment, heat recovery can occur at two levels:

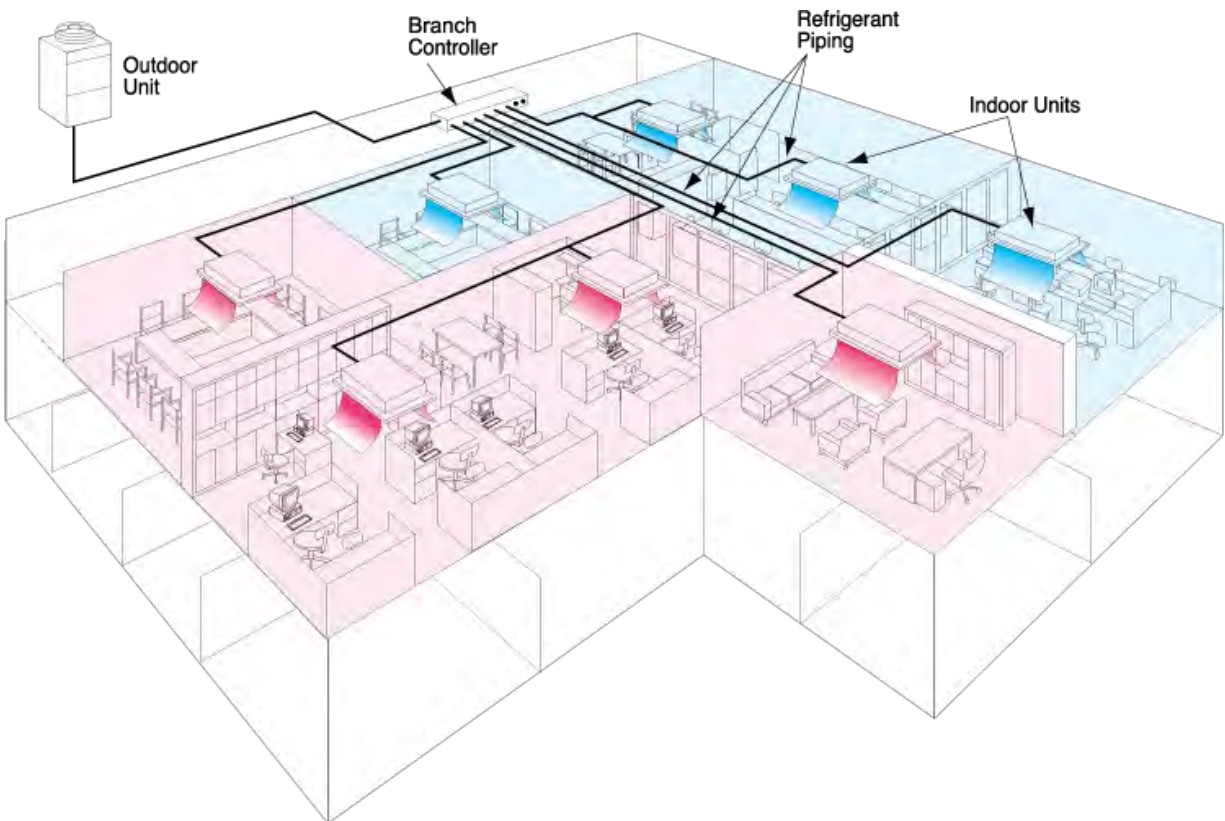
1. Intra-system, like air-source VRF-HR, where heat is exchanged between indoor units tied to the same refrigerant piping network.
2. Inter-system, where heat is exchanged between separate VRF systems through a common water loop.

The latter configuration allows heat to be exchanged across buildings in campus environments through piped water loops. The piping network size for individual VRF systems is limited by the total length of the refrigerant piping and total refrigerant volume contained in the piping network, making refrigerant-based heat exchange between buildings generally impractical. Figure 4-1, Figure 4-2, and Figure 4-3 show three possible configurations of generic VRF systems. Figure 4-1 shows an air-source heat-pump arrangement with no provision for heat recovery. Figure 4-2 shows an air-source arrangement with intra-system heat recovery. Figure

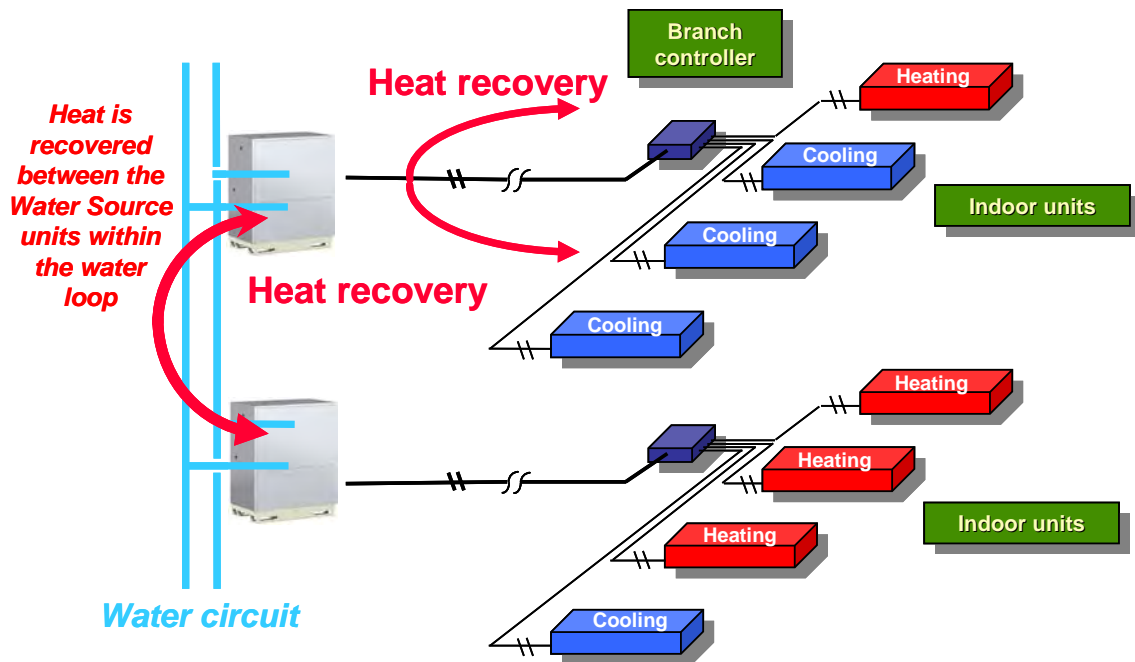
4-3 shows a water-source arrangement with intra-system heat recovery on the refrigerant side and inter-system heat recovery on the water side.



**Figure 4-1**  
Single-Mode VRF Operation—Heating Shown in Red and Cooling in Blue



**Figure 4-2**  
VRF-HR Simultaneous Heating and Cooling Operation



**Figure 4-3**  
**Water-Source VRF Heat-Recovery System with Refrigerant-Side and Water-Side Heat Recovery**

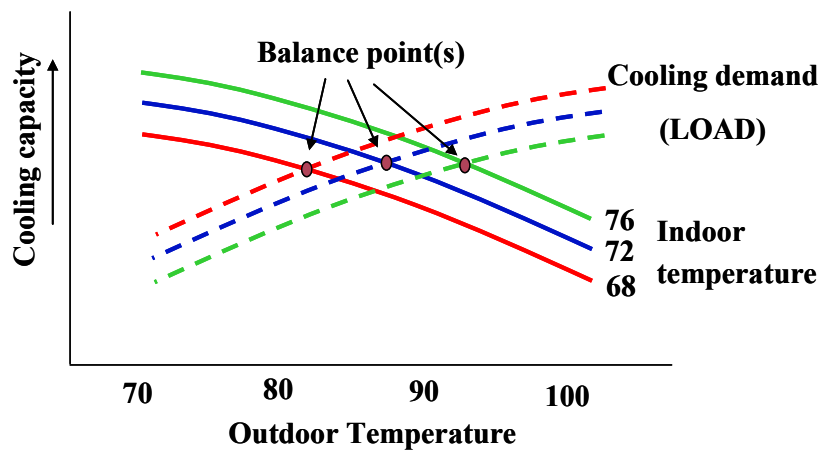
### **Zoning and Control**

A significant attribute of VRF systems is the ability to provide cooling and heating to individual zones within a building and allowing those zones to be separately controlled, such that different temperature setpoints can be maintained in each zone. A zone may comprise one or multiple rooms and have one or multiple indoor units. In HR installations, there are two levels of zoning: master zones and sub-zones. Master zones operate in a select mode (heating or cooling), depending on what mode the zone master thermostat is calling for. A master zone can be divided into sub-zones, each of which may only operate in the mode of the master thermostat but that can individually seek separate setpoints so long as reaching a setpoint does not require changing modes. Further sophistication is possible where the mode of master zones is determined by the aggregate demand of sub-zones with auto-changeover when aggregate demand switches from heating to cooling or visa versa.

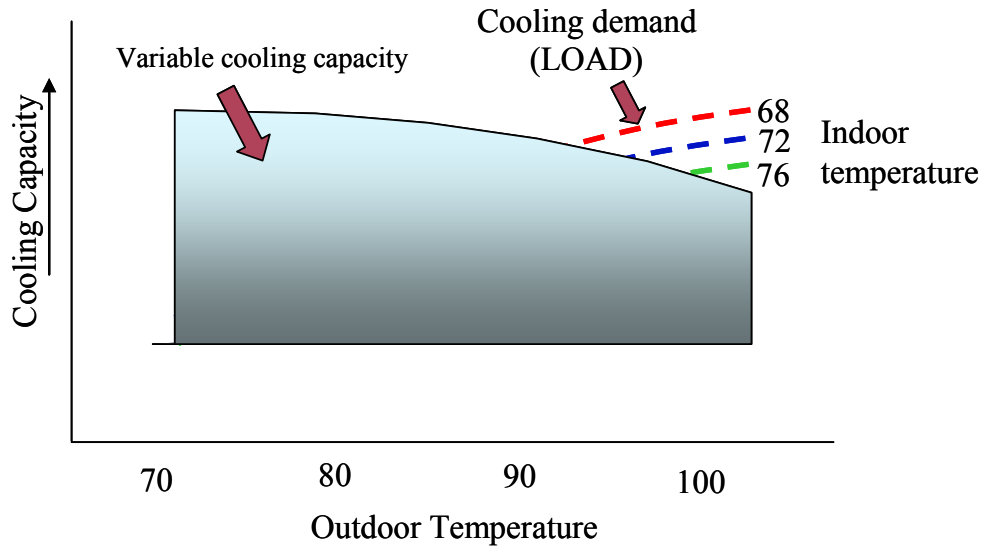
The idea of zonal control is not new. Variable air volume and chilled water fan-coil arrangements typically use varying levels of zoned control. The use of multiple unitary systems is a form of rudimentary zonal control, where sections of buildings are conditioned by ducted unitary equipment in segments of ~2 to 10 tons tied to a single thermostat. This type of arrangement is common in lower-cost commercial and retail space. Though the individual unitary systems represent building zones, they often comprise multiple rooms or offices that tie to a single thermostat, leaving one room as the determining setpoint for other spaces. Such a system can lead to unbalanced capacity delivery as load on the individual room changes over the course of a day or season, which can lead to unsatisfactory comfort for occupants of rooms not containing the thermostat.

### Thermodynamics

VRF operates through a modified reverse Rankine cycle, which is similar to other vapor-compression cycles. Having variable compressors and expansion valves, it is able to modulate refrigerant mass flow as demanded by system load, thereby changing capacity delivered to a space. Standard single-speed unitary heat pumps have a defined compressor speed, and refrigerant mass flow changes with operating conditions but cannot be changed significantly at a prescribed set of conditions. The historical method of control has been to size unitary equipment for extreme design conditions and then cycle the system ON and OFF to modulate capacity. VRF uses a different approach by allowing capacity to vary via the mechanism of changing refrigerant mass flow. Figure 4-4 shows a depiction of cooling capacity as it varies with outdoor and indoor ambient air temperature for a traditional single-speed system. The general trend is for cooling capacity to decrease with rising outdoor (condenser air) temperature and with falling indoor (evaporator) air. Variable-speed equipment follows the same trend for top-end capacity at full compressor speed but can adjust to any fractional capacity level below the maximum for a given set of conditions. This is depicted in Figure 4-5.



**Figure 4-4**  
**Example Cooling Capacity and Load Characteristics for a Single-Speed Air Conditioner**



**Figure 4-5**  
**Example Cooling Capacity and Load Characteristics for a Variable-Speed Air Conditioner**

Another major difference between VRF and unitary systems is that VRF employs multiple indoor heat exchangers, which, when operating as evaporators, do so with dedicated expansion valves. This means that while the heat exchanger is in the cooling mode, evaporation happens at slightly different temperatures and saturated pressures. The return suction pressure to the common compressor manifold is determined by the lowest operating pressure from the array of operating evaporators. Control of the expansion valves must take into account various system temperatures and pressures to determine orifice position and meter refrigerant flow for a specific evaporator. Figure 4-6 is a schematic of a generic VRF configuration with nine evaporators, and Figure 4-7 is a schematic of a generic single-evaporator unitary system. In heating mode, the VRF operates with multiple condensers, potentially at different temperatures, and the compressor discharge pressure is likewise determined by the highest required saturation temperature from an individual condenser. A somewhat similar corollary is a multi-evaporator refrigeration and freezer system commonly found in supermarkets. Such systems use staged compressors to provide stepwise control of system refrigerant mass flow along with thermostatic or electronic-controlled expansion valves to meter refrigerant to individual evaporators.

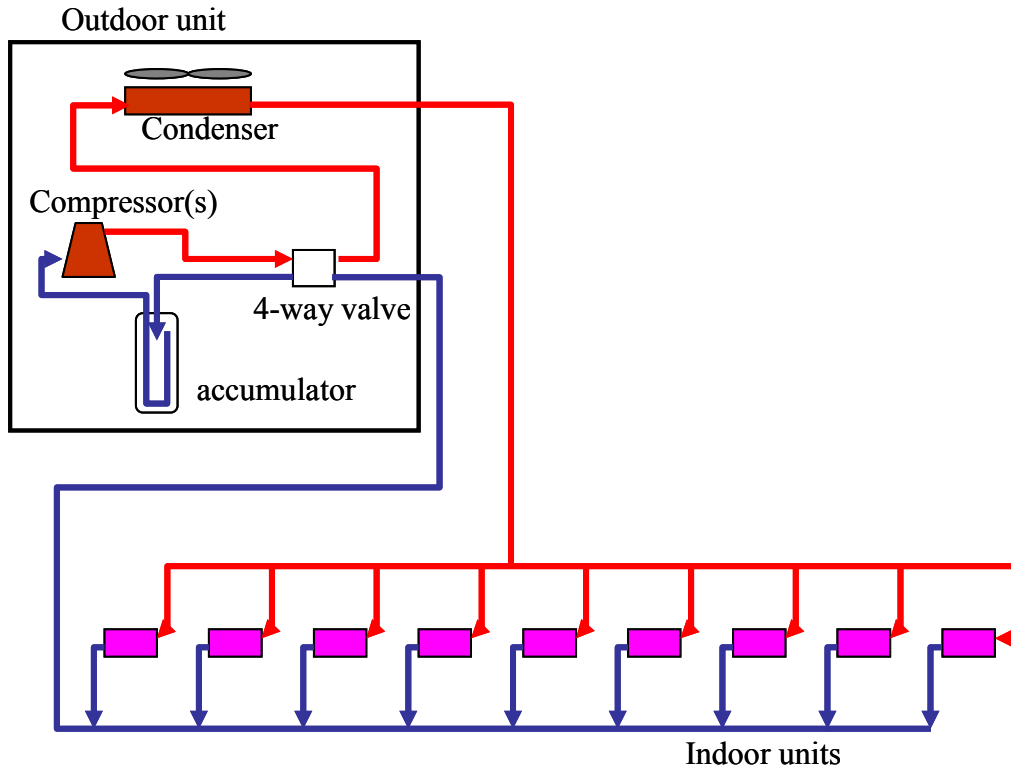


Figure 4-6  
General Schematic of a Multi-Zone Variable-Capacity DX System

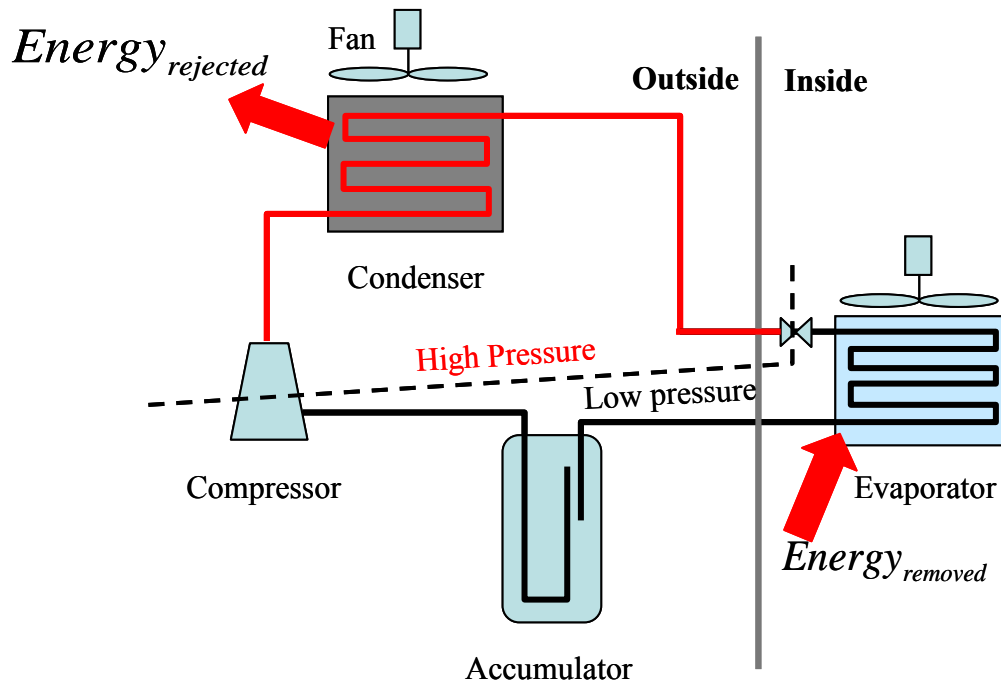


Figure 4-7  
General Schematic of a Single-Speed DX Air Conditioner

The ability to change refrigerant flow and thus evaporation pressure on individual evaporators within a certain band allows some ability to control the temperature of the evaporator coil surface and thus control the sensible heat ratio (SHR). This allows for some flexibility in controlling humidity. Variable-speed (or multi-speed) indoor unit fans also provide flexibility in both the SHR and the supply air temperature.

Heat recovery between indoor units adds another dimension to VRF systems. When operating with heat recovery, both the evaporation and condensation processes are distributed across multiple heat exchangers, and the outdoor heat exchanger acts to provide heat input or heat rejection based on the net demanded by the aggregate system. Some intra-system heat exchange may be required via refrigerant heat exchangers located in system selector boxes located within the piping network to equilibrate the internal load. Details of the specific method and control of the HR mechanisms are generally kept proprietary by manufacturers.

### Outdoor Units

VRF systems are split systems in the sense that the outdoor unit—containing the compressor, a heat exchanger, and ancillary controls—is physically separated by a refrigerant piping network from the companion indoor units containing the other heat exchangers. Like unitary counterparts, outdoor units of VRF systems contain the compressors and are the point of primary work input to the system. Most VRF systems are modular and scalable, where outdoor units can be connected in parallel via a refrigerant piping manifold to operate as a single orchestrated system. Individual outdoor modules normally contain two compressors, a single-speed scroll compressor and a companion variable-speed compressor. A common arrangement is to have two compressors of identical nominal size with the variable-speed compressor carrying load from minimum to 50%, after which the single-speed compressor takes over the base load, and the variable-speed compressor then ramps from 50 to 100+ percent capacity. Each manufacturer has specific variations on its particular compressor arrangement and operation. Additional modules, including those for ice storage and low ambient temperature boost, are available from several manufacturers. Although often referred to by the common term *condensing units* (because VRF systems are most often heat pumps), the outdoor unit can operate as an evaporator in heating mode. The outdoor unit fans are normally variable-speed, or could be multi-speed in older installations. Figure 4-8 shows a set of three coupled outdoor units in a VRF heat-pump system.



**Figure 4-8**  
**Three Paralleled Outdoor Units Comprising a Single VRF Outdoor System**

In heating mode, variable speed likewise allows flexibility of capacity, and the natural drop-off with decreasing outdoor temperature can be somewhat overcome by over-speeding the compressor and maintaining condensation temperature and refrigerant mass flow. Single-stage compression is usually adequate to outdoor temperatures of approximately -10°F (-23°C). For design conditions in the range of 14 to -13°F (-10°C to -25°C), a low ambient second-stage compression module is available. Figure 4-9 shows an outdoor arrangement coupled to a low ambient boost module. This system uses the low ambient module compressor in a two-stage inter-cooled arrangement with the outdoor unit compressors. This allows for higher compression ratios than are possible with single-stage compression and allows condensation pressure to remain high enough to produce heat at desirable indoor temperatures (~104 to 113°F, or 40 to 45°C).



**Figure 4-9**  
**VRF Outdoor Units Coupled to a Low Ambient Module**

### Indoor Units

Indoor units come in a variety of types and sizes, including floor-mount, wall-mount, and ceiling-mount ductless designs; low static horizontal mini-ducted air handlers; and high static vertical/horizontal air handlers. Figure 4-10, Figure 4-11, and Figure 4-12 show various types of indoor units.



**Figure 4-10**  
**Four-Way Ceiling Cassette Indoor Unit**



**Figure 4-11**  
**Encased Floor Standing Indoor Unit**



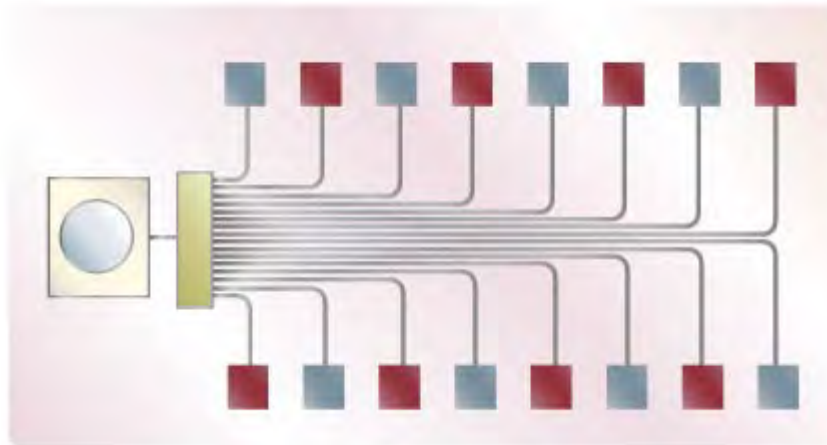
**Figure 4-12**  
**Horizontal Ducted Indoor Unit**

### Refrigerant Piping Network

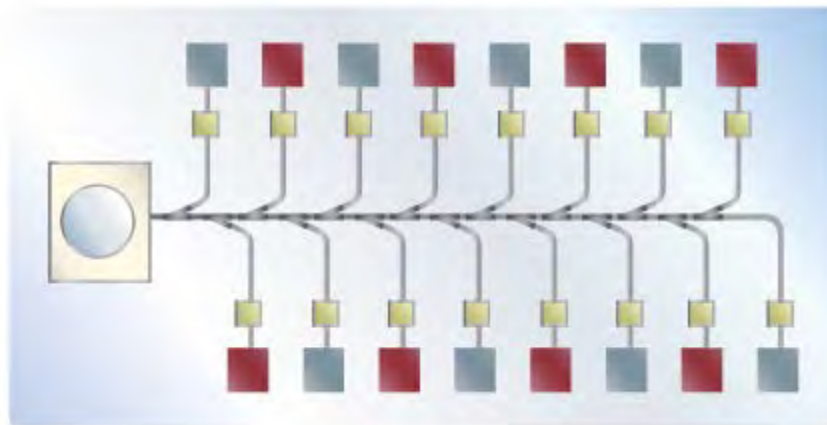
A network of copper refrigerant lines connects all of the components of VRF systems. Most manufacturers strongly suggest that long runs of rolled soft copper be used for the network in order to minimize field brazed connections and potential refrigerant leaks. Each manufacturer has its own specific requirements and limits for length of piping between various components and for total system length.

In heat-pump VRF systems, there is a two-pipe common header line-set that originates at the outdoor unit and runs through the indoor space being conditioned. Like unitary split-system piping, the larger tube serves as the suction line in cooling mode and the hot gas line in heating mode. The smaller tube serves as the liquid line in both modes. Individual indoor units tap off both lines of the header line-set through manufacturer-specific branching mechanisms. The common header line-set can split into multiple branches to serve different areas of the conditioned space, creating a star topology. Unlike typical unitary split-system installations, both refrigerant lines are insulated.

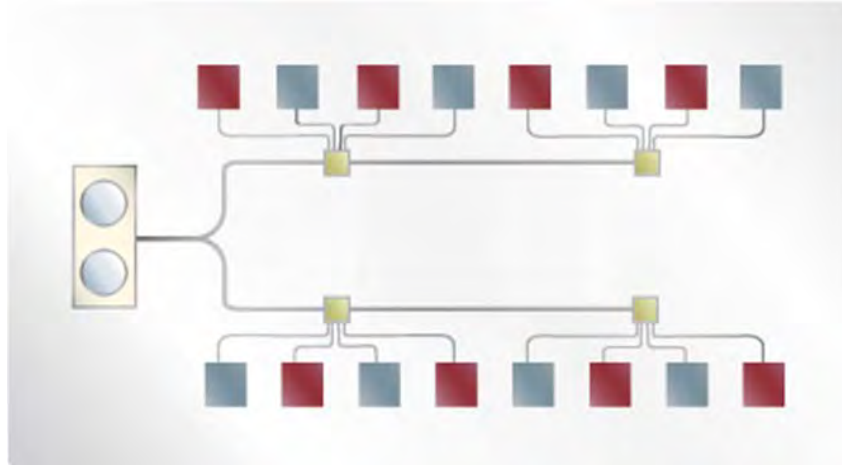
With heat-recovery systems, additional refrigerant piping is needed to accommodate the delivery of either liquid refrigerant for cooling or hot-gas refrigerant for heating to a mix of indoor units. Manufacturers approach methods for accomplishing this in slightly different ways, resulting in the two primary categories of VRF HR networks: two-pipe and three-pipe, with variations on the three-pipe architecture. Figure 4-13, Figure 4-14, and Figure 4-15 depict the three most common arrangements for zoning in VRF-HR systems: two-pipe, three-pipe with individual zone control units, and three-pipe with multi-zone control boxes.



**Figure 4-13**  
**Single Heat-Recovery Control Unit with Home-Run Piping from Indoor Units**

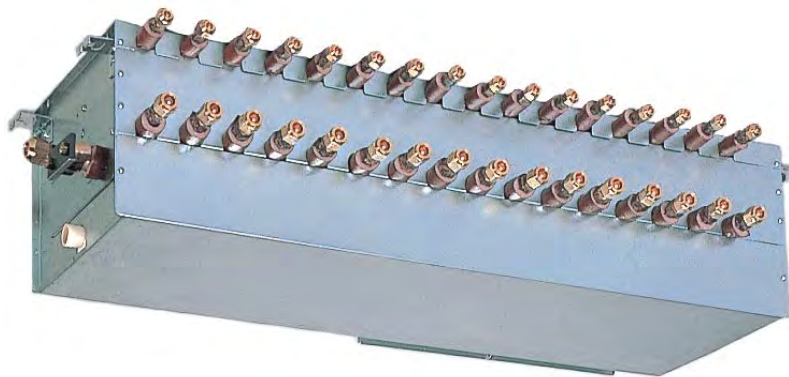


**Figure 4-14**  
**Heat-Recovery Control Unit for Each Indoor Zone**

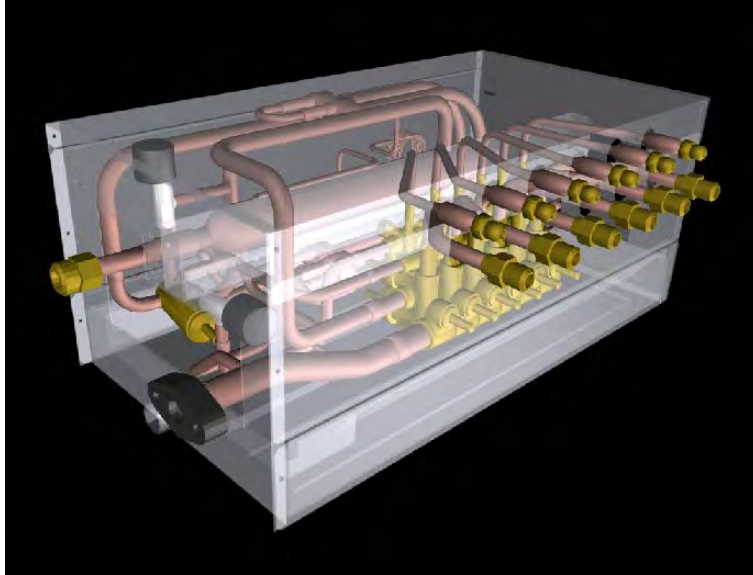


**Figure 4-15**  
**Multiple Heat-Recovery Units Each Serving Multiple Indoor Zones**

Manufacturer A uses a two-pipe arrangement, where the outdoor unit has two pipes running to a common manifold switching box called a *branch controller*, shown in Figure 4-16 and Figure 4-17. Each indoor zone is fed via two pipes from the control box. Control boxes may serve up to 24 individual separate zones. Each separately piped zone may have multiple indoor units connected to it, but all units on that pipe line must operate in the same mode. If the zone is in cooling mode, it is supplied warm liquid refrigerant from the control box and returns low-pressure vapor to the suction line. Conversely, a zone in heating mode is supplied hot gas refrigerant from the control box and returns warm condensed liquid. Some heat exchange may take place within the control box. The mode of the outdoor unit is determined by the aggregate of the connected zones and will either supply warm liquid (cooling mode) or hot gas (heating mode) to the control box.

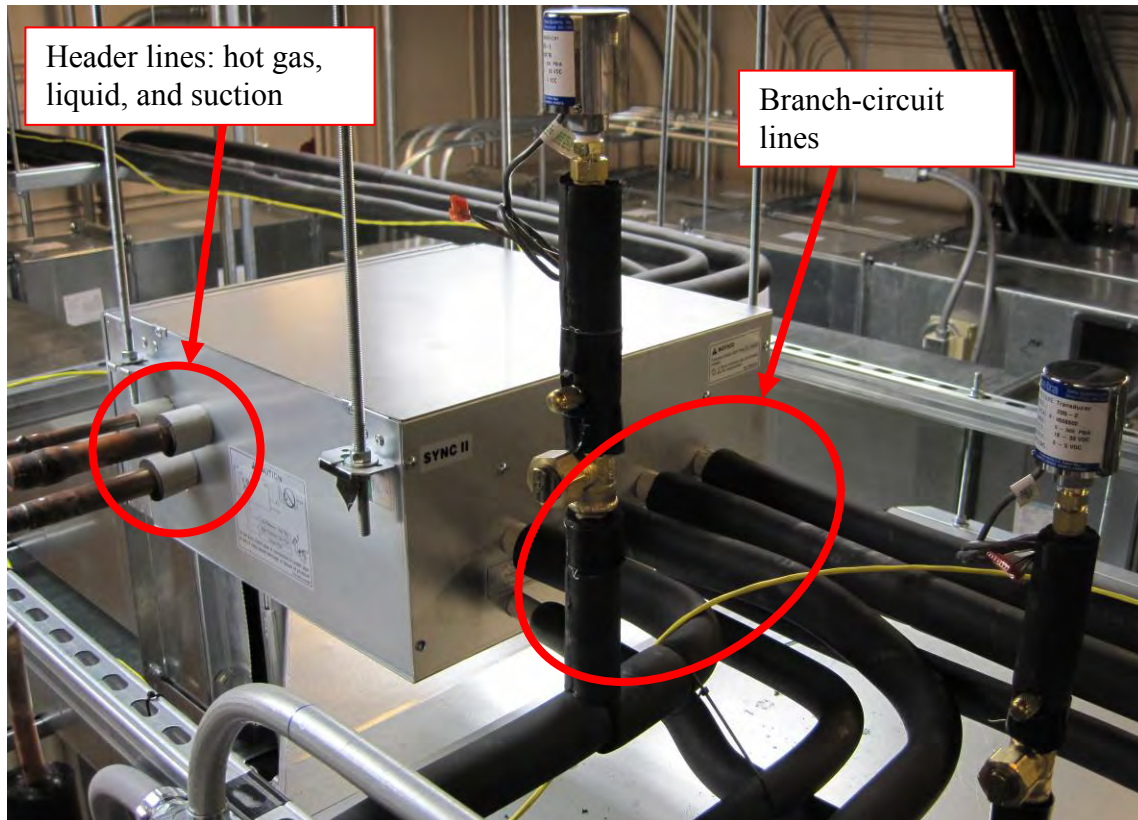


**Figure 4-16**  
**Sixteen-Circuit Branch Controller for a Two-Pipe VRF Heat-Recovery System**



**Figure 4-17**  
**Rendering of a Six-Circuit Branch Controller**

Manufacturer B uses a three-pipe common header piping network running through the indoor space, much the same as the two-pipe header used in heat-pump systems. Each zone has a dedicated control box called a *BC controller*, which connects branches via a Y-fitting to the hot-gas, liquid, and suction lines comprising the three-pipe header. The BC controller then controls the choice of refrigerant flow to the zone: warm liquid for cooling or hot gas for heating. Manufacturer C uses a three-pipe network similar to Manufacturer B, but each control box can manage up to four zones. Figure 4-18 shows a four-zone heat-recovery control box made by Manufacturer C.



**Figure 4-18**  
**Installed Four-Circuit Heat-Recovery Unit Made by Manufacturer C**

## Field Evaluation

The primary method for field evaluation is to measure power and energy profiles over time to understand how the profiles vary versus ambient temperature and humidity. In the best case, there exists a similar baseline to compare to—the VRF installation at Site B is this way. At Site B site the energy-use profiles can be compared between baseline and VRF at similar operating conditions. Having similar operating conditions is important for comparing HVAC systems, because their performance is highly dependent on them.

Climate is very important because it 1) dictates the thermal building load and 2) defines the operational efficiency of many HVAC systems. This is true for VRF as well as other traditional heat pump systems. For air-conditioning equipment, performance is always a function of the operating temperatures, as is the case for heat pumps in heating mode. Electric resistance or direct fuel-fired heating systems do not have performance dependent on ambient temperature.

## Research Objectives

The research objectives are described below:

How do VRF systems operate relative to traditional HVAC systems from an energy-use perspective?

How do they maintain comfort relative to traditional systems?

How do they integrate into buildings, and is the installation comparable to other systems?

Are there any codes and standards issues related to VRF that are different from other systems?

Laboratory measurement can be used to compare equipment performance under controlled conditions, but it cannot replicate the interaction of a piece of HVAC equipment with the building load. Space conditioning is the interaction of the equipment with the load, and that must be measured and characterized in the field. Field testing provides the truest measure of the required energy to maintain a building at a particular comfort level under a given set of environmental constraints (the climate).

The end goal of this Demonstration was to achieve both quantitative and qualitative understanding of what value as a resource for energy efficiency VRF represents. To know this, there must be an understanding of what happens in real life, real buildings. Does the technology save energy relative to others and how much? Do the savings depend on variables like climate? Seasonal, daily, or hourly variation?

Secondarily, the Demonstration seeks to learn of other aspects of the technologies that will improve, change, or adversely affect the client or end user. Comfort and ease of installation are important, not in determining the quantitative value of energy-efficiency potential, but perhaps for pushing a technology off the fence in one direction or another.

Various efforts are underway to evaluate the energy-efficiency effectiveness of VRF systems, including this Energy Efficiency Demonstration, where several installations across the United States were monitored for performance over time. For the Demonstration, four systems were operating: a small office building (Site A), a school (Site B—the site with available baseline data, Figure 4-20 and Figure 4-21), another office building in a different climate (Site C, Figure 4-19), and a retail store (Site D).



**Figure 4-19**  
**VRF Systems Installed at Site C**



**Figure 4-20**  
**Ceiling Cassette-Type Indoor Unit at Site B**



**Figure 4-21**  
**VRF System Installed at Site B**

In the years prior to the Demonstration, EPRI conducted field/lab investigations of VRF at its Knoxville facility. A system was installed serving a nine-office section of the building, and performance was compared between the existing split-system ducted air conditioning and the VRF. Data at similar operating conditions indicated a potential for energy savings between 30 and 40% for similar indoor comfort. This work laid the groundwork for instrumentation and field test design for the VRF Energy Efficiency Demonstration.

The recent adoption of the Air Conditioning Heating and Refrigeration Institute (AHRI) standard 1230 for rating VRF systems is a useful step in providing a fair mechanism for comparing equipment performance of VRF to other unitary types of systems. However, much of the potential energy efficiency benefit of VRF comes from the interaction of the system with the building, which cannot be captured by an equipment rating alone. It is necessary that further understanding and documented measured performance of VRF systems compared to other counterpart HVAC systems be gained through field studies and valid modeling.

## Research Method

Site selection was guided by the need for comparative baseline and treatment buildings. Although not always available, the need for baseline is important. If not done physically, a

baseline can be modeled. Site B has good physical baseline; others have baseline performance modeled.

To obtain performance data, EPRI measures the use profile for power and energy as a function of external driving variables, namely outdoor temperature and humidity, indoor temperature and humidity, indoor setpoint, occupancy, and time of day/season. An energy-use profile can then be compared with treatment to baseline at similar external conditions. Some of the external variables are stronger drivers than others (for example, outdoor temperature can be a very strong driver). EPRI identified the key drivers and took them into greater account when analyzing performance.

Field testing is unpredictable, and performance depends on a host of uncontrollable variables, all of which can introduce uncertainty into the analysis. Lab testing is highly controllable but is difficult to match to actual building conditions. Combinations of lab testing to gain an understanding of equipment performance combined with field testing to evaluate equipment interactions with the building/occupants are the most productive approach.

The data acquisition was built on a data logger with a local network of wired and wireless sensors. Sensors for VRF include an outdoor temperature and RH transmitter, power meters, wireless indoor temperature and relative humidity sensors, and some site-specific additional points such as carbon dioxide (CO<sub>2</sub>) transmitters or refrigerant-line temperature sensors. Data is collected from the sensors and fed through the data logger to an EPRI server/database, where automatic and manual data checking occurs.

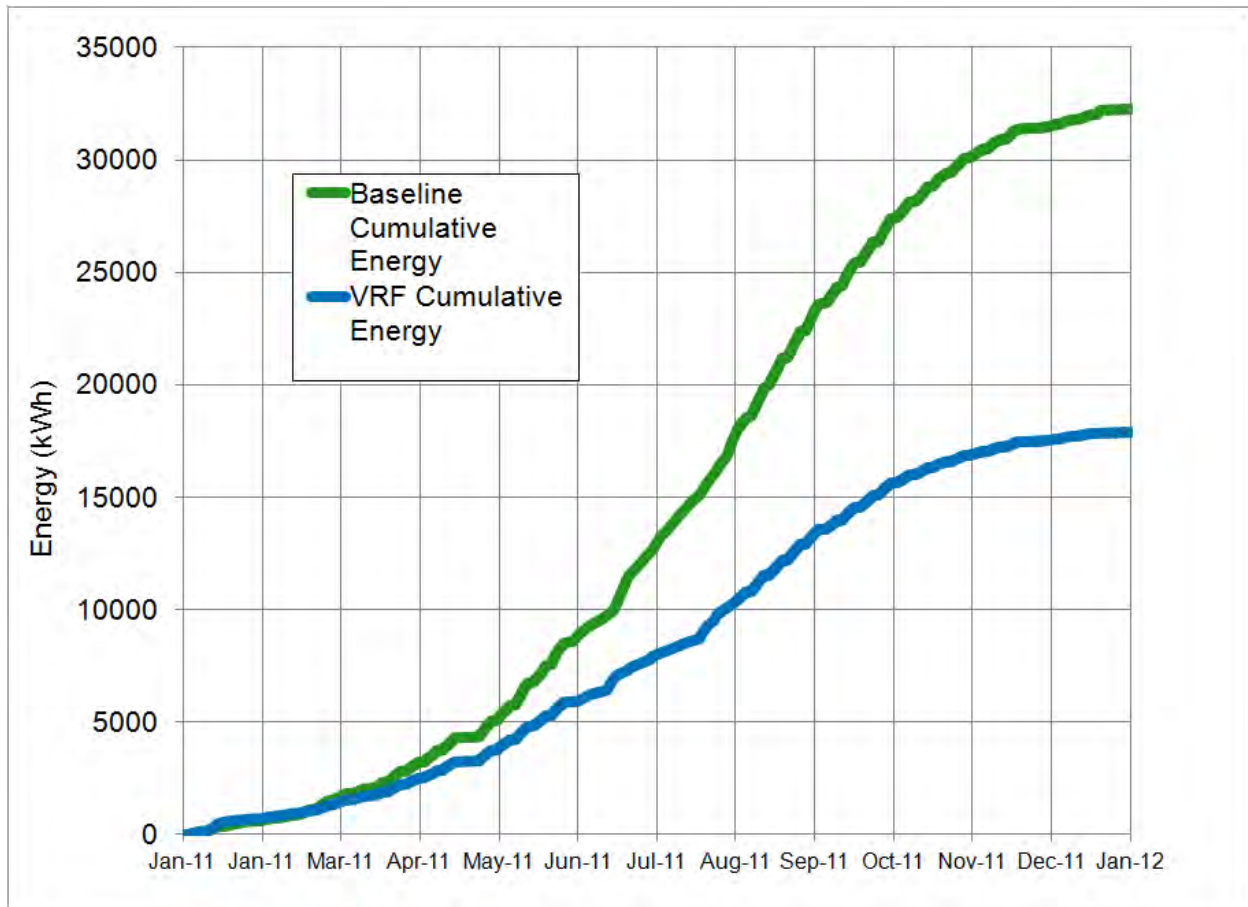
## **Laboratory Investigation**

Laboratory work was primarily performed as Program 170 base work in 2008 and 2009 and can be seen in the EPRI technical update [4-1].

## **Field Data**

### ***Site B***

Site B, which was located in a hot-humid climate, provided a side-by-side comparison of energy consumption for a baseline building conditioned with conventional air-conditioner units, with a very similar building with a VRF system. The energy consumption of each is shown in Figure 4-22 for 2011. The VRF system used 17,890 kWh, and the baseline site used 32,250 kWh over the course of the year. This equates to a 45% energy reduction over one year. The rate of energy consumption for both was highest in the summer.

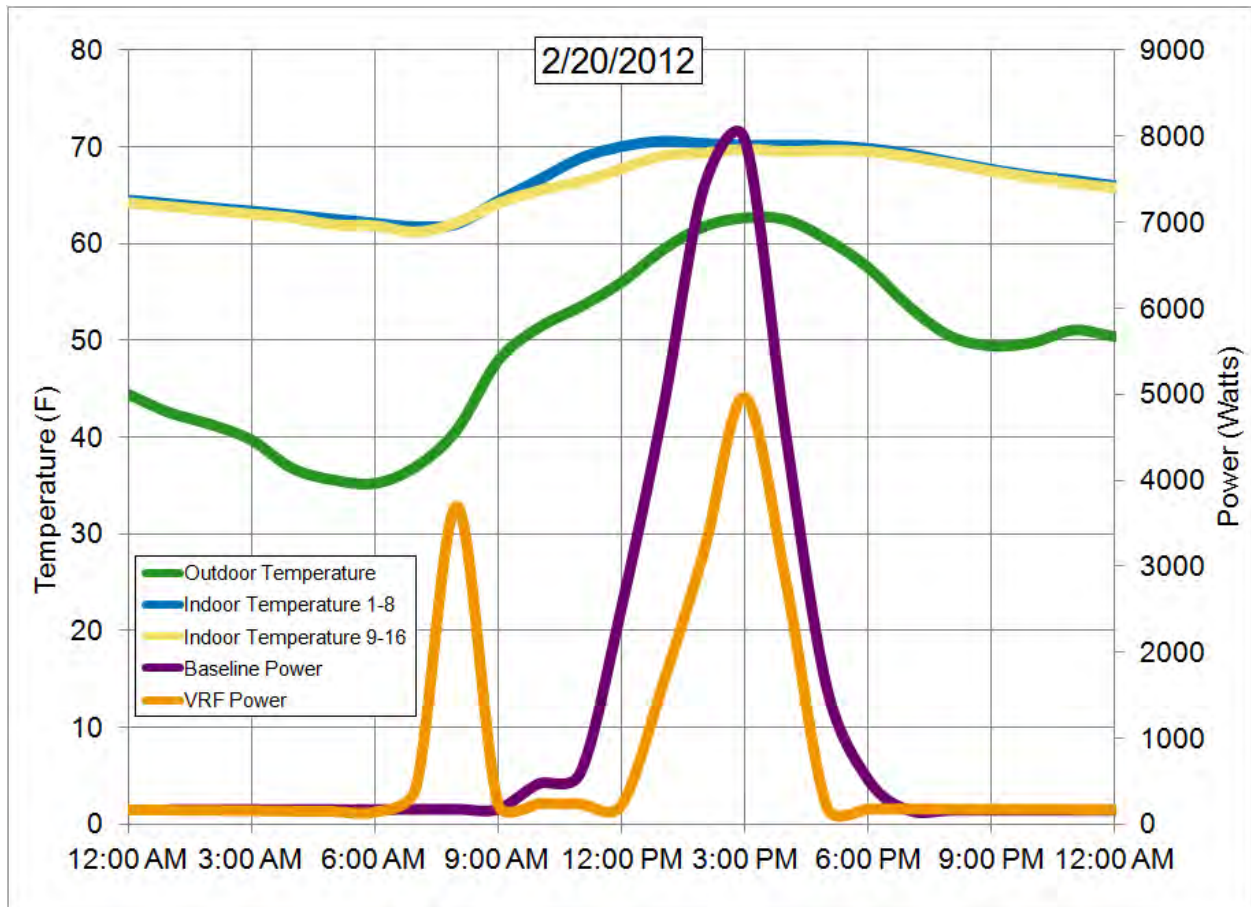


**Figure 4-22**  
**Cumulative Energy Consumption at VRF Site B**

The power is shown for a representative winter week day in Figure 4-23 with one-hour average intervals. The indoor temperature for both spaces is shown by the green and red lines; as can be seen, both units do not operate during the overnight hours, and the space cools to about 63°F (17°C). The VRF unit briefly operates in the morning, and both units operate minimally in the morning, before providing cooling during the afternoon. The occupancy load at the school may provide all of the heat required during the morning, and appears to drive cooling loads in the afternoon. Over the 24-hour period shown, the energy consumption of the baseline site was 32 kWh, and the energy consumption of the VRF site was 19 kWh. This equates to a 41% energy reduction over a period of one day. The peak power at the baseline site was 8.0 kW, and 5.0 kW at the VRF site, equating to a 38% peak power reduction for the VRF site. The monthly breakdown of energy consumption is shown in Table 4-1.

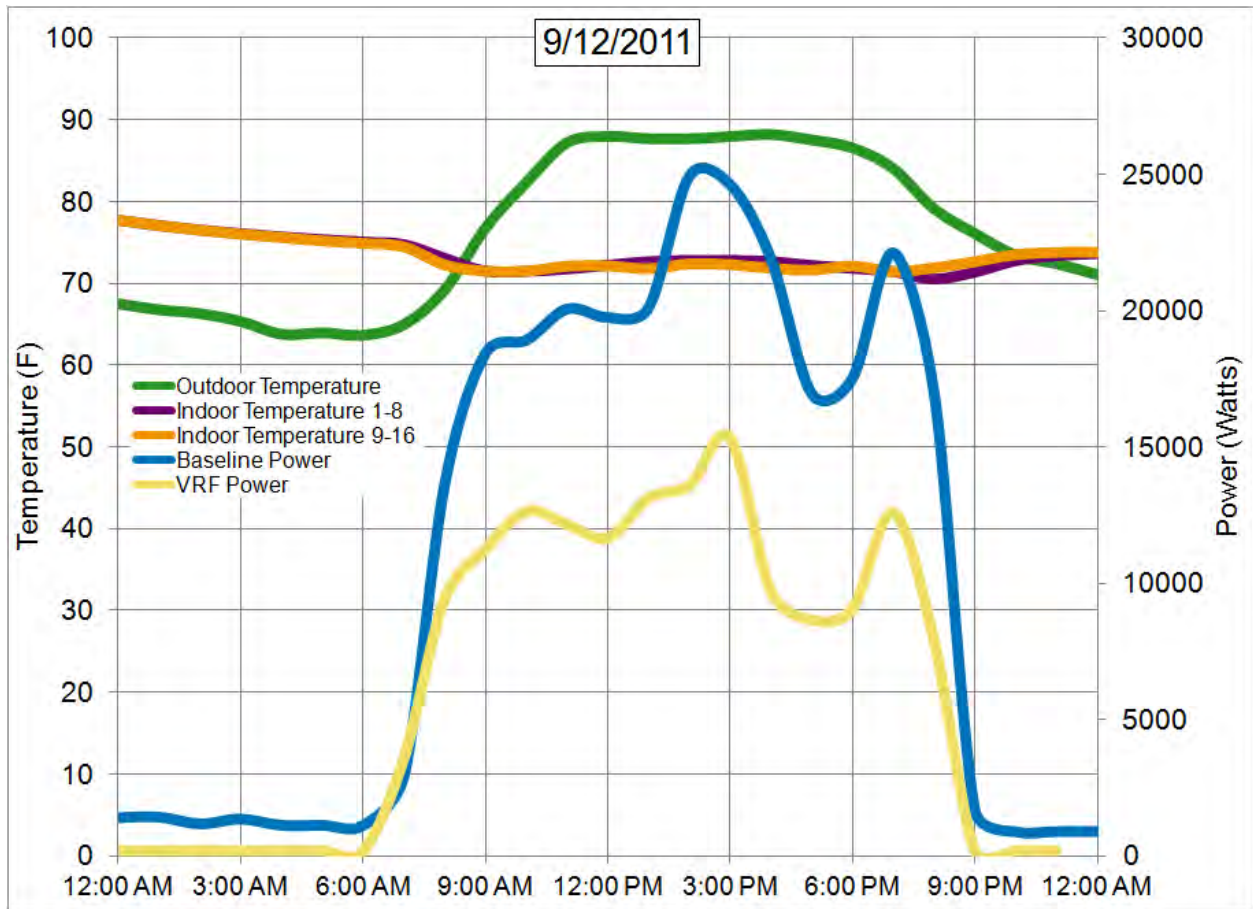
**Table 4-1**  
**Monthly Breakdown of Energy Consumption**

	<b>Base Energy (kWh)</b>	<b>VRF Energy (kWh)</b>	<b>Energy Savings</b>
January	648.2	730.7	-13%
February	947.0	655.0	31%
March	1,544	1,087	30%
April	1,926	1,283	33%
May	3,622	2,167	40%
June	3,991	2,009	50%
July	4,906	2,344	52%
August	5,600	3,067	45%
September	4,202	2,292	45%
October	2,765	1,260	54%
November	1,341	645.7	52%
December	731.4	327.4	55%



**Figure 4-23**  
**Power Consumption and Temperature at Site B VRF Sites for a Cold Winter Weekday**

A representative summer weekday is shown in Figure 4-24, with one-hour data intervals. As can be seen, the units did not run overnight, which was the case in winter. Both units began operating in the morning and reached peak power in the mid-afternoon. The VRF unit had a maximum hourly average power of 15.3 kW, while the baseline maximum was 24.9 kW. Over the 24-hour period shown, the energy consumption for the baseline was 270 kWh; for the VRF, it was 153 kWh, equating to a 43% reduction in energy use.



**Figure 4-24**  
**Power Consumption and Temperature at Site B VRF Sites for a Warm Weekday**

**Site C**

Site C, which was located in a marine climate, does not have a baseline comparison, but rather the building was modeled and simulated with the VRF system installed, as well as with a baseline HVAC system of nine heat pumps. The energy consumption from the model and field metering are shown on a monthly basis in Figure 4-25. The results are also tabulated in Table 4-2. The model projected energy savings of 14 to 27% for VRF compared with the baseline system. The actual VRF energy consumption was over-estimated during the summer months and underestimated in the winter months by the model. However, both modeled and real-world VRF energy consumption were significantly lower than the baseline modeled HVAC system for all eight months shown in the figure.

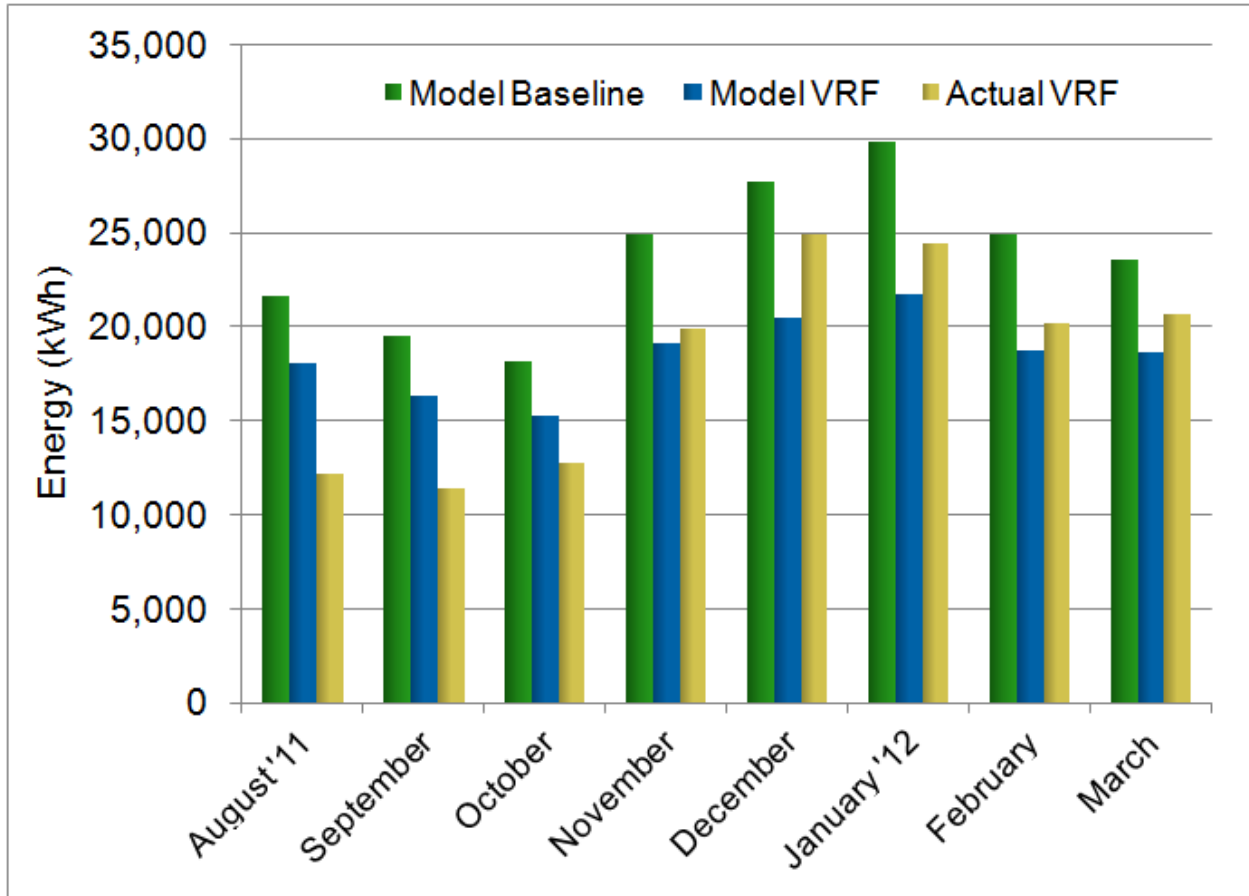


Figure 4-25  
Monthly Energy Consumption for Modeled Baseline, Modeled VRF, and Field VRF Site C

**Table 4-2**  
**Monthly Energy Consumption for Model Baseline, Modeled VRF, and Field VRF Site C**

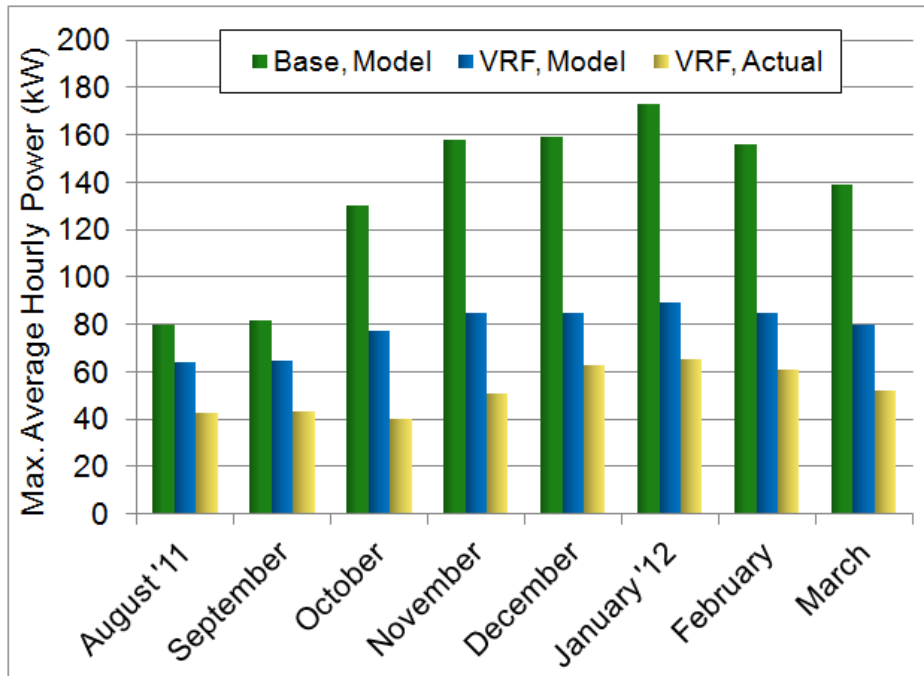
Date	Model Baseline (kWh)	Model VRF (kWh)	Difference: Model Base and Model VRF (%)	Actual VRF (kWh)	Difference: Actual and Model VRF (%)
August '11	21,659	18,030	17	12,172	32
September	19,538	16,333	16	11,457	30
October	18,139	15,282	16	12,774	16
November	24,921	19,123	23	19,867	-4
December	27,759	20,489	26	24,929	-22
January '12	29,855	21,712	27	24,390	-12
February	24,931	18,743	25	20,236	-8
March	23,585	18,616	21	20,716	-11
April	18,139	15,329	15	15,641	-2
May	17,704	15,219	14		
June	18,794	16,038	15		
July	21,278	17,448	18		

The energy consumption, normalized by square footage, is shown in Table 4-3. The building area is 20,842 ft<sup>2</sup>. For comparison, the EIA Buildings Databook shows an average space heating and cooling consumption for office buildings of 12.2 kWh/sf (including all heat sources). Extrapolating the 9 months of data shown here to a full year, the energy consumption on space heating and cooling would be 10.4 kWh/sf, a reduction of 15% [4-2]. If ventilation is included in the base number, the energy consumption of the average building would be 13.7 kWh/sf, an improvement of 24.5%.

**Table 4-3**  
**Site C Measured VRF Energy,**  
**Normalized by Square Footage**

Date	kWh/sf
August '11	0.58
September	0.55
October	0.61
November	0.95
December	1.20
January '12	1.17
February	0.97
March	0.99
April	0.75

Figure 4-26 and Table 4-4 show the peak hourly demand, per month, for the modeled base system, modeled VRF system, and the actual VRF system. Again, the projection made by the model is for significant reduction in peak demand (modeled VRF versus modeled base), ranging from 16% in June to 49% in January. In this case, the actual maximum demand measured in the building was significantly lower than modeled, ranging from 26 to 48% lower.

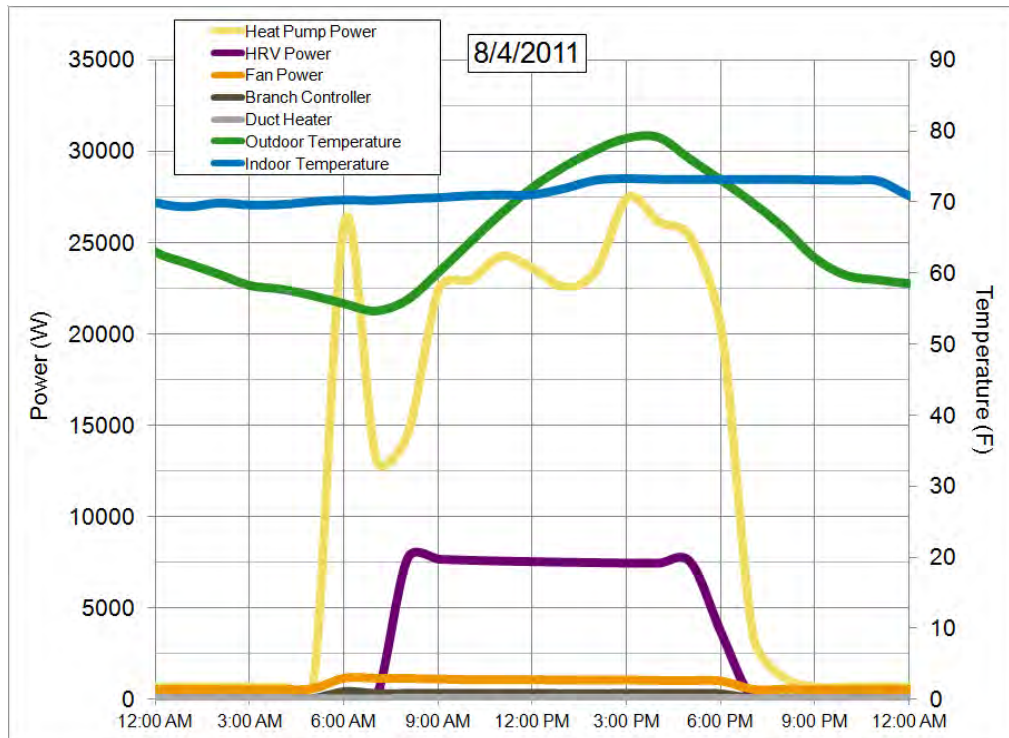


**Figure 4-26**  
**Monthly Peak Power for Modeled Baseline and VRF and Field VRF Site C**

**Table 4-4**  
**Monthly Peak Power for Model Baseline and VRF and Field VRF Site C**

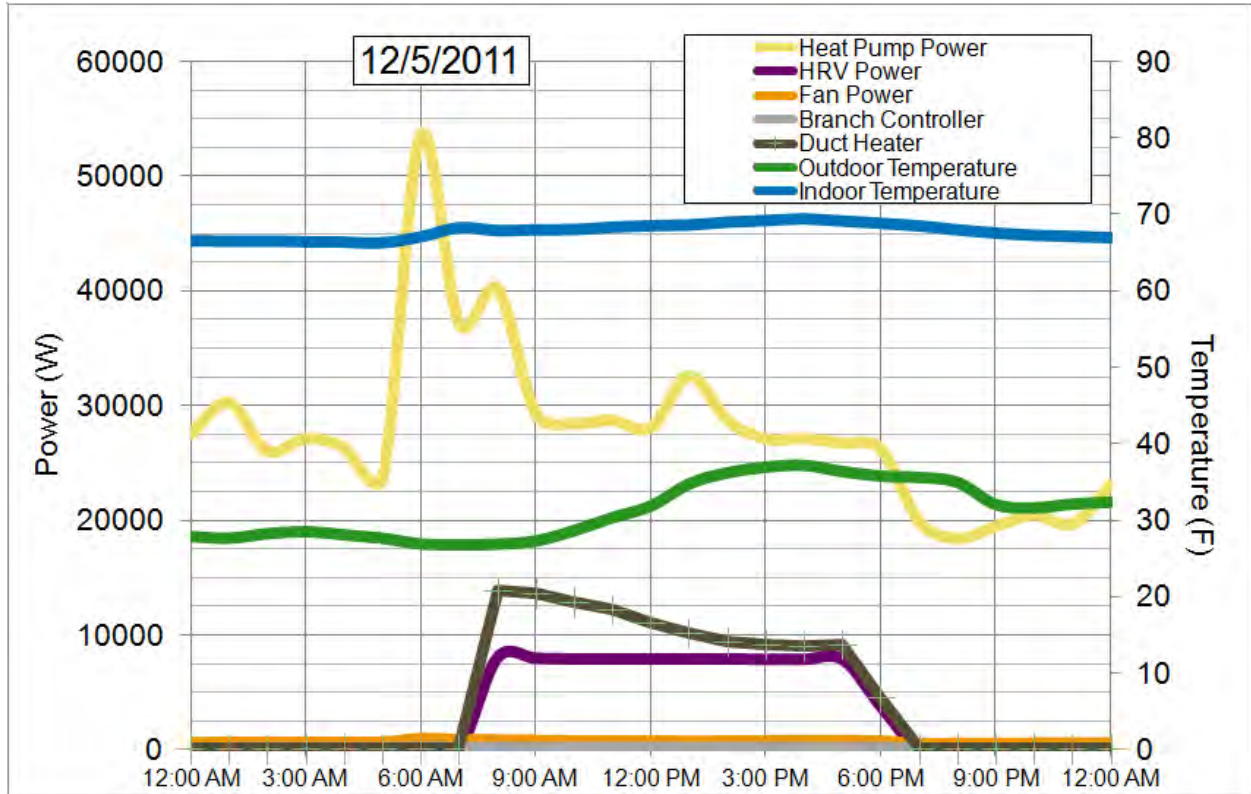
Date	Base Model (kW)	VRF Model (kW)	Difference: Model Base and Model VRF (%)	VRF Actual (kW)	Difference: Actual and Model VRF (%)
August '11	80	64	20	43	33
September	82	65	21	43	33
October	130	77	41	40	48
November	158	85	46	51	40
December	159	85	47	63	26
January '12	173	89	49	65	26
February	156	85	46	61	28
March	139	80	42	52	35
April	103	70	32	40	42
May	67	55	18	N/A	
June	69	58	16	N/A	
July	100	77	23	N/A	

The hourly power, broken down by use, is shown in Figure 4-27 for a summer weekday. The VRF systems operated for much of the day beginning at approximately 6:00 AM. There was a high demand when the unit first turned on, presumably to seek to satisfy a change in the indoor setpoint temperature. This initial load may have actually been space heating, because the overnight low temperature was 55°F (13°C) outdoors. The peak heat pump hourly demand was 27,460 W for the hour ending at 3:00 PM. The heat-recovery ventilator (HRV) operates from 8:00 AM to between 5:00 to 6:00PM, drawing 7,500 W.



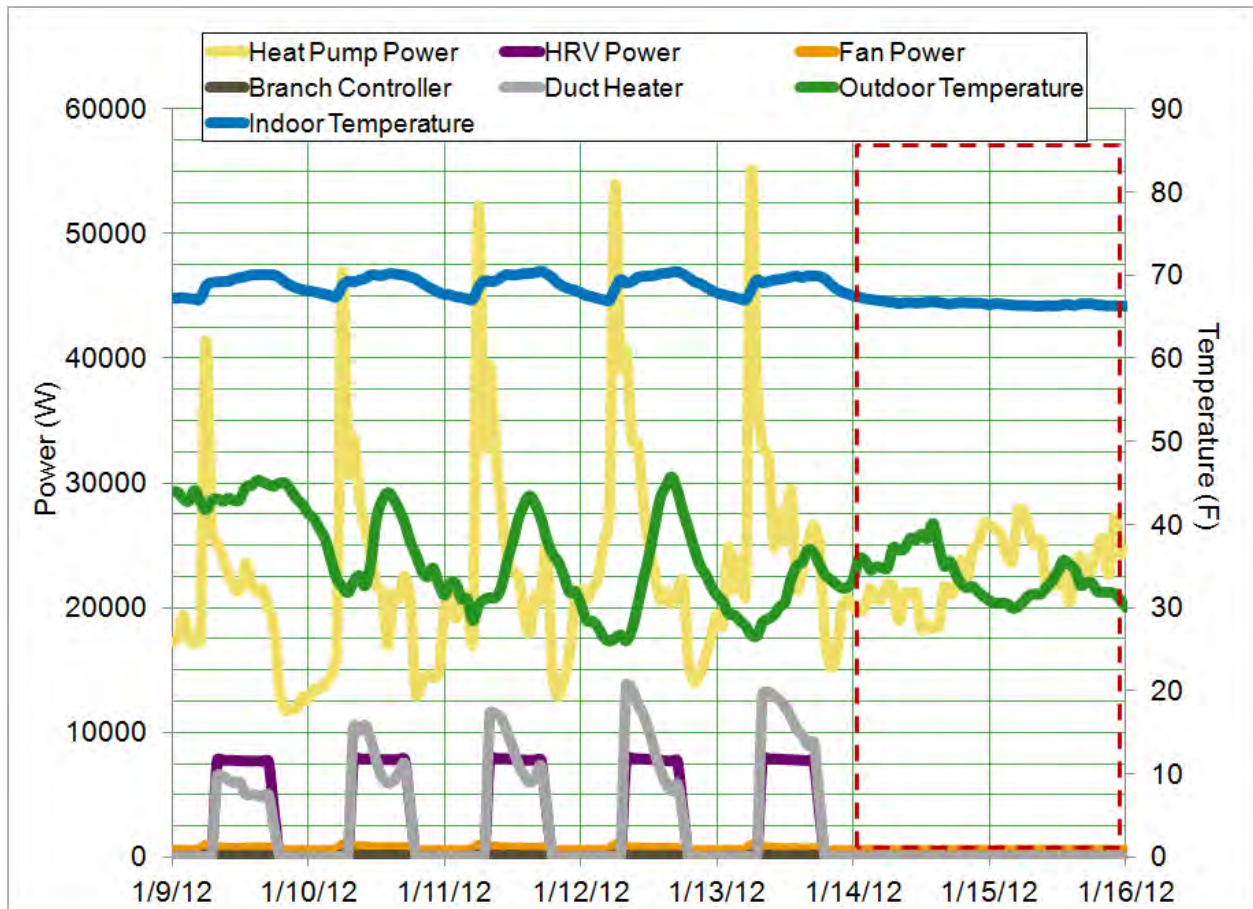
**Figure 4-27**  
**VRF Site C Power and Temperature for August 4, 2011**

Figure 4-28 shows the power for a winter day. On this day, the outdoor temperature was always below 40°F (4°C), and demand was high. The heat pumps operate for the whole 24-hour period, and the duct heaters operated at partial load during daytime hours. The highest duct heater load was 13.8 kW for the hour ending at 8:00AM, which again likely relates to a sudden increase in heating load due to an internal temperature setpoint change.



**Figure 4-28**  
**VRF Site C Power and Temperature for December 5, 2011**

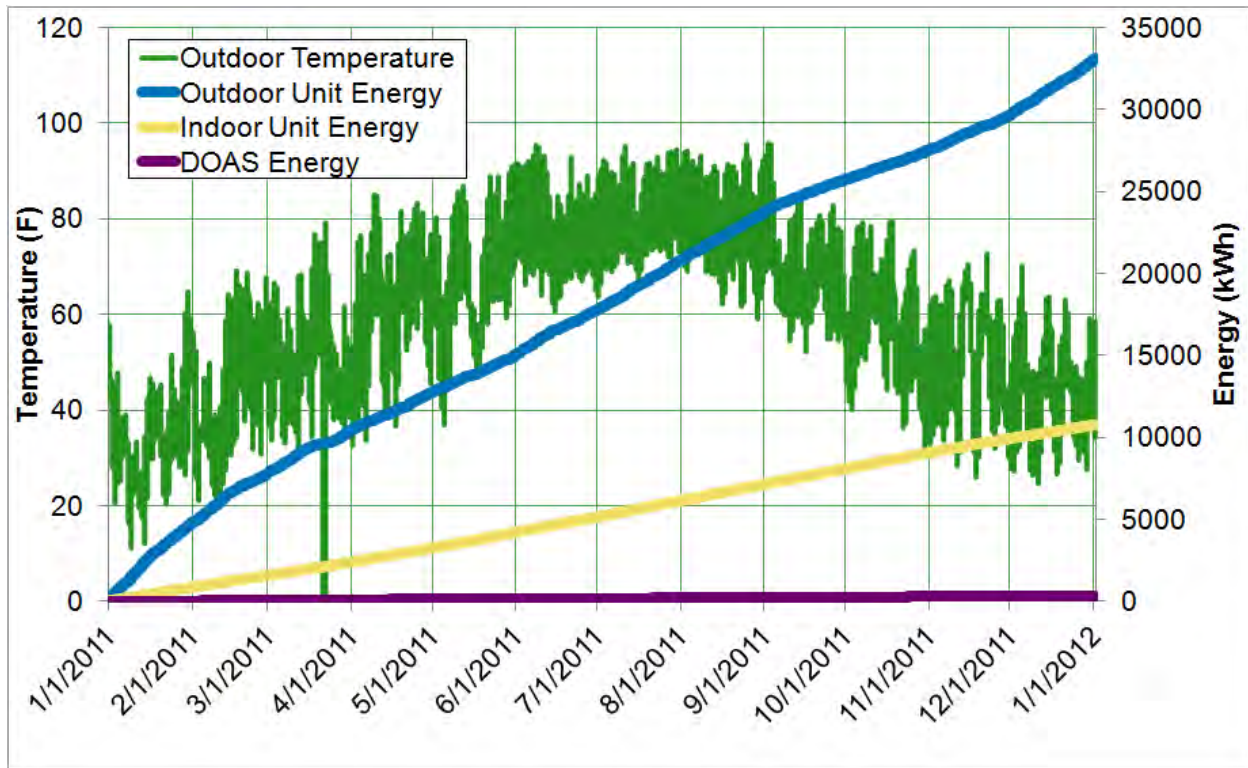
Figure 4-29 shows the power consumption and indoor and outdoor temperatures for the VRF Site C for a winter week. The weekend days are enclosed in a dashed line. As can be seen, the indoor temperature was controlled to approximately 70°F (21°C) during weekday and working hours, and it was allowed to drop much lower during off hours. The HRV and duct heaters did not operate during the weekend or overnight hours. Also, although the system still provided heating on weekends (operating with steady but low power during the weekend), it did not have the high peak of power seen on weekdays when the indoor setpoint increases.



**Figure 4-29**  
VRF Site C One-Week Winter Data

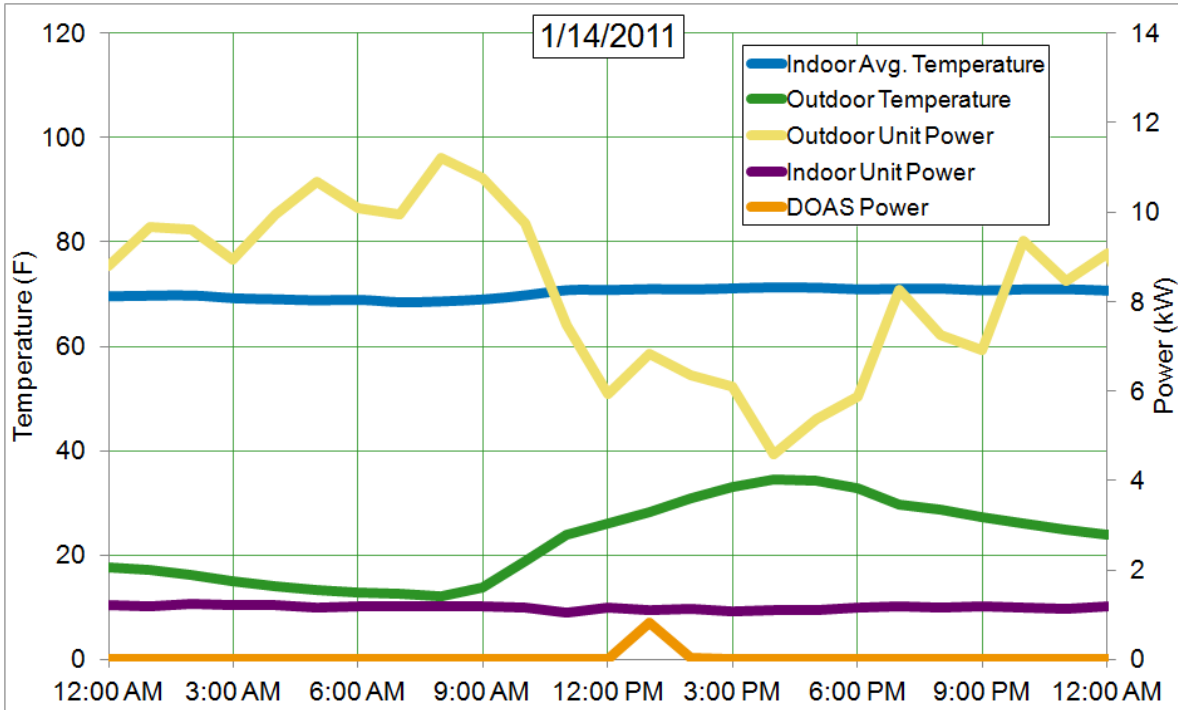
### Site A

In Site A, which was located in the mixed-humid climate, a VRF system was installed at an office building. The energy consumption of the indoor units, outdoor unit, and dedicated outdoor air system (DOAS) is shown in Figure 4-30. As can be seen, the DOAS operated very little (one hour per day on most days) during 2011. The combined energy consumption for the year was 44,250 kWh.



**Figure 4-30**  
**Site A VRF Energy Consumption**

Figure 4-31 shows a winter day, with power consumption and temperatures, for Site A. The outdoor temperature overnight was 12°F (11°C), and the VRF system operated at a maximum of 12.4 kW (11.2 kW outdoor, 1.2 kW indoor) to meet the heating load. During the daytime, the demand was considerably lower. This figure also shows what was typical of the DOAS system for 2011: about one hour of operation in 2011 and one hour of demand during the hour ending at 1:00 PM, using 800 Watts. The indoor temperature was as low as 68.5°F (20.3°C) in the early morning hours, up to 71.5°F (21.9°C) in the daytime, and the indoor units operated steadily for the entire day.



**Figure 4-31**  
**VRF Site A Power and Temperature for January 14, 2011**

Table 4-5 shows the electric utility data for Site A for three years for which records were provided, along with the measured VRF energy consumption for 2011. The average cost paid at this site was \$0.092/kWh for electricity and \$1.632/Therm.

**Table 4-5**  
**Site A, Three-Year Average Utility Data and Measured VRF System Energy**

	Average 2007– 2009		2011	2011
Date	Office Electricity (kWh)	Natural Gas (Therms)	Measured VRF Energy (kWh)	Measured VRF Energy per Square Foot (kWh/sf)
January	8640	1208	5476	0.83
February	9227	1806	3797	0.58
March	8707	1283	3463	0.52
April	8820	680	3198	0.48
May	7187	502	3310	0.50
June	8627	54	3689	0.56
July	9120	56	4006	0.61
August	6720	48	3995	0.61
September	6180	54	2976	0.45
October	5020	52	2779	0.42
November	8220	317	3038	0.46
December	8620	1127	4227	0.64

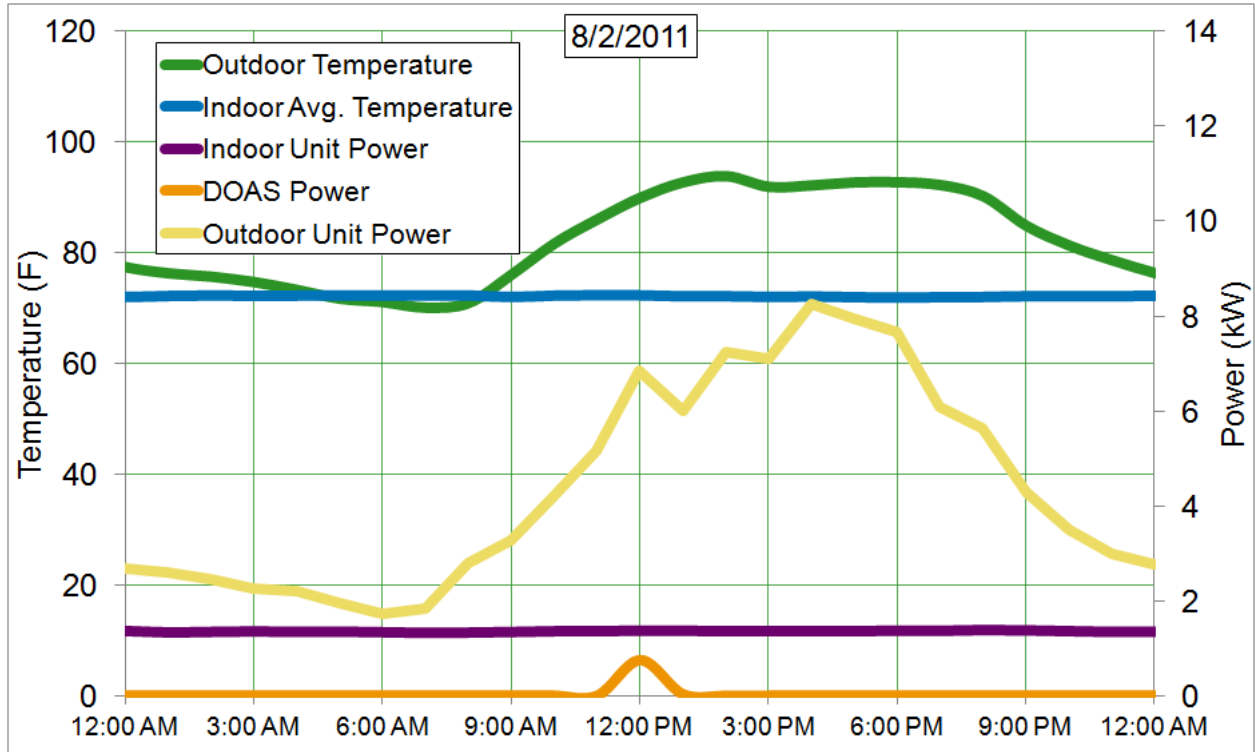
As can be inferred from the above, gas heating is a substantial expense at this site and varies seasonally quite a bit more than the electrical load. Table 4-6 shows the calculated cost of the office space electricity and estimated gas use for the portion of the facility retrofitted with VRF, combined, as a crude effort to approximate the baseline cost of the building as treated by the VRF (including HVAC and other uses). The monthly cost of operating the VRF, based on the same electricity prices, is also shown. As can be seen, the VRF costs are more level, ranging from a low of \$256 up to \$504 in winter. The costs varied much more with gas heating, ranging from \$490 up to \$1,831. It is important to note that this resolution of data for the pre-VRF energy consumption cannot be used to directly show energy savings; it is a very rough approximation. One implication that can be derived is that, with gas being the dominant cost at the site before the VRF installation, any reduction in gas heating may result in significant energy savings.

Table 4-5 also shows the energy consumption per square foot for this facility, based on the owner's estimated area of 6,600 ft<sup>2</sup>. The total energy consumption for the year was 6.7 kWh/ ft<sup>2</sup>, 45% lower than the average for EIA Databook standard office buildings.

**Table 4-6**  
**Calculated Cost of Electricity for Office Space Plus Natural Gas and VRF Energy Cost**

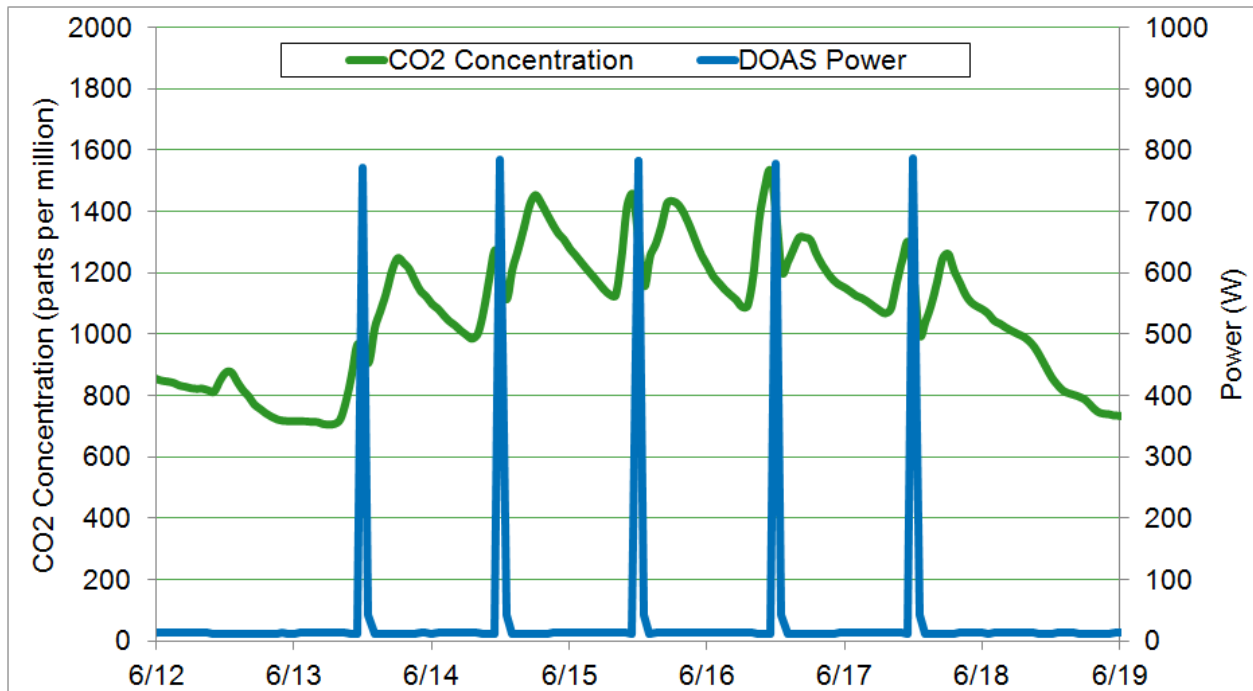
<b>Date</b>	<b>Average Cost, Office Electricity Plus Gas</b>	<b>Measured VRF Cost</b>
January	\$ 1,452	\$ 504
February	\$ 1,831	\$ 349
March	\$ 1,499	\$ 319
April	\$ 1,181	\$ 294
May	\$ 934	\$ 305
June	\$ 823	\$ 339
July	\$ 870	\$ 369
August	\$ 644	\$ 368
September	\$ 598	\$ 274
October	\$ 490	\$ 256
November	\$ 929	\$ 280
December	\$ 1,406	\$ 389

Figure 4-32 shows a summer day for the same site. The temperature was as high as 94°F (34°C) and peak power was 9.7 kW (8.3 kW outdoor, 1.4 kW indoor) at 4:00 PM. Again, the DOAS operated for one hour, this time at hour-ending 12:00 noon. The indoor temperature was held steady at 72°F (22°C) for the entire day, and the indoor units drew consistent power for the entire day.



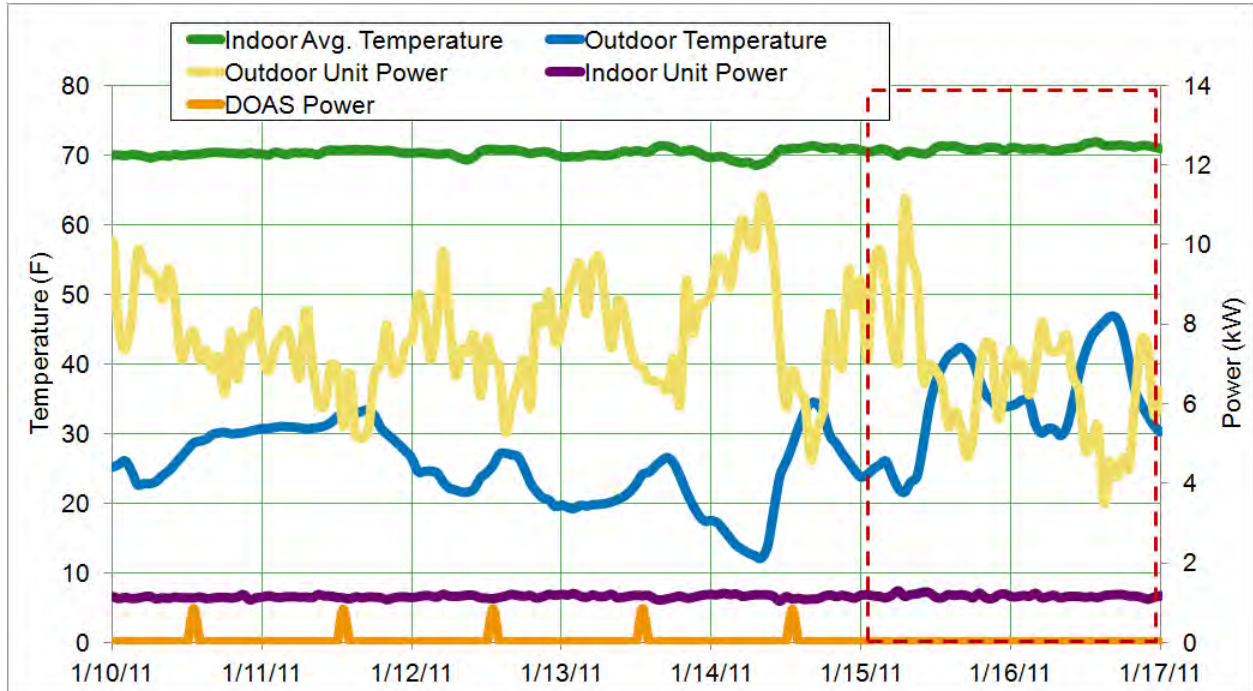
**Figure 4-32**  
**VRF Site A Power and Temperature for August 2, 2011**

Ventilation air is required in most commercial building, generally via forced ventilation. At this site, the indoor CO<sub>2</sub> concentrations were measured as an indicator of the indoor air state. A separate dedicated outdoor air system (DOAS) was integrated into the conditioning system to provide fresh air. Outdoor air CO<sub>2</sub> concentration was about 450 PPM, and indoor air should not exceed about 2000 PPM. The CO<sub>2</sub> concentrations and DOAS power are shown for one week in Figure 4-33. The CO<sub>2</sub> concentration increased with occupancy, as expected, and was significantly reduced during operation of the DOAS.



**Figure 4-33**  
**CO2 Concentration and DOAS Power for Site A**

Figure 4-34 shows the power and indoor and outdoor temperature for VRF Site A. The weekend days are enclosed in a dashed line. The high outdoor and indoor unit power, which was active at all hours (including the weekend), and steady indoor temperature suggest that this site could benefit from a thermostat set-back. The indoor temperature was maintained with the exception of a brief period on January 14, where outdoor temperatures were as low as 12°F (11°C). However, even at this condition, the indoor temperature was 68°F (20°C). This suggests that the system maintained indoor comfort well, even during particularly cold outdoor conditions. There was very little difference between weekday and weekend operation; lower power consumption seen here during the weekend corresponded with increasing outdoor temperatures.

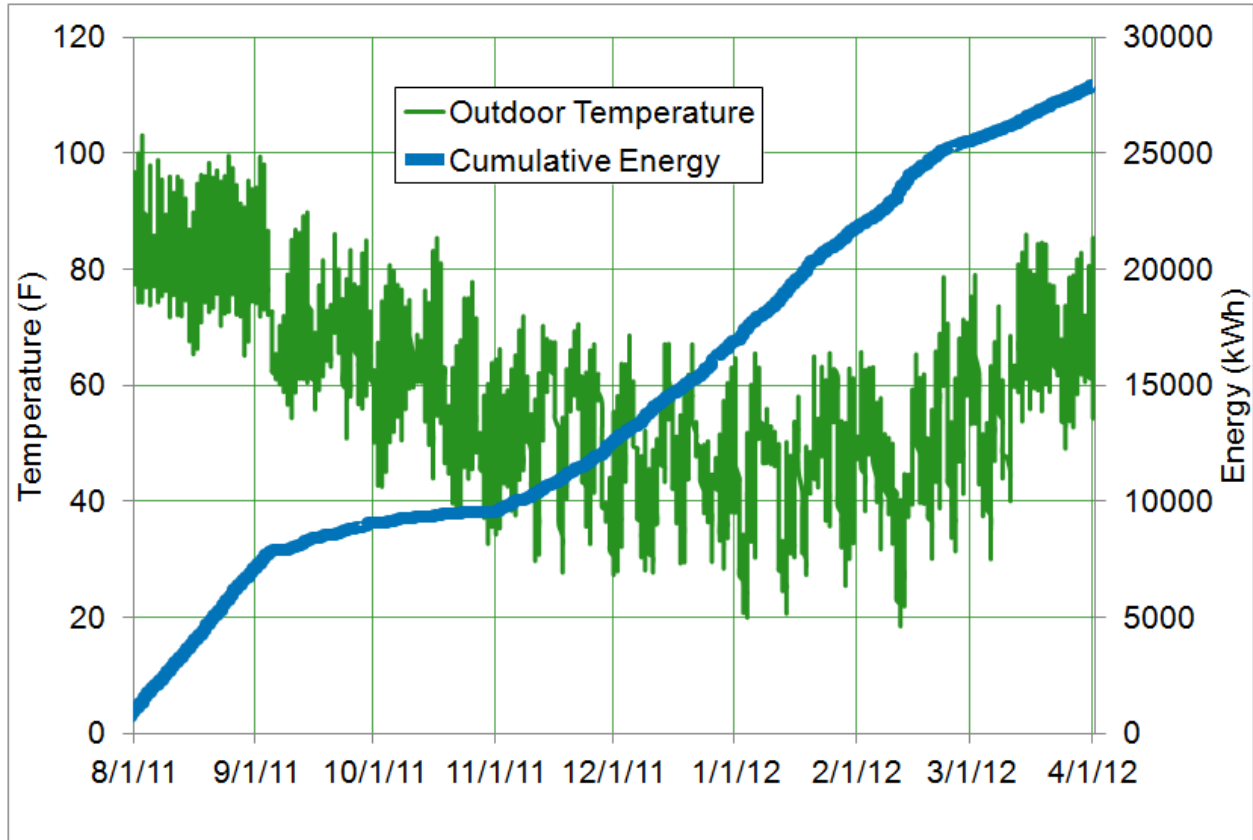


**Figure 4-34**  
**Power and Temperature for One Winter Week at VRF Site A**

**Site D**

VRF Site D, which was installed in a mixed-humid climate, is a retail space with an approximate area of 8,430 square feet, based on plan drawings of the facility. At this site, the thermostats are set with aggressive, energy-reducing set-backs. The cumulative energy consumption for this site is shown in Figure 4-35. The site has good data for August, 2011 through March, 2012.

Comparing the cumulative energy with the outdoor temperature, it can be seen that during the period of mild weather between the end of August and the start of November, the site used very little energy. As will be seen in the later figures, this is likely in large part due to the indoor temperature settings.



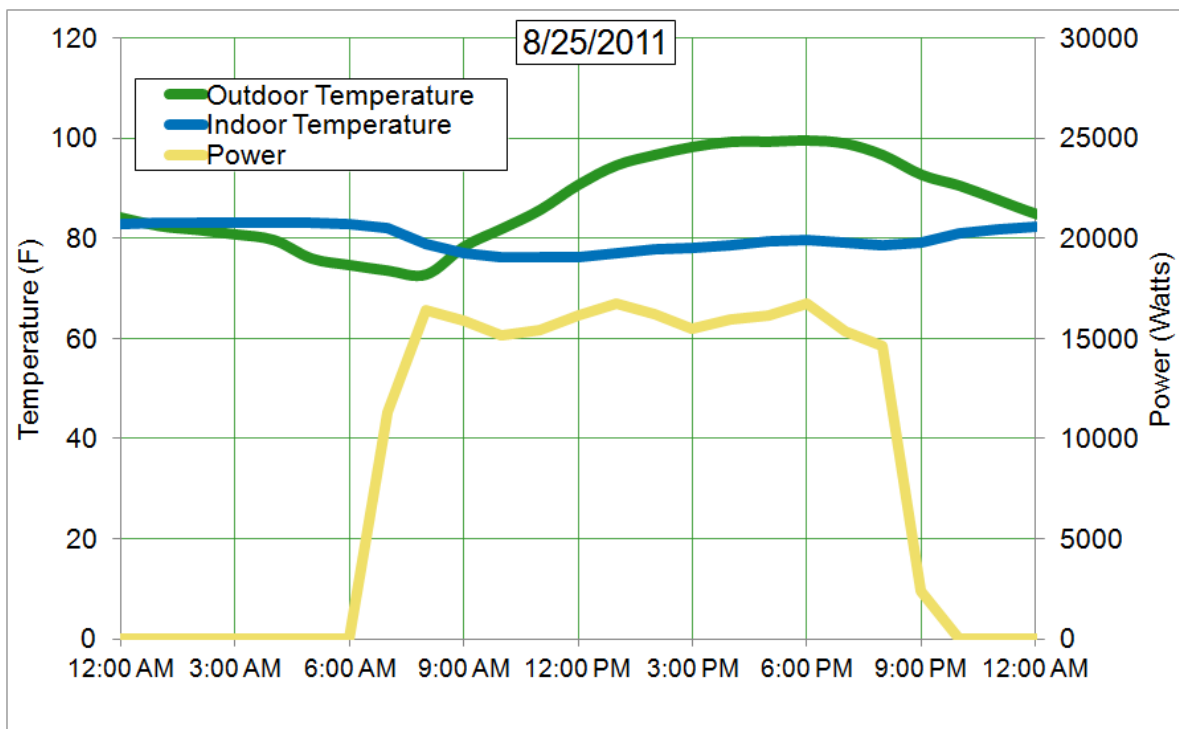
**Figure 4-35**  
**VRF Site D Cumulative Energy Consumption**

The monthly energy consumption and monthly energy consumption per square foot are shown in Table 4-7. The highest energy consumption was in August, with relatively high consumption also in December through February. In October, very little was used. Extrapolating the 8 months of data here to a full 12 months, the total energy consumption would be 40,520 kWh, or 4.8 kWh/sf, which is well below the average for retail buildings of 9.0 kWh/sf, per the EIA Buildings Databook. In fact, even extrapolating the highest-usage month to 12 months, the energy consumption would be 8.9 kWh/sf, still slightly below the average for commercial buildings. This shows that this site, with a combination of high-efficiency VRF and aggressive temperature set-backs, has very low HVAC usage.

**Table 4-7**  
**VRF Site D Energy Consumption and Consumption per Square Foot**

Date	kWh	kWh/sf
August '11	6223	0.74
September	1964	0.23
October	468.6	0.06
November	2974	0.35
December	4362	0.52
January '12	4902	0.58
February	3742	0.44
March	2377	0.28

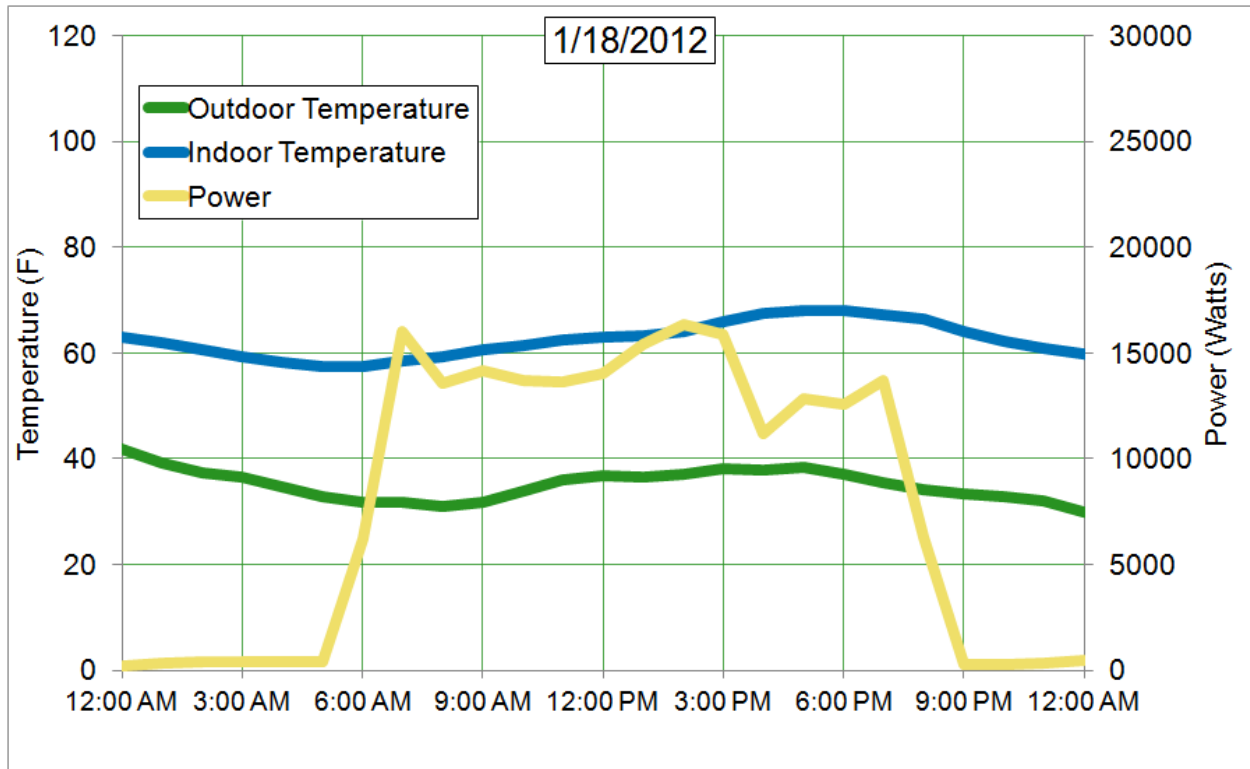
Figure 4-36 shows the on-site power consumption for a day in August. The indoor temperature was allowed to increase to about 83°F (28°C) overnight, with the VRF system not operating. During the day, the temperature was between 77°F and 80°F (25°C and 27°C). The peak HVAC power was 16.7 kW, at 1:00 PM.



**Figure 4-36**  
**VRF Site D Power and Temperature for August 25, 2011**

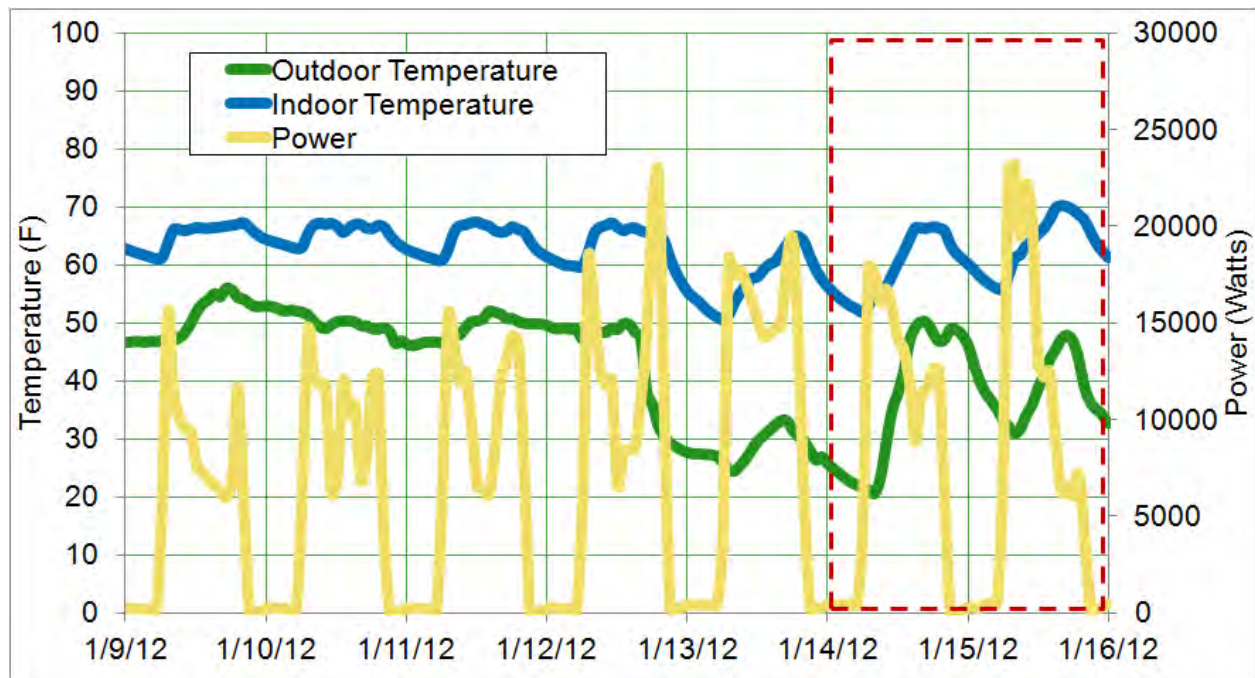
Figure 4-37 shows the VRF Site D system power on a winter day, with outdoor and indoor temperatures. The overnight low temperature was 30°F (-1°C), and the indoor temperature went as low as 57°F (14°C) while the unit was off. The indoor temperature increased to as high as

68°F (20°C) during the daytime, when the outdoor temperature was 38°F (3°C) at the highest. The peak HVAC power was 16.3 kW at the highest, for the hour ending at 2:00 PM.



**Figure 4-37**  
**VRF Site D Power and Temperature for January 18, 2012**

Figure 4-38 shows the indoor and outdoor temperature and power consumption for Site D. The fluctuation of the indoor temperature shows that the conditions were allowed to float overnight and on the weekend, with loose thermostat controls. The weekend days are enclosed with the dotted line.



**Figure 4-38**  
**VRF Site D Power for One Winter Week (Dashed Line Indicates Weekend Days)**

## Survey Results

EPRI designed two measurement instruments to determine end user satisfaction with variable refrigerant flow (VRF) heating and air conditioning. First, an online survey was distributed via the utilities to the occupants of the space where the system was installed (referred to as “occupant respondents”). This survey utilized multiple choice and open-ended questions to gauge use of and satisfaction with the VRF system and the level of comfort it provided. Nine total responses were collected, seven from the installation hosted by Site B and two from the Site D installation.

The second measurement tool utilized a detailed questionnaire provided to technicians or facility managers who installed or maintained the system (referred to as “technical respondents”). The questionnaire asked open-ended questions concerning maintainability, reliability, and installation of the VRF heating and air conditioning system. Only one response was collected, which was completed by the installing contractor for the Site B demonstration. This individual not only installed the system, but also provided maintenance during the VRF’s first two years of operation.

## Satisfaction

Overall satisfaction ratings across both installations were fairly consistent. Almost all occupants indicated that they were satisfied or very satisfied with the system overall, stating that the system cooled the room as needed and kept the space comfortable. One occupant indicated that they were neither satisfied nor dissatisfied with the system, stating that they had difficulty adjusting the temperature of the unit which allowed the space to become either too cold or too hot. Additionally, this occupant refers to problems experienced at Site B’s demonstration site that

were supported by other occupants in other portions of the survey. Detailed discussion of satisfaction by conditioning season is provided below.

Almost half of the occupants across both demonstration sites stated that they would recommend the system, with one occupant from the Site D demonstration stating that they would “tell everyone [they] can how great the system is.” Most other occupants specified that they might recommend it, and only one occupant from the Site B installation indicated that they would not recommend the VRF system, citing the issues observed during the winter as their primary concern.

### Summer

Almost all occupants were satisfied with the performance of the VRF system during the summer. Responses indicated that in general, the units were able to keep the rooms cool and comfortable with near constant circulation of the air. Several mentioned that the VRF system was preferable to the air conditioning system that was used prior to the demonstration. Some occupants did stipulate that occasional adjustment to the temperature was necessary in order to maintain comfort within the space.

### Winter

Despite some issues, most occupants indicated that they were satisfied or very satisfied with the system’s performance during the winter. Responses showed that the system seemed to work reasonably well and occupants were comfortable most of the time. Site D responses show that occupants enjoyed the system and preferred the VRF to what was installed previously, and one occupant from the Site B installation indicated that they were “very pleased with the new technology and efficiency.” Over half of the occupants at this site remarked that during the winter, heating is used only on very cold mornings, and only until occupants begin to enter the space. One of these responses mentioned that the room when the unit was turned on, it warmed the room quickly and was able to be turned off soon after it began operating.

One occupant at the Site B installation was neither satisfied nor dissatisfied, expressing that, while some issues had occurred, the problems may be resolved with time. Another occupant indicated that they were dissatisfied with the heating aspect of the system. They mentioned that heating was not needed and that, when one occupant turned on the heat, all other rooms became too hot and were not able to use the air conditioning. Similar remarks were provided for this installation in other responses throughout the study, indicating that the Site B installation would benefit more from being able to heat and cool individual rooms separately.

### **Comfort**

Almost every occupant specified that they were comfortable most or all of the time, with one occupant stating that their space was “sometimes comfortable, sometimes uncomfortable.” This response showed that the space was “cooler where air blows under the vents,” but also stipulated that the space was more comfortable in general after the installation of the new system.

As previously stated, the Site B installation did experience significant difficulty in maintaining comfort in all of the rooms. One occupant states that during the winter, “if the heater is turned on

in a different [room],” then “the classrooms needing air conditioning are unable to get any cool air.”

In terms of noise, the occupants indicated that either they noticed no difference between the new system and what was used previously, or that a significant decrease in noise was observed. Some occupants mentioned that they could “hardly hear it running” and that the VRF was “quieter than the old system.”

### ***Controllability***

Occupants at the demonstration sites indicated that, in general, they preferred the distributed control capability and enhanced controls of the VRF system compared to what they had previously. All but one of the occupant responses indicated that the thermostats were easy to understand and use, describing the controls as either “very user friendly” and “easier control” or not significantly different compared to what was used previously. Occupants at the Site D demonstration specifically stated that the new system was preferred and made it “much easier to regulate the temperature year round.” The exceptions to these opinions, including the individual who expressed difficulty with understanding and using the controls, cited the difficulty with the Site B installation’s heating capability. Here, occupants indicated that the first unit which was turned on seemed to impact the other systems, resulting in unwanted heat in the other rooms which desired cooling.

The Site B technical respondent indicated that the system has assisted in controlling space temperature, and that its associated monitoring equipment is useful in understanding the overall operation of the system. Regarding ease of use, the technical respondent described the controls as “a little more technical,” possibly requiring trained personnel on the control and/or mechanical side, but also noted that standard maintenance could be performed by facilities workers at the site.

### ***Technical Performance***

Concerning the installation, the technical respondent described the installation in two ways. According to the technical respondents, from a mechanical standpoint, the installation was “fair.” However, they also noted that from the control side, the installation was “detailed.”

In regards to technical performance, one technical respondent expressed general satisfaction with the system’s operations, but also noted that, at the Site B installation, the rooms needed the ability to heat or cool separately in order to provide satisfaction and comfort to each occupied space. This response echoed that of the occupants at the demonstration site, who mentioned several times that the VRF struggled to meet the different conditioning needs of all occupants at the same time.

When asked about expected energy savings, the technical respondent felt that, at the beginning of the demonstration, the system would provide energy savings of 20-25%. According to their estimation of the demonstration results, the respondent estimated observed energy savings to be approximately 38-40%, exceeding their earlier expectations.

The technical respondent indicated that, overall, the system was very easy to maintain and had only required two service calls within the first two years, both related to drain issues. After two years, the maintenance responsibility for the system was transferred to the site. A facility

representative from the demonstration site could not be reached to discuss any problems that may have occurred after this initial two-year period.

### **Survey Summary**

Overall, respondents expressed satisfaction with the VRF heating and air conditioning technology, indicating that, in most cases, the system increased comfort, reduced noise, and enhanced controllability. From a technical standpoint, respondents observed no severe or persistent issues, but indicated that the advanced controls may require an additional costs to account for detailed installation and training users in their use. Additionally, feedback received by occupants at the demonstration sites suggests that the capability to provide simultaneous heating and cooling between indoor units may be a necessary feature for larger installations to preserve the comfort of all occupants.

### **Summary**

This chapter provided an overview of variable refrigerant flow (VRF) technology, a description of the four VRF Demonstration field sites and analysis of data. Sites were selected in order to provide a comparative baseline and treatment, which was found to be very difficult to obtain in practice. Site B had a good physical baseline, but sites A, C and D required either the development of a computer model or use of billing data for use as a performance baseline.

Researchers measured the use profile for power and energy using many sensors: outdoor temperature and humidity, indoor temperature and humidity, indoor setpoint, refrigerant flow, occupancy, and time of day/season.

Two of the four sites were located in the mixed-humid climate (Sites A and D) and one each in the hot-humid (B) and marine (C) climates. Site B, which was located in a school, provided the most ideal configuration with a direct comparison between one part of a wing conditioned by the VRF and the other part of the wing conditioned by the baseline system, which was a split system. Site C used nine heat pumps and did not have a physical baseline, so a computer model was developed and used. The VRF for Site A was installed in an office building and the system was monitored for overall performance, especially with regard to the dedicated outdoor air system, which can be used with VRF systems to provide fresh air. Site D is a retail space with an approximate area of 8,500 square feet and the building occupants are aggressive with the thermostat set point and have energy-reducing set-backs in place.

Field testing results in a variety of measured trends because performance depends on a host of uncontrollable variables, all of which can introduce uncertainty into the analysis. In a laboratory setting the variables are controllable but difficult to vary in order to match field conditions. Researchers used a combination of laboratory testing and field testing to gain an understanding of equipment performance and to evaluate equipment interactions with the building and building occupants. The measured or modeled energy-use profile was compared under similar external conditions. Some of the external variables are stronger drivers than others, outdoor temperature for example, and steps were taken to account for the degree to which a variable impacted the results.

Key finding from the VRF demonstration were:

The annual savings in energy ranged from 20 – 45% at the four sites monitored during the Demonstration.

At a southeastern US site (Site B) with a side-by-side comparison, energy savings for the 2011 calendar year was 45%.

At the same southeastern US site (Site B) on a typical hot September day there was an approximate 40% reduction in both system peak and billing demand.

Customers generally expressed satisfaction with VRF performance and improved comfort.

The data suggests that VRF systems can achieve high efficiency, but actual measurement and verification of savings is very difficult to achieve in the field because the variables are difficult to control. For each of the four sites the systems were found to integrate well into buildings with little if any difficulty meeting local codes and standards.

### ***Readiness for Program***

The Variable Refrigerant Flow Demonstration showed that VRF has potential for significant energy savings. This is a good reason alone to move toward including VRF in utility energy efficiency programs. However, there remain questions as to what are the energy savings in different settings and how best to quantify them, which is related to difficulties during the Demonstration in determining baseline energy usage. Beyond understanding the energy savings, there are expected barriers to market adoption because of the market's unfamiliarity with VRF technology. While work continues in developing modeling capabilities to better quantify energy savings, early-deployment projects under the EPRI collaborative project Coordinated Early Deployments for Efficient End-Use Technologies are recommended to gain experience with the market and increase the opportunity for success in utility energy efficiency programs.

# 5

## DUCTLESS HEAT PUMPS

---

### Introduction

This chapter describes site selection, installation, and monitoring of ductless heat pump (DHP) systems and presents data summarizing their performance. A variety of systems have been installed by three different utilities in four states, representing several manufacturers' equipment and several different system architectures. An attempt was made, whenever practical, to provide similar baseline and treatment sites for comparison of performance in similar operating conditions in order to properly gauge the potential for energy efficiency.

The term *ductless heat pump* generally is used to describe variable-speed heat pumps employing indoor wall- or ceiling-mount fan-coil units that have no connecting ductwork. They are a subset of the broader family of variable-capacity heat pumps (VCHP), which employ variable-speed compressors, fans, and expansion valves with a wide array of options for indoor terminal units, including ductless and ducted units. The term *DHP* has become a *de facto* descriptor of the entire family of small, residential style variable-capacity heat pumps, whether ductless or ducted. In this demonstration project, several forms of indoor terminal units were used, ducted and ductless, depending on the specifics of the installations. Existing ductwork in some of the treatment homes was used with ducted terminal units to serve small zones, while ductless units were employed for rooms that did not have existing ductwork.

### Industry Overview

In the U.S., cooling and heating have been traditionally done by single-speed, single-capacity systems that cycle accordingly to modulate the amount of heating/cooling delivered to match the conditioned space load. Residential cooling is done with air-source, single-speed packaged, or split unitary air conditioners and/or with window air conditioners. Heating is with electric resistance baseboard or ceiling heat, gas-fired or oil-fired furnaces, or single-speed heat pumps with second-stage electric resistance backup.

Single-speed heat pumps have had difficulty gaining market share outside the mild southern U.S. climate because with lower the outdoor temperature, the dependence on second-stage electric heat is higher, making them progressively less attractive in northern climates. The advent of inverter-controlled variable-capacity heat pumps has enabled systems built in similar configurations to the single-speed cousins to maintain capacity over a broader range and in many cases in heating mode, to eliminate the need for electric resistance heat. The ability of the compressor to over-speed and for other system components (expansion valves and fans) to adjust accordingly enables a heat pump to maintain capacity. Additionally, system flexibility can allow

for continuous operation at reduced or varying capacity, reducing or eliminating cycling and any associated cycling losses.

Variable-speed unitary systems came to the U.S. market a decade or so ago in limited options and have progressively gained penetration. Approximately 3 to 5% of U.S. unitary compressor sales are variable-speed as of 2010, but with a substantial growth rate. Worldwide, the percentage market share penetration is significantly higher, and the growth rate is lower.

Cooling and heating loads are dynamic over any time frame (daily and seasonally), and a conditioning system intended to maintain a fixed setpoint must be able to change its capacity to match load. This has traditionally been done with cycling single-speed systems based on thermostatic control. There are perceived advantages to having a system that can vary delivered capacity to match the changing building load, most notably the elimination of cycling losses, which have been documented to be between 5 and 10%. Also, ductless units typically require lower-power fans because they have very low pressure drop on indoor air, which may lead to some small but non-negligible savings. In addition, variable-speed systems that attempt to operate at partial load at all times reduce the frequency of airflow cycling, which is perceived by some as an annoyance.

DHP systems are offered in multi-zone configurations, which address another issue: Different zones in a building have different load dynamics, perhaps necessitating very different heating/cooling capacity profiles. An easy way to visualize this is to imagine a rectangular building oriented such that the long axis of the building runs north-to-south. All other things being equal, during the morning, the east-facing side of the building will have a comparably higher load than the west-facing side, because it is in direct sunlight. The opposite is true for the afternoon. Single-zone, single-speed systems are unable to modulate the ratio of delivered capacity according to changing load. When the system is on, *X* percent goes to one space, *Y* percent to another, and *Z* to a third, regardless of what is actually needed. Such systems are typically controlled by one master thermostat that is “strategically” placed in the conditioned space, which is unable to specifically monitor or control other rooms within the same zone. Multi-zone, multispeed systems are more capable of satisfying the uneven loads based on multiple thermostats.

Single-speed heat pumps have traditionally been applied primarily in the southern climates, but variable capacity is pushing the applicability north, and in the process, it is reducing the need for electric resistance backup. Some new systems that have been tested by EPRI can provide full heating capacity in heat pump-only operation, even with outdoor temperatures well below freezing. With variable systems, design and operation can be guided to the application—low-temperature heat pumps can be designed for more northerly climates where heat pumps previously were not considered.

### ***Related Studies***

Several organizations, such as the University of Maryland and Purdue University, have performed laboratory testing on DHP systems. EPRI likewise has conducted multiple laboratory tests on DHP systems, including testing in 2010 focused on applications in low ambient temperatures. Laboratory testing principally provides insight into equipment performance under controlled operating conditions. The total effect of energy savings with new technologies such as

DHP comes from a combination of how the equipment itself performs and how the equipment interacts with the building and its occupants. Both may contribute to improvements in the energy-use profile of the technology. The field installations in EPRI's Energy Efficiency Demonstration provide data from actual field installations, which provide insight into understanding overall energy efficiency.

An effort similar to EPRI's DHP study was performed by the Bonneville Power Administration (BPA) to quantify energy savings in the Pacific Northwest, particularly during the heating season in order to offset usage of a central or zonal electric heating system. A total of 95 homes were monitored for whole-house energy, electric-resistance energy, DHP energy, and water heater energy. A subset of 35 homes also included *in situ* measurement of airflow and supply and return temperature to estimate the COP of the equipment. The average home size in the metered sample was 1,618 square feet. Most sites had one DHP outdoor unit paired with one DHP indoor unit, and 17 of the sites had two indoor units. The average nominal capacity was 1.53 tons. The sites were metered in a pre- and post-installation configuration.

The average savings from the BPA study is shown in Table 5-1. The data suggests a strong correlation between decreased savings and increased indoor temperature. Evidence suggests that occupants set the indoor temperature slightly higher after the DHP was installed. Data also suggests that the efficiency gains of the systems were strongly related to occupant control and system operation rather than the SEER and HSPF ratings of the equipment.

**Table 5-1**  
**Energy Savings for DHP from the BPA Study**

Grouping	DHP Savings (kWh/yr)		Installations Per Grouping
	Mean	Standard Deviation	
Location A	3316	2121	26
Location B	3043	2357	25
Location C	1882	1580	16
Location D	3628	2985	16
Location E	3307	3230	10
Weighted Average	3049	2424	
<b>Total</b>			<b>93</b>

Overall, the installation configuration displaced electric resistance heat and appeared to offer consistent savings. The DHP would offset a relatively consistent amount of electric heat, with the resistance heat making up for any shortfall of the DHP during very cold conditions. Full details of the BPA effort can be found in a soon-to-be-published report written by Ecotope, Inc., and the Northwest Energy Efficiency Alliance for BPA: *Summary Report for the Ductless Heat Pump Impact & Process Evaluation*.

## Research Objective

The primary objectives of this research are to quantify the potential for energy savings of field-installed DHP systems versus a typical baseline, and to qualitatively assess items and issues related to the procurement, applicability, installation, comfort, and user interface of the systems.

Research questions include:

What is the potential for energy savings regarding DHP systems in various climates and in various structures?

Do the systems satisfy load requirements?

Are the users satisfied with the systems?

Are there any concerns related to the newness of the system, such as different aesthetics or user interface?

What climate or other boundary conditions determine the applicability of DHP systems?

## Research Method

The overall method of measuring the ability to save energy is to monitor power and energy consumption of both control (baseline) and treatment (DHP) systems in similar structures and across operating conditions—indoor and outdoor air temperature and relative humidity. Systems are monitored with a network of sensors feeding a local data-acquisition system, which records data every five minutes. Supplemental information is gathered about the sites, the installation, operation, and satisfaction of the building occupants.

Field monitoring systems were in place to measure characteristics of power and energy draw of baseline and DHP systems. Because they depend on indoor and outdoor air conditions, including the user’s desired setpoints, the outdoor and indoor temperature are measured. These measurements provide load-profile information for typical and peak days and the basis for determining the difference between baseline energy and power use and DHP energy and power use.

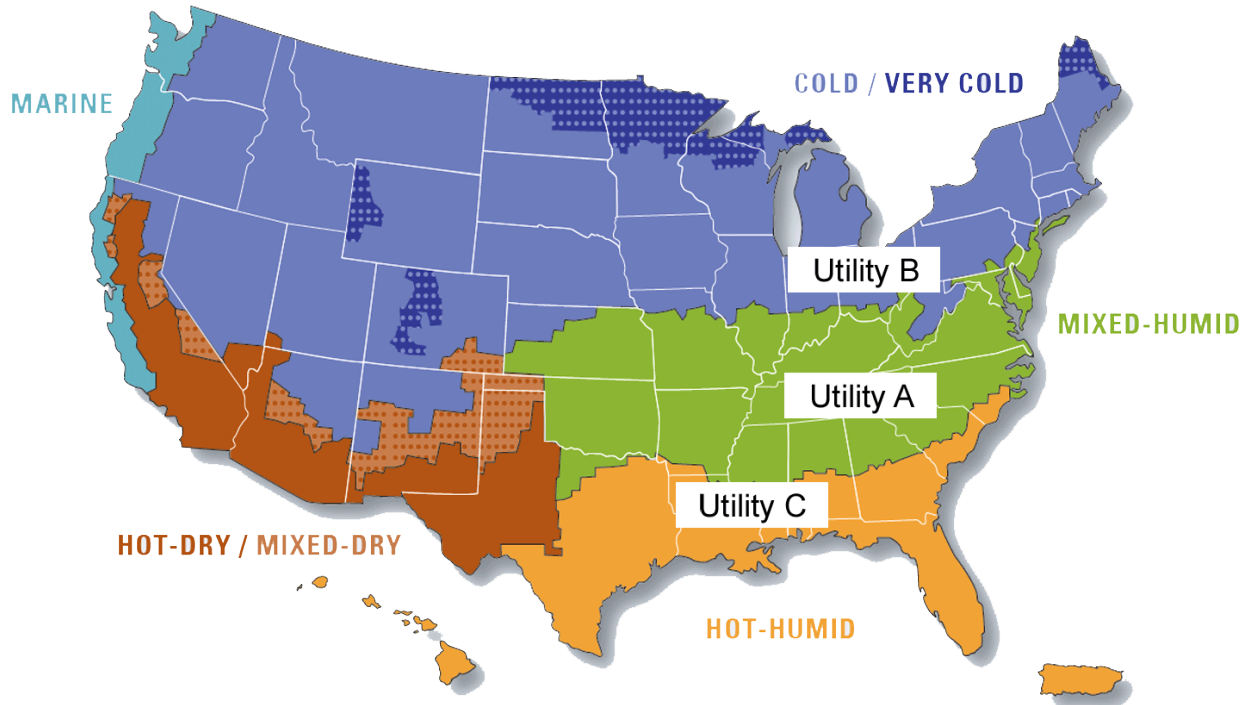
## Host Site and Equipment Summaries

The number of control and treatment sites is shown in Table 5-2. Control HVAC equipment varied by geography and sites and were either single-speed split-system heat pumps or electric resistance (baseboard or ceiling).

**Table 5-2**  
**Number of Control and Treatment Sites**

Host Utility	Number of Control	Number of Treatment
Utility A	3	16
Utility B	1	7
Utility C	3	3

Site-selection surveys were conducted by each utility, and the results were delivered to EPRI to determine whether a site was a suitable candidate for DHP. Once a site was approved, the utility engaged a designer/contractor to specify equipment and submitted the bill of materials (BOM) to EPRI for purchase. Figure 5-1 shows the climate zones of the participating utilities.



**Figure 5-1**  
Climate Zones of DHP Installations

**Utility A**

Utility A’s sites are all single-family residences with a mix of single and multi-split systems employing both ducted and wall-mount, ductless terminal units. Figure 5-2, Figure 5-3, and Figure 5-4 show photos from one of the Utility A sites. It uses two systems, one multi-zone (larger), and one single-zone (smaller).



**Figure 5-2**  
**Utility A Residential Site**



**Figure 5-3**  
**Two Variable-Capacity Heat Pumps at a Utility A Site**



**Figure 5-4**  
**Non-Ducted Wall-Mount Terminal Unit**

### ***Utility B***

Utility B's sites are single-family residences that had electric heat of some form: baseboard, ceiling, or ducted electric furnace styles. DHP retrofits, similar to the Utility A sites, employed a variety of residential style of variable-capacity heat pumps, single and multi-zone, and ducted and non-ducted indoor terminal units. One site used all wall-mount units; the rest used a combination of wall-mount units and ceiling- or crawl-space-installed air handlers. The baseline site had baseboard electric heat. Figure 5-5, Figure 5-6, and Figure 5-7 show photos from one of the Utility B sites.



**Figure 5-5**  
**Utility B Residential Site**



**Figure 5-6**  
**Two Zones in a Utility B Site Being Served by Separate Wall-Mount Terminal Units**



**Figure 5-7**  
**Outdoor Unit at the Utility B Site (Refrigerant Lines Hidden by the Gutter Line-Hide)**

### ***Utility C***

The Utility C sites are all at a military training camp. Three sets of identical buildings were chosen for retrofit of three styles of DHP equipment. In each building set, one remained as the control while the other was retrofitted with the DHP system. One building set is training buildings with a baseline five-ton single-speed heat pump and treatment of four individual single-zone DHP systems. The second building set is junior-officer barracks consisting of six separate rooms. The baseline building is served by single-zone, older-model mini-split heat pumps, and the treatment is two sets of three-zone multi-split systems, with one zone serving each room. The baseline systems are six separate mini-split heat pumps. The third building set is enlisted officer barracks with an open floor plan. Baseline is four two-ton older model mini-split heat pumps, and the treatment is two mini VRF multi-zone systems. Figure 5-8 and Figure 5-9 show the treatment enlisted barracks building and baseline, respectively.

---

*Ductless Heat Pumps*



**Figure 5-8**  
**Enlisted Barracks Treatment (DHP) Building**



**Figure 5-9**  
**Junior Officer Barracks Baseline Building**

### **Installed Equipment**

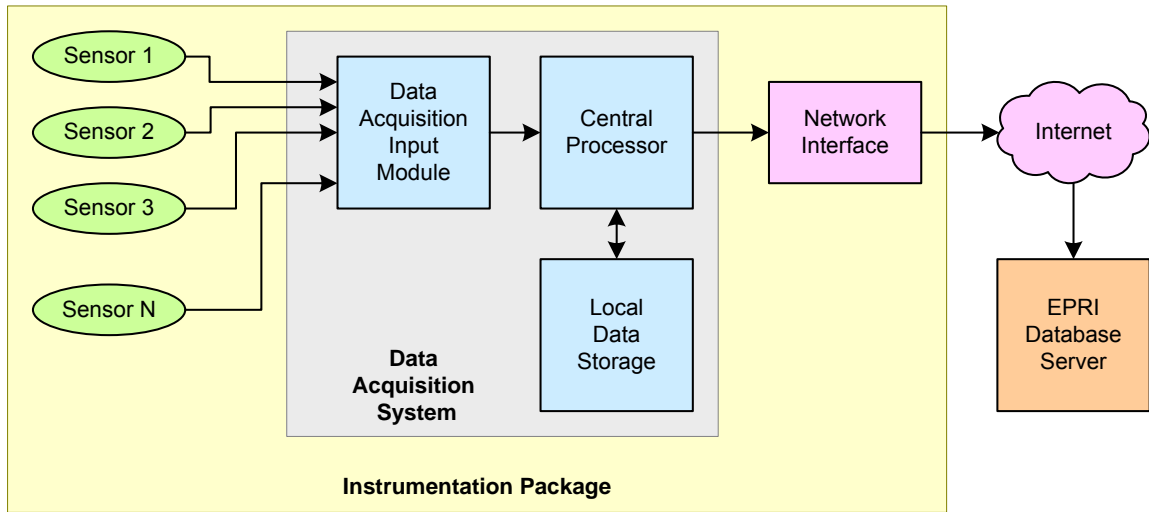
A variety of equipment models was used. Some were truly “ductless” heat pumps, others were mini-ducted, and some used American-style vertical high-static ducted air handlers. The mini-ducted units are what are termed *low static*, meaning they have relatively low-power fans capable of delivering air through short duct runs over the range of a few rooms, as shown in **Figure 5-10**. Low static air handlers are low-profile and designed to mount horizontally in a ceiling plenum or crawl space and are one of the choices of indoor units for multi-zone systems. High static vertical air handlers (what is commonly seen as the indoor unit of a traditional split-system in American homes) are a more recent addition to the available options for residential DHP systems and are presently only available in single-zone arrangements. They are currently available from several manufacturers for use with commercial variable refrigerant flow (VRF) systems and will likely be introduced to the residential lines in the next year or so.



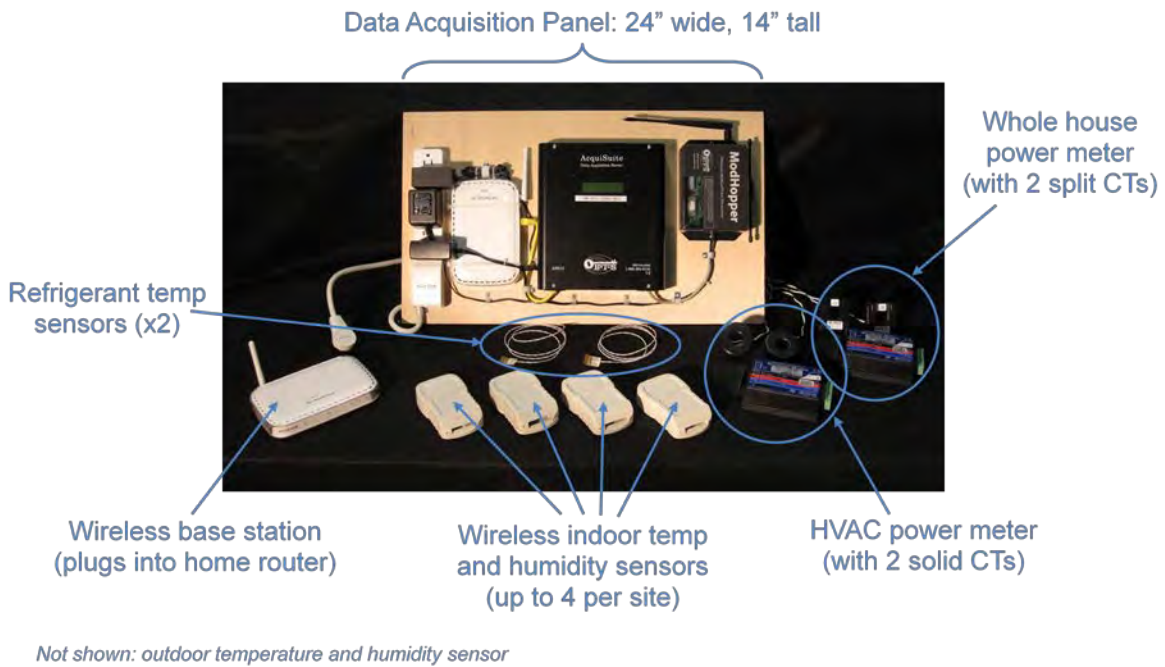
**Figure 5-10**  
**Low Static Air Handler**

### **Field Monitoring**

All installed DHP systems were field monitored to measure their energy use and power use profiles as functions of ambient air conditions. This provides a measure of performance and energy-savings ability, which depends on operating conditions. The measurement and data-collection systems are built on the same architecture used throughout the Demonstration. Individual sensors for temperature, relative humidity, and power connect to a local data logger, which in turn feeds data to an EPRI server. The general system architecture is shown in Figure 5-11, and a photo of an actual DHP data-acquisition system is shown in Figure 5-12.



**Figure 5-11**  
Instrumentation of a DHP Installation



**Figure 5-12**  
DHP Data-Acquisition Panel

### **Instrumentation**

The instrumentation package at each site includes:

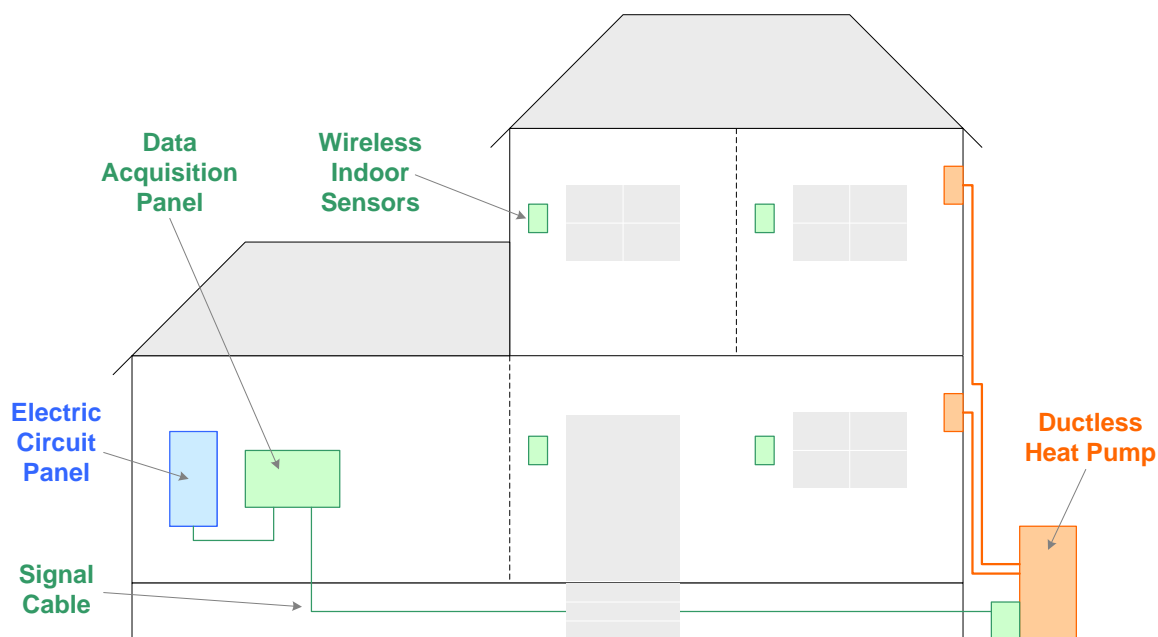
A power meter to measure the consumption of electricity by both the whole house and another for the DHP system (includes two CTs for the whole house and two for the DHP).

Up to four indoor temperature and humidity sensors.

An outdoor temperature and humidity sensor.

Two refrigerant temperature sensors.

A data-acquisition device with wireless transmitter (WiFi) that plugs into the home router.



**Figure 5-13**  
**Location of DHP and Instrumentation**

## Survey

After the DHP and instrumentation are installed and data is validated from the data-acquisition system, a post-installation survey was completed by the installing contractor and returned to EPRI. This survey documents the details about the installation, type of equipment, and other characteristics for EPRI records. After the user has experienced the DHP system for six to twelve months, the user completed an operational survey, which was also sent to EPRI upon completion.

## Laboratory Investigation

Lab work was performed on related equipment, including a hydronic variable-speed heat pump and on several low-temperature variable-speed heat pumps. Additional laboratory work is ongoing to study multi-zone high static residential systems, which are currently in pre-production.

## Field Data

### Utility A Sites

Figure 5-14 shows the total annual energy consumption for Utility A's baseline and DHP sites for March, 2011 through March, 2012. As can be seen, there are many sites in the Utility A territory and the energy consumption varies significantly. Generally, the energy totals increase

---

*Ductless Heat Pumps*

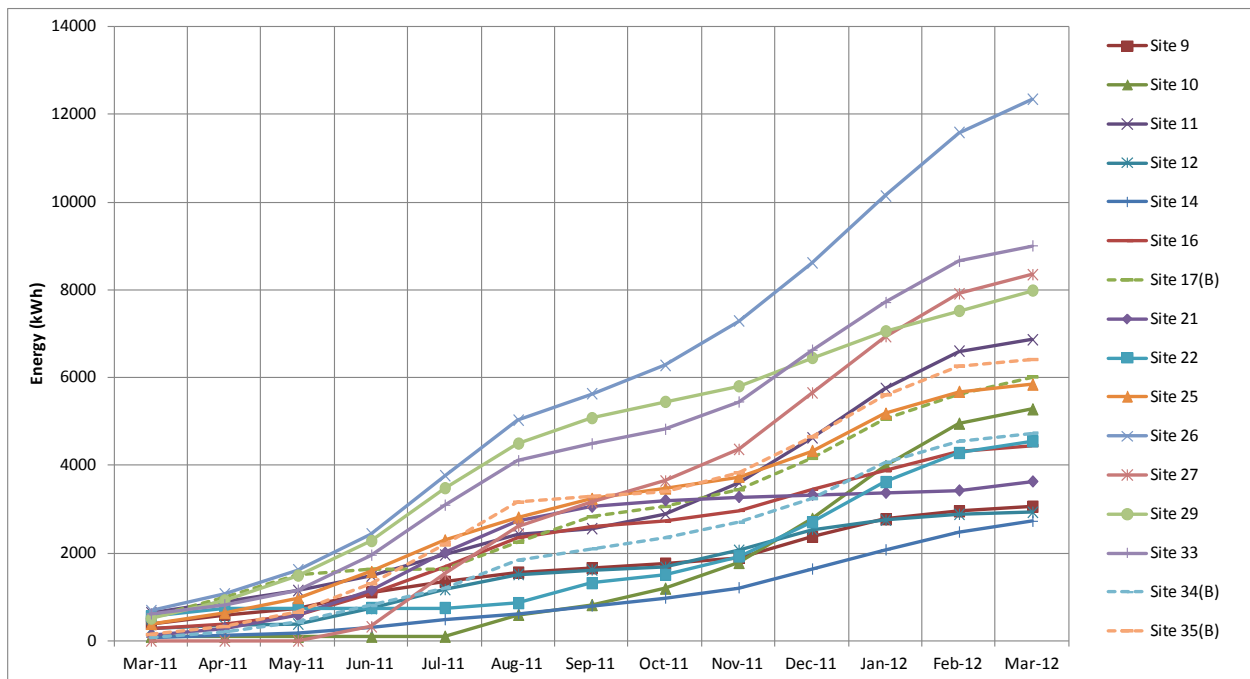
more rapidly in the winter and the summer, as is to be expected. The three baseline sites (Site 17, Site 34, and Site 35) are towards the middle of the range of total energy consumption. The monthly energy consumption and indoor temperature data are also summarized in Table 5-3 and Table 5-4.

**Table 5-3  
Utility A Monthly Site Overview, March 2011 – August 2011**

	Site:	9	10	11	12	14	16	21	22	25	26	27	29	33	17B	34B	35B
March, 2011	Avg ID Temp	67.2		75.7	62.0	67.2	70.8	71.6		75.3	71.6	71.6	70.1		70.1		
	Energy	391.8	98.2	644.4	276.0	82.4	283.2	134.1	560.7	389.5	692.0	0.0	509.6	618.4	545.3	90.6	147.5
	Number of Hours w/ ID Temp Data	616	0	621	548	603	627	646	0	658	656	0	271	0	628	0	0
April, 2011	Avg ID Temp	70.5		76.6	67.1	69.6	72.8	73.1		76.0	72.2	73.1	71.1	66.9	71.1		
	Energy	203.5	0.0	247.3	74.0	45.0	105.8	159.6	191.4	247.3	380.7	0.0	416.1	209.2	453.3	126.8	181.1
	Number of Hours w/ ID Temp Data	697	718	0	382	611	668	622	697	0	720	720	0	665	614	631	0
May, 2011	Avg ID Temp	70.4		77.1	68.4	69.8	73.1	72.8		75.4	70.6	72.8	70.7	65.3	71.8		
	Energy	143.0	0.0	257.2	35.3	60.5	210.4	284.1	0.0	342.4	549.6	0.0	563.7	329.2	503.0	212.3	324.5
	Number of Hours w/ ID Temp Data	744	0	743	447	740	437	744	0	744	744	0	737	730	568	0	0
June, 2011	Avg ID Temp	76.4		80.4		71.6	73.8	73.0		75.5	71.6	73.0	70.4	66.2			
	Energy	371.5	0.0	328.1	353.6	120.4	474.2	579.3	0.0	593.0	817.9	322.4	786.9	797.0	132.1	376.9	646.8
	Number of Hours w/ ID Temp Data	696	0	483	0	692	495	703	0	668	685	380	697	691	0	0	0
July, 2011	Avg ID Temp	82.3		81.5	74.7	70.9	73.9	73.0		76.1	71.8	73.0	70.1	67.2			73.5
	Energy	237.7	0.0	480.7	431.9	179.1	625.5	852.6	0.0	720.4	1325.6	1199.1	1204.6	1138.9	0.0	401.8	906.0
	Number of Hours w/ ID Temp Data	744	0	744	744	744	744	744	0	744	744	703	737	744	0	0	331
August, 2011	Avg ID Temp	81.7	76.8	81.5	76.5	71.4	73.8	72.8	76.7	76.6	71.1	72.8	70.0	66.1	73.2	77.8	73.2
	Energy	210.8	498.0	477.7	344.2	137.7	656.9	722.2	110.2	519.3	1263.9	1097.9	1015.8	1013.4	617.6	632.0	958.2
	Number of Hours w/ ID Temp Data	744	628	743	376	720	744	744	58	538	744	744	744	744	492	488	744

**Table 5-4  
Utility A Monthly Site Overview, September 2011 – February 2012**

	Site:	9	10	11	12	14	16	21	22	25	26	27	29	33	17B	34B	35B
Sep-11	Avg ID Temp	74.2	73.4	78.2	72.1	71.0	73.0	72.1	75.4		70.3	72.1	70.4	65.6	72.3	78.3	73.3
	Energy	99.3	222.4	123.8	103.3	173.2	247.9	325.5	454.7	425.9	603.1	537.3	579.8	384.6	577.1	259.4	126.4
	Number of Hours w/ ID Temp Data	693	598	720	720	688	635	720	590	0	638	720	720	714	720	720	683
Oct-11	Avg ID Temp	65.6	72.0	75.1	62.9	70.0	72.5	71.3	72.9	74.8	69.6	71.3	69.5	67.0	71.0	78.4	67.2
	Energy	104.1	374.0	328.8	61.3	180.3	124.2	149.0	191.4	235.8	644.3	487.8	370.2	330.2	237.0	256.3	119.4
	Number of Hours w/ ID Temp Data	722	646	722	720	618	600	714	539	117	642	723	723	722	663	721	640
Nov-11	Avg ID Temp	60.4	71.5	75.4	64.9	69.5	70.3	71.7		76.0	70.9	71.7	69.2	68.2	70.5	78.6	66.6
	Energy	136.2	584.9	705.5	384.5	235.0	246.1	74.1	417.6	268.6	1013.7	719.3	354.9	623.0	376.1	350.5	419.3
	Number of Hours w/ ID Temp Data	701	601	702	701	664	684	704	0	541	570	702	697	688	703	672	622
Dec-11	Avg ID Temp	55.4	70.0	75.1	66.2	68.1	70.4	72.1		76.4	69.6	72.1	69.4	68.7	70.6	77.4	66.7
	Energy	478.2	1005.8	1034.1	478.2	425.8	481.2	49.5	778.9	587.7	1321.9	1286.7	645.1	1179.7	718.0	534.7	819.2
	Number of Hours w/ ID Temp Data	740	683	740	740	689	650	698	0	93	642	470	740	667	740	701	666
Jan-12	Avg ID Temp	55.9	70.8	74.6	62.7	68.2	69.7	72.0		75.9	70.4	72.0	69.4	69.2	70.0	77.7	66.7
	Energy	397.6	1202.3	1122.4	211.1	437.5	421.5	46.3	915.5	849.7	1521.8	1283.3	607.8	1084.7	893.7	832.7	956.2
	Number of Hours w/ ID Temp Data	744	677	740	744	718	510	713	0	272	666	651	744	709	744	682	651
Feb-12	Avg ID Temp	56.6	70.7	74.7	63.2	68.8	70.3	71.8	30.4	75.7	68.9	71.8	69.9	68.5	69.8	77.5	67.0
	Energy	180.1	965.5	853.2	131.1	405.2	430.2	53.3	662.3	497.4	1449.8	974.4	463.7	941.2	575.9	481.7	659.5
	Number of Hours w/ ID Temp Data	589	600	696	696	662	460	667	4	638	638	609	696	611	696	665	605

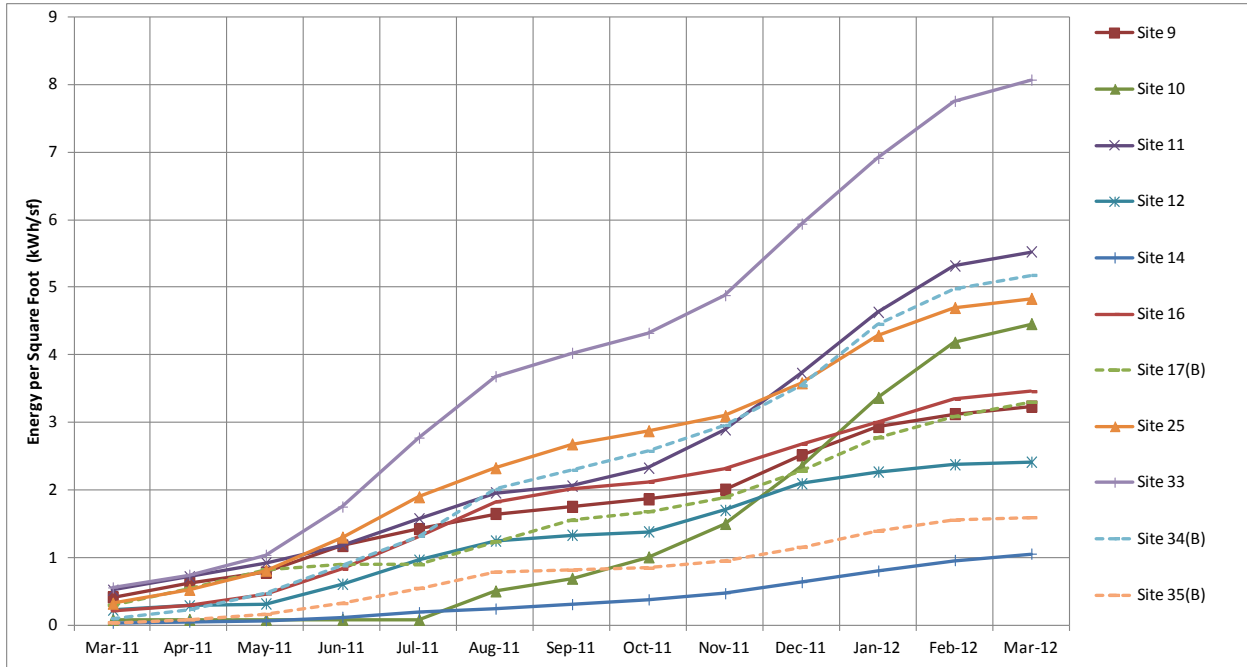


**Figure 5-14**  
**Total Energy Consumption, Cumulative, March 2011 – March 2012 for Utility A Sites**

Eleven of the 16 sites with good data for most of this twelve-month period also had square footage available (see Table 5-5). Figure 5-15 shows the data normalized for square footage, for those sites for which square footage was available. Again, there was a substantial range of performance, with one baseline site using the second-to-least amount of energy and another using the third-to-most. Also, Site 33, a DHP site, can be seen to use exceptionally much energy relative to the home area. Observation of indoor temperature data (shown in Table 5-3 and Table 5-4) shows that this site maintained a significantly lower indoor temperature during the cooling season than others: For example, in July and August the average indoor temperature was approximately 66°F (19°C), while no other site had an indoor temperature below 70°F (21°C), and many had monthly average temperatures approaching or exceeding 80°F (27°C). This example underscores the importance of behavioral factors in interpreting field data.

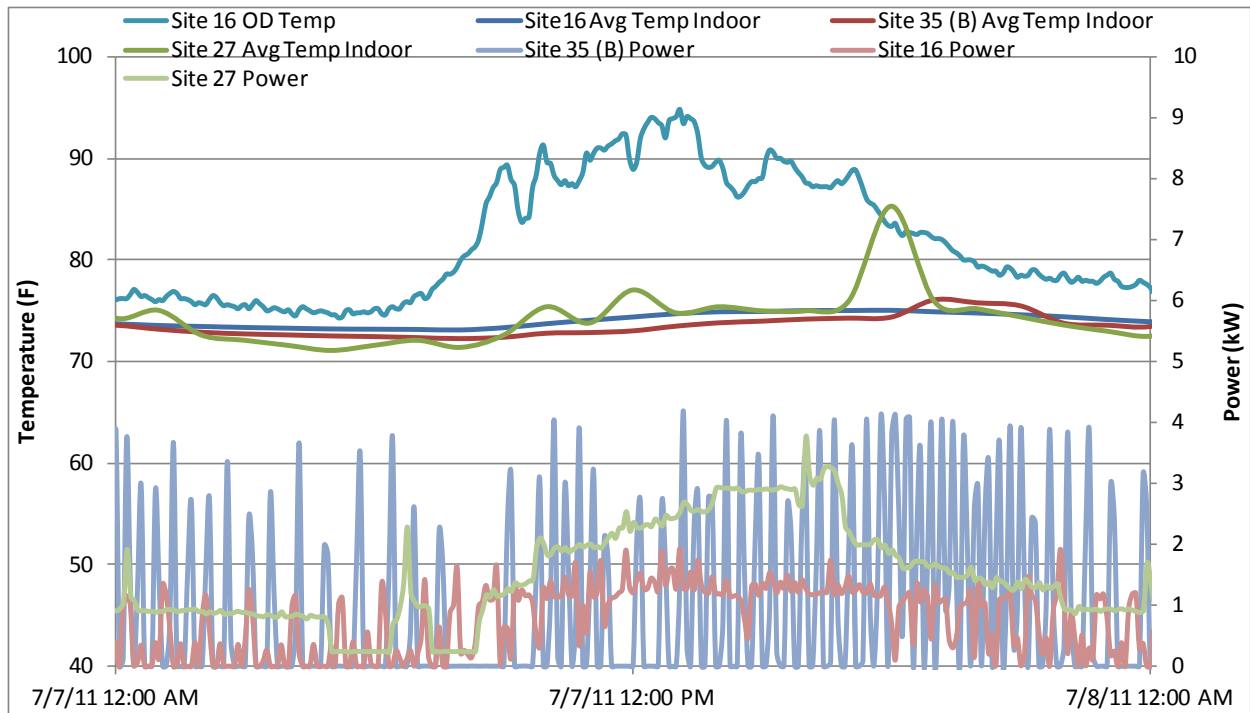
**Table 5-5**  
**Utility A Site Square Footages**

<b>Site</b>	9	10	11	12	13	14	21	22
<b>Square Footage</b>	945	1184	1242	1214	1512	2585	No Data	No Data
<b>Site</b>	25	26	27	29	33	17 (B)	34 (B)	35 (B)
<b>Square Footage</b>	1209	No Data	No Data	No Data	1116	1822	915	4026



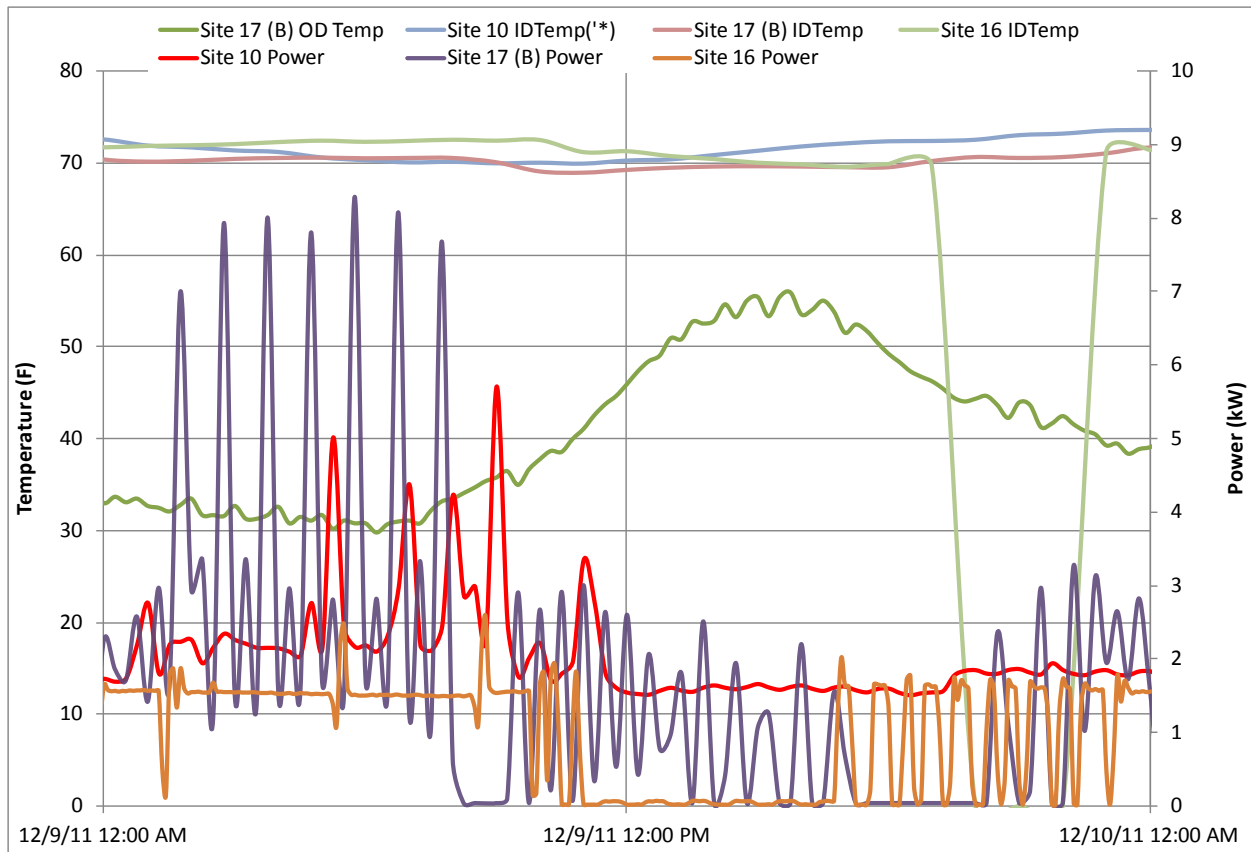
**Figure 5-15**  
**Total Energy Consumption Normalized by Square Footage, Cumulative, March 2011 –**  
**March 2012 for Utility A Sites**

Figure 5-16 shows the power and indoor temperature for three representative sites for July 7, 2012. Site 35, the baseline site, is the largest house of the group, so the system is likely a large-capacity, and power data associated with it is expected to be higher. The results for Site 35 show the system cycling frequently, even during the peak heat of the day; the DHP unit at Site 16 operated at relatively low average power during the night hours and was mostly on during the heat of the day. The unit at Site 27 ramped up power with the heat of the afternoon. It should be noted that the indoor temperature at Site 27 approaches the outdoor ambient temperature in the evening, with the DHP unit still operating. This suggests that the homeowner may have opened doors and/or windows, without disabling the air conditioning. Investigation of other days shows that this indoor temperature increase occurred on a number of days. This again underscores the complexity that behavior introduces into comparisons.



**Figure 5-16**  
**July 2011 Utility A Sites Selected Data (5-Minute Interval)**

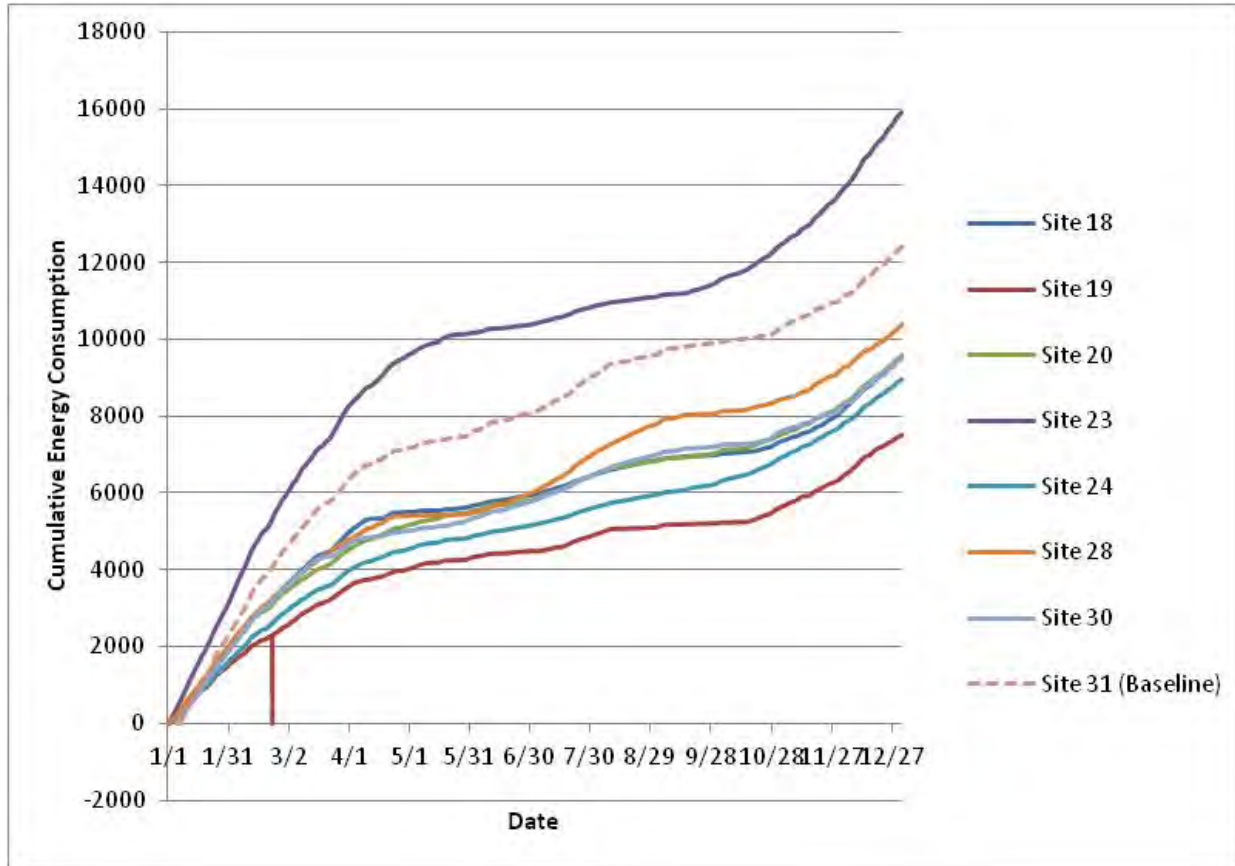
Figure 5-17 shows the power consumption of three sites for December 9, 2011. The baseline site, Site 17, had frequent periods of high power (likely electric resistance heat) during the low-temperature, overnight hours. The DHP unit at Site 10 appears to also have resistance heat, but it was used with less frequency; the unit at Site 16 operated at steady but relatively low power overnight and did not appear to use resistance heat. The indoor temperature sensor at Site 16 briefly did not transmit data, which is reflected in the sharp drop off shown in the Figure. All sites maintained similar indoor temperatures.



**Figure 5-17**  
**December 2011 Utility A Sites Selected Data 5-Minute Intervals**

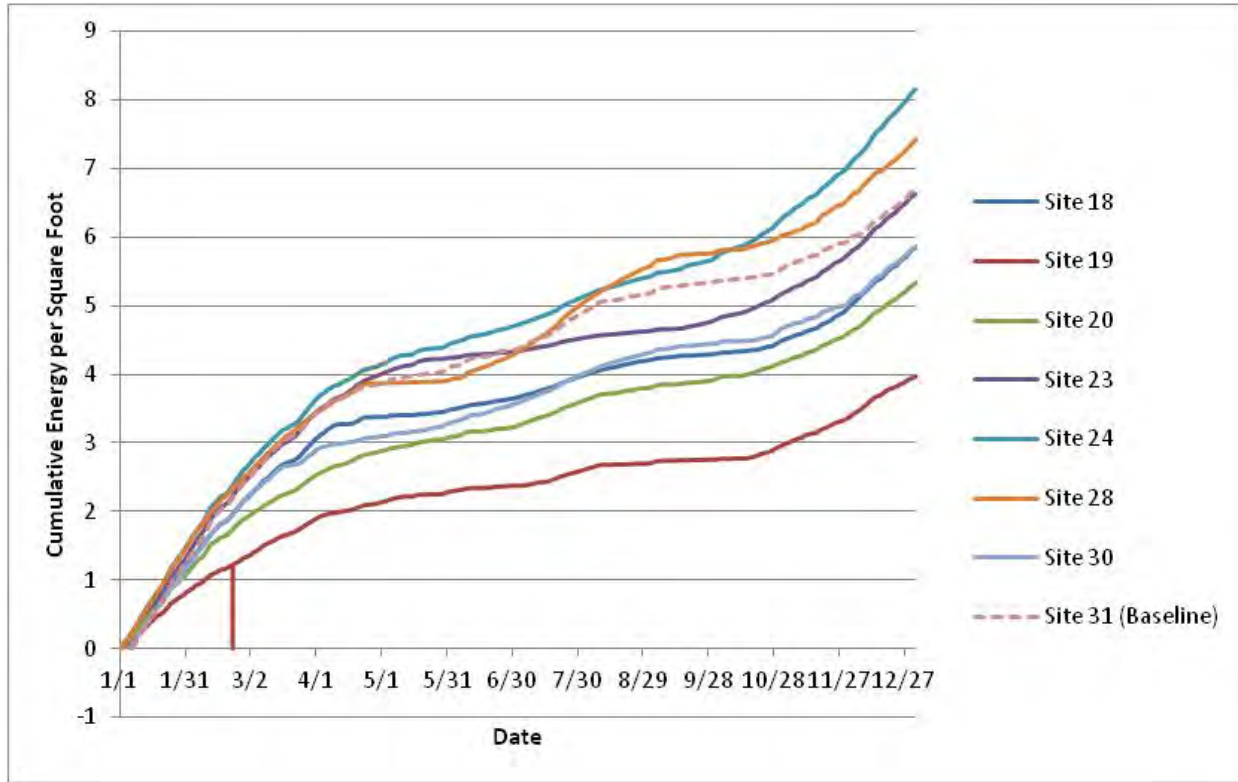
**Utility B Sites**

The field sites in Utility B territory had excellent data continuity with minimal interruptions. The annual energy consumption for each site is shown in Figure 5-18 for the entirety of 2011. The same data, normalized for house square footage, is shown in Figure 5-19. The square footage is shown in Table 5-6. Observation of Figure 5-18 shows that, among the eight sites in the territory, the most energy was consumed at Site 23 (a site with two DHP units, where all other Utility B treatment sites had one) and the second most was at Site 31 (the baseline site). The energy for the year at Site 23 was 15,900 kWh. For Site 31 it was 12,400. The remaining six DHP sites averaged 9,300 kWh.



**Figure 5-18**  
**Utility B Cumulative Energy for Each Site, 2011**

Because one of the very important factors in how much energy will be consumed at a site (and one of the only factors that can be easily accounted for) is the size of the home, the energy consumption per square foot may be of more interest. The data in Figure 5-19 shows that Site 23, which consumed the most energy total, actually consumed slightly less on a per-square-foot basis than the baseline site, Site 31. From Table 5-6 it can also be seen that Site 23 is the largest site, at 2400 square feet, while the baseline site is 1850 square feet (slightly larger than average for the group). Normalized by area, the most energy was consumed at Site 24, followed by Site 28, and then the baseline site, Site 31. It is also of interest to note that Site 31 was constructed in 1988, Site 19 in 1995, and Site 30 in 1989. The remaining five sites were constructed between 1972 to 1978. The older homes may be expected to have poorer building construction, which may explain some of the difference in energy consumption.

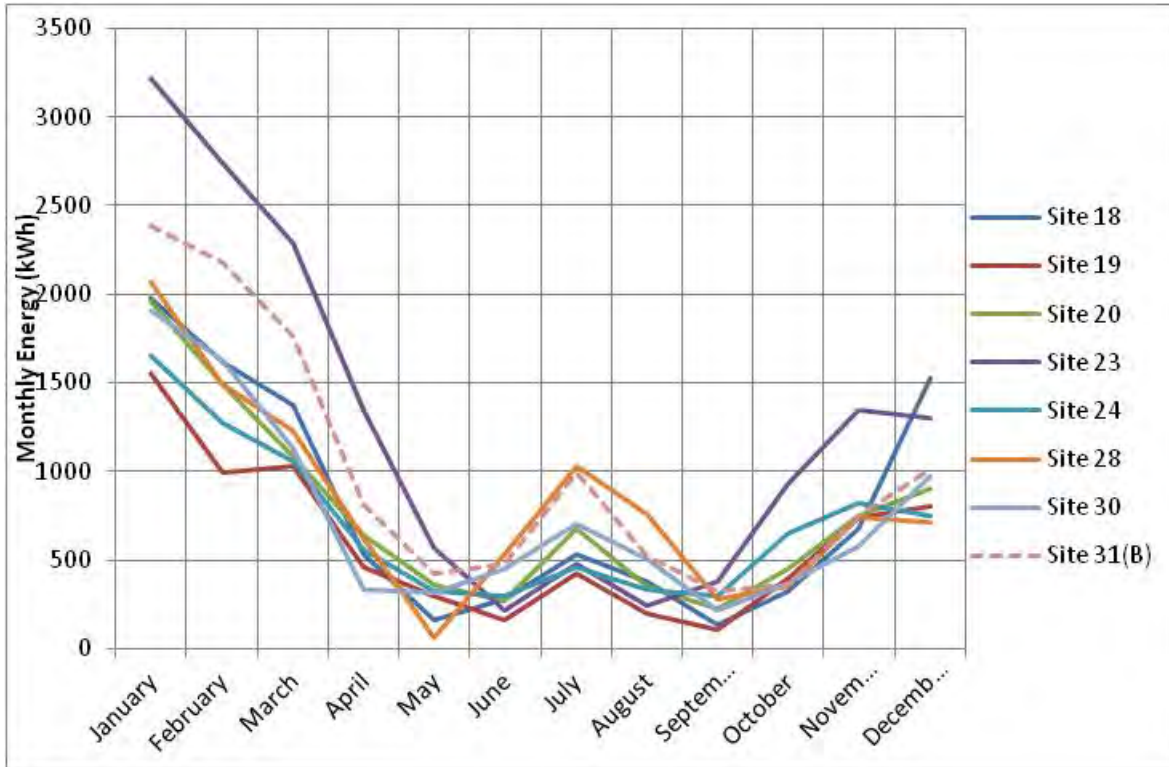


**Figure 5-19**  
**Utility B Cumulative Energy per Square Foot for Each Site, 2011**

**Table 5-6**  
**Home Area of Utility B Sites**

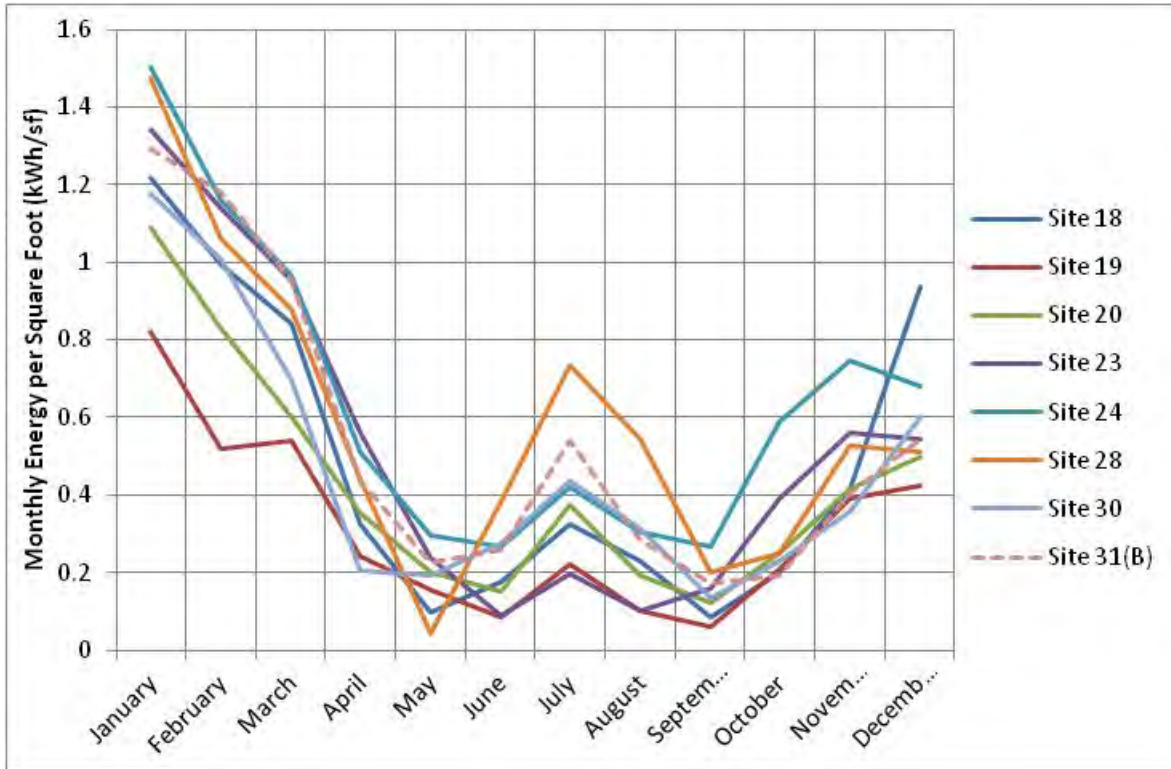
Site Number	18	19	20	23	24	28	30	31 (B)
Square Footage	1625	1900	1800	2400	1100	1400	1620	1850

A summary of monthly data for all Utility B sites is summarized in Table 5-7 and Table 5-8. The energy consumed per month is shown in Figure 5-20. This shows the general and expected trend in heating-dominated climates of high energy consumption during the winter months, very low energy consumption during the “shoulder seasons,” and a smaller peak in energy consumption during the summer. It may be noted that the winter of 2011/2012 was relatively mild compared with the winter of 2010/2011. Observing the data for Site 31, it can be seen that the baseline site was the second- or third-highest consumer during most months; during periods of lower loads, the difference between sites was less pronounced.



**Figure 5-20**  
**Utility B Monthly Energy for Each Site, 2011**

Figure 5-21 shows the monthly energy consumption of each site, normalized for square footage. The data is generally more clustered in this view, but a few trends can be observed. During the winter months of January through March, Sites 31, 23, 24, and 28 consumed similar, relatively high amounts of energy. Site 19 used little. The sites used similar amounts of energy until July, when a summer peak of consumption occurred. In July, Site 28 used the most energy, followed by the baseline site, Site 31, followed by a cluster of other sites. Site 19 and Site 23 used substantially less energy during July.



**Figure 5-21**  
**Utility B Monthly Energy per Square Foot for Each Site, 2011**

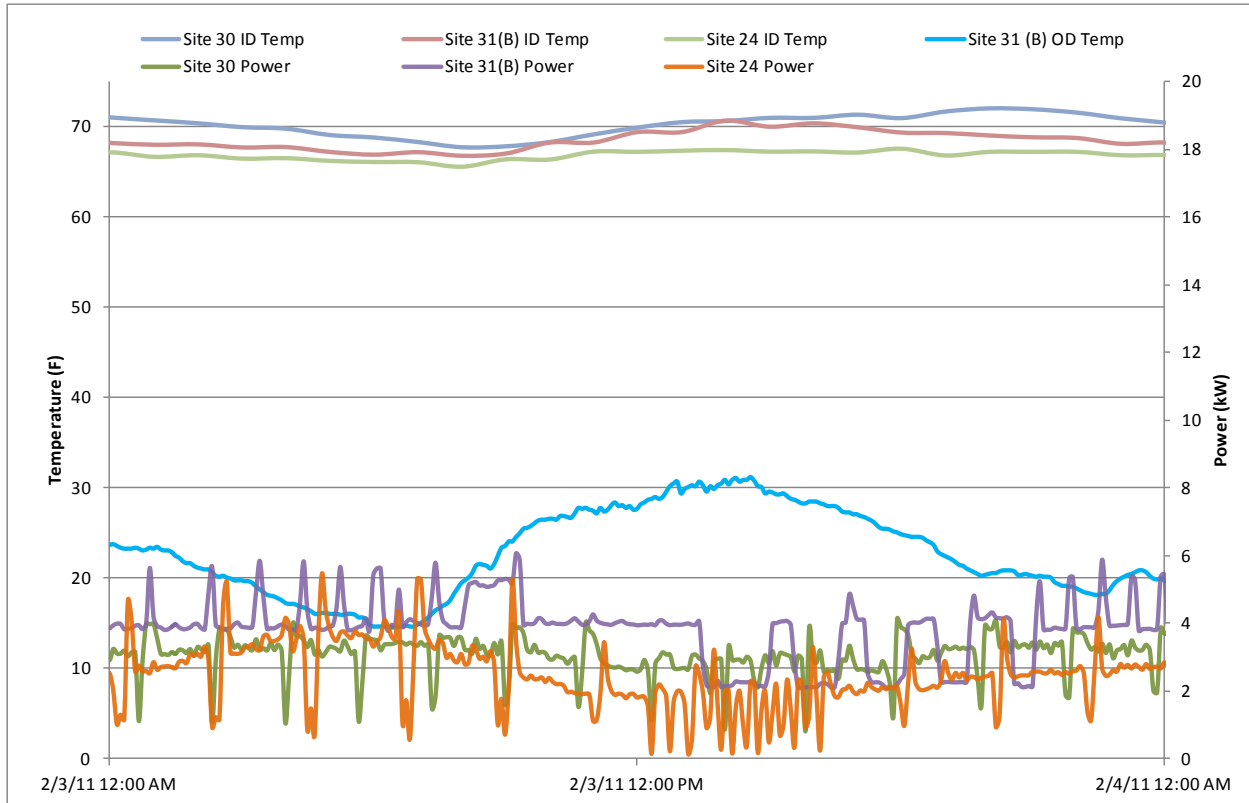
**Table 5-7**  
**Utility B Summary Monthly Data for January-June, 2011**

Site:		18	19	20	23	24	28	30	31 (Base)
January	Avg Indoor Temp (F)	70.3	74.6	71.3	74.9	67.3	71.6	68.5	68.3
	Number of Hours w/ Temp Data	717.00	717.00	717.00	717.00	717.00	717.00	611.00	584.00
	Energy (kWh)	1979.3	1556.4	1963.4	3219.6	1652.9	2066.1	1907.1	2387.2
	Energy per Square Foot (kWh/sf)	1.22	0.82	1.09	1.34	1.50	1.48	1.18	1.29
February	Avg Indoor Temp (F)	70.9	73.9	70.4	75.0	67.9	71.2	69.1	68.9
	Number of Hours w/ Temp Data	669	617	669	590	669	43	669	669
	Energy (kWh)	1616.5	989.1	1490.2	2734.4	1274.4	1487.9	1628.7	2180.8
	Energy per Square Foot (kWh/sf)	0.99	0.52	0.83	1.14	1.16	1.06	1.01	1.18
March	Avg Indoor Temp (F)	71.2	74.2	70.3	75.8	68.6	69.0	67.1	68.8
	Number of Hours w/ Temp Data	676	616	618	678	647	503	592	603
	Energy (kWh)	1370.6	1028.7	1084.2	2288.5	1060.7	1230.8	1129.3	1764.3
	Energy per Square Foot (kWh/sf)	0.84	0.54	0.60	0.95	0.96	0.88	0.70	0.95
April	Avg Indoor Temp (F)	68.9	70.9	70.0	76.6	70.1	68.6	67.4	68.8
	Number of Hours w/ Temp Data	720	648	633	669	662	662	720	680
	Energy (kWh)	528.3	462.6	638.8	1348.6	562.2	618.5	334.9	809.3
	Energy per Square Foot (kWh/sf)	0.33	0.24	0.35	0.56	0.51	0.44	0.21	0.44
May	Avg Indoor Temp (F)	69.1	74.3	69.6	75.7	72.0	70.4	69.2	70.6
	Number of Hours w/ Temp Data	743	744	744	744	744	744	744	744
	Energy (kWh)	161.5	295.1	360.7	568.3	323.5	59.7	311.3	419.6
	Energy per Square Foot (kWh/sf)	0.10	0.16	0.20	0.24	0.29	0.04	0.19	0.23
June	Avg Indoor Temp (F)	70.1	75.4	71.2	73.4	70.1	73.6	71.3	72.6
	Number of Hours w/ Temp Data	684	686	672	672	703	674	681	697
	Energy (kWh)	282.5	162.8	271.9	215.9	293.6	534.4	448.9	480.0
	Energy per Square Foot (kWh/sf)	0.17	0.09	0.15	0.09	0.27	0.38	0.28	0.26

**Table 5-8  
Utility B Summary Monthly Data for July-December, 2011**

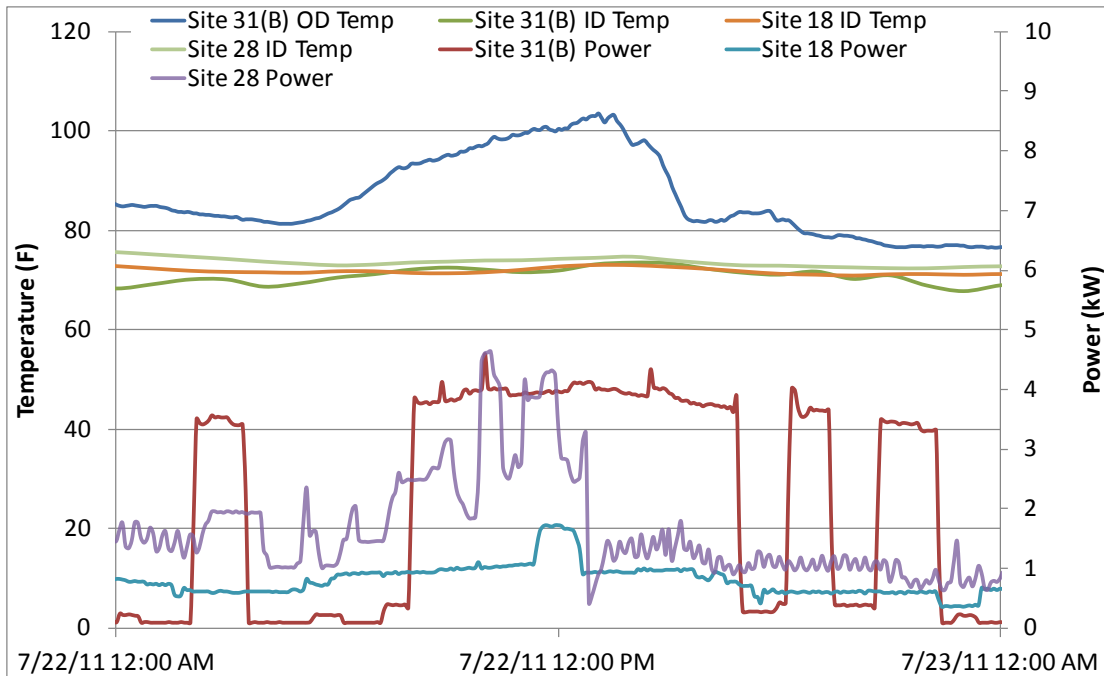
	Site:	18	19	20	23	24	28	30	31 (Base)
July	Avg Indoor Temp (F)	71.5	75.7	71.6	73.8	71.3	73.4	71.2	72.4
	Number of Hours w/ Temp Data	744	744	743	744	744	744	744	744
	Energy (kWh)	529.8	424.1	674.0	476.1	461.0	1028.8	703.7	996.9
	Energy per Square Foot (kWh/sf)	0.33	0.22	0.37	0.20	0.42	0.73	0.43	0.54
August	Avg Indoor Temp (F)	72.0	76.1	72.6	73.9	70.7	72.2	71.6	73.5
	Number of Hours w/ Temp Data	743	743	744	742	744	741	741	744
	Energy (kWh)	375.6	192.7	349.8	242.1	333.7	759.8	504.2	521.8
	Energy per Square Foot (kWh/sf)	0.23	0.10	0.19	0.10	0.30	0.54	0.31	0.28
September	Avg Indoor Temp (F)	71.5	74.2	70.6	74.3	72.5	71.4	71.6	71.7
	Number of Hours w/ Temp Data	690	720	720	660	678	600	614	720
	Energy (kWh)	138.1	110.5	223.1	377.7	294.7	281.2	217.8	319.8
	Energy per Square Foot (kWh/sf)	0.08	0.06	0.12	0.16	0.27	0.20	0.13	0.17
October	Avg Indoor Temp (F)	68.6	71.4	69.8	76.0	73.2	69.5	67.6	68.5
	Number of Hours w/ Temp Data	699	715	602	660	602	618	636	690
	Energy (kWh)	328.0	393.7	453.9	934.3	646.2	352.4	370.9	357.8
	Energy per Square Foot (kWh/sf)	0.20	0.21	0.25	0.39	0.59	0.25	0.23	0.19
November	Avg Indoor Temp (F)	70.2	74.0	69.4	76.8	72.4	70.1	66.5	68.9
	Number of Hours w/ Temp Data	654	698	681	659	643	651	629	651
	Energy (kWh)	674.8	742.8	746.9	1346.4	820.2	736.2	578.4	747.0
	Energy per Square Foot (kWh/sf)	0.42	0.39	0.41	0.56	0.75	0.53	0.36	0.40
December	Avg Indoor Temp (F)	72.0	72.1	68.3	77.0	69.4	71.0	68.5	68.4
	Number of Hours w/ Temp Data	454	638	641	739	739	724	709	739
	Energy (kWh)	1525.1	806.0	900.3	1302.0	748.8	714.0	972.9	1006.9
	Energy per Square Foot (kWh/sf)	0.94	0.42	0.50	0.54	0.68	0.51	0.60	0.54

Figure 5-22 shows the indoor average temperature and power consumption in 5-minute intervals for February 3 for Sites 24, 30 and 31. All three units had high power consumption during the overnight low temperatures, which fell well below 20°F (-7°C). Site 31 appears to have operated most frequently at 4 kW, with an additional cycling to 6 kW during cold periods.



**Figure 5-22**  
**February, 2011 5-Minute Power and Temperature for Selected Representative Utility B Sites**

Figure 5-23 shows the power and average indoor temperature for a selection of sites for July 22, 2011. The indoor temperature was similar for each site. The power was lowest at Site 18 during most periods and highest at Site 31 for much of the time.

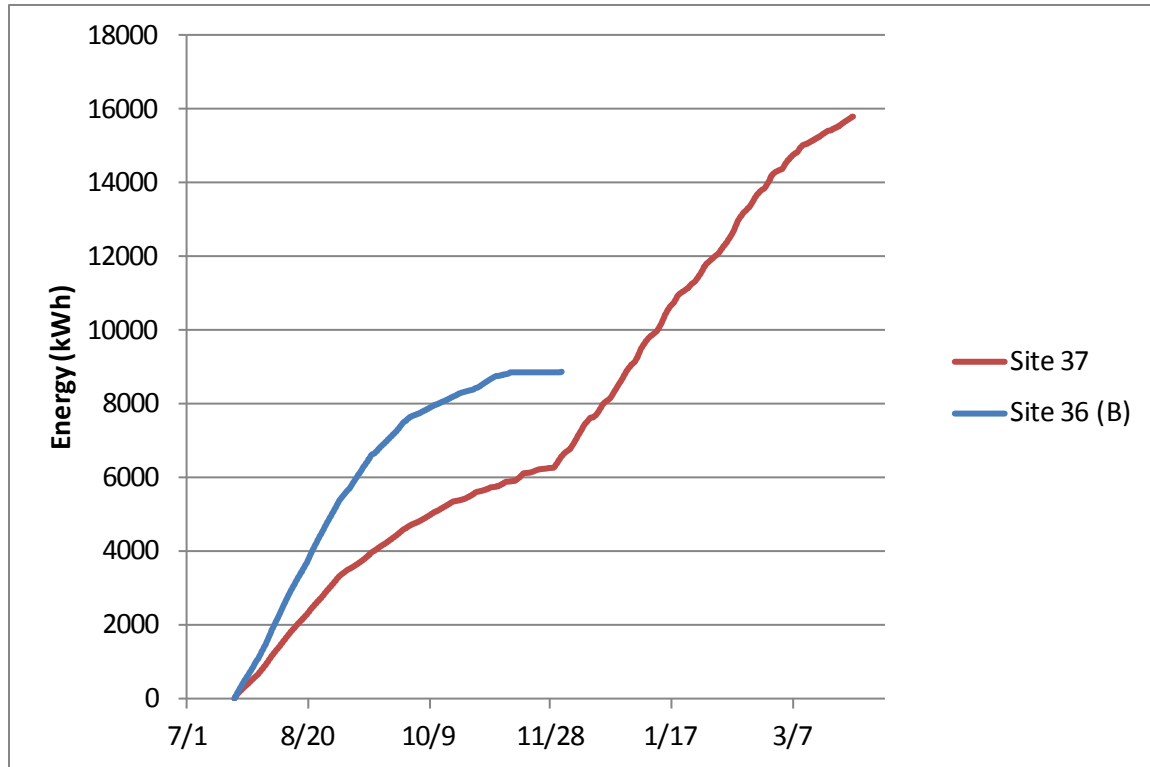


**Figure 5-23**  
**July, 2011 5-minute Power and Temperature Data for Selected Representative Utility B Sites**

### Utility C Sites

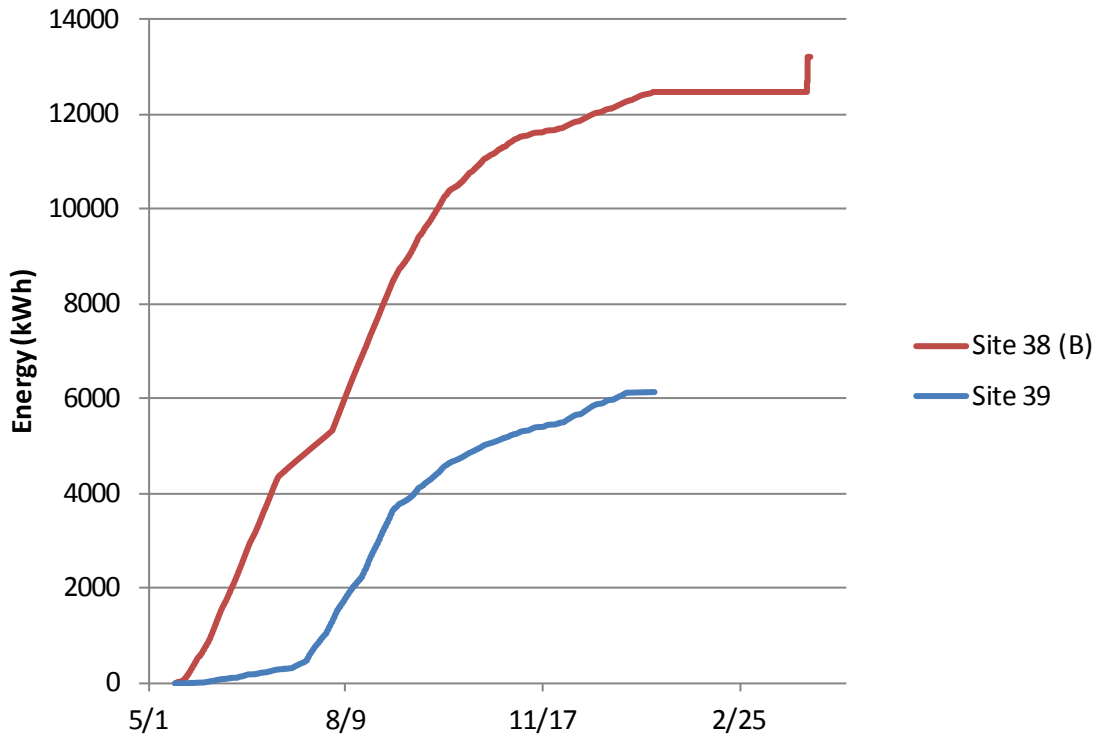
The sites at Utility C’s military training camp operated reasonably well from Summer, 2011 into Winter 2011/2012. There is some uncertainty associated with behavior at these sites; sites were periodically shut off via service breakers (disabling data collection) when the buildings were expected to be unoccupied, and at least one unit was reported to be in cooling mode during the winter. Nevertheless, comparisons can be made using periods of good data collection. Monitoring of these sites will continue in a separate supplemental project through 2012.

Figure 5-24 shows the cumulative energy consumption for Sites 36 and 37. Site 36 is a baseline barracks building, and Site 37 is a DHP barracks building. Site 36 has six single-zone mini-split heat pumps. Site 37 has two sets of new, three-zone mini split systems, with one zone for each room. Both sites had good data beginning in late July, 2011. As can be seen, the baseline site consumed significantly more energy during the period of operation. In August and September, 38% and 18% more energy was consumed at the baseline site. Site 36 had very low usage in October, with a brief period of usage in early November before the system was disabled on November 12, 2011. Site 37 had high energy consumption during December through March.



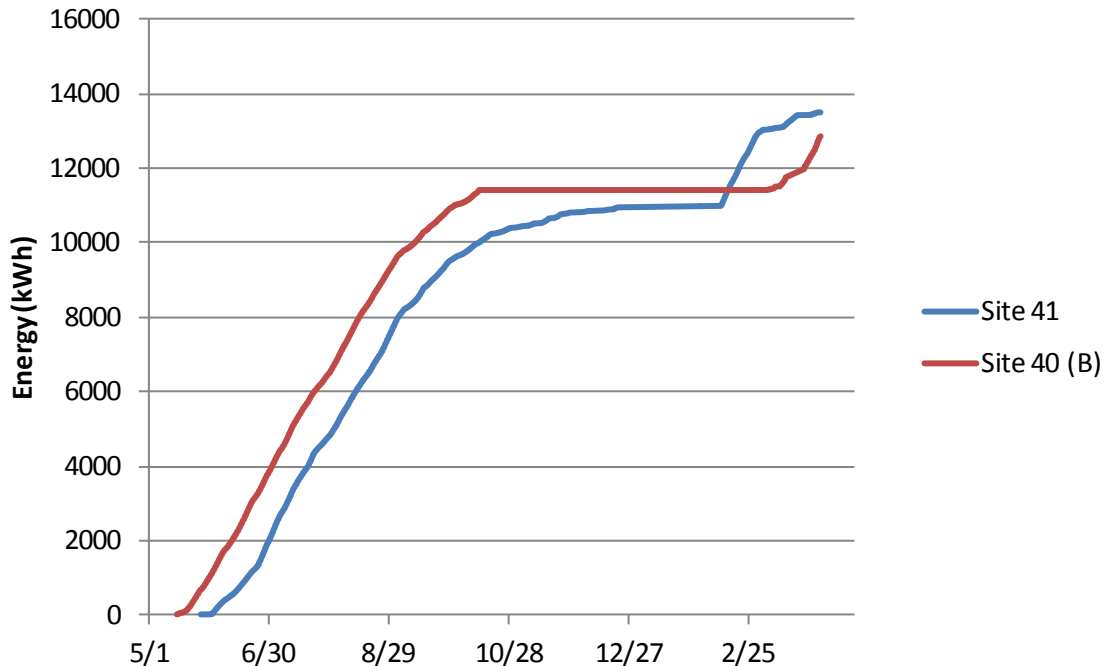
**Figure 5-24**  
**Utility C Sites 36 and 37 Cumulative Energy**

Figure 5-25 shows the energy consumption for Site 38, a baseline officers' Barracks, and Site 39, a DHP officers' barracks. Site 38 has four two-ton mini-split heat pumps, and site 39 has two mini VRF multi-zone systems. While both systems were installed and monitored starting in May, 2011, they did not have comparable occupancy and usage until August. In August, the baseline site consumed 24% more energy than the DHP buildings; in September, the baseline used 44% more energy; in October, the baseline used 43% more energy. In November and December, each site was reduced to have only one unit operating, with other spaces likely unoccupied. The power to some units in Site 38 was observed to have been cut off. The energy consumption was low, but similar: The baseline used 20% more energy in November and 30% less energy in December.



**Figure 5-25**  
**Utility C Sites 38 and 39 Cumulative Energy**

Figure 5-26 shows the cumulative energy consumption for Site 40, a baseline classroom, and Site 41, a DHP classroom. Site 40 has a single five-ton, single speed heat pump. Site 41 has four individual, single zone DHP units. The systems used similar amounts of energy in the summer, though Site 40 was observed to have an average indoor temperature of 75°F (24°C) during August, and Site 41 had an average indoor temperature of 71°F (22°C), suggesting that the comparison may not be ideal. In September, the average temperatures were closer (70°F [21°C] in Site 40 and 71°F [22°C] in Site 41), and the baseline site used 17% more energy. Site 40 was disabled on October 13 and remained off.



**Figure 5-26**  
Utility C Sites 40 and 41 Cumulative Energy

## Survey Results

Customer satisfaction regarding the ductless heat pumps was examined using an online survey instrument. It was provided to representatives at the host utilities, who then provided the survey link to their participating customers. EPRI was able to collect 11 responses total, four from participants from Utility A’s demonstration, and seven from Utility B’s. Questions included in the survey instruments sought input from customers on their use of and satisfaction with the ductless heat pump heating and air conditioning system.

### Satisfaction

Concerning overall satisfaction, most customers were highly satisfied with their ductless heat pump system, citing energy and bill savings, comfort, performance and controllability as the primary drivers for this rating. One customer remarked, “When a system does what you ask each and every time, how can one not be highly satisfied? If we had ANY issues, the HVAC contractor was quick to address and resolve [them].” Others enjoyed the fact that they could “go from heating to air conditioning at the press of a button” with “immediate” results and being to program the units as they saw fit. Many customers expressed their gratitude both for the opportunity to participate in the demonstration and for the unit itself. Another response indicated that the ductless heat pump system was a benefit to their family and an increase to their homes’ resale values, with one individual referring to the system’s air conditioning as a “blessing.”

While no customers expressed dissatisfaction with their heating and air conditioning systems, some did indicate that they were only “satisfied” with the overall performance of their ductless heat pumps. Almost all of these respondents indicated that the controls were not easy to understand and use, which could suggest that difficulty in controlling the system was a

significant driver behind this rating. Additionally, one customer indicated that they found the individual wall-mounted units large and unattractive. This customer also mentioned that controls for three rooms were determined by a single set point location, resulting in some rooms being warmer or cooler than what was preferable. Finally, one of the customers that provided this rating did not receive adequate cooling in persistent, extremely warm conditions. Further information concerning seasonal satisfaction is provided below.

All but one respondent specified that they would consider purchasing a similar unit, while the remaining individual stated that they still might consider it. This customer did report difficulty with the controls, and actually requested a more detailed manual for understanding how to program the units. All participants indicated that they would recommend the ductless heat pump to friends and family.

Only one individual reported that they had experienced technical issues, stating that the “drip pan in the attic crawlspace was overflowing.” The respondent indicated that the situation was resolved quickly and that no additional problems had occurred. This participant maintained an overall satisfaction rating of “highly satisfied.”

### **Summer**

Almost all customers were highly satisfied with the performance of their ductless heat pump system during the summer. Participants indicated that the system met their cooling needs quickly and completely while allowing for temperature set point preferences for individual rooms or spaces. Only two participants did not indicate high satisfaction, stipulating that they were “satisfied” instead. One of these respondents explained that their conditioned space was large and that they believed “the units did all they could” and were “able to keep up if the high heat days did not run together.”

### **Winter**

Similarly, most participants were highly satisfied with the heating capability of their ductless heat pump system during the winter. Survey respondents indicated that the system provided sufficient comfort while reducing their energy bills. One Utility A customer commented on the resiliency of the system, stating that during the first year, “conditions got to zero on several occasions and the house remained comfortable.” Once again, participants seemed to enjoy the enhanced controllability, with some choosing to heat only the rooms which they used.

Three participants indicated that they were only “satisfied” with the system’s performance during the winter. One of these respondents experienced difficulty controlling the temperature from room-to-room, noting that the units seemed “to run high in the bedrooms even on the lowest setting.”

### **Comfort**

Almost all customers felt that they were able to maintain a comfortable environment, no matter what the season, with only one customer indicating that their home was not more comfortable all or most of the time. Specifically, one customer indicated that it was more comfortable to sleep during the summer. Another stated that they could now enjoy cooking during hot, humid days, where, prior to the installation of their new unit, they were “embarrassed to have company over because the house was so hot.” The only respondent to indicate that they were “sometimes

comfortable, sometimes not” was the previously discussed individual who expressed both difficulty in using the controls and having one unit that controlled the temperature for three rooms. While other participants were generally comfortable, they noticed that areas of their home that did not have individual units were not able to maintain comfort during the winter if the doors were closed.

Most respondents did not have to use their previous equipment unless there were exceptionally cold winter conditions or a portion of their house was not conditioned by the ductless heat pump. One customer who had baseboard heating was required to leave the system operational with a set point temperature of 60°F (16°C) to maintain the system’s integrity. About half of the participants still chose to use fans, space heaters, or fireplaces to supplement their need for heating or cooling, but this seemed to be on an as-needed or preferred basis.

In addition to comfort related to temperature, some participants noted other changes to comfort. One customer remarked that their house had been “less dusty” than before they received the ductless heat pump, and another mentioned that recent health conditions demanded a need for adequate air conditioning, which the system was able to provide. One other individual stated that during the summer, the humidity was higher inside the house than when they utilized window air conditioning. However, the customer did not designate whether this was bothersome or preferred.

All but one customer indicated a marked decrease in noise over what they had been using previously, including window air conditioners and even base board heating systems. One participant responded that while the units themselves were quieter than their previous HVAC system, the water discharge pump produces some additional noise. However, other customers described the noise output by the ductless heat pump as “unnoticeable” or “silent.”

### ***Controllability***

Respondents seemed to enjoy the ability to set the temperature for each room and enjoyed the enhanced controls. When asked if they preferred the distributed control via multiple thermostats, or the single-point of control of their previous systems, about half indicated that the distributed control of the ductless heat pump was preferable, including one respondent that had reported difficulty using the controls. Others expressed no preference, with two indicating difficulty understanding and using the controls. Finally, two customers specified that they preferred the single point of control that their previous system provided, both of whom also noted that they had experienced trouble using the controls.

One other customer mentioned a potential improvement to controllability, suggesting that they would prefer to be able to set each unit to “maintain a constant temperature, whether air conditioning or heat is needed,” eliminating the need to manually switch the units from one mode to the other.

### ***Savings***

Almost all customers surveyed noted changes in their energy bill. Most reported decreases, but the time of year when they observed these decreases varied customer to customer. All Utility A customers indicated decreases to their electricity bill, with one customer remarking that the cost to heat their home during the winter decreased by as much as \$100, despite extremely cold

temperatures. Customers at Utility B's demonstration sites provided more variable responses. Over half of these participants indicated noticeable decreases in their electricity bill with an increase in the comfort of their home. Two customers indicated an increase in their electricity bill during the summer, but both specified that they did not have a central air conditioning system prior to the installation of the ductless heat pump. One of these respondents indicated that their heating bills were comparable to what they had previously, and the other observed a decrease in their energy bill during the winter. One other Utility B customer indicated winter savings, but observed no real change in their bill during the summer.

In general, most participants expressed high levels of satisfaction with the ductless heat pump heating and air conditioning systems. Responses indicated that most customers experienced increased comfort, enhanced controllability, decreased noise, and noticeable energy savings. While no significant technical issues were observed, several respondents felt that the controls for the system were not easy to understand or use. Some customers indicated that they had difficulty maintaining comfort, but in almost all of these cases, respondents mentioned either that they had trouble with controlling the system or that the system's installation may not have been designed properly in terms of unit placement or zone controls. These results suggest that larger scale installation efforts should focus on ensuring proper design considerations and educating customers on proper use of the controls.

## **Summary**

For the sites from Utility A, the performance difference between systems was ambiguous. Data showed that behavioral factors significantly impacted the energy consumption at each site. For example, one DHP site used an exceptionally high amount of energy per square foot during the cooling season. Analysis of indoor temperature data revealed that this site was typically maintaining temperatures 4°F (2.2°C) cooler than the next coolest household. Similarly, analysis of the daily data from another site suggested that the homeowner may have been opening doors and/or windows but leaving the air conditioning on. The data suggests that behavior from the homeowner caused the DHP to consume much more energy than it would if the building were sealed or the unit were turned off when outdoor air was being let in.

The sites in Utility B's territory showed that five of seven of the DHP sites used less energy, per square foot of living space, than the site with baseboard resistance heat.

The Utility C sites provided a strong comparison, because the building types were identical, but had behavioral complications associated with occupancy changes. During periods at the Utility C sites when the systems did have comparable operation, the DHP sites used less energy in most cases. For example, the savings ranged from 18 to 44% in August and September, 2011.

Overall, the results suggest that savings are attainable with DHP systems, although those savings depend upon site-by-site variables, including customer behavior and preferences. As with many technologies, contractor, installer, and technician training is highly important. Most customers were satisfied with DHP system performance, reliability, controllability, comfort, and savings.

## **Readiness for Program**

The results of the DHP demonstration show that energy savings are possible, but the savings that were achieved during testing varied significantly with home size and design and behavior of the

occupants. The variations are not easy to quantify, so prediction of energy savings is difficult. The positive experiences with DHP adoption in the market located in the Pacific Northwest clearly indicates that the technology is already accepted in that market, the likelihood of adoption in other climates is not clear, and the neither are the expected energy savings. EPRI suggests a Coordinated Early Deployment Project in one or more climate zones in order to better understand the potential for actual energy savings and to gain experience from which utilities will be able to develop DHP programs with a higher likelihood of success.



# 6

## LIGHT-EMITTING DIODES FOR STREET AND AREA LIGHTING

---

### Introduction

In 1938, the first mercury vapor lights were installed to illuminate streets. According to the same DOE study [6-1], 15% are still installed today. More than one out of every ten fixtures still uses a technology originally implemented when Roosevelt was president. Light fixtures are long lived; if LEDs are adopted, they will likely remain in place for a long time. That's why it's important to make sure the LEDs installed are worth installing in terms of energy efficiency, performance, reliability, and customer satisfaction compared to the existing technologies.

EPRI's role in the Energy Efficiency Demonstration of LED Technology for Street and Area Lighting is to measure the key characteristics in the lab and in the field. This chapter presents actual data from field installations on energy consumption, light levels, and reliability and performance over time.

The results demonstrate that not only do LEDs offer significant savings, but the data suggests that even more savings, up to 10% more, are possible by improving driver efficiency, compensating for temperature effects, and correcting improperly placed control sensors.

### Industry Overview

Solid-state lighting (SSL), has exhibited rapid ongoing improvement. The growth is rapid enough that many street and area lighting engineers are considering the use of LED technology as a replacement for traditional technology, such as metal halide and high-pressure sodium. The industry receives a lot of attention because solid-state technology has a history of increasing performance and decreasing cost. The DOE has an entire program on SSL with the stated goal of acting as a catalyst to drive research and development breakthroughs in efficiency and performance and to equip buyers to successfully apply SSL [6-2].

Although the cost of installing LED lighting is greater than the installation cost for conventional lighting (up to ten times higher in some cases), budgeted costs for the maintenance of conventional lighting far exceed the initial cost of their installation. LEDs also last longer than HID lighting—a lifespan as much as 100,000 hours according to some manufacturers—which also reduces the maintenance costs.

### *Savings Potential*

While the DOE's SSL program encompasses all lighting applications, the Energy Efficiency Demonstration is focused on roadway lighting and parking lighting. Roadway lighting divides into two categories: street fixtures and highway fixtures. Street fixtures are used on local and collector roads. Highway fixtures are used on interstates, freeways, and expressways. The

installed base of roadway fixtures in 2010 was 52.6 million, which includes 26.5 million street fixtures and 26.1 million highway lighting fixtures. Parking lighting is divided into two sub-categories: lighting for covered parking garages and lighting for parking lots. Parking lots were included within the LED study because of lower risk of liability, ease of installation, and ease of monitoring. Covered garages were not included in the study. The exact number of existing parking lights is not known, but the DOE estimates 15.8 million, leading to an estimated electricity savings of 8.6 TWh per year (2011) if replaced by LEDs.

## **Technology**

During most of the 20th century, about the only LED you normally saw was the one that lit up when your stereo was on. By the nineties, tiny light-emitting diodes were illuminating the display and keypads of your mobile phone. Today they are backlighting your laptop screen, flat-panel TV, and may soon replace the incandescent and compact fluorescent light bulbs in your home.

This revolution in lighting comes from the ever-greater bang per buck that the LED delivers. With every decade since 1970, when the red LEDs hit their stride, they are 20 times brighter and 90% cheaper per watt.

The forerunners of the white LEDs were the chips that backlit handsets starting about a decade ago. Back then, they used tens of milliamps and consumed a watt for every 10 lumens of light they produced. They were also tiny—just 300 micrometers on a side. Since then, the chips have more than tripled in size (to a millimeter square or more), current has shot up to an ampere or so, and efficiency has rocketed to more than 100 lumens per watt (lm/W). While cost per watt has decreased consistently, cost remains a hurdle.

The development of LED technology has caused their efficiency and light output to rise exponentially, with a doubling occurring about every 36 months since the 1960s, in a way similar to Moore's law. The advances are generally attributed to the parallel development of other semiconductor technologies and advances in optics and material science. This trend is normally called *Haitz's Law*, after Dr. Roland Haitz, and it applies also to yellow and blue LEDs, which were commercialized much later. A timeline for LED development is given below:

1907 – First observation of light emitted from a diode junction (cat's whisker radio detector).

1927 – Published article describes light emitted from junction diodes in radio equipment.

1955 – Bell Labs reports infrared emission from a GaAs semiconductor and other alloys.

1961 – Texas Instruments patents the LED.

1962 – GE develops first visible LED.

1964 – IBM uses LEDs on a printed circuit board as indicators.

1972 – Yellow LEDs are introduced (10x high brightness of red LEDs).

Late 1970s – Nichia of Japan develops first blue LED using InGaN.

1980s – LEDs undergo constant refinement (brighter, cheaper).

1990s – First high-brightness LEDs appear (blue and then green); white LEDs appear near the end of the decade.

2005 – Cree announces 100 lm/W from standard 5-mm LED.

The technology also benefits from advances in power electronics. Specifically, the improvement in switch-mode power supply technology that today easily achieves a conversion efficiency of greater than 90%. This is compared to linear supplies of the past with an efficiency of less than 50%. Magnetic ballasts that power most of the high-intensity discharge (HID) lamps in use today have an efficiency that varies as a function of size; the higher the wattage, the higher the efficiency (see Table 6-1). A common fixture size (150 W) has a ballast efficiency of only 80%.

**Table 6-1**  
**Efficiency as a Function of Lamp Size for High-Pressure Sodium Fixtures**

Lamp Wattage	Ballast Efficiency (%)
70	67
100	77
150	80
250	83
400	87

Although they are an improvement over traditional lighting sources, LEDs still fall short using a laboratory lumen-per-watt measurement. The real value of the LED is seen in the field. LED technology allows the designer to correctly size the fixture for the application. The reason for this is because traditional street and area lighting emanates from a point source, and light is thrown in all directions, causing absorption within the fixture, light radiation in the upward direction, and light radiation behind the fixture. In typical operation, a large portion of the light from a traditional source is wasted. With an LED-based fixture, multiple sources of light are used. Light is directed only to where it is desired. If a rectangular pattern of light is desired, only a rectangular pattern is produced. So while LEDs are not more efficient as measured using traditional laboratory techniques, the application efficiency is higher. Manufacturers suggest potential maintenance savings because of their longevity.

The solid-state lighting industry is evolving. To help navigate the options, the DOE has developed guides and standards on a range of topics from performance and life to design and selection of manufacturers. A comprehensive list of industry standards is found on the DOE website: <http://www1.eere.energy.gov/buildings/ssl/standards.html>.

Of particular interest are the following sources of information on LED lighting:

#### DOE Municipal Solid-State Street Lighting Consortium

From the website: “The DOE Municipal Solid-State Street Lighting Consortium shares technical information and experiences related to LED street and area lighting demonstrations and serves as an objective resource for evaluating new products on the market intended for street and area lighting applications. Cities, power providers, and others who invest in street and area lighting are invited to join the Consortium and share their experiences. The goal is to build a repository of

valuable field experience and data that will significantly accelerate the learning curve for buying and implementing high-quality, energy-efficient LED street and area lighting.”

### **MSSLC Retrofit Financial Analysis Tool**

The Retrofit Financial Analysis Tool, developed by the DOE Municipal Solid-State Street Lighting Consortium in collaboration with the Clinton Climate Initiative, provides municipalities, utilities, and other organizations a method of analyzing the cost and return-on-investment from lighting efficiency projects. Visit:

<http://www1.eere.energy.gov/buildings/ssl/financial-tool.html>

### **IES LM-80-2008, Approved Method for Measuring Lumen Depreciation of LED Light Sources**

Specifies a standard method for measuring the lumen depreciation of LEDs, allowing calculation of LED lifetime. Electronic copies may be purchased online through the Illuminating Engineering Society (IES) store.

### **Research Objective**

Utilities are looking for technologies to reduce load, meet energy savings goals, and to offer customers ways to reduce their energy bills. LED technology offers the potential for significant energy savings and customer bill savings. However, minimal data exists to substantiate the energy savings and performance claims of manufacturers. The data from the Energy Efficiency Demonstration will serve to inform not just utilities for their energy efficiency programs but the industry as well, in ways that may lead to improvements in the technology.

EPRI’s research is designed to answer the following questions:

What are the actual energy savings compared to both manufacturers’ estimates and design estimates? Is it possible to accurately predict energy savings?

What is the actual performance of LED-based fixtures in the field, both initially and over time? How does this compare to both the control and the modeled performance? Traditional fixtures are a well-known quantity. What additional considerations are needed because of LED technology?

What are the differences in terms of efficiency and driver performance among manufacturers? Many vendors now offer LED products. What makes one better than another? How does the light from an LED differ from a traditional source? Just as metal-halide lamps differ from high-pressure sodium, so too do LEDs. EPRI will investigate the differences and how they impact design.

Is the light output stable? What about degradation over time and secondary effects such as temperature?

How does the distribution pattern compare? Is it possible to substitute an existing fixture for one using an LED technology? What changes are needed?

Does the type of control circuit affect energy savings? Control circuits can include timers, photocells, and computers. What is the effect of each on energy savings?

Are the fixtures reliable? If they are installed in the field, what is the expected mean time between failures?

Do users accept the lighting? Lighting is subjective. How do users accept the change in technology?

The overall objectives of the demonstration were to assess LED technology, to find its strengths and weaknesses, to make recommendations to both manufacturers and utilities with regard to the worthiness of the technology, and to comment on the technical barriers that still impede widespread adoption.

## **Research Method**

Early demonstrations showed that LED technology could adequately illuminate an area and save energy. These demonstrations proved that the light levels and the light color are sufficient. The work of the LED Demonstration was to go the next step and provide additional data.

The research method included laboratory measurements, modeling, and field measurements. Surveys were used to justify the comparison between the control and treatment sites.

### ***Laboratory Measurements***

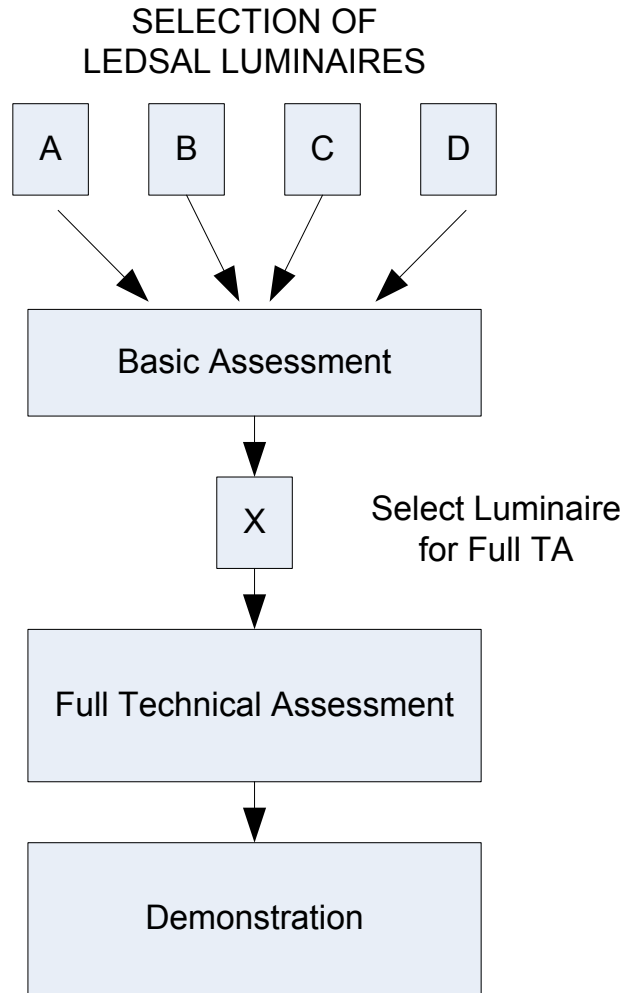
In addition to the field measurements, the laboratory was used to support the design and selection of the fixtures as well as to baseline performance. Laboratory tests included:

Thermal imaging

Light pattern

Temperature effects

The laboratory assessment of LED for Street and Area Lighting (LEDSAL) is summarized in Figure 6-1.



**Figure 6-1**  
**EPRI's Workflow Diagram for Laboratory Assessment of LED Street and Area Lighting Fixtures**

### ***Field Measurements***

Field measurements are difficult. Most sites do not offer ideal conditions for measurement setup and collection of data that is suitable for comparison. For example, in fixture height and pole spacing complicate the comparison among sites. In general, the criteria for site selection was as follows:

Ready access for installation and monitoring without disruption of traffic flows (pedestrian or vehicle).

Minimal public-safety issues (not a major thoroughfare).

All lights on a single electrical circuit.

Pole spacing and mounting heights compatible with LED lights.

Enough traffic to allow before-and-after installation surveys of users of the lighted space.

Makes good use of the strengths of LED lights (color rendition, minimal light trespass).

Has buy-in of local users of the lighted space (residents and/or business owners).

There are no other factors that might impact light-level measurements (such as vegetation or new structures) over time.

Field measurements compare data from a control technology and treatment technology. The control (the existing lighting) is monitored for several weeks, and then yearly energy is extrapolated using the total number of darkness hours for the geographic location of the demonstration site. The treatment (the LED equipment installed for the test) is monitored for at least a year, and energy is directly measured. The energy savings is the difference between the control consumption and the treatment consumption over the course of a year or more.

### Installation of Monitors

The energy meter selected for the Demonstration is manufactured by Electro Industries (model number Shark 200). Figure 6-2 shows an example installation. Several different configurations of current transformers were used, depending on the specifics of the monitored circuit. For indoor locations, EPRI contracted locally in Knoxville, Tennessee, to have the meter mounted within a UL 508A approved enclosure to minimize exposure to liability, as shown in Figure 6-3.



**Figure 6-2**  
**EPRI's Energy Monitor on a Light Pole**



**Figure 6-3**  
**An Energy Monitor Installed in a UL 508A Enclosure**

Communication of data back to the EPRI server in Knoxville was via either Ethernet connection (preferred) or cell modem (\$60/month). The meter measured and recorded all of the standard electricity metrics (power, power factor, and so on). The schematic varied by site. It was very difficult to find a site with the ideal monitoring circuit. Usually, a subset of the total fixtures was monitored—for example, six of ten fixtures.

In addition to the energy monitor, a test protocol for data collection onsite was created and is included in Appendix B.

The general procedure for the field demonstration was as follows:

1. The participating utility identifies possible sites.
2. EPRI reviews candidates and provides a recommendation.
3. A participating utility agrees to host the site.

4. The host provides as much electrical and physical layout information as possible. EPRI begins documentation package.
5. The host and EPRI determine the configuration for power monitoring and send a power monitor to the site for pre-installation data collection.
6. EPRI uses lighting and power data to determine the best candidates for LED fixture providers to send a request for a quotation (RFQ).
7. After receipt of quotes, EPRI works with the utility host to select the fixtures for the site.
8. EPRI and the host procure and install fixtures.
9. The host monitors energy use and measures photometric data (once per quarter).

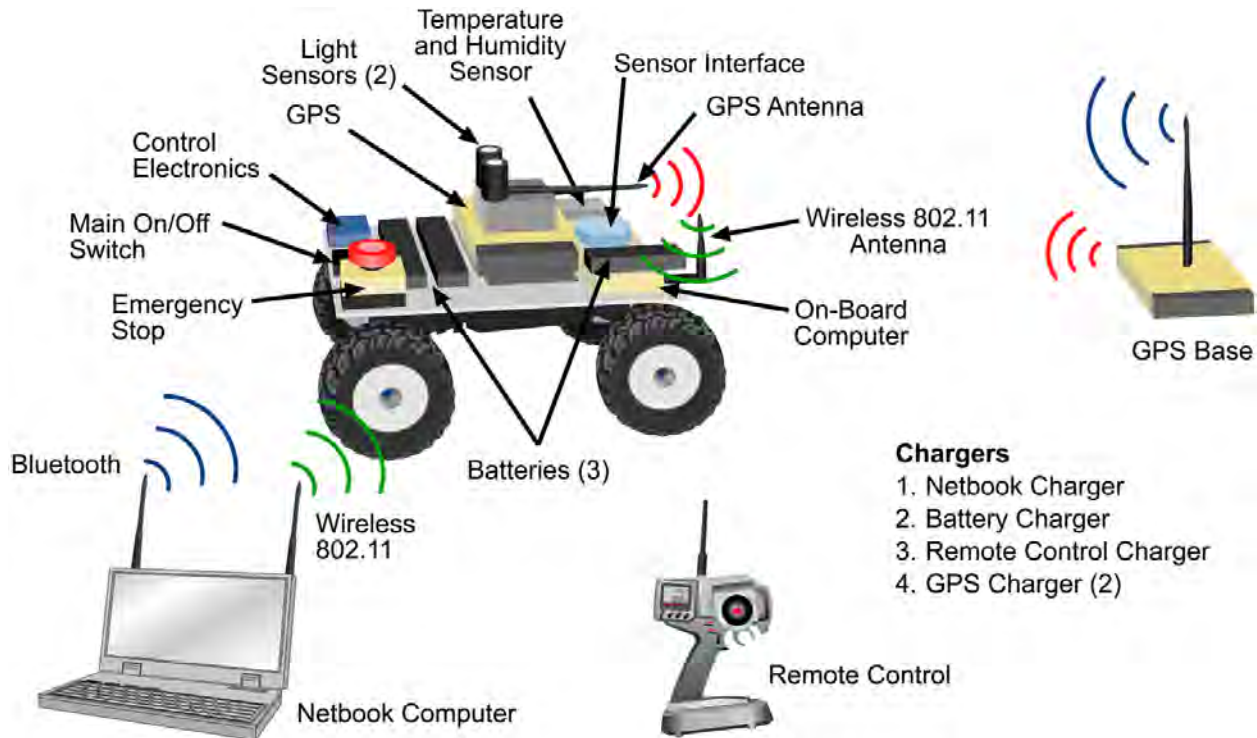
### Scotty

Collecting photometric data is a significant measurement challenge. For the EPRI LED Demonstration, engineers determined that measurements should be made near the ground where light is incident upon walking surfaces. Moreover, the measurements should be made on an exact grid. These two requirements—the height of the measurement and its grid location—posed a difficulty for engineers.

Accurate, timely, and repeatable measurements of LED light levels are possible using the computer-controlled Light-Measurement System, nicknamed “Scotty,” a four-wheel, technology-laden, remotely controlled robot, shown in Figure 6-4. Using a global positioning system, Scotty aims its precision light meters skyward, recording light data onto its onboard computer at up to five times per second as an operator maneuvers the mobile device throughout a high-resolution grid. This robot is a versatile device and can measure all types of lights, including LED. Figure 6-5 shows the complete system.



**Figure 6-4**  
**The Scotty, a Mobile Light-Measurement Platform**



**Figure 6-5**  
**The Various Subsystems That Comprise the Scotty**

EPRI developed the light-measurement system with precision global positioning satellite (GPS) technology and photometric instrumentation to methodically record the required information and log it to a laptop computer.

The Scotty offers engineers a number of benefits because it decreases measurement time from hours to minutes, increases measurement accuracy from ten-foot grid spacing to two-foot grid spacing, and increases repeatability with the determination of sensor position to within a few centimeters. The Scotty also increases safety by keeping test engineers out of roadways, and for the first time, it makes practical the measurement of efficacy on location.

Typically, efficacy is measured in the laboratory. Scotty allows measurement in the field. Field measurement allows researchers to measure light degradation over time without removing the fixture and shipping it back to the lab. EPRI typically measures light output once a quarter. Field measurement allows researchers to determine performance, taking into account dirt buildup on the fixture.

The Scotty has a number of features, including:

Differential GPS accurate to within several centimeters.

Precision light meters for photopic and scotopic measurements.

Position and light-meter data acquired at  $> 3$  Hz.

Temperature and humidity sensor.

Onboard computer.

Integration into project server for post-processing.

Overall, the Scotty is a new tool that allows for more and better measurements than ever before. Data is acquired faster and with more precision.

### Laboratory Investigation

The following describes the work performed within EPRI's Knoxville laboratory to prepare for installation of fixtures in the field. The objectives of the laboratory investigation were to 1) better understand the technology and learn how to effectively and successfully place the fixtures in the field and 2) to ensure selection of quality fixtures, fixtures that would not immediately fail or fail soon after installation.

### Physical Construction

The photographs below show the differences in physical construction from a variety of manufacturers. No two fixtures are the same. Some use many LEDs at low drive current. Others use few LEDs with high drive current. Most use an optic device to focus the light in a specific pattern. One manufacturer uses many LEDs and no optical devices to distribute light. With traditional lighting, it is not easy to determine the manufacturer just by the physical construction of the fixture. With LED fixtures, it is easy to determine the manufacturer.

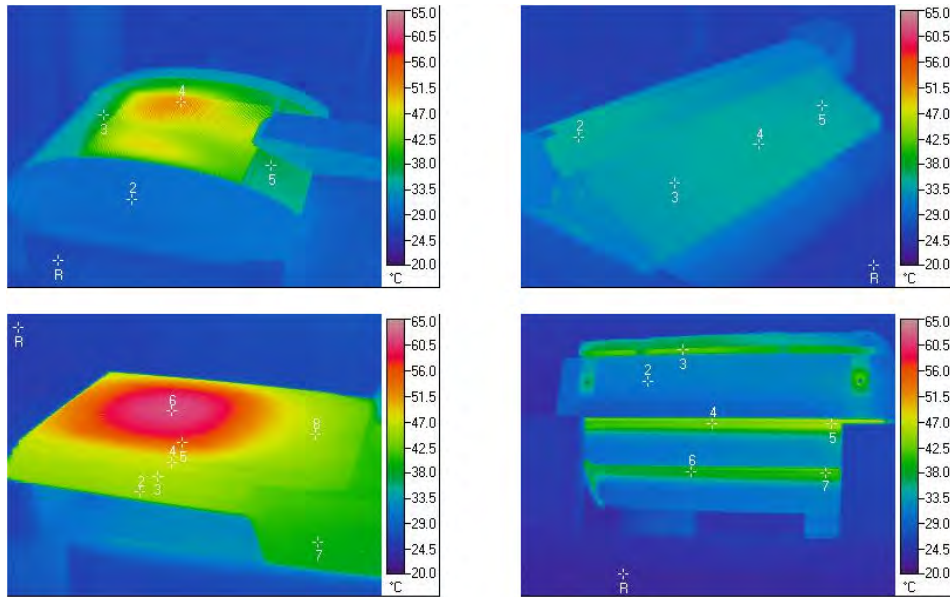


Figure 6-6  
A Wide Variety of Form Factors for LED Fixtures

### Thermal Inspection

A thermal camera was used to profile the temperature of LED fixtures from various manufacturers. The thermal characteristics of LED fixtures are as varied as the form factors. Each manufacturer of LED fixtures has a unique thermal design. Most use the housing of the

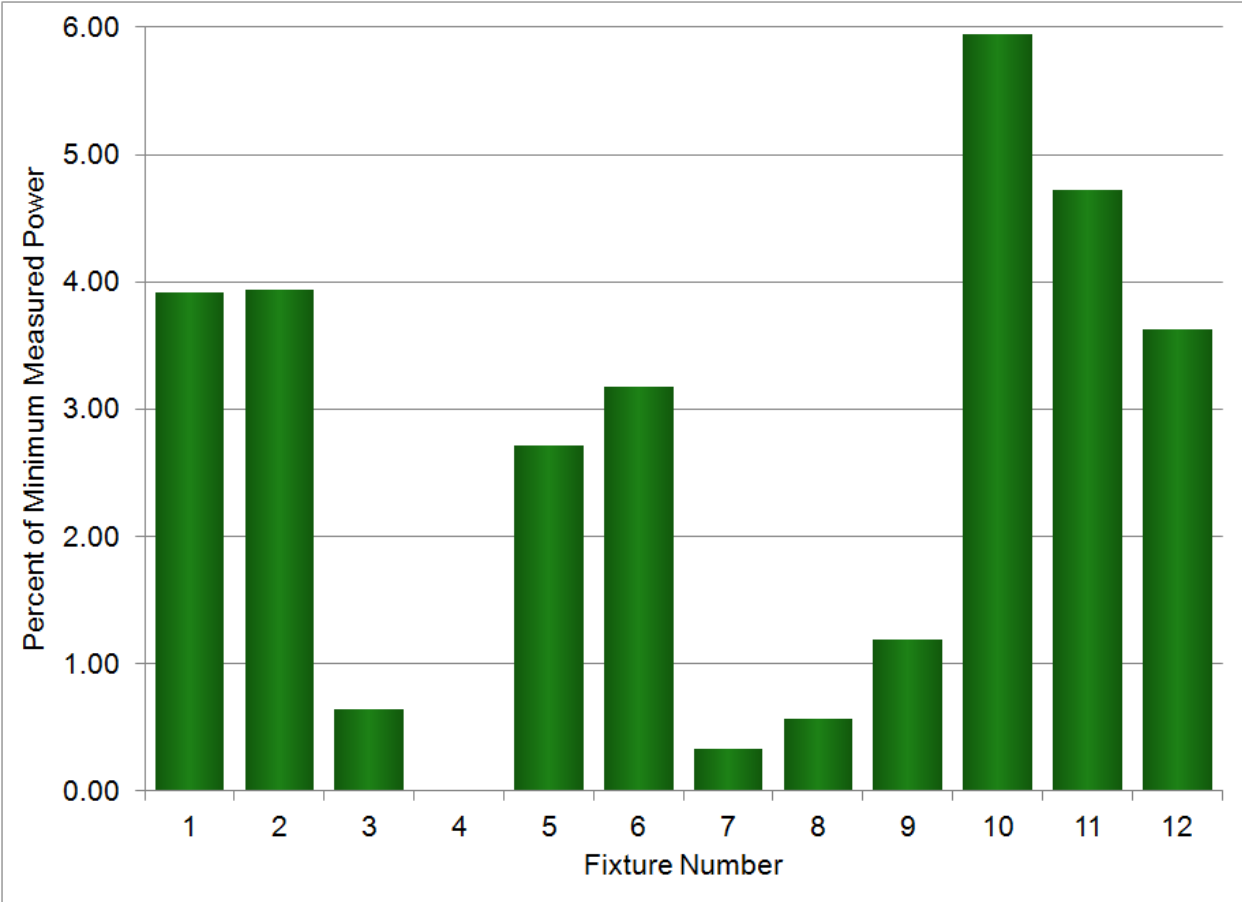
fixture to dissipate the heat generate by the LEDs. Several designs have a housing temperature above that of hot water, meaning that if a lineman were to contact the housing with bare skin, a burn is possible. Standards for the upper limit of housing temperature are needed to ensure safety for repairmen.



**Figure 6-7**  
**Thermal Images Showing Differences in Thermal Management for Four LED Fixtures**

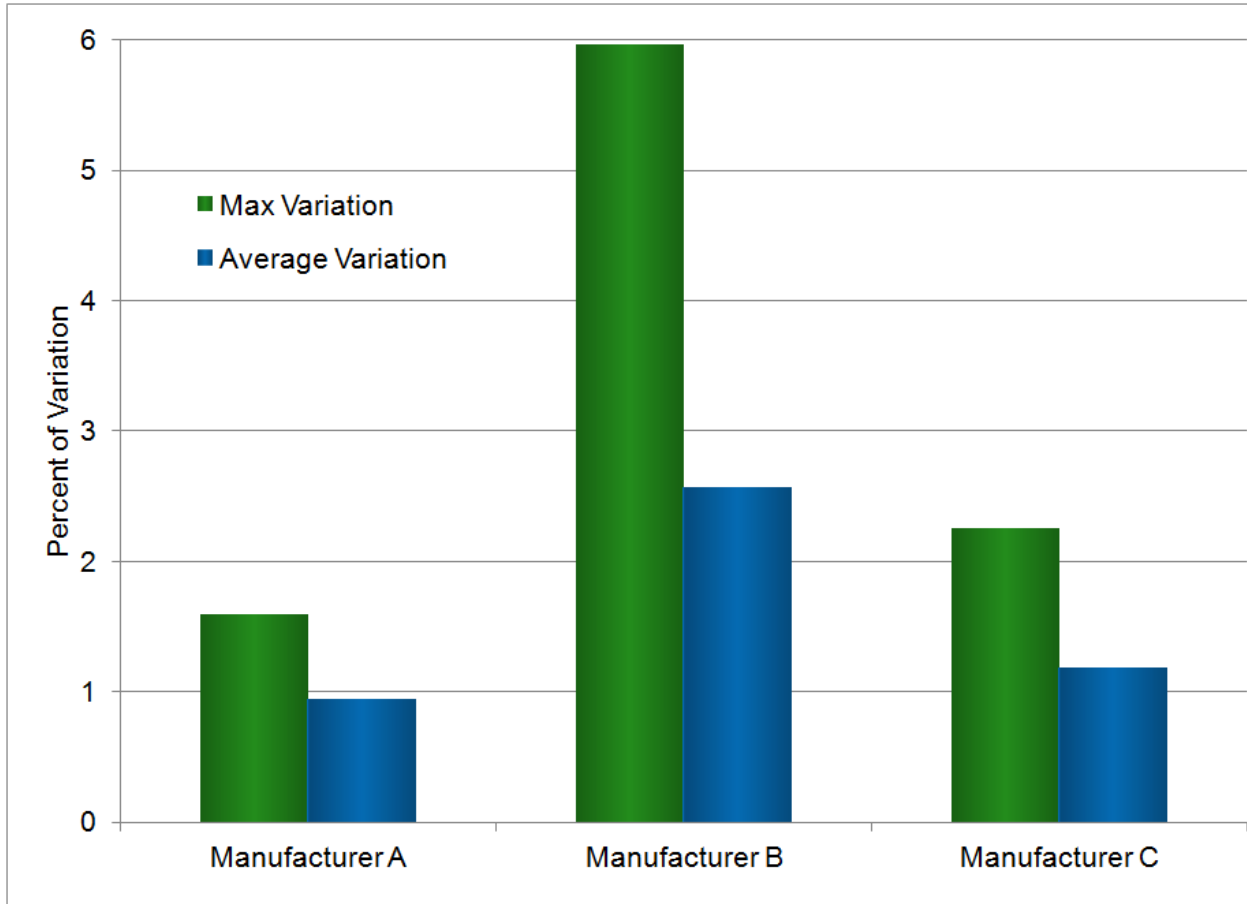
### ***Power Draw (Compared to Data Sheet)***

As shown in Figure 6-8, the measured power consumption of 12 same-model fixtures shows significant variation in manufacturing tolerance. The graph shows the variation from the minimum value. Based on the 12 units received from one manufacturer, the maximum energy consumption peaked at almost 6% higher than the minimum. Because of the variation, overall energy savings will suffer.



**Figure 6-8**  
**Variation in Power Consumption After Warm-Up of Twelve Identical Fixtures**

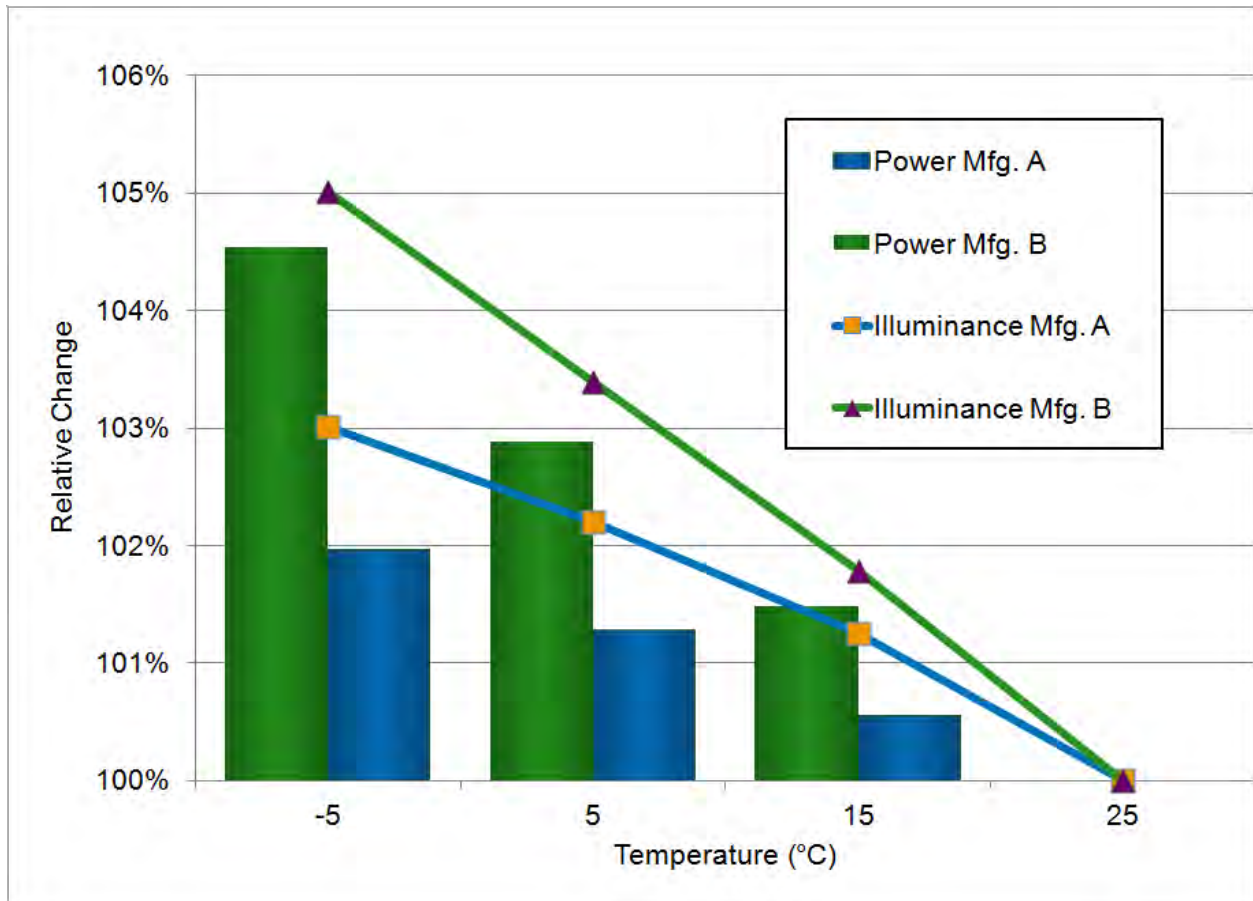
Not all manufacturers are the same. Some variations in power consumption are less than others, as shown in Figure 6-9. The variation stems from variations in the driver efficiency and variations in the manufacturing of the LEDs.



**Figure 6-9**  
**Maximum and Average Variation in Input Power for Three Leading Manufacturers of LED Fixtures**

### ***Thermal Chamber Test***

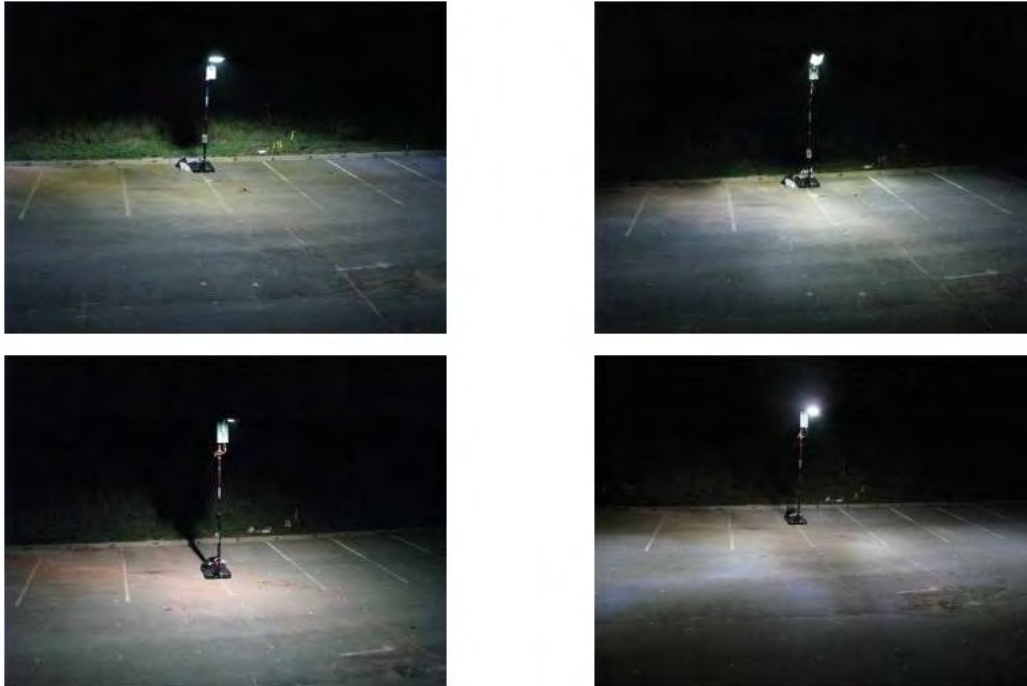
Results of testing in the thermal chamber show a temperature dependence of LED fixtures, as shown in Figure 6-10. This temperature dependence was also present in the field data. LED fixtures use more energy at cooler temperatures than at warmer temperatures, which suggests a negative temperature coefficient. This attribute may have a negative impact on energy efficiency because cooler temperatures typically coincide with longer darkness hours (winter). EPRI suggests that manufacturers include a circuit for temperature compensation (see “Field Data” section for an estimate of possible savings).



**Figure 6-10**  
**Relative Change in Input Power as a Function of Temperature for Two Fixtures from Two Different Manufacturers**

### ***Distribution Pattern***

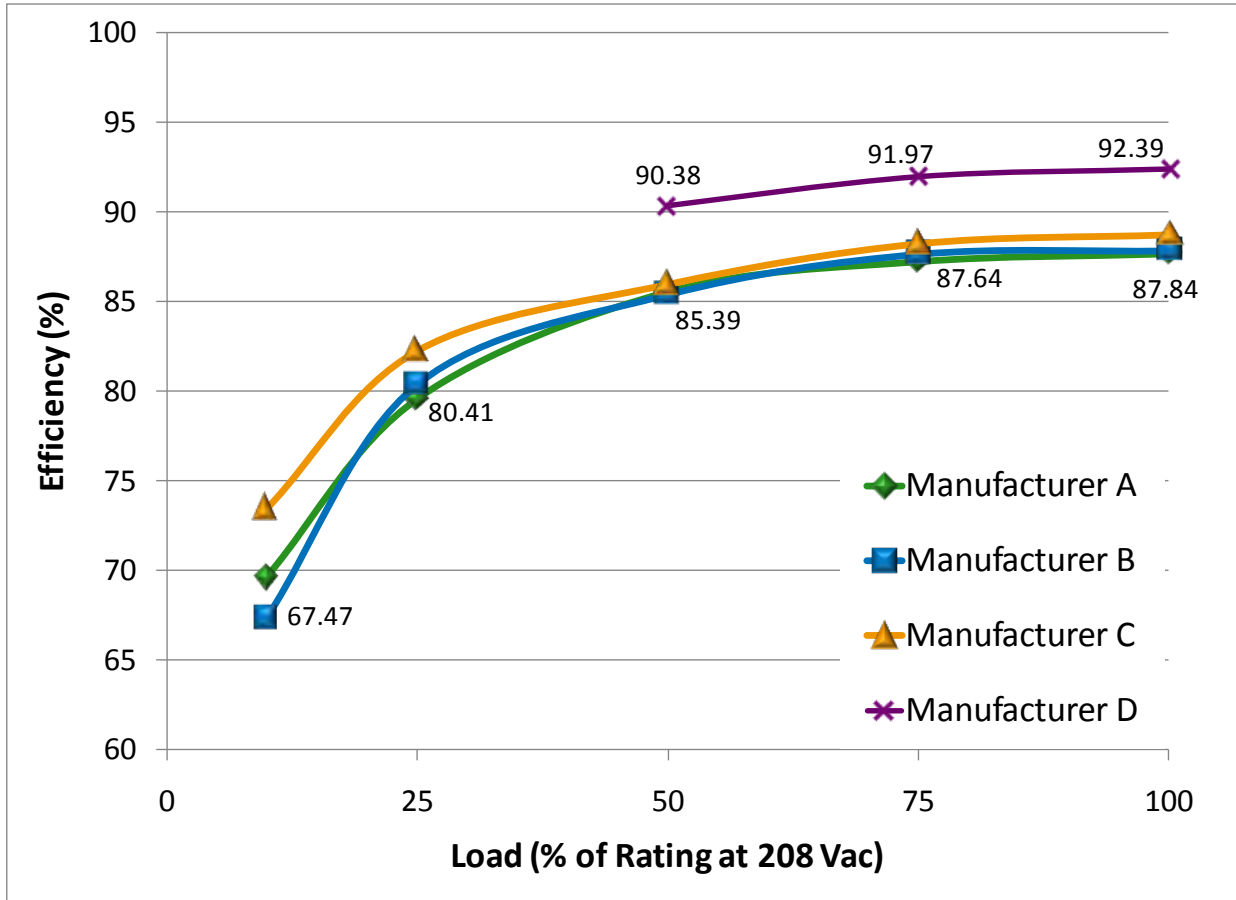
There are two main metrics for light pattern. The first is the overall shape, and the second is the shape of the intensity of the distribution—a flat distribution of light or a peaky (cosine) distribution (bright spot beneath the lamp). As shown in Figure 6-11, these patterns vary among manufacturers. The metric is not possible to tell from the data sheet. Manufacturers need to provide the results of independent photometric tests. The industry is not clear on the advantage or disadvantage of the variation in distribution patterns. As an industry, manufacturers of LED outdoor lighting need to work more to determine whether one is better than another and what applications warrant one over the other.



**Figure 6-11**  
**Variations in Distribution Pattern for Four Different Models of LED Fixtures**

### ***Drivers***

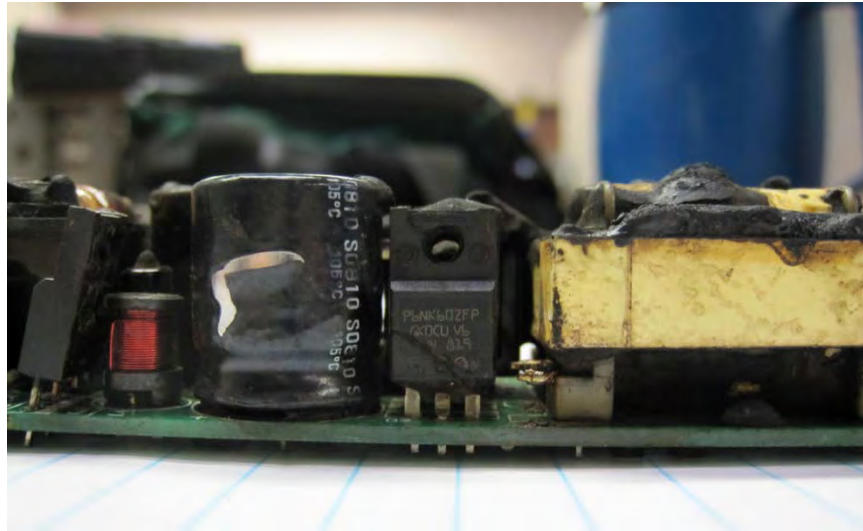
A driver controls the flow of energy to the LEDs and is roughly analogous to a power supply. Laboratory measurements show driver efficiency as an area for significant improvement. While one manufacturer has efficiency above 92%, the rest peak at about 88%, as shown in Figure 6-12. Driver efficiency can be improved by the use of specifications.



**Figure 6-12**  
**Plot of Driver Efficiency (AC In/DC Out) for Four Different LED Drivers**

Laboratory testing also found that the efficiency of the LED fixtures decreased when used on a circuit rated 480 V. Ballasts tested were designed to a maximum voltage of 277 V. For use on 480 V circuits, rather than modify the ballast, manufacturers added an autotransformer to step the voltage down from 480 V to 277 V. The addition of the transformer increased the fixture power consumption by 7.1%.

In addition to efficiency, the reliability of the driver poses a significant risk of failure. Electrolytic capacitors and other components (which are often set in potting material) are common points of failure. For example, Figure 6-13 shows the aftermath of a catastrophic component failure (capacitor, left, and a transistor). The transistor failed most likely because of a void within the potting material that led to overheating. More work is needed by the industry to standardize manufacturing techniques and to create standards that address both the performance and reliability of the driver.



**Figure 6-13**  
**A Failed LED Driver**

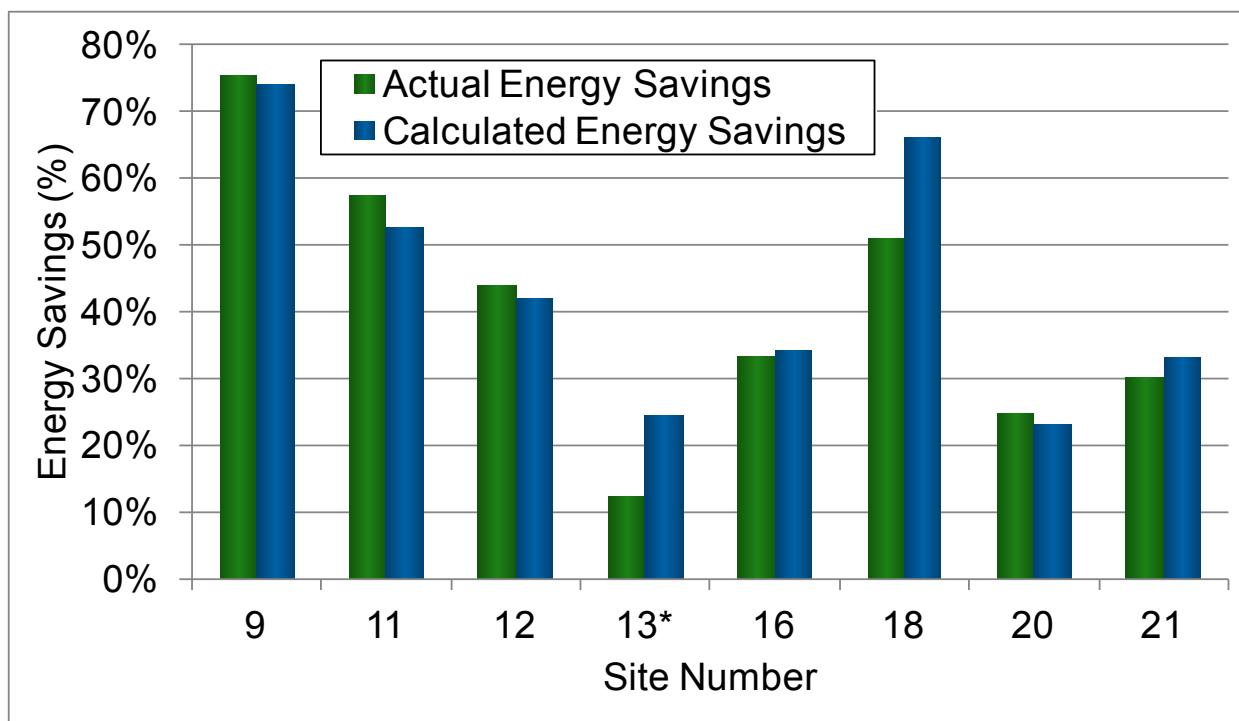
## Field Data

The following provides results from the various field demonstrations of LED fixtures at locations around the country.

The demonstration installed monitors at over 21 sites. It is interesting to note that in spite of best efforts to acquire data, only eight sites had sufficient data to provide a comparison of estimated versus actual energy savings. Field monitoring of street fixtures is not easy. Coordination is required between stake holders, and there is often difficulty separating the electrical circuits. Circuits for street and area lighting are designed for least cost, not to facilitate the connection of measurement instruments. Combined, these obstacles often defeated the best effort to monitor and verify energy savings.

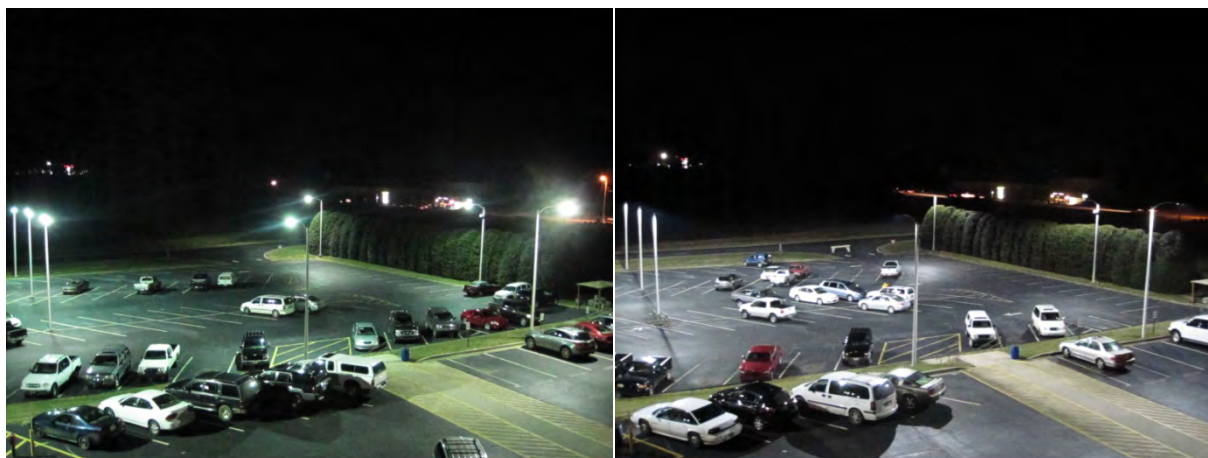
## ***Projected and Actual Savings***

Figure 6-14 shows the results from eight sites with data collected over a one-year period. Figure 6-15 shows the results of retrofitting a parking lot with LED fixtures: less up-light, more even distribution, and higher color temperature. The projected energy savings in all cases indicates that energy savings are possible. The savings ranged from 25% to over 70%. The reasons for the variation are many and include factors such as over-lighting and different types of control technology. The most critical factor appears to be the ability to right-size the lighting to the application and prevent the illumination of areas that do not require illumination, which is possible given the control provided by LED technology.



\*Site 13 uses estimated usage values for actual energy savings. The other sites use an initial measurement from the first site visit.

**Figure 6-14**  
Plot of Projected and Actual Savings for Eight LED Demonstration Sites



**Figure 6-15**  
Before (Left) and After Photographs Demonstrating Less Up-Light, More Even Distribution, and Higher Color Temperature Afforded by LED Fixtures

Site eleven is unique because the location of the light sensor was moved after the control fixtures were removed. The original location was very poor, resulting in the lights not properly turning on and off concurrently with the hours of darkness (see Figure 6-18). After installation of the LED fixtures, the sensor was moved to the top of the building, and the energy performance significantly improved.

The following three charts (Figure 6-15, Figure 6-16, and Figure 6-17) show the energy use over one year for three different sites. Because the control was only monitored for a short period of time the energy use of the control was projected (extrapolated) for the remainder of the year. The projected treatment show in the charts is based on the calculations performed during the design and takes into account the geographically corrected number of darkness hours.

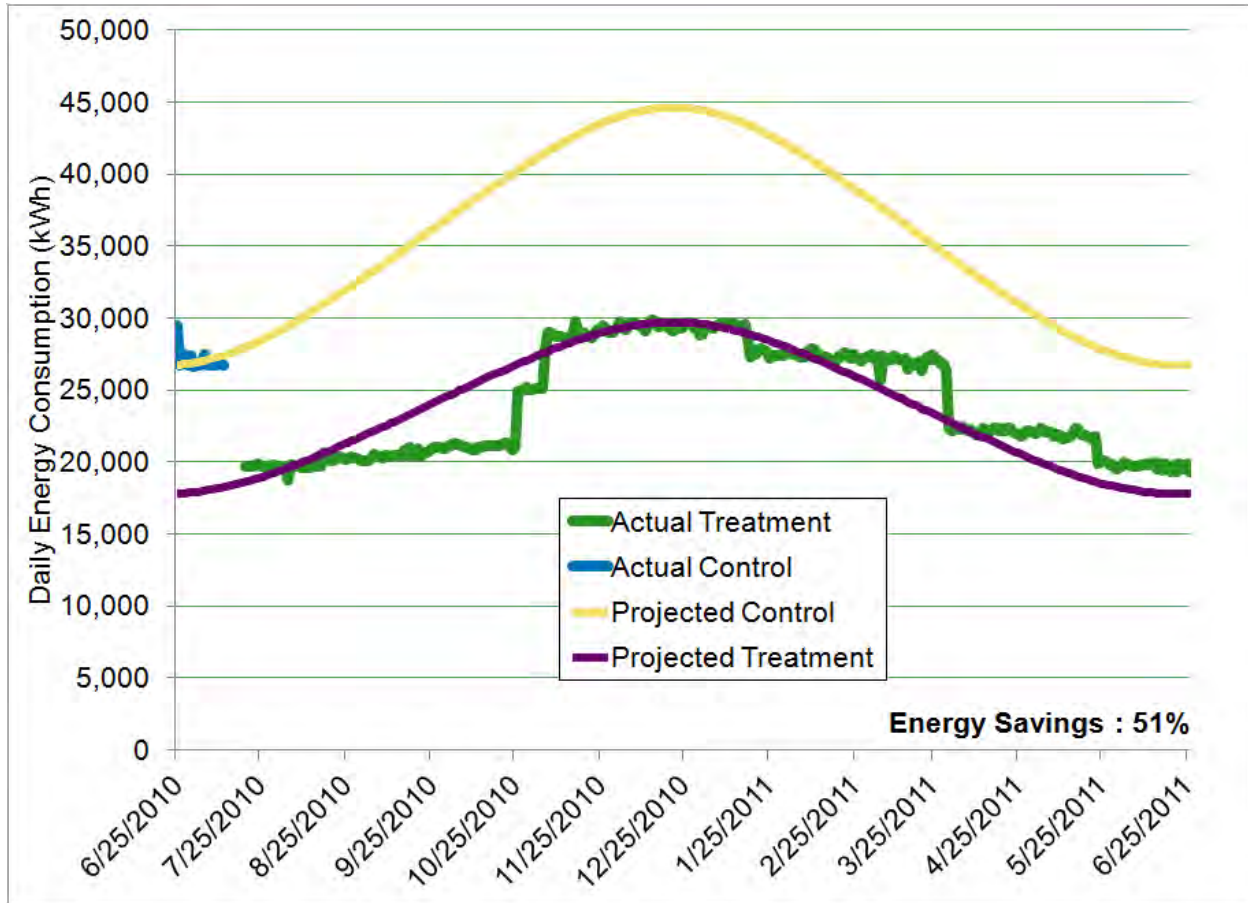


Figure 6-16  
Daily Energy Consumption over One Year at Site 16

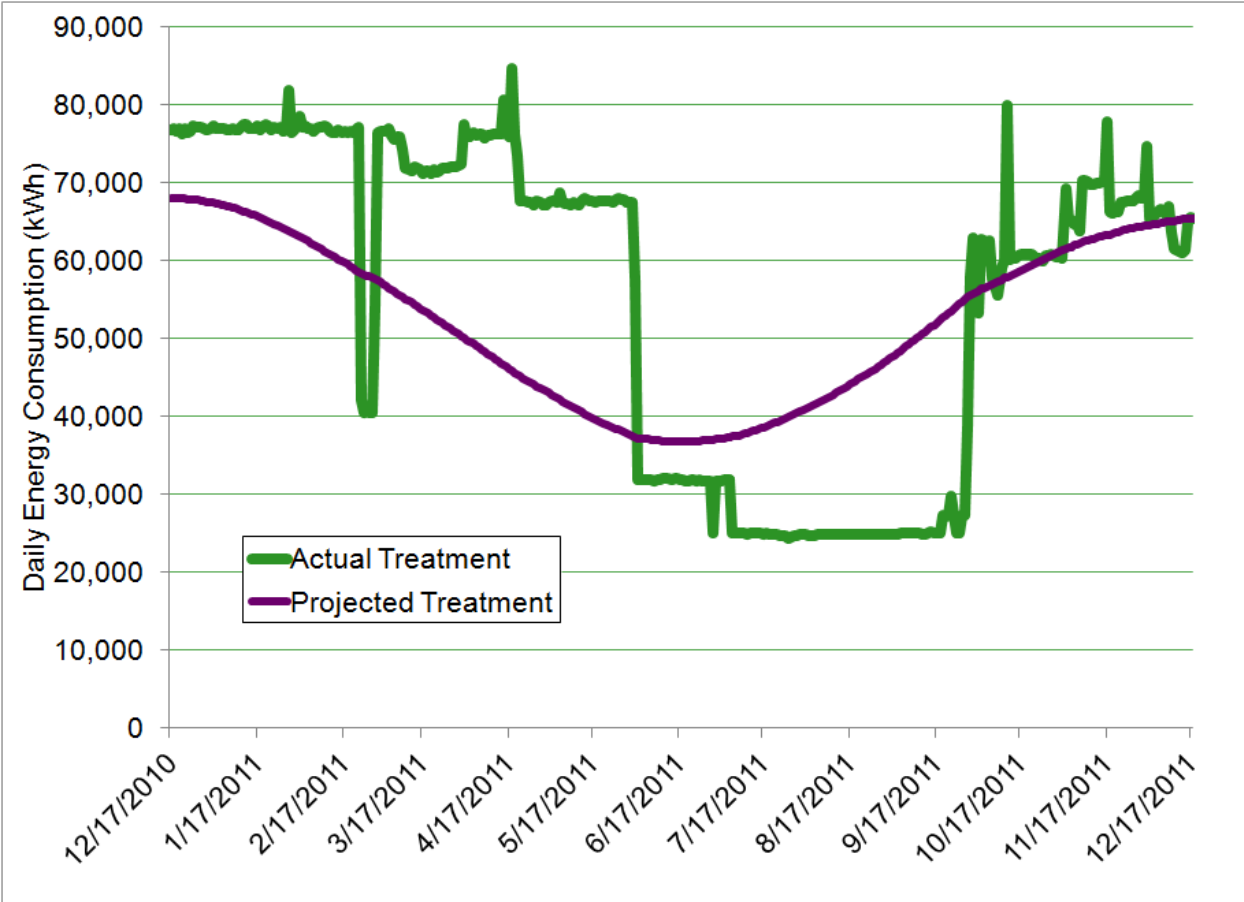
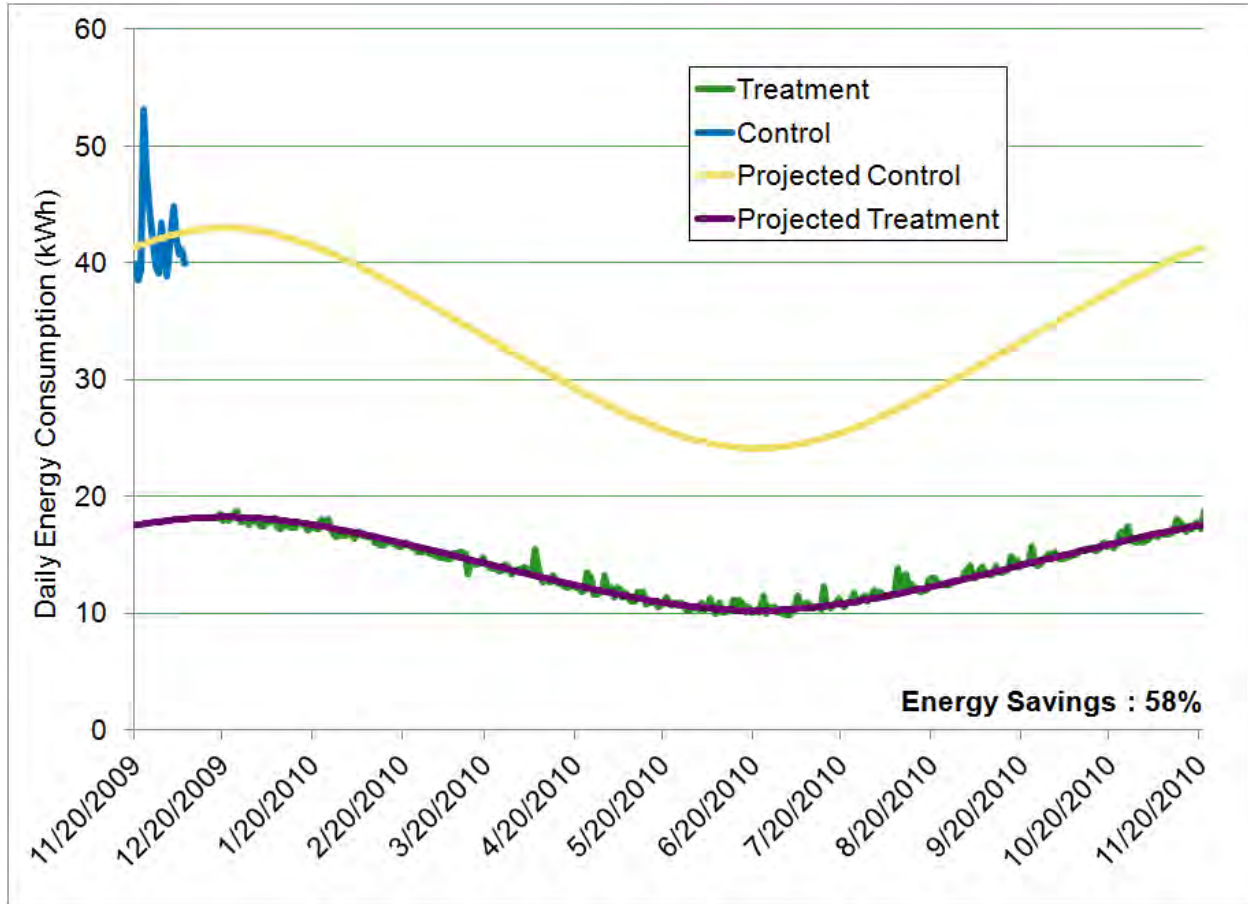


Figure 6-17  
Daily Energy Consumption over One Year at Site 23

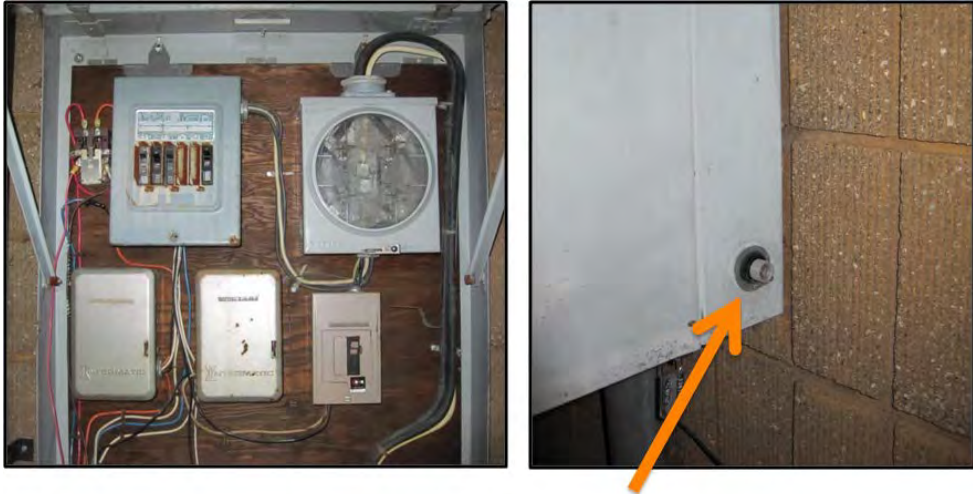


**Figure 6-18**  
**Daily Energy Consumption over One Year at Site 11**

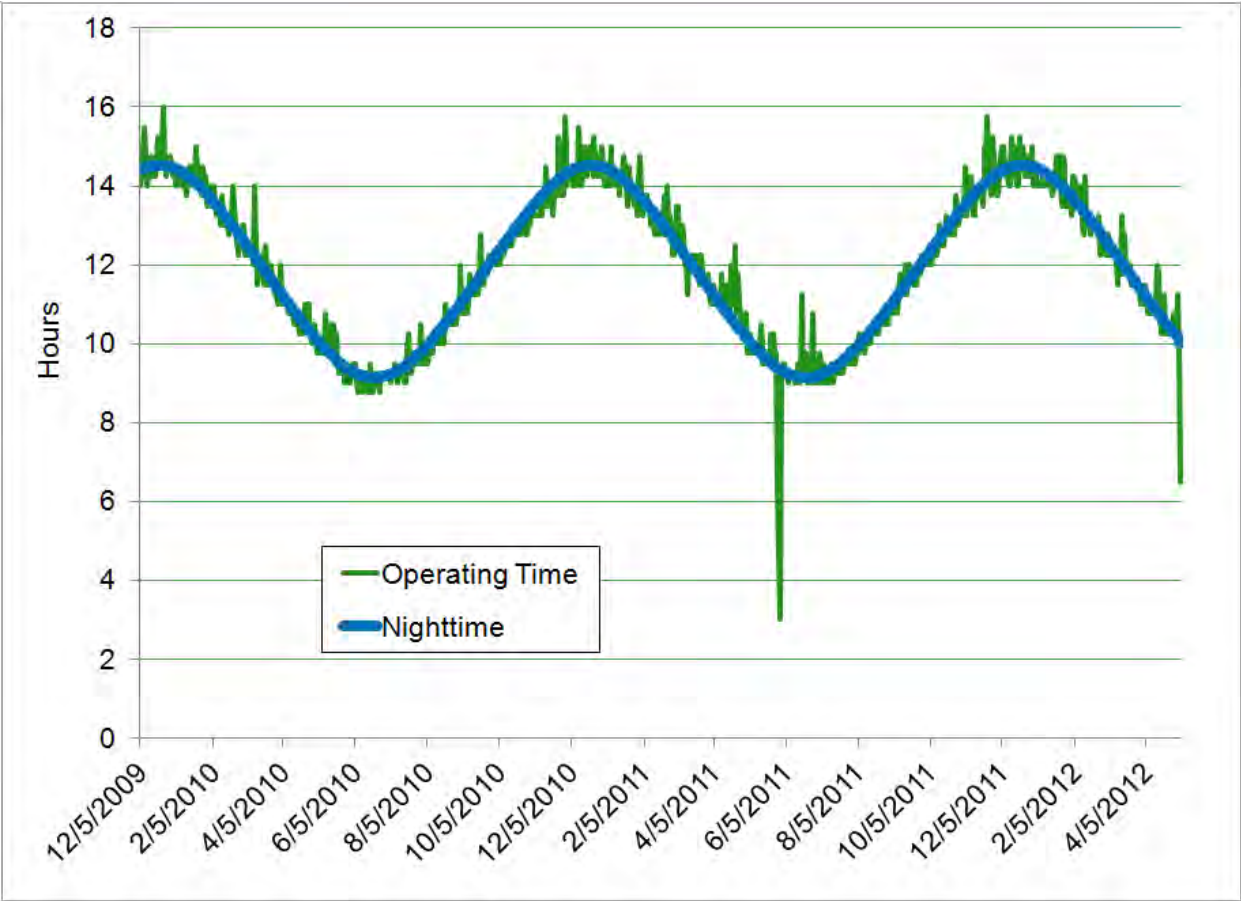
### Lighting Control

While the lighting technology is important to energy use, the field data also showed the importance of the technology use to turn the lights on and off, which varied by site. Some sites used photocells, while some used computers. In the case of photocells, the location of the photocell is important. Figure 6-18 shows a poor placement of a photocell and in Figure 6-17 (control) and Figure 6-20 the corresponding poor correlation between operation time and hours of darkness. In general, photocells should be placed with clear access to the sky; ideally above the top of buildings and above or away from trees, which can cast shadows and increase energy consumption by turning on the lights before sunset. In Figure 6-17 (treatment) the performance improves after the photocell was moved to a better location). Figure 6-19 shows the ideal configuration, where the operational time of the lighting closely matches the hours of darkness.

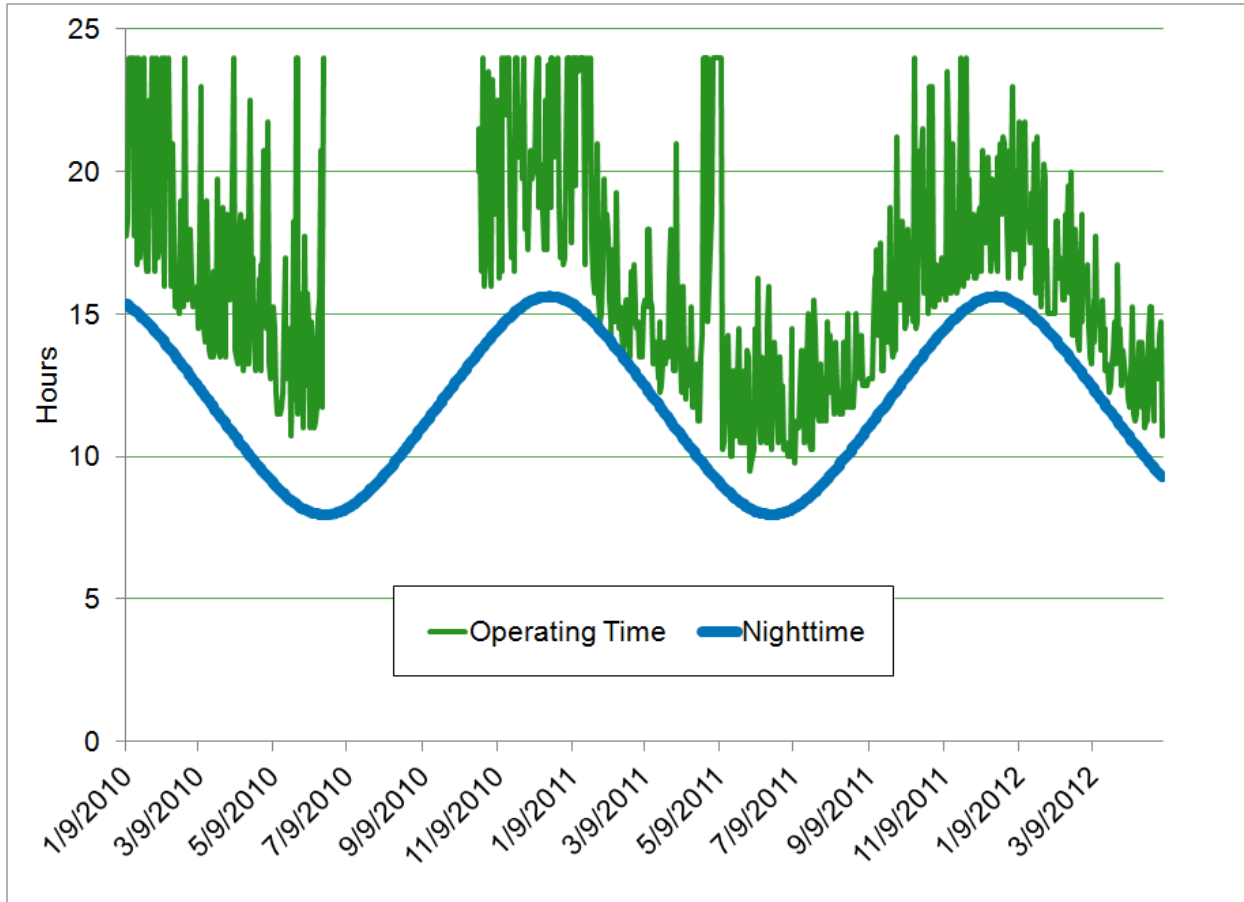
The field data shows that computer control is problematic as well (see Figure 6-21). Typically the data showed a failure for the computer to automatically adjust to changing hours of darkness. Instead, control of on/off time seemed manually set by facility personal, who, it is surmised, often forgot or were delayed.



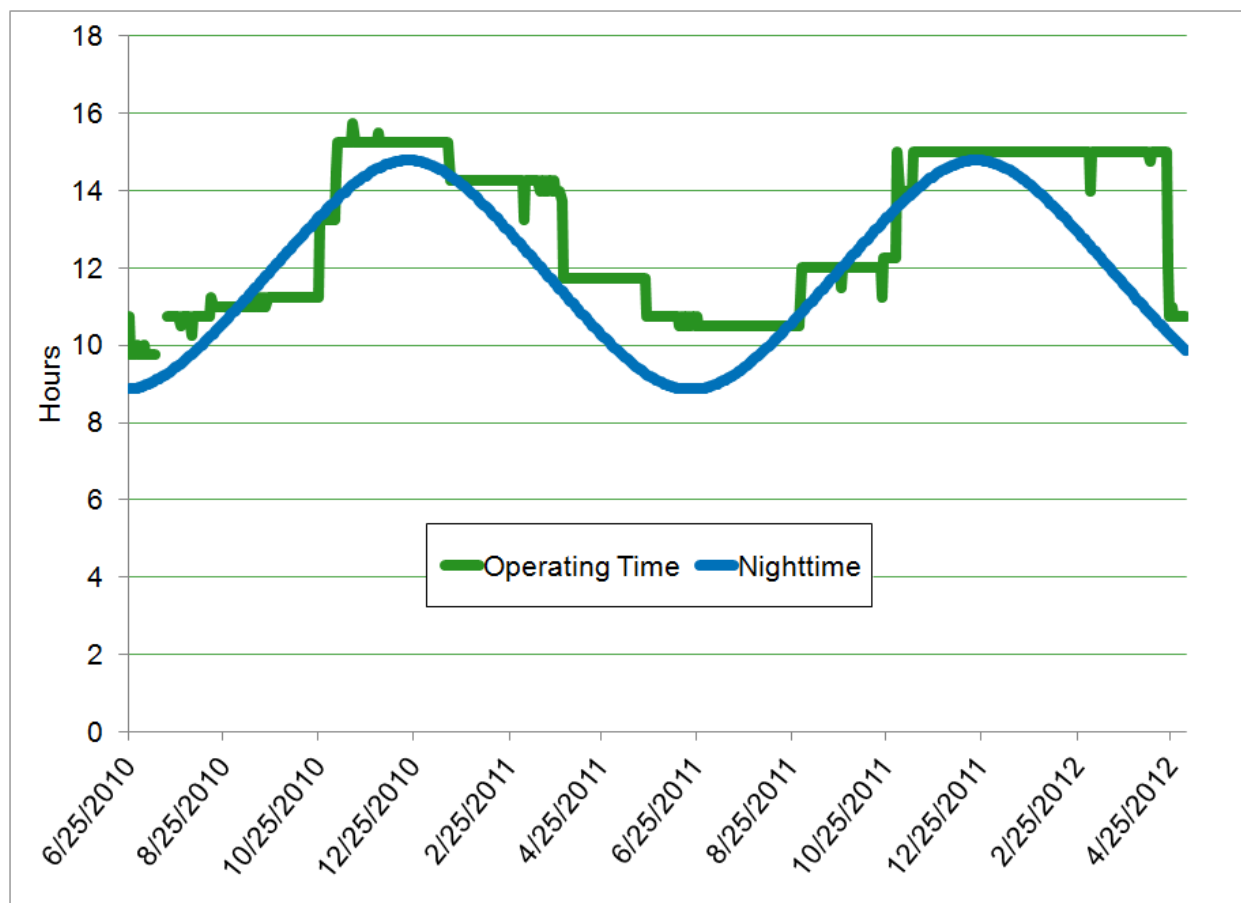
**Figure 6-19**  
**Poor Placement of a Photocell at a Demonstration Site**



**Figure 6-20**  
**A Plot of Darkness Hours and the Amount of Time That the Lights Were Energized Over Several Years for Site 12**

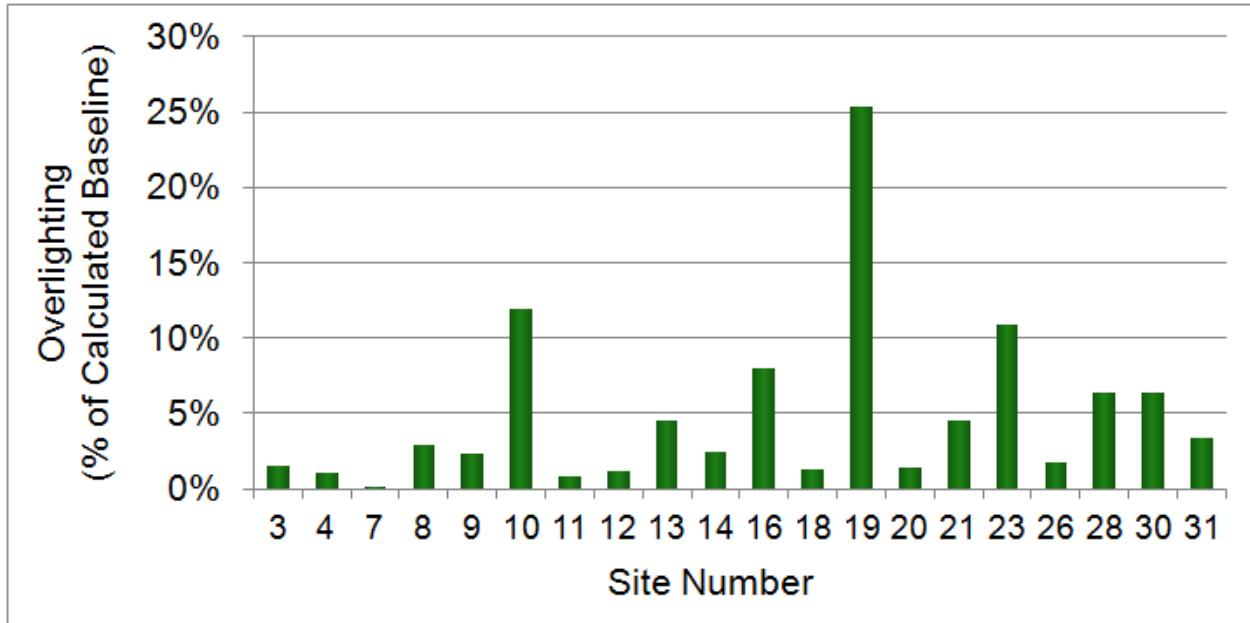


**Figure 6-21**  
**A Plot of Darkness Hours and the Amount of Time That the Lights Were Energized Over Several Years for Site 19**

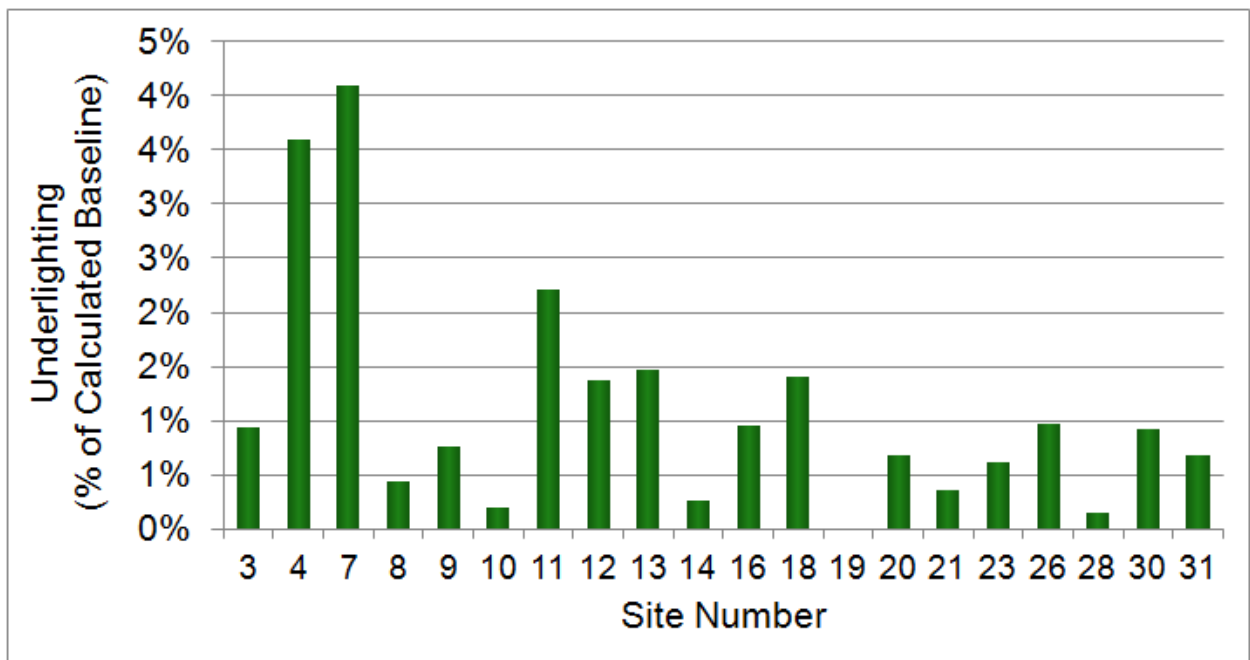


**Figure 6-22**  
**A Plot of Darkness Hours and the Amount of Time That the Lights Were Energized Over Several Years for Site 16**

Why are the turn-on and turn-off times important? For sites that poorly track the darkness hours, some days the lights are on less—some days more. The days when the light are on less than the actual hours of darkness represent times of increased potential liability, such as someone tripping in an under-lit parking lot. The control of the lighting could create these types of issues, and the building owner or utility could be potentially liable. In the case when the light is on longer than actual darkness, energy is wasted. Figure 6-22 shows the percent of over-lighting (energy loss) for several sites. Figure 6-23 shows the percent of under-lighting for several sites.



**Figure 6-23**  
Over-Lighting Among Sites, Indicating the Potential for Energy Savings If the Location of the Control Sensor Is Improved

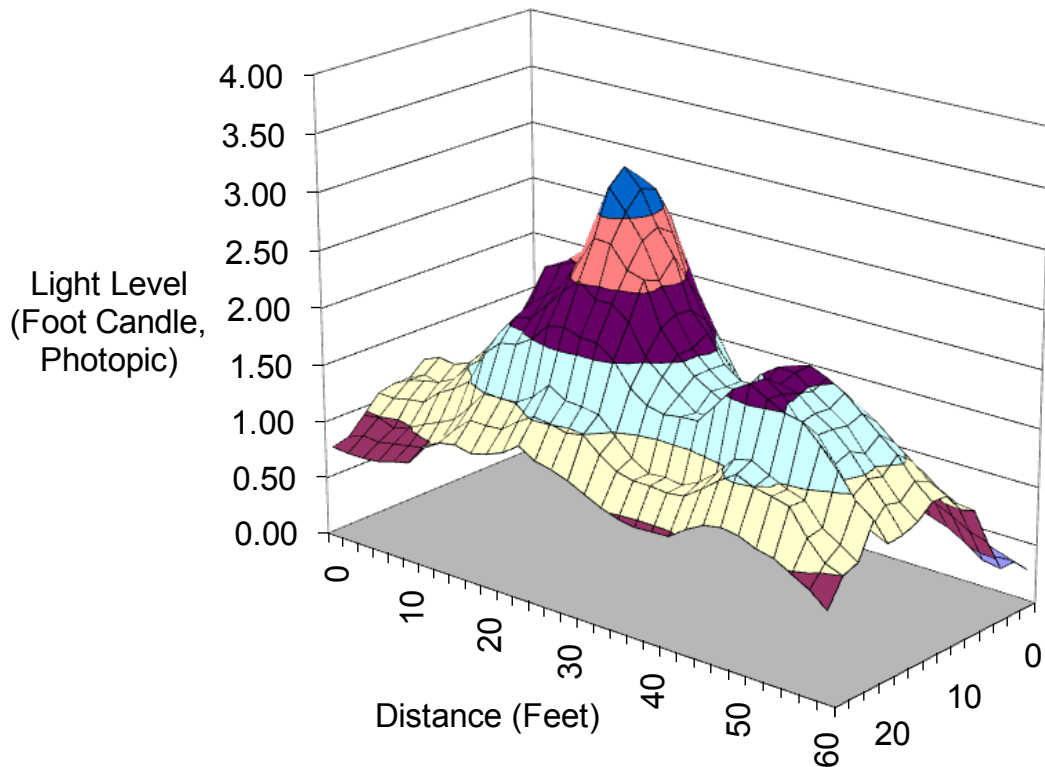


**Figure 6-24**  
Under-Lighting Among Sites, Indicating the Potential for Liability Issues and Artificial Energy Savings

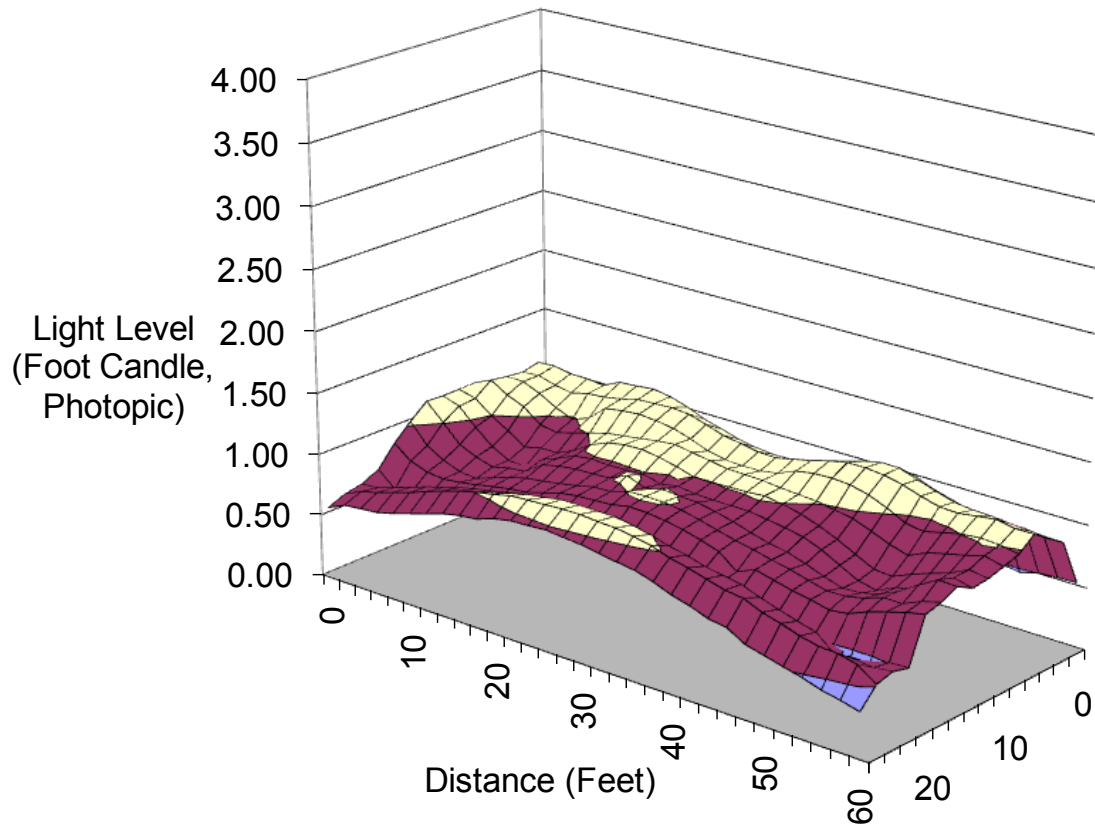
### **Defined Area Efficacy**

Use of the Scotty allows for a unique view of the light produced by the fixtures. Figure 6-24 and Figure 6-25 show 3D orthogonal plots of data from the Scotty, which measured light under fixtures on a 30-by-60-foot grid with a grid spacing of 2 feet. The light levels—given in photopic

foot candles—show a dramatic difference between the control fixture and treatment fixture. The control technology has a peaky distribution, while the treatment has a flat distribution. Integrating the light level allows a calculation of *defined area efficacy*. In this case, even though the data sheet for the treatment indicates fewer lumens per watt, the actual application efficacy, as measured by the Scotty, indicates that the LED fixture has more effective lumens per watt than the control, about 5% more. This is due to the more efficient use of light in the application—less light lost in the fixture reflector and better placement of light. Interestingly, not all LED fixtures are designed for the efficient flat distribution. Some of the demonstrations sites used LED fixtures with a peaky distribution. A distribution pattern for an induction fixture is shown in Appendix C.



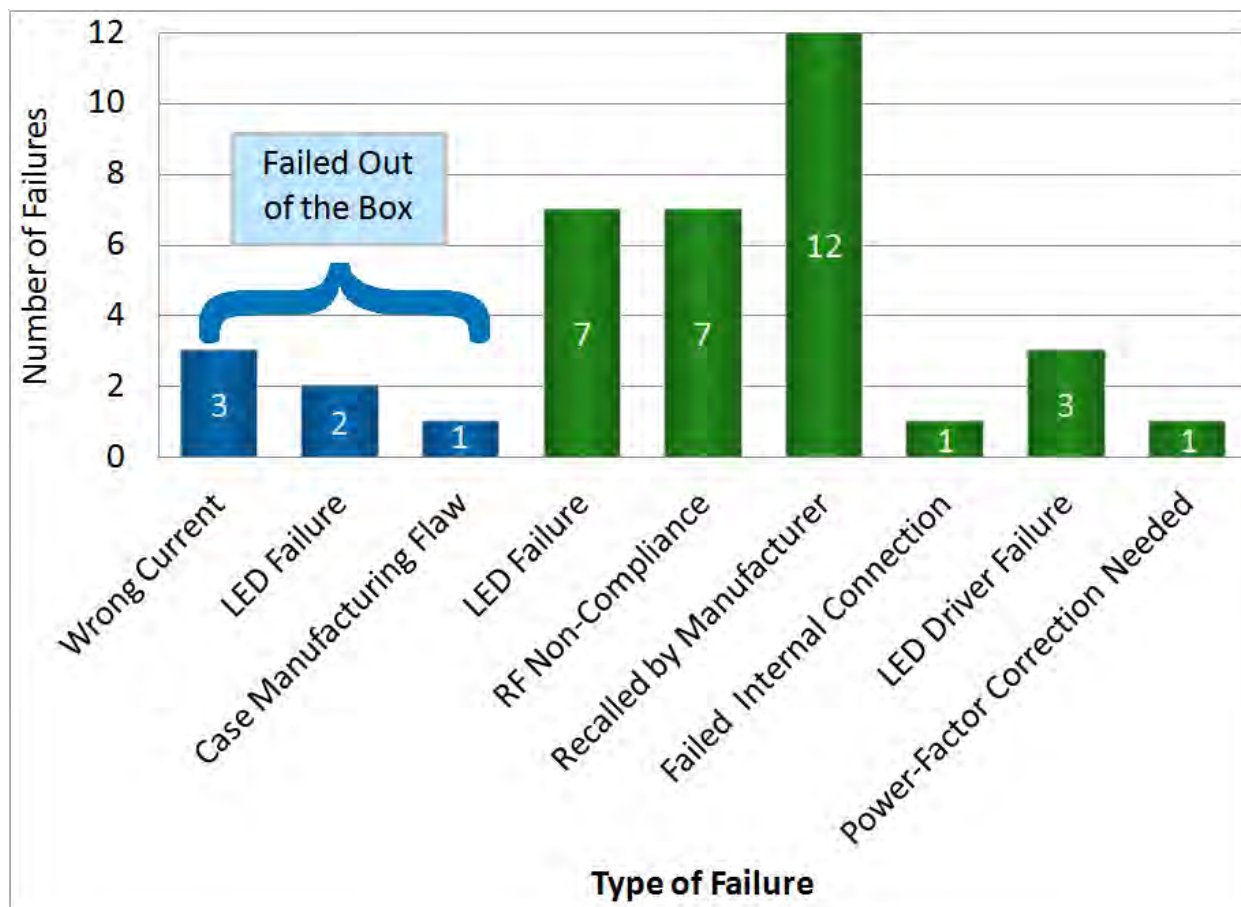
**Figure 6-25**  
**Light Levels Produced by an HID Control Fixture**



**Figure 6-26**  
**Light Levels Produced by an LED Treatment Fixture (Same Location as Control).**

### **Reliability**

Figure 6-26 shows the number of failures by type for all failures observed both out of the box and in the field. Overall, the demonstration experienced a 15% failure rate. Two and a half percent were out of the box, and 12% were in the field. The total number of samples was 239.



**Figure 6-27**  
**LED Failures, Both Out of the Box (Blue) and in the Field for the LED Energy Efficiency Demonstration**

The type of failure had considerable variation—everything from poor manufacturing to failure of LEDs. Note that given the limited number of samples and variety of manufacturers, the percentage given is not statistically significant. However, the point is that LED technologies, like all technologies, are not immune to failures. As the industry evolves, manufacturers will need to improve on the reliability of the product.

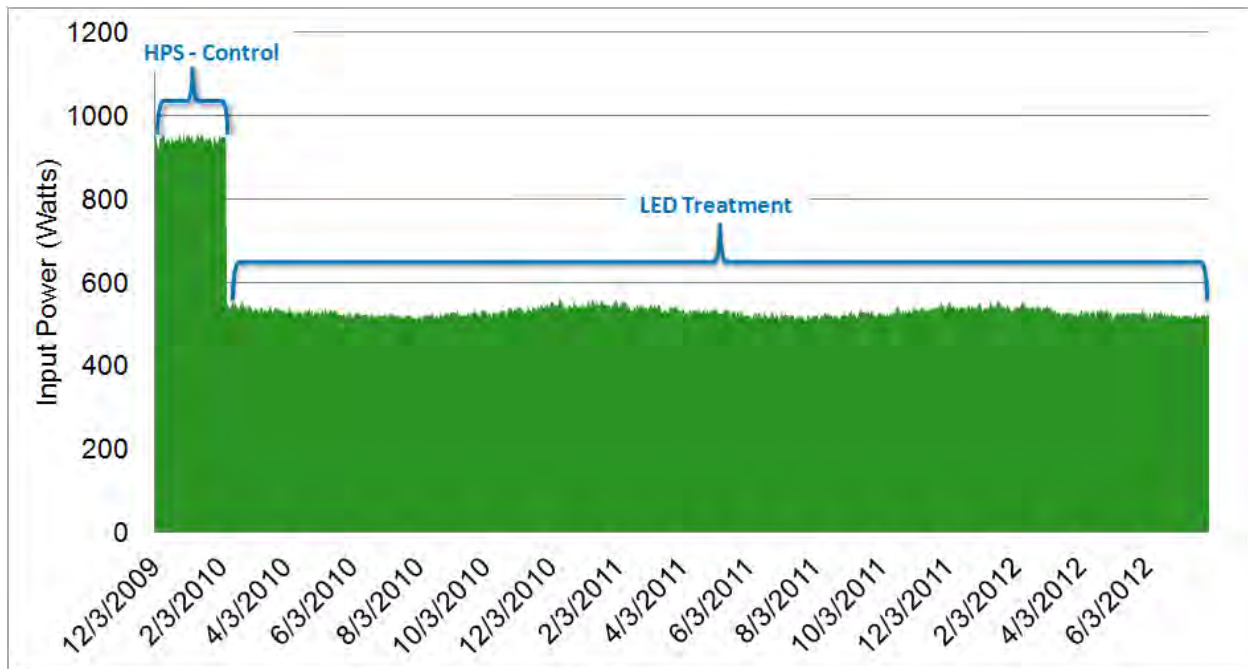
Because of the use of power electronics and laboratory testing, researchers expected to see a sizeable number of field failures due to electrical transients such as lightning and capacitor switching, but the number of failures in the field was insignificant. Inspection of the LED fixtures indicated that most manufacturers include a surge protection device (SPD), typically metal oxide varistors (MOVs), to protect against transient voltage and thus prevent failures from transients. Nevertheless, the researchers still consider the LED fixtures susceptible to electrical transients and caution that a large number of failures could occur in areas prone to lightning depending on the design of the LED fixture and the severity of the lightning. In the case of lightning protection more is not necessarily better and the knowledge base of how to protect sensitive electronics such as the driver circuit within the LED-based fixture while connected to the distribution system is not well established and standards are evolving.

Also of note is that some manufacturers do not consider the failure of one individual LED a failure. Rather, up to three LEDs must fail before qualifying for a warranty repair or replacement.

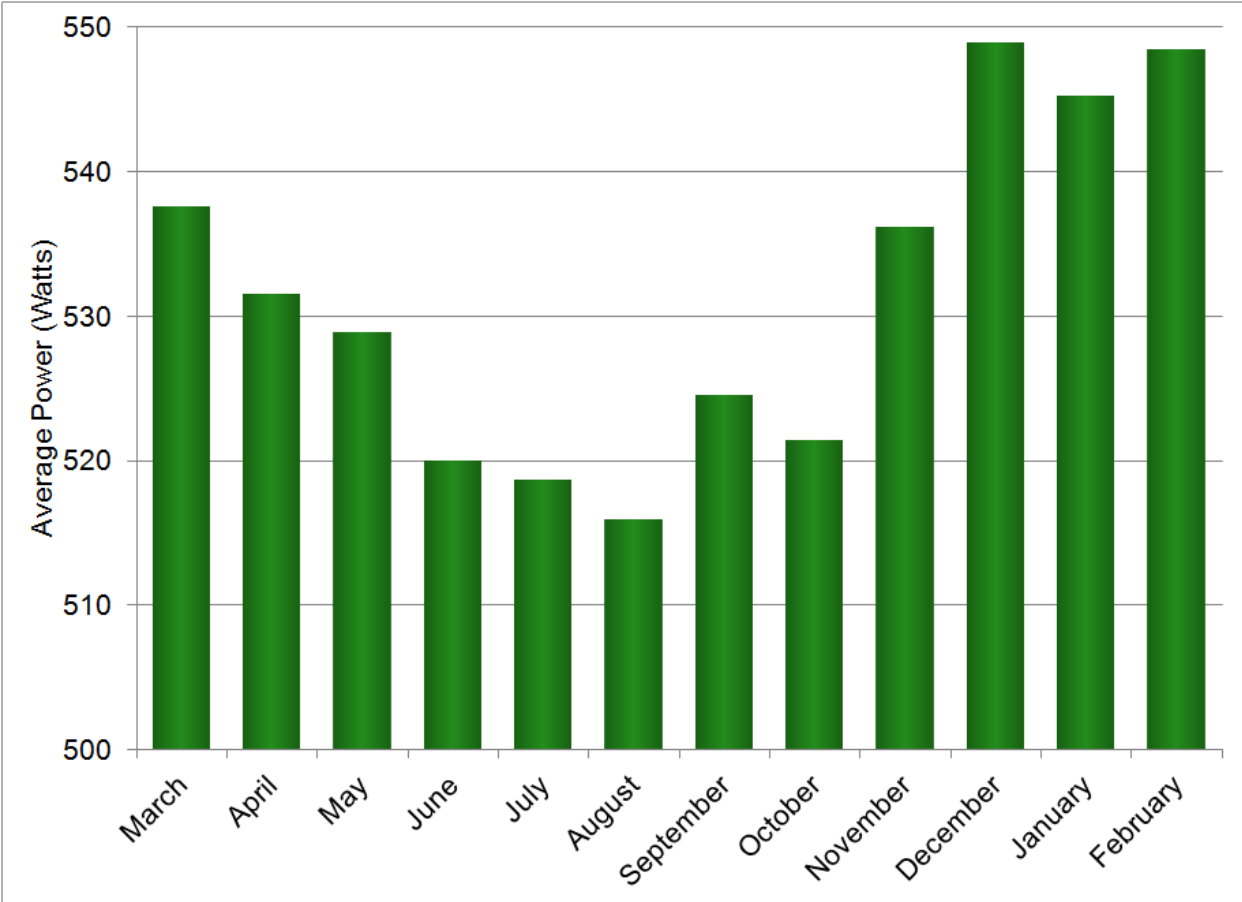
### Temperature

Both the laboratory and field data indicate that LED performance depends on ambient temperature. Most manufacturers' published ratings of LEDs are for an operating temperature of 25°C (77°F). EPRI data suggests that LED light output actually increases at colder temperatures. This indicates a negative coefficient of temperature for the forward voltage. Forward voltage describes a characteristic of the LED (the diode junction) that varies as a function of the current through the LED. As temperature increases, the forward voltage decreases. If the drive current is a constant, the power to the fixtures decreases.

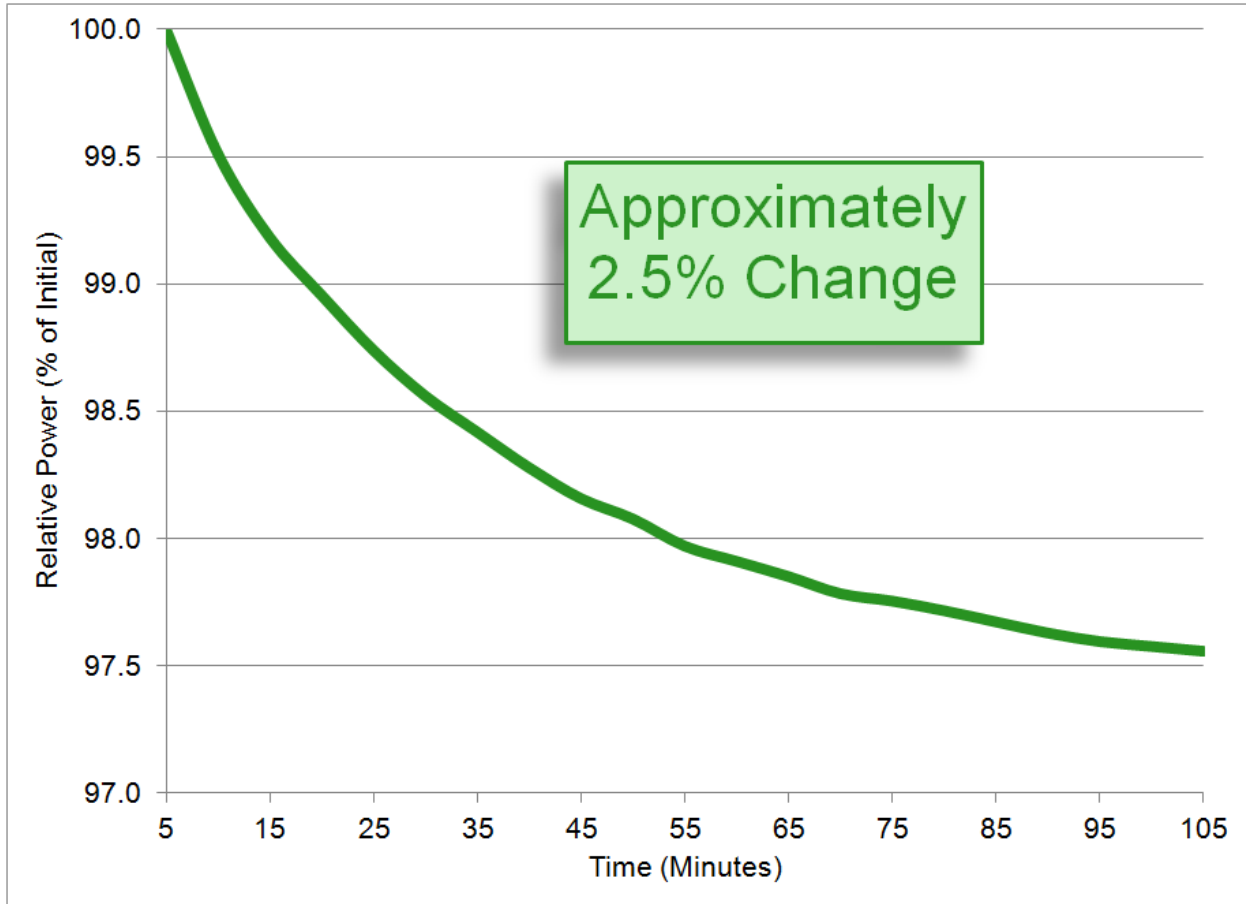
Figure 6-27 shows the variation in power to a site over many months. The plot shows the initial decrease in energy consumption with the installation of treatment lights and the effect of temperature on the treatment fixtures. Note the difference in power by comparing the summer months to winter months. Figure 6-28 is a plot of average watts by month for a site in the Midwest. Power decreases during summer months and increases during winter months. This temperature effect was verified in the laboratory. Figure 6-29 shows that the specific fixture under test exhibited a 2.5% decrease in input power until its temperature stabilized, while the ambient temperature was held constant. More than an hour was needed to stabilize the fixture.



**Figure 6-28**  
**Input Power to a Demonstration Circuit Over Several Months**



**Figure 6-29**  
**Average Power per Month for a Demonstration Site in the Midwest Showing Temperature Dependence of Power**



**Figure 6-30**  
**Laboratory Data Showing Warm-Up Time for a Fixture**

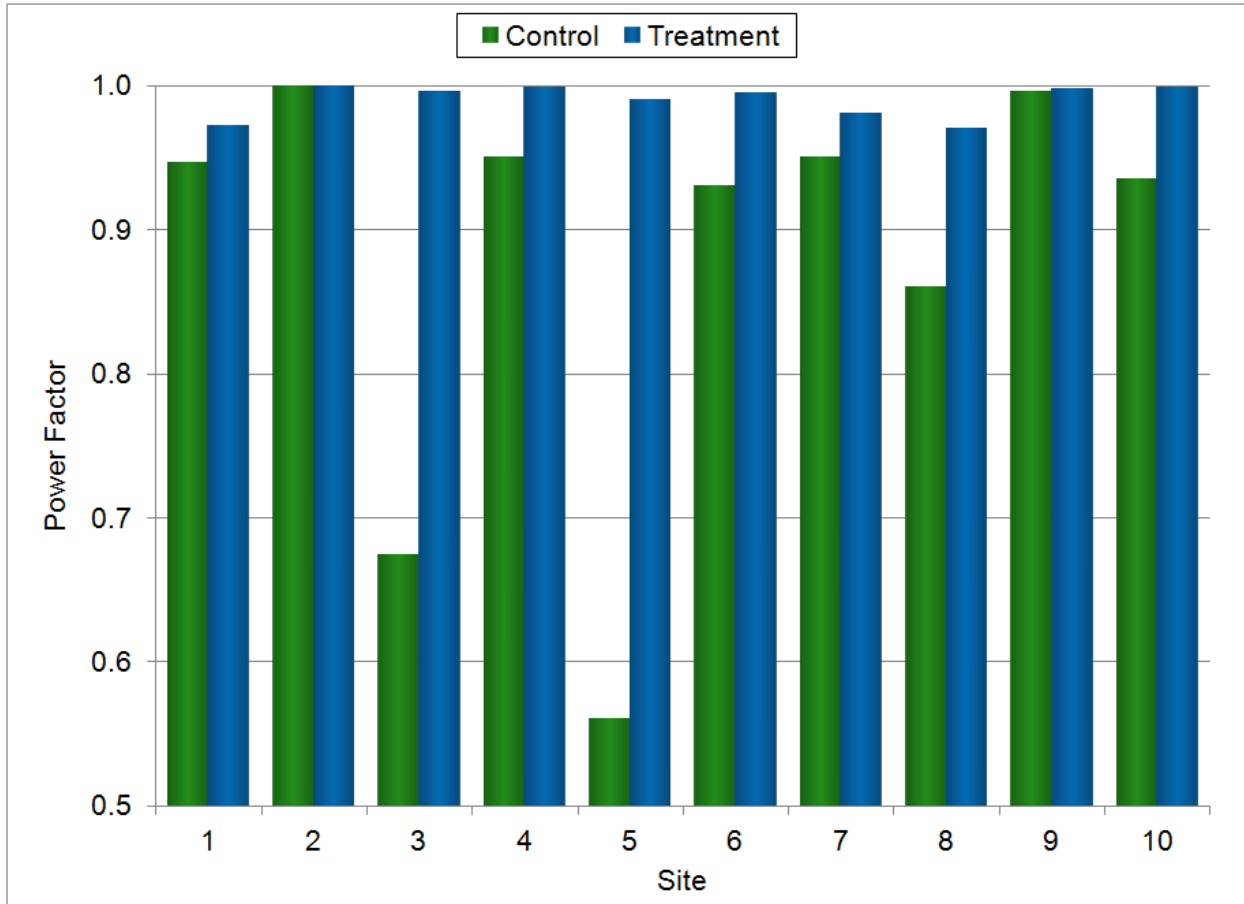
Figure 6-30 shows the percentage gain in energy savings if manufacturers were to include a temperature-compensation circuit. A temperature-compensation circuit is designed to send a control signal to the driver that automatically adjusts the LED current to maintain constant input power.



**Figure 6-31**  
**The Potential Savings Possible Through Use of a Temperature-Compensation Circuit**

**Power Factor**

Figure 6-31 shows the power factor for ten sites, both before installation of the LED fixtures (control) and after (treatment). The results clearly show that LED offers good power factor, with all fixtures at the sites offering high power factor.



**Figure 6-32**  
**Power Factor for Ten Sites (Control and Treatment)**

### **Radio Interference**

The driver circuit within the LED-based fixtures at one site generated enough radio frequency interference to upset a homeowner enough to report the installation of the LED fixtures to the Federal Communication Commission. In response, EPRI researchers determined the LED-based fixtures as the source of the interference and remedied the problem by modifying the installed fixtures by adding suppression devices (ferrite cores). Around the same time visual inspection of fixtures received by other manufacturers showed that some manufactures had begun to include devices that suppress radio emissions within their products. Nevertheless, the researchers still consider the LED fixtures as possible sources of both electromagnetic and radio frequency interference and acknowledge that the interaction between the fixtures and the distribution circuit remains not well known and therefore the design of the solutions may not work.

### **Labeling**

Most utilities place a sticker beneath a fixture to indicate the bulb wattage, usually dropping the least significant digit. For example, a “20” on the bottom of a fixture will indicate a 200-watt lamp. A new way of identifying fixture wattage from the ground is needed. The new ANSI standard C136.15, released in 2011, addresses the issue and provides a simple, uniform method for identifying the type and wattage rating of fixtures used for roadway and area lighting. Types

include high-intensity discharge, fluorescent, compact fluorescent, LED/solid-state lighting, induction, and plasma technologies.



**Figure 6-33**  
**A Traditional Cobrahead Showing Location of Identifying Label**

## **Survey**

The measurement of customer satisfaction with LED street and area lighting took two forms. First, online and print-formatted field evaluation surveys were distributed via the utilities to individuals who frequented the demonstration sites (referred to as “field evaluation respondents” below). This survey implemented a 10-point rating scale for evaluating the quality and adequacy of the lighting, night-time safety of the area, and general opinion of the area. On this scale, higher scores represented more favorable ratings, with 1 representing a “poor” rating and 10 representing “excellent.” Additionally, open-ended questions allowed respondents to provide feedback and comments about the Demonstration’s LED lighting.

The second measurement tool involved a detailed questionnaire submitted to utility representatives, on-site technicians, and facility managers at the Demonstration locations (referred to as “technical respondents” below). This instrument consisted of open-ended questions to collect detailed performance, reliability, and satisfaction input from individuals who interacted with or observed the technology from a technical or functional standpoint. Information obtained from both surveys is discussed in detail below.

## **Overall Satisfaction**

Overall, technical respondents were satisfied with the technology and indicated that they had received positive feedback from other individuals. Facility managers at the participating sites seemed to find the demonstration fixtures attractive. These respondents indicated that they appreciated the superior color rendition provided by the LEDs.

In general, LEDs were observed by both field evaluation and technical respondents to deliver noticeably brighter, more evenly distributed light at ground level. While some individuals felt

that it took some time to get used to the different type of light produced by the new LEDs, the general consensus was positive with perceived increases in light quality, elimination of glare, and decreases in shadows. Specifically, survey participants stated that the LEDs “put out a much better quality light,” “appear brighter and more evenly distributed,” and “[cover] a much greater area with the same number of lights.” Technical respondents indicated that the higher color rendition allowed for greater visibility via security cameras, indicating a possible increase in the safety of the demonstration area.

### ***Installation***

Technical respondents indicated that the LED fixtures were compatible with both pole spacing and height. However, several noted that the mounting of the fixtures proved difficult. In one case, original poles had to be modified with additional holes to fit the heavier LED fixtures; in another case, the mounting hardware packaged with the fixtures did not fit the existing poles and had to be replaced.

Technical respondents indicated that manufacturers could improve the units by reducing the overall weight and implementing a universal mounting bracket so that additional pole modifications are not needed. Some also commented that the wide variation in form factor does not pose a logistical concern (such as inventory control) for them.

### ***Technical Performance***

Some field evaluation participants perceived an increase in the total amount of light delivered. Some customers voiced concern over the directionality and spacing of the LEDs. One respondent at a utility’s demonstration noted that “the new lights seem brighter but also come off as covering a smaller area than the old ones” and suggested that “maybe one or two additional light structures are needed.” Additionally, respondents at another utility’s installation also commented that while the light produced by the LEDs was favorable, the roadway lighting seemed less spread out and therefore did not achieve a “very good distribution” of light delivered.

While technical respondents felt that it was too early to comment on reliability. However, some technical respondents indicated that if LED fixtures failed or required maintenance, the respondents were unsure how to repair the fixtures or obtain replacement parts.

When asked about the technology’s benefits, the technical respondents, which included on-site managers and utility contacts, noted improved effectiveness, energy savings, reduced maintenance, an attractive appearance, and “green appeal.” Specifically, technical respondents from a Demonstration site also mentioned that the higher color rendition allowed for greater visibility via security cameras. Additionally, a technical respondent for one utility’s site indicated that the fixtures “improved lighting in previously darker areas outside of the main parking area, such as sidewalks and driveways.” They also stated that one of the most significant benefits is “not having some fixtures flicker off [for no apparent reason] and having to reset” the lamps.

### ***Bill Savings***

On-site managers and utility contacts estimated that the actual savings for LEDs would amount to approximately 40%, accounting for manpower and installation costs.

## **Safety**

Some field evaluation respondents indicated that, in general, visibility had improved and shadows were minimized as a result of the new lighting. Technical respondents from a specific demonstration site indicated an increase in the safety of the area, citing brighter light and its higher color temperature. They stated that the “color is more like daylight,” which allows “security cameras [to] render the light well.” These respondents also indicated that the area appeared “significantly brighter” and that the people in charge were “very happy with the LED light quality.”

However, some field evaluation respondents at a few of the demonstrations voiced safety concerns regarding the overall area. One field evaluation respondent who specified nighttime safety concerns about the area also indicated that the quality and adequacy of the light was not sufficient.

## **Future Implementation**

Technical respondents provided input regarding future implementation of LED street and area lighting, including their opinions on technical and market barriers to adoption. In general, these questionnaire participants recommended LED fixtures for street and/or area lighting, but several recommended LED fixtures only under certain conditions. One respondent said that LED street lighting has “no capacity value” and that “parking garages are a better candidate economically.” Another stipulated that ideal installations for LED fixtures would include those “where LEED (Leadership in Energy and Environmental Design) points matter and the higher initial costs have some offset mechanism.”

When asked about potential technology barriers, technical respondents mentioned the heavy fixture weight, additional installation work, and uncertainty regarding future maintenance. Furthermore, respondents indicated that the market for LEDs could benefit from future standards that account for increased spacing that could “allow fewer poles for the same area, providing greater savings.”

Most technical respondents placed an emphasis on the high initial cost as a barrier to larger-scale adoption. A respondent from one utility indicated that her calculated payback period exceeded the fixture’s life expectancy, so “price would need to come down by about half” before LEDs would become an economic choice to address the lighting needs of the utility. Other respondents stated that “higher initial costs will delay replacement until failures occur,” citing “budget considerations” and the need for utility cost sharing to make retrofits possible. This need for utility rebates and support to offset high initial fixture costs was echoed by several of the technical respondents.

## **Summary**

LED fixtures differ from traditional light sources such as metal-halide and high-pressure sodium lamps. LEDs are a white light, similar to metal-halide but significantly different from the yellow hue of high-pressure sodium lamps.

The actual performance of the LED-based fixtures at the various sites of the demonstration varied. Energy savings ranged from 20% to over 70%, with the variation largely due to

differences in design constraints (pole spacing, use of security cameras, adequacy of existing designs, and so on).

LEDs are not as efficient as traditional sources when measured using traditional laboratory techniques. However, energy savings in the field result from less light being delivered. This outcome is a result of conservation (using less light) rather than energy efficiency (using less energy to achieve the same light). Often, but not always, a site is over-lit (over-designed) by traditional lighting, with light spilling behind the fixture and sideways, causing glare and creating light pollution. Because fixtures based on LED technology use multiple LEDs, as opposed to a single-point source as with traditional lamps, the lighting designer is able to judiciously place the light with a resulting savings in energy.

Cases where LED technology does not necessarily perform well are street corners, which require a wide spread of light, applications with wide spacing between poles, and applications such as city streets with buildings on either side and parked cars on the street, which need a fairly high level of light to fill the space between cars and buildings and provide a sense of safety. The bottom line is that while LEDs can and do save energy, they do so only in specific applications and with specific attention paid to the photometric design.

It may or may not be possible to substitute an LED fixture for existing fixtures. The answer depends upon the design standard. Lighting is subjective. Despite the lower light levels, many consider the design equivalent to the design of high-pressure sodium fixtures, perhaps because the color temperature of the LED fixtures is typically higher than high-pressure sodium. In the end, standards, which are being developed, are needed to assist in decision making.

In general, the LED-based fixtures performed as modeled, indicating good correlation between available modeling software and actual performance. It is interesting to note that the modeling software is designed to provide light levels and is not designed to estimate the fixture energy consumption and does not take into account manufacturing tolerance, temperature, and geographic location. On data sheets, manufacturers simply provide a wattage rating.

Regarding light degradation over time, subjective evaluations indicate that the level of light did not significantly change over the relatively brief measurement period (approximately two years). Determination of light degradation in the field is complicated by the temperature sensitivity of the fixtures. Moreover, the technology is changing at a rapid pace. The LEDs installed during the Demonstration are not as advanced as the LEDs produced today. Today, laboratory testing and extrapolation is the only indicator of reliability and lumen maintenance.

While failure from transients were low, the results showed a higher-than-expected level of failures for reasons that were typically manufacturing-based rather than technology-based. As the volume and experience of manufacturers increase the reliability of the LED fixtures is expected to increase. As with any product, the reliability depends on the manufacturer.

Another finding from the field relates to temperature. The LED-based fixtures were found to have a negative temperature coefficient. Simply, at colder temperatures, the fixtures use more energy (they also generate more light). Unlike traditional fixtures, which exhibit constant energy consumption with temperature, the temperature sensitivity means that the energy consumption of the fixtures is not constant with geographic location, and utilities should consider a geographically corrected value for the energy consumption of the fixture.

Another reason for variation in expected energy use is the circuit controlling the on/off time of the fixtures. Researchers found several cases where either the photocell used to control the on/off time of the fixtures was poorly located, or the computer that controlled the on/off time did not automatically adjust for the daily variation in darkness hours. The data suggests that simply paying attention to the control circuit will provide energy savings, which could be significant and will depend on the number of fixtures controlled by the circuit and the severity of the error between on/off time and hours of darkness.

In spite of often delivering less light than the control fixtures, the opinion of survey respondents with regard to performance was favorable. Most if not all indicated that the lights were equivalent if not better than the existing design. Particularly in the case of the LED technology versus the yellow hue of high pressure sodium, survey respondents seemed to appreciate the LED technology. But as mentioned above, less light is not always better, and there are locations where LED technology may not achieve the design objective and energy savings. Particular cases are when a lot of light is needed. The efficiency of traditional technology increases with wattage rating, so savings are more difficult to realize. Another consideration is the line voltage. Laboratory testing found that all drivers tested were designed for a maximum voltage of 277 V. On a circuit powered by 480 V, a step-down transformer is needed. The step-down transformer was found to increase power consumption by 7.1%, which subtracts from the benefit of LED technology.

The efficiency at 480 V is just one area where more savings are possible. Another is in ballast design. Laboratory testing showed that one manufacturer clearly outperformed others, and most manufacturers can improve the efficiency of their ballast by an additional 5%.

Today, many manufacturers are producing fixtures using LED technology. Not all fixtures are equal. Key design considerations are ballast, light engine, and housing. As mentioned above, the ballast must have good efficiency. The light engine, which is where the new technology lies, should deliver the light as efficiently as possible with good color rendition and good quality distribution. The fixture serves to conduct the heat away from the LEDs, self-clean, and allow linemen to safely install and repair the fixture. To help, the Municipal Solid-State Lighting Consortium offers a model specification for use by stakeholders to help assemble an effective specification.

Both laboratory and field results support the claim that a fixture using LED technology can in some applications provide acceptable illumination and energy savings. Saving *money*, however, is another issue. Many city engineers and politicians are surprised to learn that a 50% reduction in fixture energy use does not typically equal a 50% reduction in their electricity bill. The savings may be closer to 15%, depending on the utility's tariff for street lighting. The other 35% covers infrastructure costs such as pole and wire depreciation and maintenance. Care is needed when calculating simple payback.

The ultimate test of a new technology is its application in real-world conditions. Lab data is useful, but field data is critical. Results from the Demonstration show energy savings. It also shows that up to 10% additional savings are possible with improvements in driver efficiency, the addition of a circuit for temperature compensation, and improved design of on/off controls.

### ***Readiness for Program***

Based on the results of this Demonstration and on a case study conducted in the 2011 Coordinated Early Deployments Project [6-3], EPRI qualified LED technology for street and area lighting as ready for energy efficiency programs at utilities. The technology passed the program-readiness criteria developed in the Coordinated Early Deployments Project: energy savings must be proven, there must be line of sight to acceptable total resource cost test and payback period, there must be positive adoption experiences, and there must be a robust supply chain. Cost is the primary barrier, and while there appears to be acceptable costs in the future, today's cost must be considered by each utility within the context of the utility's portfolio of options. For example, if other aspects of the technology, such as energy savings and customer choice, override the high cost, then LED street lighting may well be worth including in a utility's energy efficiency program.

# 7

## HYPER-EFFICIENT APPLIANCES

---

### Introduction

EPRI targeted several important “white goods”—refrigerators, clothes washers, and electric clothes dryers—for this energy-efficiency demonstration and performance-measurement project. Together, these appliances use about 15% of the residential electricity consumed in the U.S., according to the Energy Information Administration. Refrigerators account for about 8% of an average household’s electricity use, washers about 1% (this excludes water-heating use), and dryers 5.8%

Manufacturers have improved the energy efficiency of these products in recent decades, spurred by federal energy-efficiency standards, rating and labeling programs, and financial incentives from utilities and others. For example, refrigerators manufactured today for the U.S. market use only about a third as much electricity as their counterparts of 30 years ago. Nevertheless, additional savings are still possible because of relatively recent advances in compressor design for refrigerators, low water use and high spin speed in washers, advanced control algorithms for termination control in dryers, and the fact that market penetration of high-efficiency designs is still relatively low.

ENERGY STAR has been successful as, among other things, a benchmarking program allowing consumers to compare the energy costs among different makes and models based on laboratory test results. In order to level the comparison, assumptions are made. For example, to approximate the additional energy loss within refrigerators due to door openings and closings, the ambient temperature at which the refrigerator is tested is raised from the standard 70°F to 90°F (21°C to 32°C). While ENERGY STAR laboratory tests provide a reasonable approach for comparison, the Energy Efficiency Demonstration compares the energy performance and load profiles of high-efficiency (also called *hyper-efficient*) appliances to that control refrigerators, clothes washers, and electric clothes dryers by measuring the energy use and operation of appliances located within real households. In “treatment” sites, home occupants received a new, hyper-efficient appliance. In “control” sites, an existing appliance was metered. In some cases, these two sites were combined, with existing appliances measured for a period of time, followed by measurement of the hyper-efficient replacement appliances (pre/post method).

### Industry Overview

#### ***Refrigerators***

##### Overview

Figure 7-1 is a representation of a refrigerator showing its main parts. Refrigerators and freezers are categorized by:

Configuration (side-by-side, top freezer, bottom freezer, single door refrigerator and freezer, single door refrigerator only, chest freezer, and upright freezer):

Per the DOE, models with top-mounted freezers use 10 to 25% less energy than bottom-mount or side-by-side models

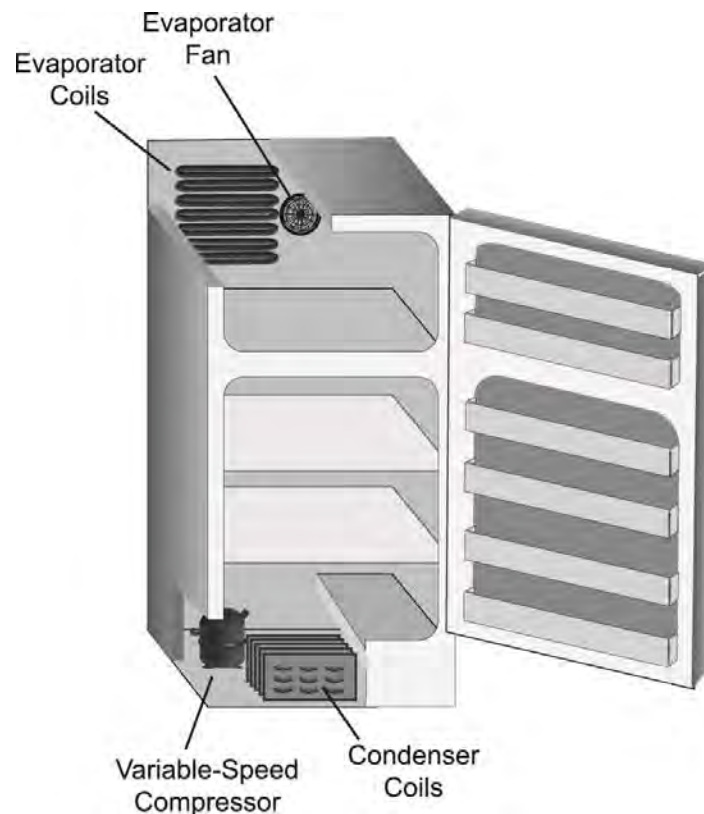
Automatic or manual defrost:

For efficient operation, the evaporator coils inside the freezer should remain free from excess frost build up so that air can easily pass through the coils and reach the refrigerator section. Every eight hours or so, depending on the type of defrost timer or control, the compressor and fans will shut off, and the machine will enter defrost mode, during which an electric heater is turned on to melt the accumulated ice from the evaporator coils.

Per the DOE, manual defrost refrigerators are generally more efficient than automatic defrost refrigerators because they do not use a heater, but only if the frost is periodically removed (when greater than one inch thick).

For refrigerators, whether or not they have through-the-door ice service:

Per the DOE, automatic ice makers and through-the-door dispensers increase energy use by 14 to 20%



**Figure 7-1**  
**Representative Configuration of a Refrigerator with Top-Mounted Freezer**

ENERGY STAR has identified four categories of refrigerators based on an adjusted volume. Adjusted Volume (AV) for refrigerators is calculated as follows:

$$AV = (\text{Fresh Volume}) + 1.63 \times (\text{Freezer Volume})$$

For freezers, the adjustment factor is 1.73, so the calculation is:

$$AV = 1.73 \times \text{Freezer Volume}$$

Fresh Volume is the total volume of the main refrigerator compartment. Freezer Volume is the total volume of the freezer compartment. The volume ranges are as follows:

< 16 ft<sup>3</sup>

16 –19 ft<sup>3</sup>

19.1 – 24 ft<sup>3</sup>

> 24 ft<sup>3</sup>

## Timeline

The following is a brief timeline for the development of the refrigerator[7-1] .

**1904** A self-contained mechanical refrigerator is displayed at the St. Louis World’s Fair by Brunswick Refrigerating Co., which specializes in designing small refrigerators for residences and butcher shops. The ammonia refrigerating system is mounted on the side of a wooden icebox-type refrigerator.

**1927** Gas-fired household absorption refrigerators that do not require electricity are marketed to rural areas in the United States. One, the Electrolux, marketed in Sweden since 1925, becomes very popular.

**1927** General Electric introduces the first refrigerator to be mass-produced with a completely sealed refrigerating system.

**1950/60s** Invention and wide-spread adoption of automatic defrosting and automatic ice making.

**1987** The National Appliance Energy Conservation Act mandates minimum energy efficiency requirements for refrigerators and freezers, as well as room and central air conditioners.

**1987** The Montreal Protocol serves as an international agreement to begin phasing out CFC refrigerants, which are suspected of contributing to the thinning of the earth’s protective, high-altitude ozone shield.

## Market Statistics

Below are some statistics about refrigerators[7-2]:

As of 2008, 145 million standard-sized refrigerators were installed in U.S. homes.

Virtually every home (99%) in the United States has one or more refrigerators, and about 26% have two or more.

Only three out of ten refrigerators sold are ENERGY STAR qualified.

Forty-four percent of the refrigerators that are replaced by new refrigerators are not disposed of but are maintained in service as second refrigerators, sold or given away.

In general, while efficient options for refrigerators are available, consumers are hanging on to their old refrigerators longer and are opting to purchase less efficient models.

### Refrigerator Options and Advances

A number of design options are available for reducing the energy consumption of refrigerators and freezers. These all rely on vapor-compression technology. Although a few alternatives to vapor-compression refrigeration technologies have been tried in the lab, or used for niche products, none are on the horizon that are expected to affect standard-size, mass-market refrigerators in the near term.

The system efficiency achieved by combining and integrating different types of components and materials is the design challenge for product engineers. While striving for greater energy efficiency, they must consider tradeoffs between efficiency measures and desirable functions and features such as the amount of interior space for food storage, ease of door opening, and, of course, cost.

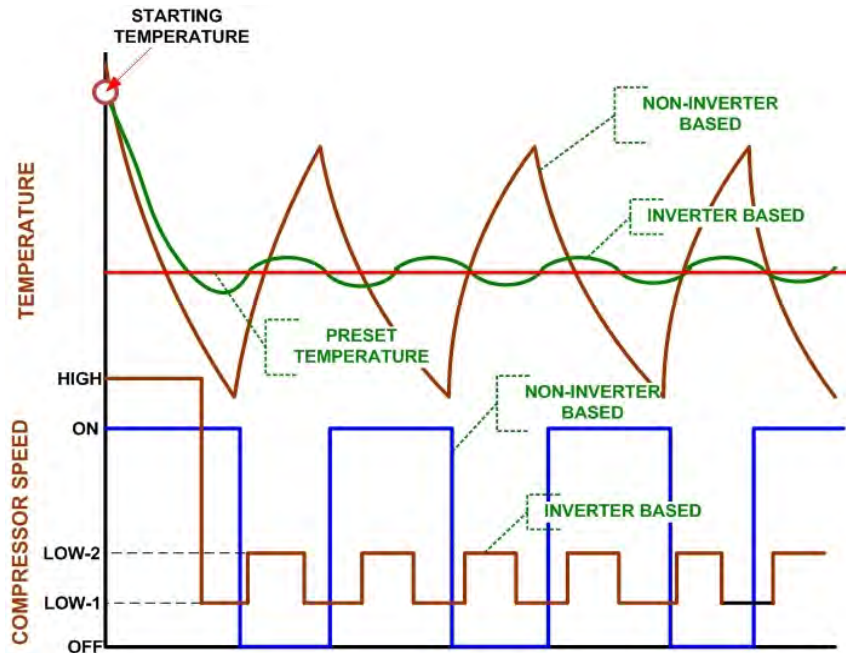
A number of design options are available that can be used singly or in some combination to increase the energy efficiency of refrigerators and freezers. Several rely on a trend toward increased use of electronics for greater control.

Some key design and technology options for refrigerators include:

1. **Higher-efficiency compressors and variable-speed compressors.** The compressor is the heart of the refrigerator system. It is the major power-using component in refrigerators and freezers; therefore, increasing its efficiency increases the energy efficiency of the appliance. The majority of compressors rely on induction motors and reciprocating compressors. The induction motors are typically resistance start/capacitor run.

Most compressors operate at a single speed, but variable-speed compressors can operate at multiple speeds rather than just in ON mode, as shown in Figure 7-2. As a result, the compressor can better match the load, running at lower speeds for longer periods of time. The fan runs longer, which uses more energy, but losses during the OFF cycle are reduced, and heat exchangers operate more effectively as well.

Electronic controls enable variable speed, typically with inverter-driven induction motors or permanent-magnet motors. The electronics used for control of variable-speed compressors makes the units more expensive than single-speed units.



**Figure 7-2**  
**Operation of Inverter-Driven Variable-Speed Compressor Versus Single-Speed Compressor**

2. The 2009 DOE preliminary technical support document cites studies from the late 1990s that reported energy savings from use of variable-speed versus single-speed compressors of 4% to 25% [7-3][7-4]. The Consortium for Energy Efficiency estimates that a variable-speed compressor has potential for a 10% efficiency gain [7-5].
3. Higher-efficiency motors on fans used to increase heat transfer at the evaporator and condenser.
4. Adaptive defrost technologies, where the defrost cycle is not based on a timer but is performed only when needed.
5. Improved (lower conductivity) insulation or vacuum panel insulation.
6. Other components, materials, and design strategies, such as the use of different refrigerator configurations, including multi-compartment or drawer units, better sealing doors and gaskets, alternative refrigerants, and enhanced evaporator heat exchange performance.

## ***Clothes Washers***

### **Overview**

Automatic machines use various cycles to fill, empty, wash, spin and heat in an attempt to remove dirt and kill germs without too much fading of dyes, wrinkling and excessive use of energy and water. Advanced models offer high spin speed to remove water from fabrics in order to reduce the amount of water removal in the dryer. Newer washers have integrated heating elements to either heat the water or boost the temperature of the water for sterilization.

## Timeline

**1908** First electric-powered washing machine is invented by Alva J. Fisher.

**1911** Whirlpool Corporation (Upton Machine Co.) begins producing electric motor-driven wringer washers.

**1915** The first electrical clothes dryers appear.

**1930s** John W. Chamberlain of Bendix Aviation Corporation invents a machine that can wash, rinse, and extract water from clothes in a single operation.

**1947** The first top-loading automatic washing machines are introduced by the forerunner of the Whirlpool Corporation.

**1950s** Wash cycles and products are developed for new fabrics and a greater range of wash conditions.

**1994** Maytag introduces the first domestically-produced high-efficiency washer, the Maytag Neptune.

**1998** Whirlpool launches the first energy- and water-efficient top-load washer.

## Options and Advances

Clothes washers are powered by electricity, but traditionally, only about 10 to 20% of the energy used directly operates the machine. Eighty to ninety percent of energy use has been for water heating, so reducing the water needed for washing is an important component of reducing residential energy use. Moreover, because it is more efficient to remove moisture via the spin cycle than to remove it by evaporative drying, the spin speed of the washers is also an important consideration for energy efficiency of laundry.

Reducing water use was the impetus for development of residential front-loading or horizontal-axis washing machines. The introduction of the Maytag Neptune horizontal-axis machine in 1997, which EPRI helped develop and test, helped spur major manufacturers to introduce more energy-efficient models, and as of 2005, horizontal-axis machines constituted about 8% of the installed clothes washers in the U.S.

Reducing water volume is one of the key energy-saving features of modern washing machines. For example, DOE estimates that ENERGY STAR washers use 31% less energy and 55% less water than new standard clothes washers. The water-saving feature and other options that can increase the efficiency of clothes washers are listed below:

**Front loaders and advanced top loaders reduce water requirements** and thus reduce the energy used to heat water. The most radical change in clothes washer design is the emergence of models that use significantly less water than clothes washers of yesteryear. These are typically horizontal-axis and front-loading designs, although advanced top-loader models also increase efficiency using altered agitator designs and cycling of clothes through a reduced stream of water. Use of high-pressure sprays for rinsing rather than using full tubs of water also decreases water use. The washer selected for the Energy Efficiency Demonstration is a front loader with low energy and water use. The EnergyGuide label estimates usage at 136 kWh/yr. The water factor of this treatment washer is 3.4, which means that 3.4 gallons are needed to wash each cubic foot of

laundry. The lower the water factor (WF), the better; the federal standard for washers in 2011 is a WF that is no higher than 9.5. The water factor is a measure of the number of gallons of water needed for each cubic foot of laundry, and the requirement is intended to reduce energy use for heating water for laundry as well as conserve water (see Appendix D).

**The efficiency of motors**, which move the agitator or spin the drum, also affects energy efficiency. To reduce energy requirements, many appliance manufacturers use washer designs that rely on permanent-magnet synchronous motors instead of split-phase, AC induction motors [7-6]. Eliminating the belt transmission system and connecting the motor directly to the drum can also reduce energy use.

**High spin speeds** reduce overall laundry energy use. Efficient motors spin the washer drum two or three times faster, ideally at about 1,400 to 2,000 rpm, to extract water. The effect of moisture retention in laundry loads is the reason that federal regulations use a “modified energy factor” (MEF) as a metric to measure washer efficiency. It incorporates not only the energy factor (kWh/cu ft) but also the moisture-retention factor (MRF).

**Advanced software, sensors, and controls** permit greater automation of washing machine operation. Water levels, motor operation, wash time, and spin speed can be more precisely controlled as more sophisticated controls are built into the system. The treatment washer used in the Energy Efficiency Demonstration features advanced sensors and controls.

**Future Technology.** One change in the washer technology currently being explored is to alter the chemistry of the water used in the washer rather than just using heated water and detergent. For example, Samsung introduced the SilverCare washer a few years ago, which creates silver ions that are released in the water to help sterilize the clothes. The Haier Wash20 washer (available only in Europe, not in the U.S.) splits water molecules. The Samsung silver ion technology is supposed to clean clothes well in cold water, achieving 99.9% sterilization. However, because the silver ions can easily enter waste water during washing, “potentially disrupting helpful bacteria in wastewater treatment facilities, or endangering aquatic organisms in lakes and streams, the U.S. Environmental Protection Administration (EPA) decided to regulate this form of nanotechnology as a pesticide” [7-7]. A search of the Samsung appliances website in 2011 found no reference to the SilverCare washer or its presence on the U.S. market, so it is likely that it has been pulled from stores. Haier claims that the main feature of the Wash20 washer is that it requires no detergent. It also claims effective cleaning in cold water. Environmental effects of this technology have not been researched by EPRI. The washer used in the Energy Efficiency Demonstration does not feature technologies such as those described above that alter water chemistry.

## **Clothes Dryer**

### **Overview**

Most dryers consist of a rotating drum called a *tumbler*, through which heated air is circulated to evaporate moisture from the clothing. The tumbler is rotated to maintain air space between the articles in the load. The exhaust is hot, humid air that is typically vented outside. The heated air is created using either one or more resistive elements or the combustion of natural gas or

propane. Most dryers operate on the same principle, so the government does not have an efficiency program for dryers.

### Options and Advances

Clothes dryers offer opportunities for improvements in energy efficiency in the U.S. The greatest strides in dryer efficiency for electric-evaporative designs have been from better termination controls and added insulation.

No major technology breakthroughs or major leap in efficiency has been achieved as yet in the U.S. clothes dryer market (apart from washers extracting greater amounts of moisture in the spin cycle, thus reducing energy required for evaporative drying by the dryers). However, introduction of heat pump clothes dryers, which use only about half of the electricity used by electric evaporative dryers, could begin to alter the energy efficiency of U.S. dryers in coming years. Initially, the Energy Efficiency Demonstration planned to field-test heat pump clothes dryers (HPCD), but none were yet UL-approved in the U.S. As of 2012, manufacturers are still in the product-development stage for the North American market. Several manufacturers are working on prototypes, looking at modifying the HPCDs in Asia or Europe, where the technology is commercially available.

Despite the probable emergence of HPCDs in coming years, evaporative clothes dryers are likely to dominate the market in the near term, and they can achieve greater energy efficiency through a number of features:

- **Higher spin speed in the washer.** As noted in the list of design features of efficient washers, water extraction in the washer spin cycle has been the primary means of reducing dryer energy use in the U.S. market (the Energy Efficiency Demonstration treatment washer has a high spin speed of 1400 RPM).
- **Advanced software, sensors, and controls.** Incorporation of moisture sensors and advanced controls into dryers enables shutoff before clothes overdry, reducing operating time and saving energy. The sensitivity of sensors and the software used in clothes dryers enable more precise automated operation. For instance, the manufacturer of the dryer used in the Demonstration claims their advanced software enables better termination control that can reduce dryer energy use by up to 40% for small- and medium-size laundry loads. Tests of dryers indicate that newer dryers with advanced automatic termination controls are more efficient than counterparts without advanced controls [7-8].
- **Drum upgrades,** such as drum design and reverse tumble options.
- For vented models, **recycling of exhaust heat and preheating of inlet air.**
- **Enhanced motor efficiency.**

### **Standards**

In today's market, many appliances are available that use 20 to 30% less energy than federal standards require. These are typically rated as ENERGY STAR models and are provided tiered efficiency ratings by the Consortium for Energy Efficiency (CEE). CEE is a private non-profit organization that has established efficiency performance tiers that utilities and others can voluntarily adopt for use in local programs. CEE ratings are given under the auspices of the CEE Super-Efficient Home Appliance Initiative (SEHA), which complements ENERGY STAR. The

program has been in effect since 1997 to define “super-efficiency” (see [www.cee1.org](http://www.cee1.org) for more information).

In the United States, a major impetus for increased energy efficiency of residential appliances has been federal standards that came into being in 1987, when Congress passed the National Appliance Energy Conservation Act (NAECA). NAECA required levels of minimum energy efficiency for thirteen residential appliances, including refrigerators and clothes washers, but not clothes dryers, and required the DOE to periodically review and update the standards with the goal of maximum improvement that is both technically feasible and economically justified.

In subsequent years of 1992, 2005, and 2007, Congress enacted additional laws that established standards. The Energy Independence and Security Act (EISA) of 2007 is the most recent. A summary of the standards affecting residential appliances is provided in Appendix D.

Although the efficiency of residential appliances has increased substantially over the past three decades—as older units have been replaced and federal standards for many appliances have required greater energy efficiency—there is still considerable potential for improved energy performance. This is true in terms of the opportunity to increase the market penetration of the higher-efficiency models (such as appliances rated for ENERGY STAR), as well as in terms of the technical potential for manufacturers to increase the energy efficiency of appliances in the entire range of models that they offer. DOE reports that in 2009, the national share of the types of appliances used in the Demonstration that were sold with an ENERGY STAR label were [7-9]: Clothes washers – 48%; Refrigerators – 35%. Currently, many of the most efficient units are premium-priced models (although strides are being made on improving the energy efficiency of the lower-priced models).

Changes in U.S. federal energy standards will require a higher minimum energy efficiency for refrigerators and for clothes dryers in 2014. Energy-efficiency standards for clothes washers will remain the same, although a WF requirement will be put into effect in 2015 for clothes washers.

With new and updated federal efficiency and water-use standards imminent, it is a good time for utilities to consider how utility efficiency and market-transformation programs will influence and operate in the residential appliance market that manufacturers are planning for. As the average efficiency of residential appliances continues to increase through standards, utility programs need to respond to determine the cost effectiveness of appliances that are considerably more efficient than products that meet the new standards. Although the Demonstration is not intended to test cost effectiveness, but rather the technical performance of appliances, the data being collected provides performance data that will be of value when addressing estimates of energy and water use.

Utilities should keep in mind that their programs can influence manufacturer production. For example, DOE representatives interviewed refrigerator manufacturers about their production of ENERGY STAR units and found that:

Manufacturers noted that they often do not necessarily maintain their margins for higher-cost ENERGY STAR units because they believe that consumers do not think that the additional costs can justify the relatively modest savings. To date, however, many have produced ENERGY STAR units because they need them to have their product line marketed via major retail chains, to sell to government, and to have their products part of utility rebate programs [7-10].

## Refrigerator

If energy-efficient appliances had a poster product, it would be the refrigerator. Today's average size unit uses less than a third of the electricity required by its counterpart of the 1970s. The 1970s model used about 1800 kWh/yr. In 1980, the average size unit used 1276 kWh/yr, and today an average model, now somewhat larger, requires less than 500 kWh/yr [7-11]. However, despite this major improvement in efficiency, refrigerators can improve even more. This is evidenced by the fact that new U.S. federal energy efficiency standards will require a standard that will decrease energy use of refrigerators by 20 to 25% starting in 2014 [7-12].

Federal standards for refrigerators and freezers in 2011 have been in effect since 2001 and are expressed in maximum allowable kilowatt hours per year, according to the unit's adjusted volume. Table 7-1 provides the current standards (in effect until 2014) for a few common refrigerator product classes.

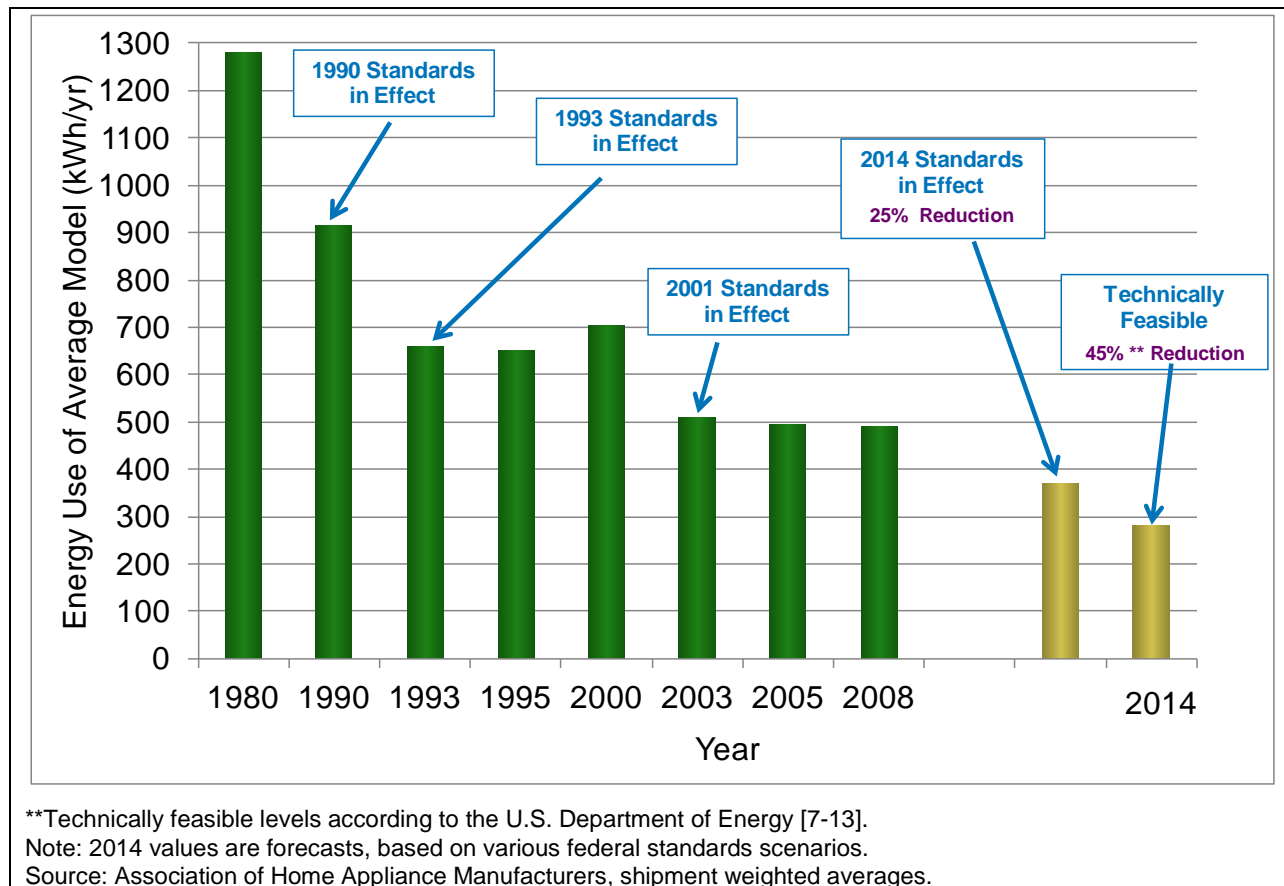
**Table 7-1**  
**U.S. Energy-Efficiency Standards for Common Refrigerator/Freezer Types**

Refrigerator or Freezer Type	Requirement (kWh/yr)	Examples	
		Adjusted Volume	Maximum Allowable Energy Use (kWh/yr)
Refrigerator-freezers with automatic defrost with bottom-mounted freezer (without through-the-door ice service)	$4.60AV^* + 459.0$	22 cu. ft.	560.2
Refrigerator-freezers with automatic defrost with top-mounted freezer (without through-the-door ice service)	$9.80AV + 276.0$	22 cu. ft.	491.6
Refrigerator-freezers with automatic defrost with side-mounted freezer (with through-the-door ice service)	$10.10AV + 406.0$	22 cu. ft.	628.2
Upright freezers with automatic defrost	$12.43AV + 326.1$	24 cu. ft.	624.4
Chest freezers and all other freezers except compact freezers	$9.88AV + 143.7$	24 cu. ft.	380.8
Compact refrigerators and refrigerator-freezers with manual defrost	$10.70AV + 299.0$	7 cu. ft.	373.9
Compact refrigerator-freezers with partial automatic defrost	$7.00AV + 398.0$	7 cu. ft.	447

\*AV = adjusted volume

The Energy Efficiency Demonstration includes units with bottom-mounted freezers (both with and without through-the-door ice) and top-mounted freezers. No side-by-side refrigerator, which is the configuration that uses the most energy, was being tested in the Demonstration. A side-by-side refrigerator of the same adjusted volume as a top- or bottom-mounted freezer model will use more energy per Table 7-1.

Figure 7-3 shows what energy use might be in 2014 for an average-size model with reduced electricity use by 25%, and by 45%, which is considered technically achievable according to the U.S. Department of Energy [7-13].



**Figure 7-3**  
**Energy Consumption of Refrigerator-Freezers**

Preliminary engineering analyses of technical and economic feasibility are available in the DOE preliminary Technical Support Document on refrigerators and freezers published by DOE in November 2009 [7-13]. For the economic analysis, including how changes would affect the manufacturer's selling price, DOE used the 45% figure as the upper boundary of technical feasibility, although for some product classes higher efficiency levels are possible. The units used in the Energy Efficiency Demonstration are labeled as ranging from 20% to 30% better than current standards.

Refrigerators are sold with EnergyGuide labels, many are ENERGY STAR rated, and the CEE also has developed tier ratings for this appliance. A comparison of ENERGY STAR and CEE ratings is shown in Table 7-2.

**Table 7-2  
Refrigerator ENERGY STAR and CEE Ratings**

Efficiency Level	Percentage Above Federal Standards	
	Compact Refrigerators	Standard-Size Refrigerators*
ENERGY STAR®	20%	20%
CEE Tier 1 (same as ENERGY STAR)	20%	20%
CEE Tier 2	25%	25%
CEE Tier 3	30%	30%
EE Demo Model 1		30%
EE Demo Model 2		25%
EE Demo Model 3		30%
* Capacity greater than or equal to 7.75 ft <sup>3</sup> . Note: Federal standard depends on the size and configuration of the refrigerator or freezer.		

How ENERGY STAR and CEE ratings will change relative to the new federal energy-efficiency standards for refrigerators, which will require most product classes to be about 20 to 25% more efficient than they are now, is being determined. Refrigerators are in virtually every household and operate 24 hours a day, 7 days a week. This makes this appliance a prime target for increased energy efficiency, and refrigerator-freezers also offer some potential for peak demand management.

### Clothes Washer

Like refrigerators, consumers have benefitted by the successful application of standards to reduce the amount of energy and water used to wash clothes. Table 7-3 shows the qualifying criteria for ENERGY STAR and CEE efficiency ratings for clothes washers. These ratings can be used as guides for consumers and utilities to gauge the level of energy efficiency of appliances (along with EnergyGuide labels, which list kWh/year use and average cost per year, based on national average electricity costs).

**Table 7-3**  
**Clothes Washer ENERGY STAR and CEE Ratings**

Efficiency Level	Modified Energy Factor (MEF) <sup>a</sup>	Water Factor (WF)
Federal standard	1.26	9.5
ENERGY STAR®	2.00	6.0
CEE Tier 1 (same as ENERGY STAR)	2.00	6.0
CEE Tier 2	2.20	4.5
CEE Tier 3	2.40	4.0
EE Demo washer	2.64	3.4

<sup>a</sup> MEF = how many cubic feet of laundry can be washed and dried with 1 kWh. The higher the number, the higher the efficiency.

<sup>b</sup> WF = water factor, the number of gallons of water needed for each cubic feet of laundry. The lower the number, the better.

### Clothes Dryer

Clothes dryers are not ENERGY STAR rated and do not display an EnergyGuide label. This is because all clothes dryers have been considered by the DOE as being fairly equal in energy use. However, a federal standard for clothes dryers is set to increase by 24% in 2015. A summary table of the federal standards for clothes dryers is given in Table 7-4 and Table 7-5.

**Table 7-4**  
**Existing Federal Standard for Clothes Dryers**

<i>Manufactured Between May 14, 1994—January 1, 2015</i>	
<i>Product Class</i>	<i>Energy Factor (lbs/kWh)</i>
<b>Electric, Standard</b> (4.4 ft. <sup>3</sup> or greater capacity)	<b>3.01</b>
<b>Electric, Compact</b> (120 V) (less than 4.4 ft. <sup>3</sup> capacity)	<b>3.13</b>
<b>Electric Compact</b> (240 V) (less than 4.4 ft. <sup>3</sup> capacity)	<b>2.90</b>
<b>Gas</b>	<b>2.67</b>

**Table 7-5  
Upcoming Revision to the Federal Standard for Clothes Dryers**

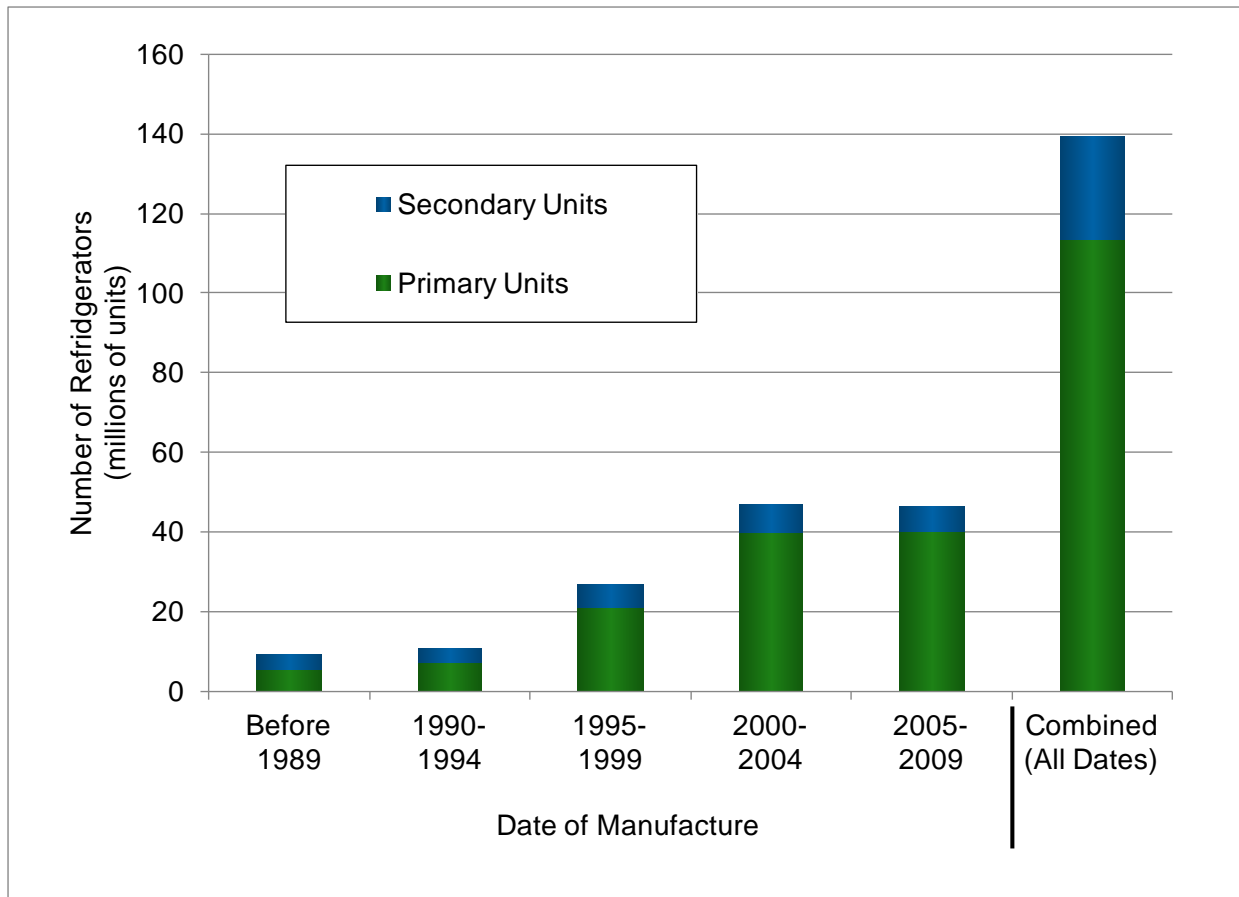
Manufactured After January 1, 2015	
Product Class	Combined Energy Factor (lbs/kWh)
Vented Electric, Standard (4.4 ft. <sup>3</sup> or greater capacity)	3.73
Vented Electric, Compact (120 V) (less than 4.4 ft. <sup>3</sup> capacity)	3.61
Vented Electric Compact (240 V) (less than 4.4 ft. <sup>3</sup> capacity)	3.27
Vented Gas	3.30
Ventless Electric, Compact (240 V) (less than 4.4 ft. <sup>3</sup> capacity)	2.55
Ventless Electric, Combination Washer/Dryer	2.08

## Potential Savings

### *Refrigerator*

There are over 145 million units in homes across the United States [7-14] [7-2]. Almost every home has a refrigerator (primary unit), and around 26% have more than one (secondary unit). Refrigerators account for about 15% of total energy use within homes, making them a prime target for potential energy savings.

Figure 7-4 shows a breakdown of the installed refrigerator base by date of manufacture as well as a combined total number of installed refrigerators for both primary and secondary refrigerators. A large portion of refrigerators are nearing the end or are well past their expected lifespan of twelve years. Of all of the refrigerators in service, 35% are over ten years old, 39 million (27%) are 10 to 19 years old, and 12 million (8%) are over 20 years old.



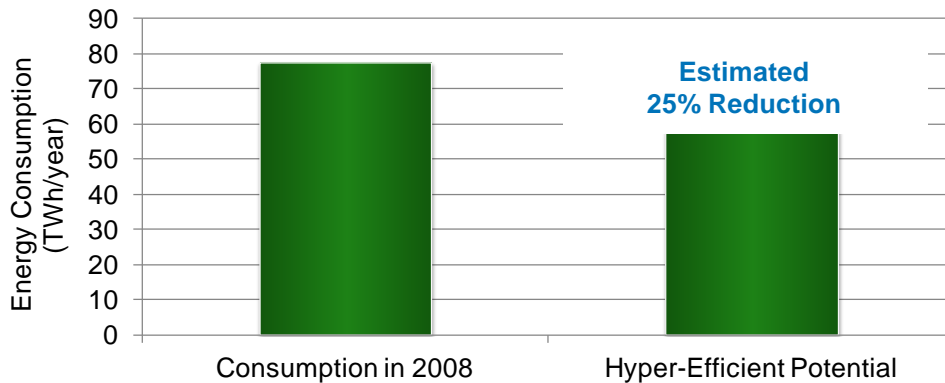
**Figure 7-4**  
**Date of Manufacture of Residential Refrigerators as of 2009**

The energy consumption of refrigerators has decreased over time largely because of the introduction of federal standards in 1993 and a modification to the federal standard in 2001. As shown in Table 7-6, the size of refrigerators has increased over time, but the average energy consumption has decreased over time. The median energy consumption of refrigerators found in homes in 2008 was about 535 kWh per year compared to 624 kWh per year for federal standards and 500 kWh per year for ENERGY STAR. Many refrigerators exceed federal standards, but there are also many that fall below the standard. The 2012 ENERGY STAR catalog of refrigerators ranged in consumption from 171 to 632 kWh per year and ranged in size from 7.75 cubic feet to 38 cubic feet. The standard-size for household refrigerators has a range of 18 to 22 cubic feet.

**Table 7-6  
The Annual Energy Consumption for Different Types of Refrigerators in 2008**

2008 Refrigerator Annual Electricity Consumption				
	Median Consumption (kWh/yr)	Max Federal Standard (kWh/yr)	Max. ENERGY STAR (kWh/yr, % of Median Consumption)	
Top Freezer	454	477	382	16%
Bottom Freezer	482	573	458	5%
Bottom Freezer (w/lce)	554	689	551	1%
Side-by-Side	580	661	529	9%
Side-by-Side (w/lce)	607	722	578	5%
<b>Average</b>	<b>535.4</b>	<b>624.4</b>	<b>499.60</b>	<b>7%</b>

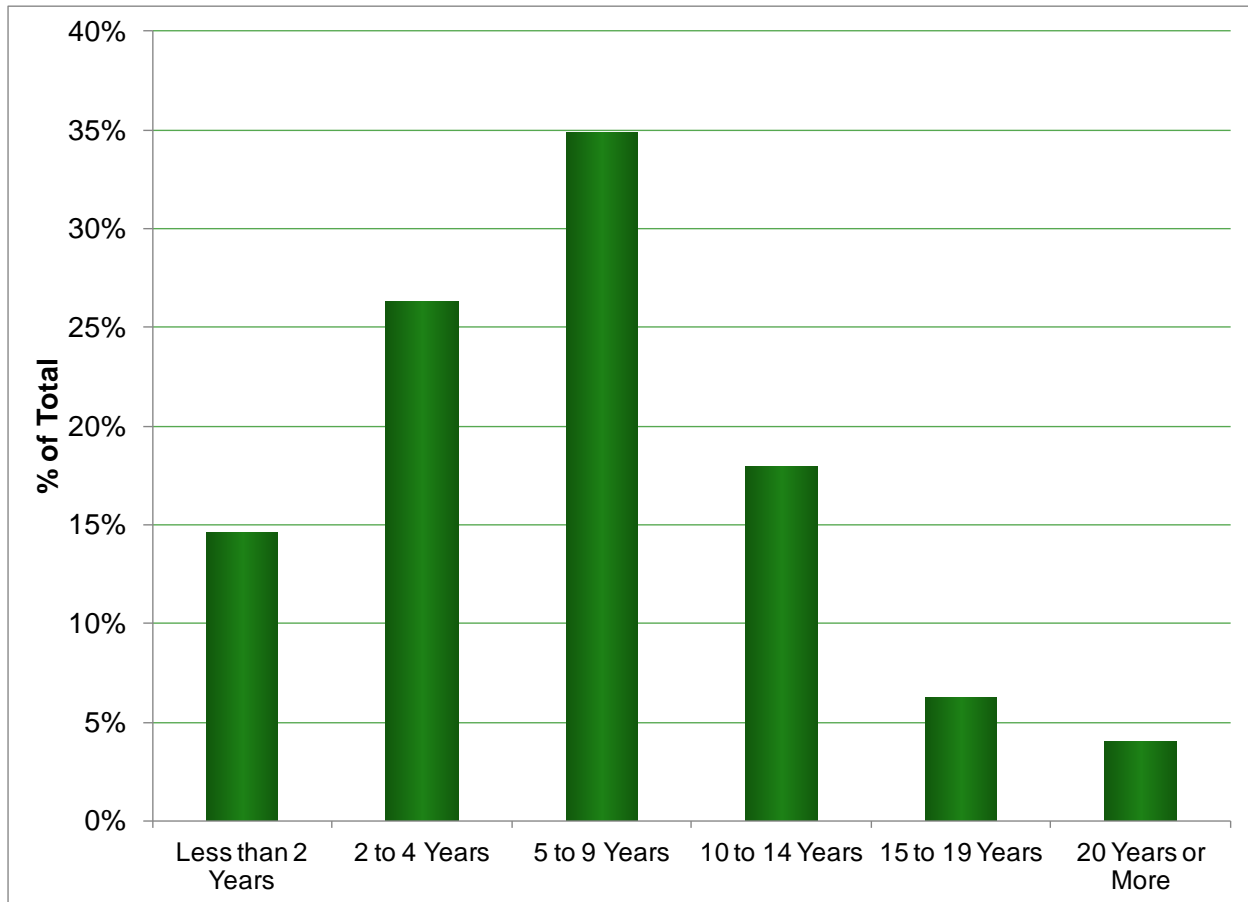
If all 145 million refrigerators in the U.S. were replaced with those that fall into the highest efficiency category (30% better than federal standards), the possible energy savings is 19 TWh per year (a 25% reduction), roughly equivalent to seventeen 250-MW power plants operating at 50% utilization (see Figure 7-5) . Each homeowner could expect to see a 4% reduction in annual energy consumption as long as they are not part of the 10% of the population that keep their old refrigerator as a secondary unit. An average home consuming 12,000 kilowatt-hours a year would reduce that consumption by 480 kilowatt-hours and save \$48 per year.



**Figure 7-5  
The Potential Savings of Hyper-Efficient Refrigerators Compared to 2008 Usage Statistics**

**Clothes Washer**

The EIA states that 82% of U.S. homes have electric clothes washers and 79% of homes also have electric dryers [7-2]. That accounts for 93.2 million washing machines in the United States. Twenty-eight percent (25.3 million) of the washing machines are over ten years old, and 4% (3.6 million) are older than 20 years (see Figure 7-6).

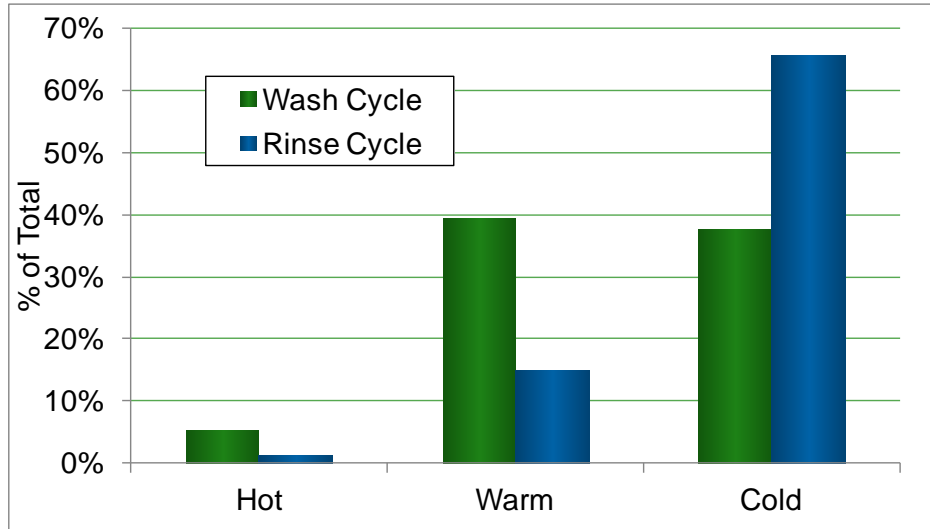


**Figure 7-6**  
**Age of Clothes Washers in Homes as Reported by the 2009 EIA RECS**

According to the EPA, clothes washers account for only about 1% of household energy but are the second largest water user in the home. A typical household laundry load takes about 40 gallons of water for each full load. [7-15]. ENERGY STAR units use close to half of the water of a standard washing machine.

Additional savings could be achieved in other ways, such as by reducing the water temperature of the wash cycle. The EIA published in its 2009 survey that 37% of people use cold water for the wash cycle, and 80% of people use cold water for the rinse cycle. The other portion of clothes washer users choose to use warm or hot water for their laundry cycles (see Figure 7-7) [7-2]

If every home in the United States switched to hyper-efficient models, which have modified energy factors of over 2.4 and a water factor at or below 4.0, then there would be an estimated potential savings of 18 Terawatt-hours and 648 billion gallons of water per year. The ENERGY STAR estimates that a homeowner could see a savings of about 192 kilowatt-hours (approximately \$19) and around 7,000 gallons of water per year, which is roughly equivalent to sixteen 250-MW power plants operating at 50% utilization (see Table 7-7).



**Figure 7-7**  
The Temperature of Wash Cycles Used in Homes

**Table 7-7**  
The Potential Savings If All Clothes Washers Were Converted to Hyper-Efficient Models

	Standard*	2012 ENERGY STAR**	Savings (kWh, Dollars)	
Household Electricity Use (kWh/year)	331	139.4	191.6	\$19.16
Household Water Use (gal/year)	12,117	5,162	6,955	\$52.16
National Electricity Use (TWh/year)	30.8	13.0	17.9	---
National Water Use (billion gal/year)	1129	481.1	648.2	---

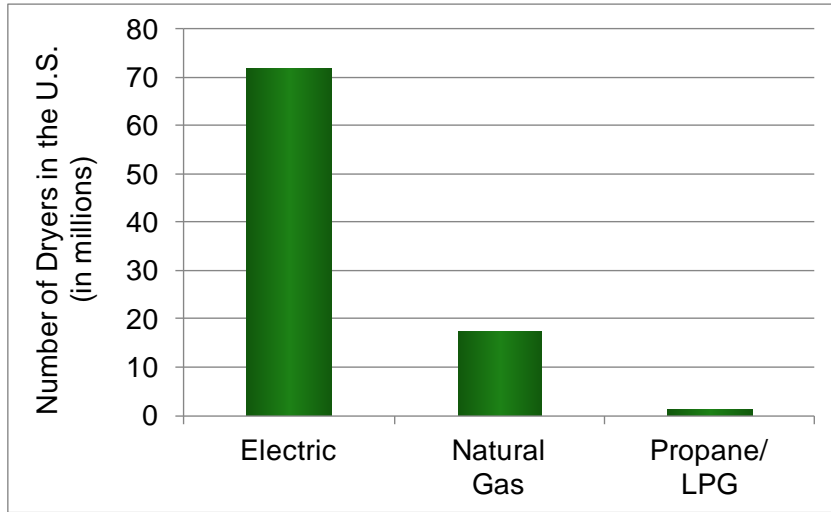
\*Calculated from the DOE ENERGY STAR calculator [7-16].  
 \*\*Pulled from 2012 listing of ENERGY STAR washers that had a MEF  $\geq$  2.4 and WF  $\leq$  4.0.  
 Note: Estimated values are assuming 7.5 loads per week, \$0.10 kWh, \$7.50 per 1000 gallons. Calculations include water heater energy usage (electric water heater).

Although clothes washers are not a huge load on the home, their performance does impact other devices in the home that consume a considerably larger portion of household energy use. A reduction of hot water use will reduce the load on water heaters, which account for 35% of total household energy usage. If clothes washers are paired with heat pump water heaters, additional savings could be expected. Field results are provided in the section titled Field Test Results. Clothes dryers, which account for 6% of total household energy use, will use less energy if the laundry placed in the dryer contains less water due to the washer spin cycle.

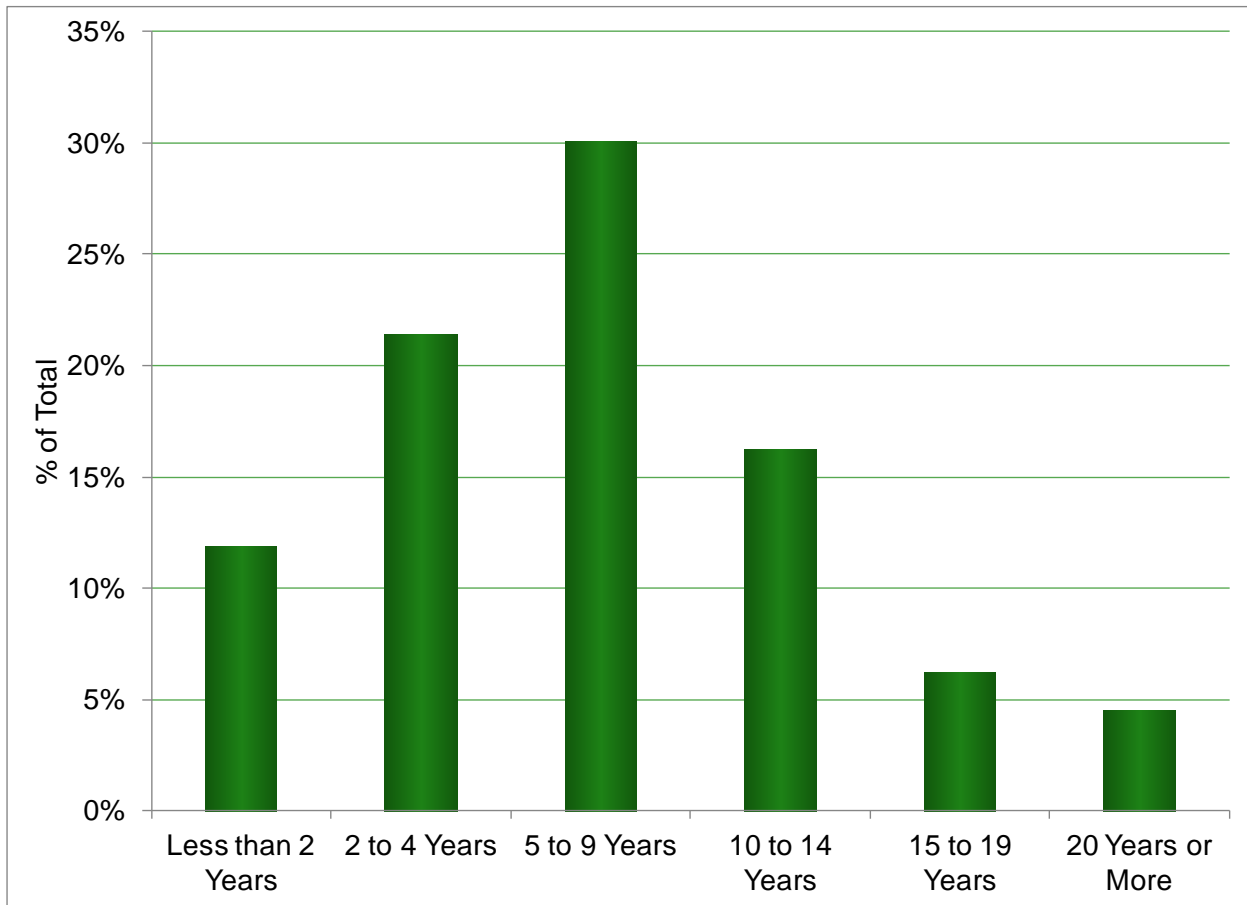
### **Clothes Dryer**

There are 90.3 million clothes dryers in homes [7-2]. Of those, 80% (71.8 million) are electric, followed by 19% (17.5 million) that use natural gas, and 1% (1 million) that use either propane or liquid propane gas (LPG) (see Figure 7-8) [7-2]. Although most clothes dryers fall in the age

range of five to nine years, 30% are ten or more years old, and 5% (4.5 million) are 20 years or older (see Figure 7-8 and Figure 7-9).



**Figure 7-8**  
Market Share of Appliances by Type of Fuel



**Figure 7-9**  
Age Estimate of Clothes Dryer in Service

Not everyone who has a clothes washer owns a clothes dryer. Some prefer to air dry their clothes. Also, not everyone who owns a clothes dryer uses it for every load of laundry. EIA reports that 83% of people use a dryer every time clothes are washed, but 15% do not use a dryer every time, and 2% use their clothes dryer infrequently.

The energy savings of switching to hyper-efficient clothes dryers would come from the advanced controls, so savings would vary depending on the paired washing machine and the size of the laundry loads. One manufacturer claims up to 35% energy savings when paired with its energy-efficient washing machine.

## **Key Research Questions**

### ***Clothes Washers and Dryers***

The primary research questions for washers and dryers are:

1. What is the energy savings in terms of both electrical energy and energy needed to produce hot water?
2. How much water is saved?
3. What is the power profile for clothes washers and clothes dryers?
4. What is the amount of energy used per laundry cycle and how does it compare to ENERGY STAR?
5. What is the load profile of advanced washer, and dryers compared to the control?
6. What is the difference in operating time between control and treatment washer and dryers?

### ***Refrigerator/Freezers***

Key research questions for refrigerator/freezers are:

1. What is the energy savings of the treatment refrigerators compared to the control and to ENERGY STAR refrigerators?
2. How does the load profile change?
3. Are there differences in energy use per household?

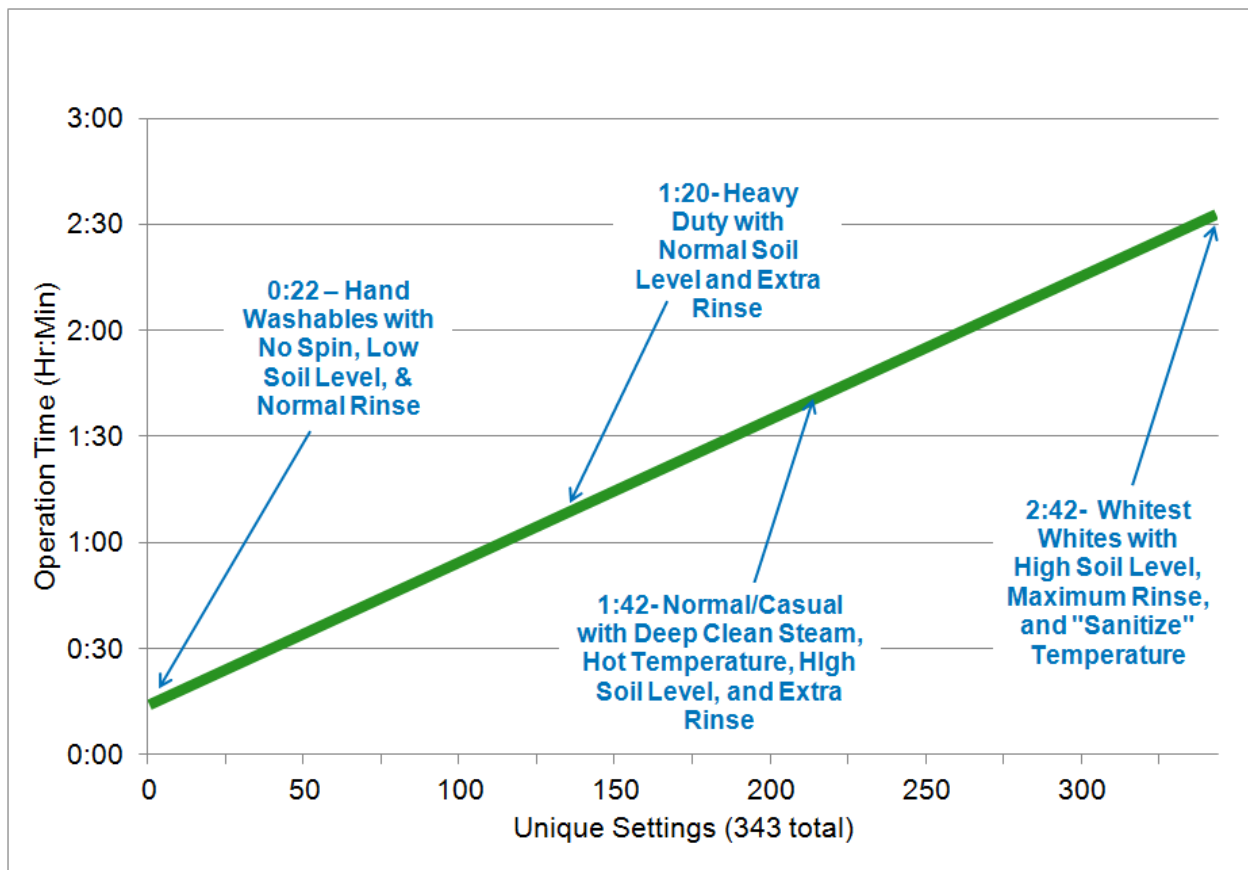
## **Laboratory Testing**

Along with advances in energy efficiency, the treatment washers and dryers have new features and enhanced settings to make washing and drying clothes more precise and convenient. This new variety of settings makes for a wide range in the operating times of both washers and dryers and may have an impact on energy savings. Refrigerators were not lab tested as part of the Demonstration.

### ***Washer and Dryer Operating Times***

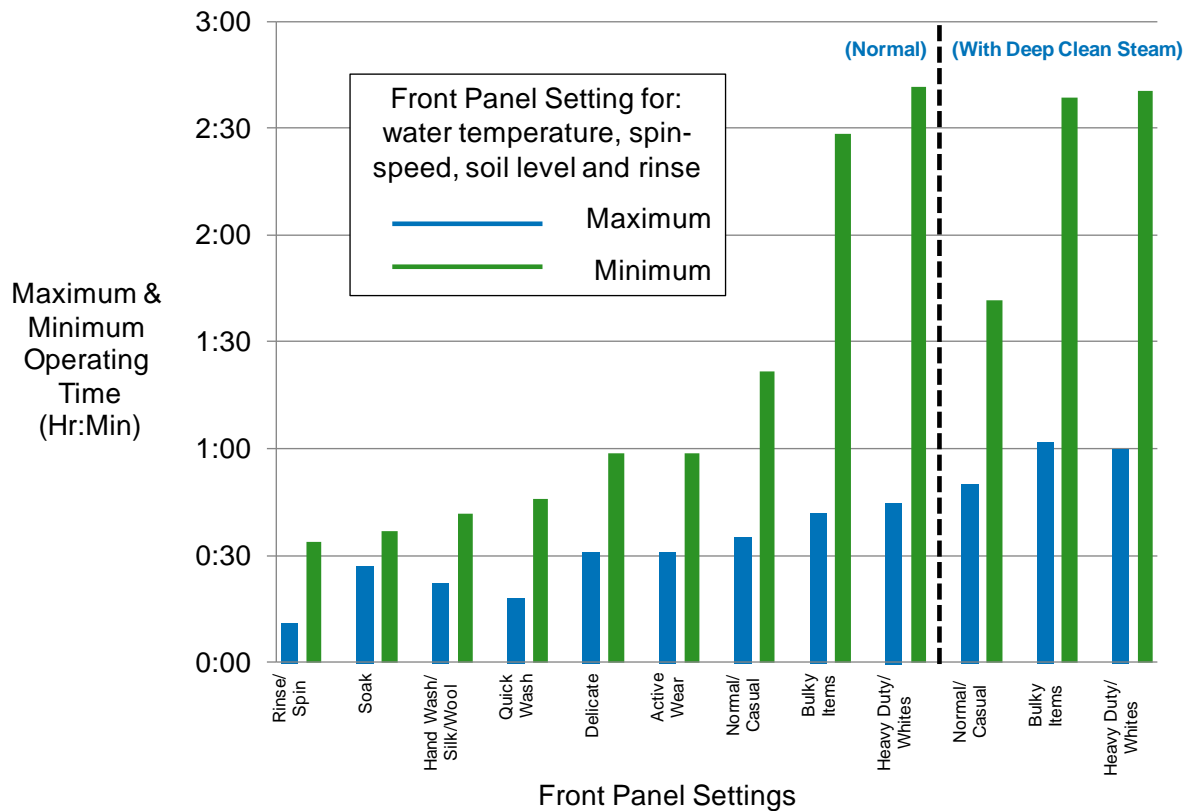
Laboratory work was performed to better understand the range of settings and times for both the clothes washer and dryer. Based on changes in dial and button settings, a washer cycle lasted anywhere from 1 to 262 minutes (see Figure 7-10). Calculations of operating times are based on

the preset runtime. Actual operating times were subject to change because of the appliances' smart sensors, which attempt to increase efficiency by adjusting operating times within the cycle based on weight and dryness of the clothes.



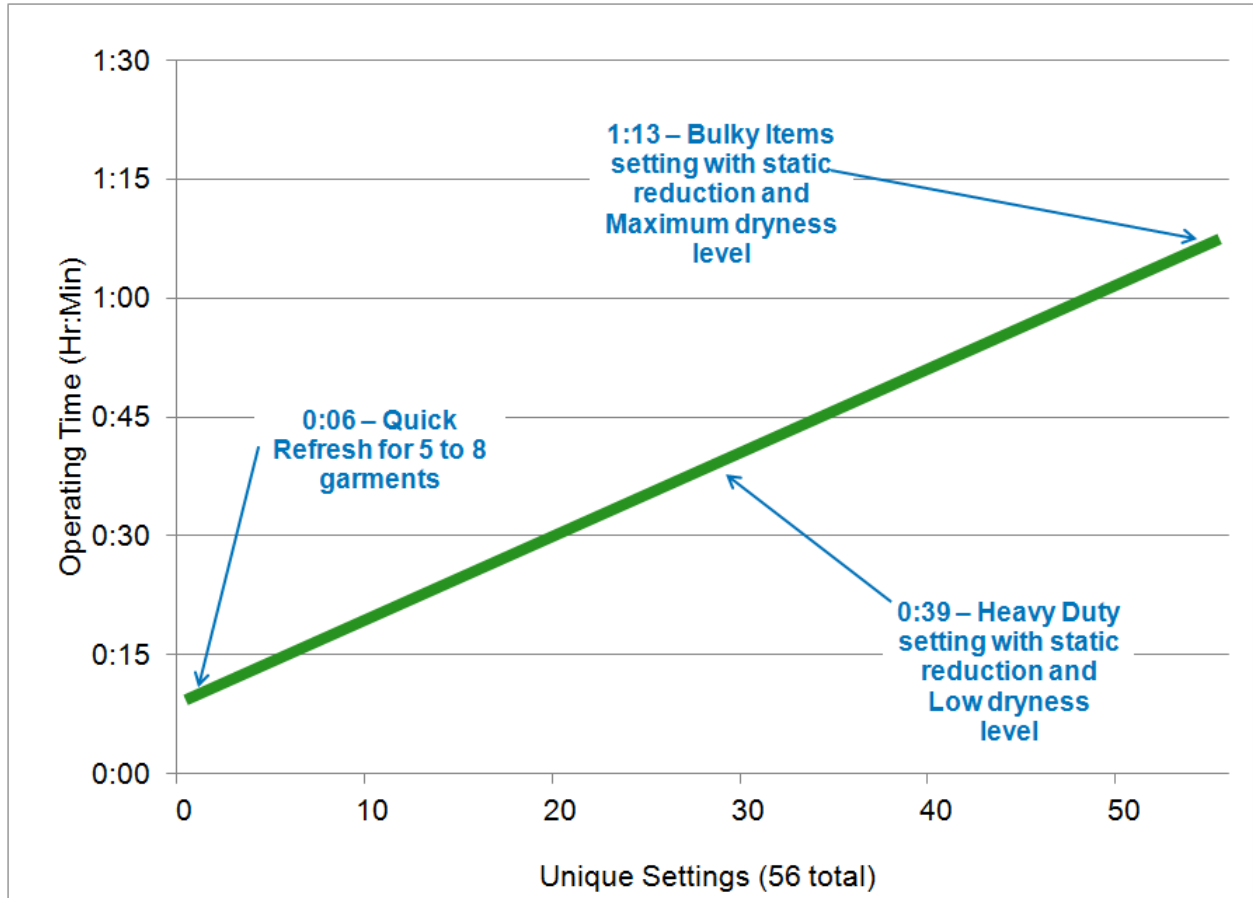
**Figure 7-10**  
**Trend Line of Washer Operating Time by Setting**

In washers, rinse/spin cycles took the least amount of time, while whites and heavy-duty loads took the most. The addition of deep clean steam (a new feature designed for enhanced stain removal) increased operating time even more. For each dial setting, front panel buttons can be used to adjust water temperature, spin speed, soil level, and rinse. The adjustment of these minor settings can cause large differences in operating time, as shown in Figure 7-11, which shows the maximum and minimum operating times for each of the main dial settings.



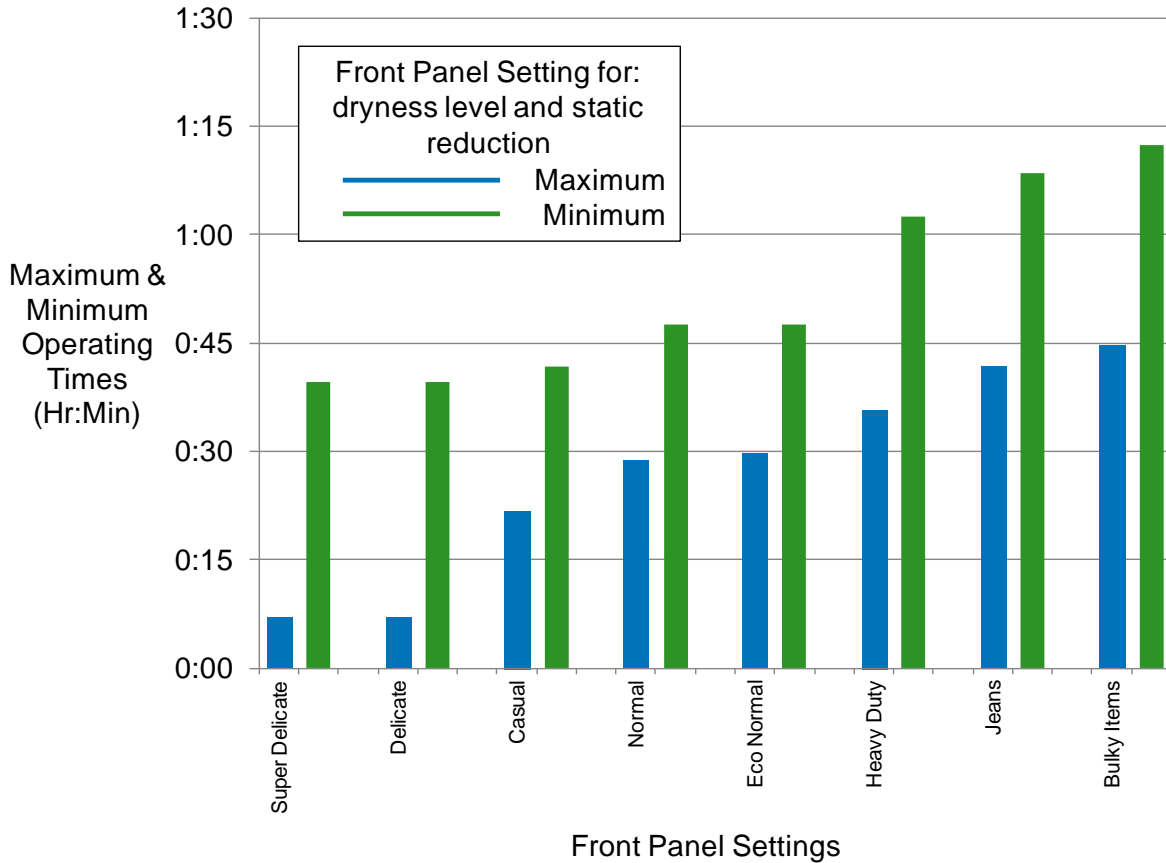
**Figure 7-11**  
**Maximum and Minimum Washer Operating Times by Setting**

For dryers, the difference in operating time varied less than that of washers, but a substantial difference still existed between the shortest cycle (1 minute) and the longest (73 minutes). The dryers also offer fewer setting configurations, with over 50 possible options compared to over 300 settings for the washer (see Figure 7-12).



**Figure 7-12**  
Trend Line of Dryer Operating Time by Setting

The chart of maximum and minimum operating times for each dryer dial setting shows the impact that the adjustment buttons have on dryer operating time (see Figure 7-13). A delicate load lasted anywhere between 7 and 40 minutes, depending on the set dryness level and static reduction.



**Figure 7-13**  
**Maximum and Minimum Dryer Operating Times by Setting**

For each dryer load, there are various main settings such as Delicates, Normal, Jeans, or Bulky Items. Within each of these main settings, smaller choices about temperature, static reduction, and dryness level can be selected. While adjusting the temperature had no effect on operating time, selecting the Reduce Static option increased it by 3 minutes, regardless of other settings.

The most interesting correlation between these minor settings and dryer operating time occurred with the dryness level. Although not adjustable for every type of cycle, the user often has the ability to choose for the clothes in the load to be less dry, normal dryness, or more dry. For all main settings, the higher the dryness level, the longer the operating time. The difference between the operating times of Less Dry and More Dry loads, when all other settings were the same, was anywhere between 15 (in EcoNormal) and 30 minutes (in Jeans).

## Data Collection

### Overview

In order to collect the data necessary to answer the key research questions, a customized instrumentation kit was designed that collected the following variables:

Washers and Dryers:

- volts, amps, power, energy, power factor
- Inlet cold water temperature and flow (gallons)
- Inlet hot water temperature and flow (gallons)

Refrigerators:

- volts, amps, power, energy, power factor
- Ambient temperature and relative humidity

These variables were measured by sensors connected to a local datalogger, which via an Internet connection sent back data to the servers in EPRI's Knoxville location every eight hours. The datalogger collected each of these variables at one-minute intervals.

In addition to the numerical data collected by the instrumentation, two participant surveys were conducted to gather qualitative data on the behavior, attitudes, satisfaction with appliance performance, and demographics data, such as number and age of occupants. The survey was performed at the start of the demonstration and at the conclusion of the demonstration when equipment was removed. If participants received new appliances, a new set of surveys were conducted on the new appliance.

### ***Data Collection Methods and Sites***

The control (baseline) group was formed using an assortment of existing appliances. Of course, the age, style, and model of the appliance varied. The treatment group varied depending on the utility overseeing the installations. Two of the utilities conducted a pre/post-measurement, where control units are instrumented for 60 days, and then treatment appliances are installed and instrumented in the same home.

An alternative method was used for the other utilities, where separate control and treatment sites were concurrently instrumented.

Although the analyses of the clothes washers, clothes dryers, and refrigerators were all separate, each site may have included more than one. The site came in three configurations: washer and dryer only, refrigerator only, and washer, dryer, and refrigerator. Clothes washers and clothes dryers always came as a pair.

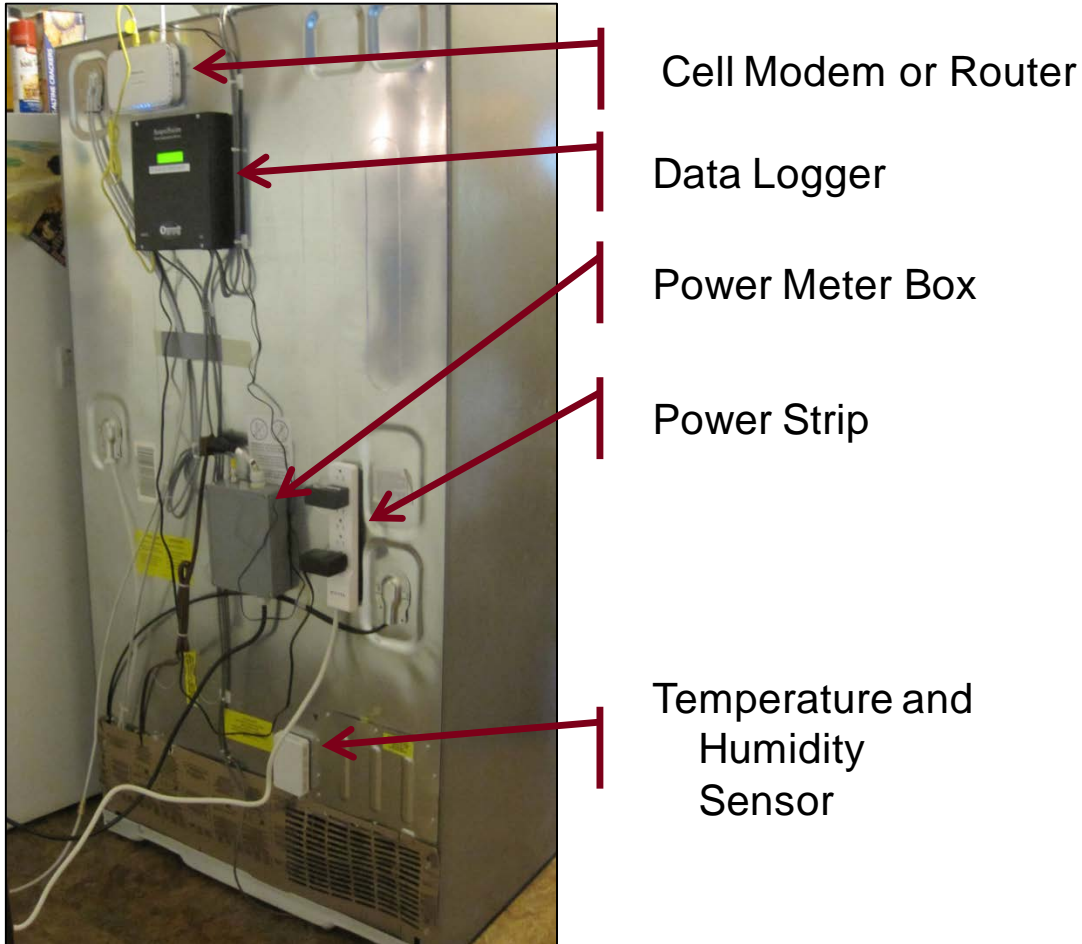
For the clothes washers and clothes dryers, the treatment group consisted of front loading washers with high spin speed and dryers with dryness control. The control group was a mixture of criteria such as vintage, fill volume, spin speed, and dryness control. The intent of the study was to compare, in aggregate, the performance of new washer/dryer pairs to a sample of the installed stock. Because of the aggregate comparison, no particular criteria were given to the type of washer/dryer pairs used as the control.

### ***Instrumentation***

Because the appliances under test were typically located in highly visible locations in residences, all instrumentation was selected to be as nonintrusive as possible. Instrumentation was placed on the back exterior of the appliance or on the wall behind the appliance (see Figure 7-14). Detailed

installation instructions including diagrams were created for each instrumentation package to aid technicians during installation.

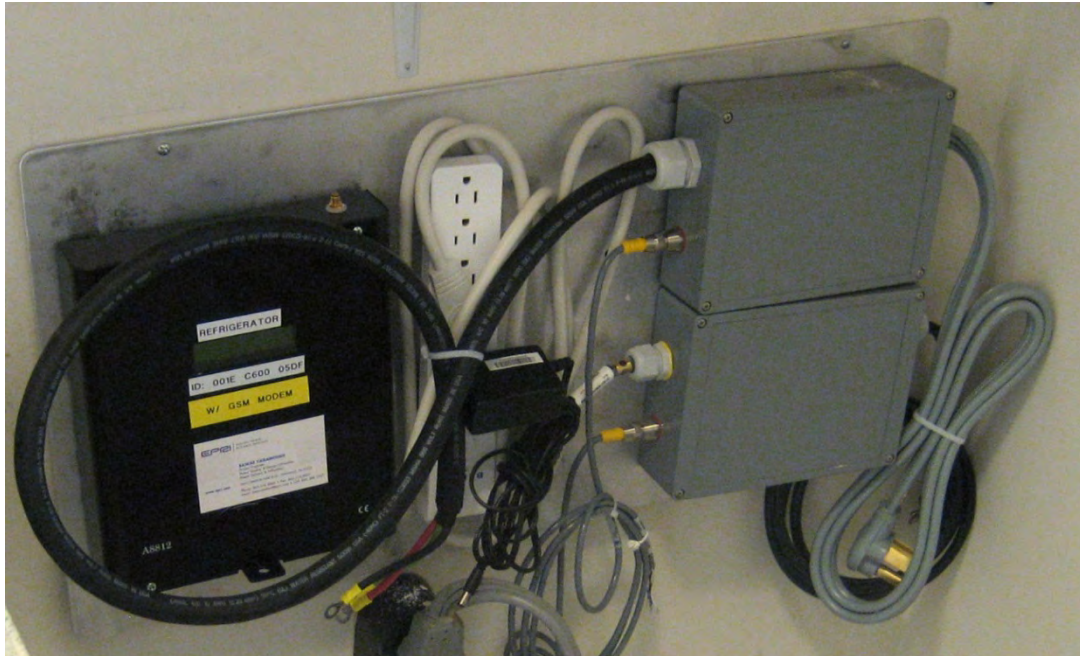
The refrigerator instrumentation came in two configurations. One contained a communications device (router or cell modem), a data logger, a power-meter box, and an ambient temperature and humidity meter. The other configuration was used when the refrigerator was paired with a washer and dryer combination in the same home. This configuration had an additional wireless communications device to allow wireless transfer of data with the datalogger located on the dryer instrumentation panel. The instrumentation was mounted to the back of the refrigerator, out of the way of occupants, using Velcro-like tape (see Figure 7-14).



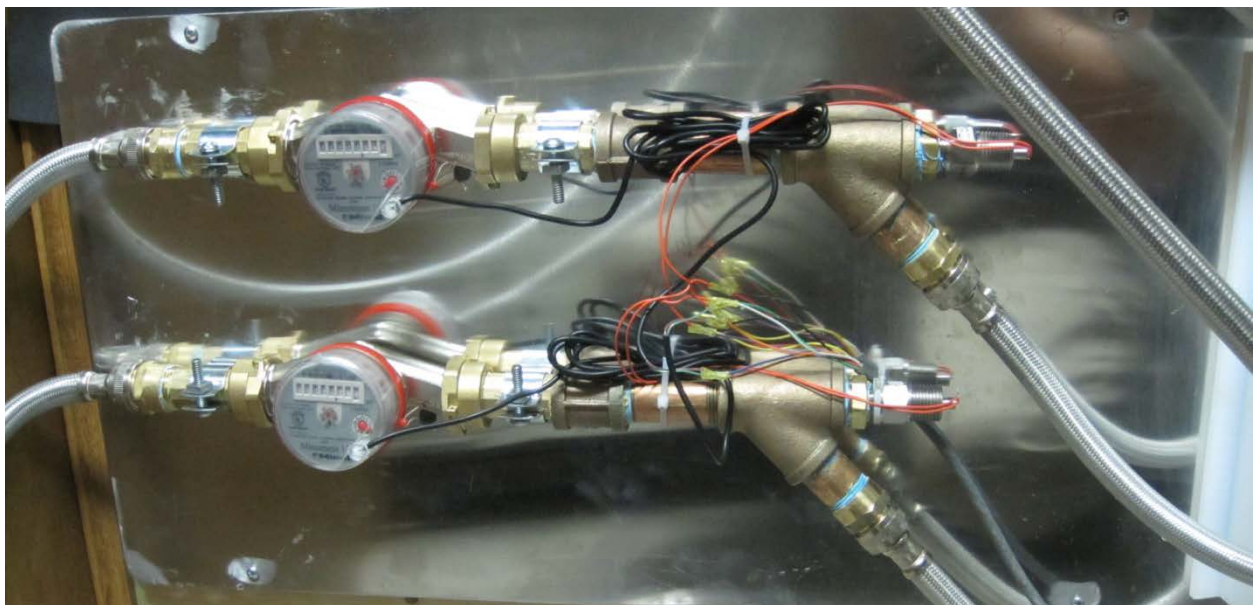
**Figure 7-14**  
**Instrumentation Mounted on the Back of a Refrigerator**

The clothes washer and clothes dryer were installed as a pair, so the instrumentation panels were shared. The dryer panel, as shown in Figure 7-15, contained a datalogger and power-measurement boxes for both the clothes washer and the clothes dryer. If the site was paired with a refrigerator, a wireless device was also present on this panel to receive the data collected from the refrigerator. The washer and dryer panels, as shown in Figure 7-15 and Figure 7-16, contained the flow meters, temperature sensors, and associated hardware to quickly and easily monitor water parameters. Both panels were mounted to the back of the pedestals onto which

was placed the washer and dryer. Doing so typically avoided having to modify the building structure to accommodate mounting of instrumentation.



**Figure 7-15**  
**Instrumentation on the Back of the Clothes Dryer**



**Figure 7-16**  
**Instrumentation Mounted on the Back of the Clothes Washer to Measure Hot/Cold Water Temperature and Flow**

## Installed Appliances

A list of appliances used within the Demonstration is provided in Table 7-8. The appliances chosen are a good representation of what is available in the market place that offers high efficiency. The selected appliances were also from mainstream manufacturers and were readily available with options to purchase warranties. Each of the appliances had ENERGY STAR labels, with the exception of the dryers, where an ENERGY STAR label is not available. The 4.5-cubic-foot, front-loading clothes washer installed for field testing had an MEF of 2.64 and a WF of 3.4, with a “Fan Fresh” option. The 7.2-cubic-foot, front-loading clothes dryer installed for field testing had an “Eco Normal” setting and advanced algorithms for termination control.

**Table 7-8**  
**Appliances Tested in the Energy Efficiency Demonstration**

Equipment Type	Technology	Capacity	Vendor	Door Type
Refrigerator	Multi-speed compressor	25.5 cu. ft.	Mfg. 1	French doors, freezer on bottom
Refrigerator	Efficient compressor and evaporator fan	21.9 cu. ft.	Mfg. 2	Two door, freezer on bottom
Refrigerator	Efficient compressor and configuration	18.9 cu. ft.	Mfg. 3	Two door, freezer on top

## Customer Surveys

Customer satisfaction regarding high-efficiency residential appliances was examined using online and mailed survey instruments. The surveys were provided to representatives at host utilities, who either forwarded the online survey links or mailed the print surveys to participating customers.

### **Survey Results: Refrigerators**

All customers indicated that they were satisfied with the performance of their energy-efficient refrigerators, and two respondents stated that they were “very satisfied.” Some comments provided reasons for their satisfaction, including adequate performance, ease of cleaning, and being “just the right size” to fit their family’s needs. Some customers also expressed a few complaints. One noted that the capacity of the water filter was “too small,” requiring them to change it more frequently than desired. This customer also indicated that “a part [fell] off of some component in the freezer compartment,” which was not easy to replace. Another customer indicated that the original refrigerator that they received during the demonstration broke and was replaced prior to the administration of the survey. Yet another customer noted that while they were satisfied with the performance of the unit, the configuration was not ideal with a “large hump in the middle on top by the interior,” making it “awkward to place tall items on the top shelf.”

When asked about the ease of access to stored food within the refrigerator, half of the respondents provided a rating of “easy,” and the other half “adequate.” Most customers also indicated that the refrigerator was easy to clean, with two respondents providing a rating of “adequate.”

Most customers found the noise level acceptable, but two indicated that this was not the case, with one citing “loud popping sounds” coming from their unit. The other customer remarked that the ice-maker was noisy at night, and that “ice falling into the bin sometimes [sounded] like burglars in the house.”

Customer feedback concerning high-efficiency refrigerators was in general positive, indicating overall satisfaction with the units’ performance. Some technical issues and equipment failures were observed, but repair or replacement seemed to remedy these issues without affecting customer acceptance. Negative feedback seemed to focus on design elements that likely vary from model to model and did not impact customers’ satisfaction of the high-efficiency refrigerators.

### ***Survey Results: Clothes Washers and Dryers***

Overall, most respondents indicated that they were very satisfied with the performance of their efficient laundry equipment. One respondent indicated that they were not satisfied with the performance of their washer, because it was not properly draining their clothes at the time the survey was administered. Another customer indicated that the drum of the washer had to be replaced within a year of its installation. Customers indicating high satisfaction cited reasons including excellent and reliable cleaning and drying performance, quiet operation, water and energy savings, attractive appearance, ease of use, provision of a steam cycle, and a wide selection of automatic settings.

All customers indicated that they were satisfied with the cleaning performance of the clothes washers, and almost all customers felt that the capacity of the washer was adequate to fit their needs. That said, one customer felt otherwise, indicating that the dryer’s capacity may be excessive. In general, most customers felt that the duration of their dryer’s operation was adequate, although one respondent indicated that the duration may be inadequate and that their washer was currently not draining their clothes properly. Because the washer’s spin cycle is designed to reduce the required drying time, this customers’ need for increased drying time may be explained by the issues experienced with their clothes washer.

Customer satisfaction concerning efficient clothes washers and dryers was positive. Despite some reported issues, participants indicated satisfaction with the equipment’s functional performance, energy savings, appearance, ease of use, and extensive offering of automatic operating modes.

## **Field Test Results**

### ***Clothes Washer and Dryer***

#### **Data Description**

Table 7-9 lists the number of control sites and treatment sites by utility and provides a total for each utility and the overall total of sites included in the analysis. The treatment data used in the

analysis include 14,267 days of data for dryer energy; 17,894 days of data for washer energy; and 18,002 days of data for water consumption for washers. For control installations: 12,716 days of dryer energy; 12,588 days of washer energy; and 12,608 days of washer water data. The counts of data apply for average-per-day calculations for both weekend days (Saturday and Sunday) and weekdays (Monday through Friday). Counts are the same for the data used to analyze load shape.

As discussed previously, some utilities chose to have separate control and treatment installations. Utility 4 is unique with a pre-post configuration. This means that the existing appliances were monitored for a period of time (typically sixty days), then the appliances were replaced with the treatment equipment. The pre-post configuration has the advantage of maintaining the same household demographic compared to the control-treatment sites, which did not control for household demographic.

An algorithm was used to determine the number of washer and dryer loads. There were a total of 12,438 dryer loads and 10,100 washer loads analyzed. Out of the dryer loads, 5,988 used treatment clothes-dryers, and 6,450 used control clothes dryers. Out of the washer loads, 4,308 used control clothes washers, and 5,792 used treatment clothes washers.

In this demonstration, the comparison of control and treatment groups was conducted using energy (kWh), demand (kW), and water consumption instead of using water factor or other washer/dryer metrics which allows for electric utilities to relate the technology’s savings potential to the impact on their industry.

**Table 7-9  
Total Installations for Appliances Demonstration**

Utility	Control Installations (Existing Residential Appliances)		Treatment Installations (High-Efficiency Residential Appliances)		Total Number of Individual Appliances Measured
	Washer Units	Dryer Units	Washer Units <sup>†</sup>	Dryer Units <sup>†</sup>	
3	6*	6*	7*	8*	27
4	9*	9*	3+10*	3+9*	43
5	3	3	10	10	26
6	10	10	7	7	34
Total	28	28	37	37	130

\* Pre-treatment sites.  
† All treatment units were the same model clothes washer and clothes dryer.  
Note: Some installations experienced interruptions in data, and some units had to be removed from the analysis.

## System Impact

### *Energy*

Figure 7-17 and Figure 7-18 show the energy in kWh for all treatment and control washer and dryers. The machine energy value is the average daily value for all washers and dryers, excluding the energy content of water. Three cases are given: weekday, weekend day, and average day. Weekday and weekend day were chosen to highlight the difference in time of energy use—more laundry is cleaned on the weekend. Average day is given to enable comparison with the ENERGY STAR rating. Included, but broken out with a separate color, is the energy content of the heated water. Figure 7-17 provides results with water heated using resistive elements (a standard electric water heater). Figure 7-18 provides the results with water heated using a heat pump water heater. For both cases, the energy value is calculated using the coefficient of performance determined using data from the heat pump water heater (HPWH) portion of the Energy Efficiency Demonstration.

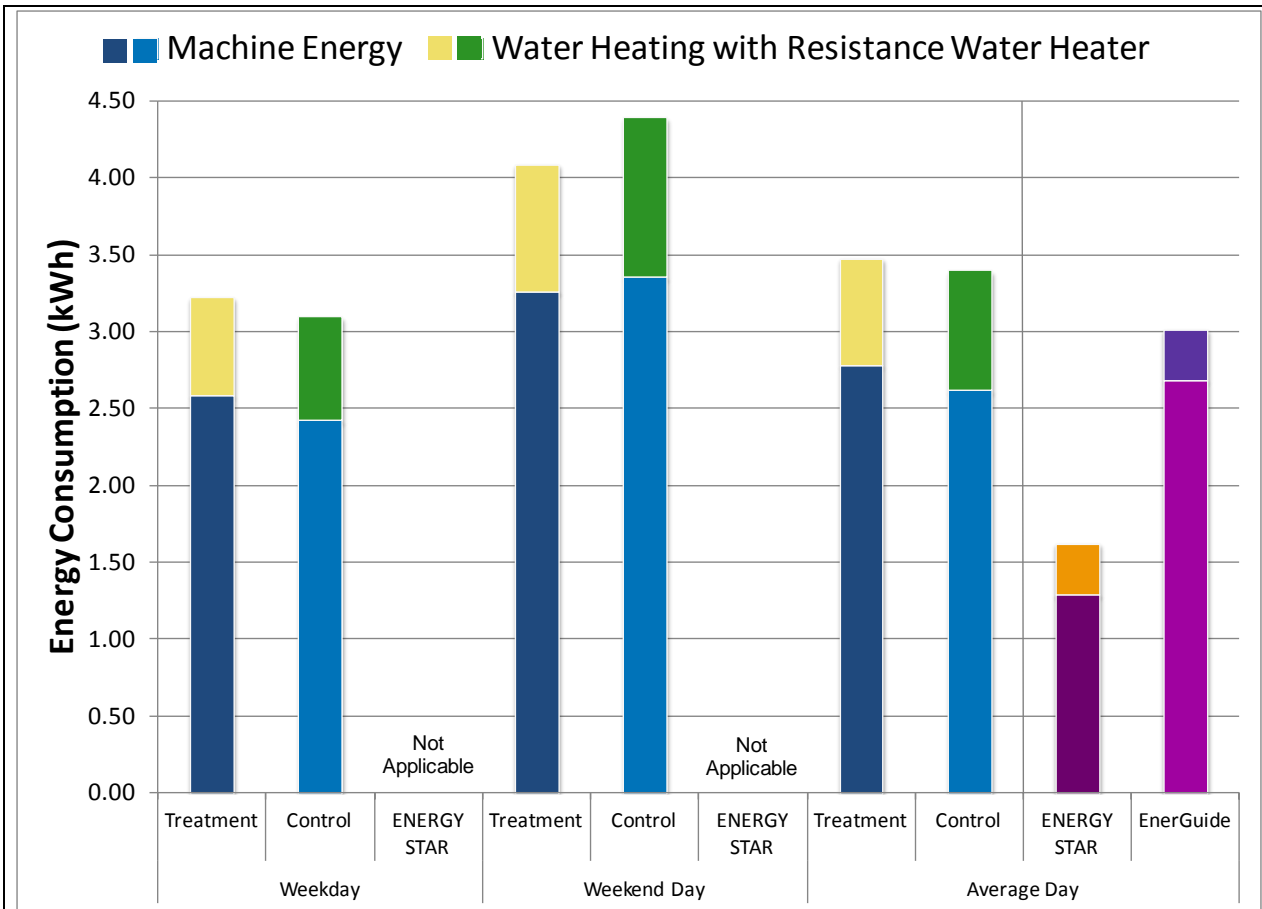
Comparison of energy for any of the cases does not show a significant energy savings of the treatment over control. During the weekday, the treatment washer and dryer used slightly more energy than the control. In the case of the weekend day, the control used slightly more energy than the treatment. And for an average day, the treatment again used slightly more than the control.

Because energy savings in the laundry cycle is directly related to the spin speed in the washer and because no significant energy savings were seen between aggregated control and treatment groups, it is likely that the control group in this study included a significant number of washers with a high spin speed feature.

Four washers in the control group consumed over 40 gallons per load. These are likely deep fill washers. While not extensible because of the small number of samples and uncertainty of the vintage, fill volume, spin speed, and presence of dryness control, analysis of the data for the four washer/dryer pairs with washer water consumption over 40 gallons per load compared to the aggregated treatment group resulted in energy savings of 31% (1089 Wh), 10% (12 minutes) reduction in total run time, and 62% reduction in water consumption (29.7 gallons).

Because of the mix of washers in the control group, it is not a result of the study that high efficiency (high spin speed, low water fill) washers have the same efficiency as conventional (low spin speed, deep water fill) washers.

ENERGY STAR certifies clothes washers only, not clothes dryers. However, based on ENERGY STAR assumptions, it was possible to calculate a value for the combined energy use of an ENERGY STAR washer/dryer pair. Data from the demonstration shows that both the control and the treatment used approximately double the energy calculated for ENERGY STAR while the value from the Canadian equivalent of EnergyStar, EnerGuide, which includes a listing for the dryer, approximately agrees with control and treatment average day energy use



NOTES

ENERGY STAR values are derived from U.S. Department of Energy data and apply only to washers.

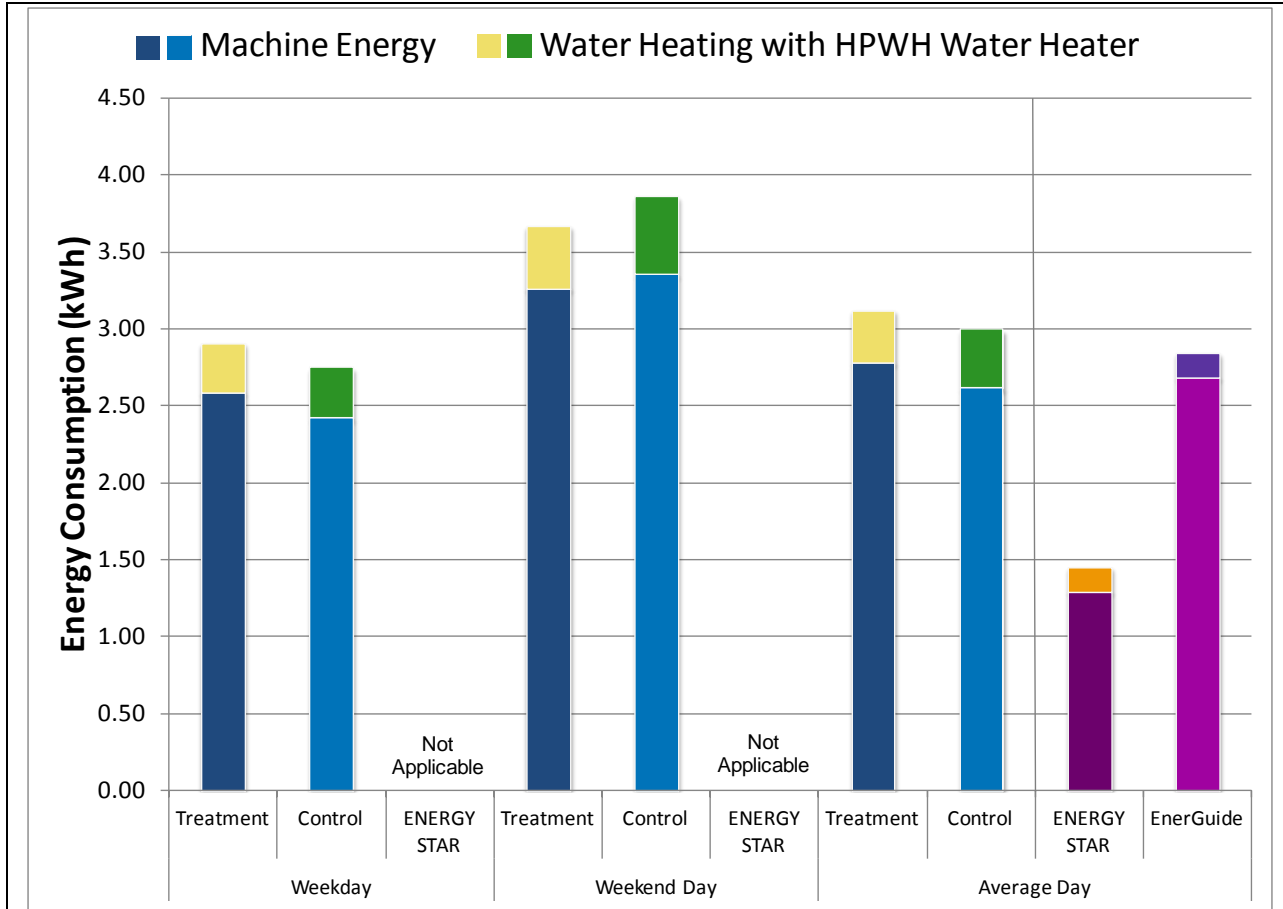
Because ENERGY STAR does not provide dryer consumption measurements, values were obtained from two sources, ENERGY STAR consumption calculators and EnerGuide in Canada. It was confirmed that the Canadian and US models are identical.

Savings are expressed for washer and dryer cycle only. ENERGY STAR assumes 392 loads per year (8 loads per week) and includes energy consumption of water and 445 kWh for a dryer paired with an ENERGY STAR clothes washer.

Energy required for heating water based on demonstration measured cold temperature of 50°F (10°C) and hot temperature 125°F (52°C).

The COP assumed for resistive water heaters is 0.83 and is derived from an average of the results from the HPWH portion of the Demonstration.

**Figure 7-17**  
**Energy Savings of Treatment Washer and Dryer Pairs with a Calculated Cost of Hot Water Energy Using Water Heaters with Resistive Heating Elements**



NOTES

ENERGY STAR values are derived from U.S. Department of Energy data and apply only to washers.

Savings are expressed for washer and dryer cycle only. ENERGY STAR assumes 392 loads per year (8 loads per week) and includes energy consumption of water and 445 kWh for a dryer paired with an ENERGY STAR clothes washer.

Because ENERGY STAR does not provide dryer consumption measurements, values were obtained from two sources, ENERGY STAR consumption calculators and EnerGuide in Canada. It was confirmed that the Canadian and US models are identical.

Energy required for heating water based on demonstration measured cold temperature of 50°F (10°C) and hot temperature 125°F (52°C).

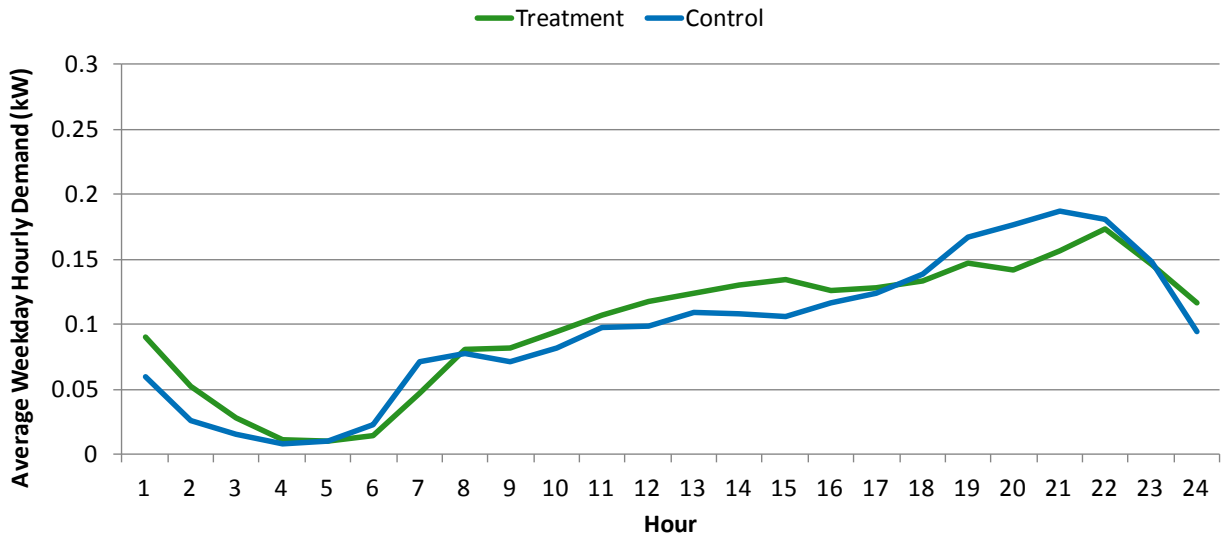
The COP assumed for HPWHs was 1.69 and is derived from an average of the results from two models in the HPWH portion of the Demonstration.

**Figure 7-18**  
**Energy Savings of Treatment Washer and Dryer Pairs with Calculated Hot Water Energy Cost Using Heat Pump Water Heaters by Type of Day (Weekday, Weekend Day, Average Day) Compared to Both the Control Installations and the ENERGY STAR Rating**

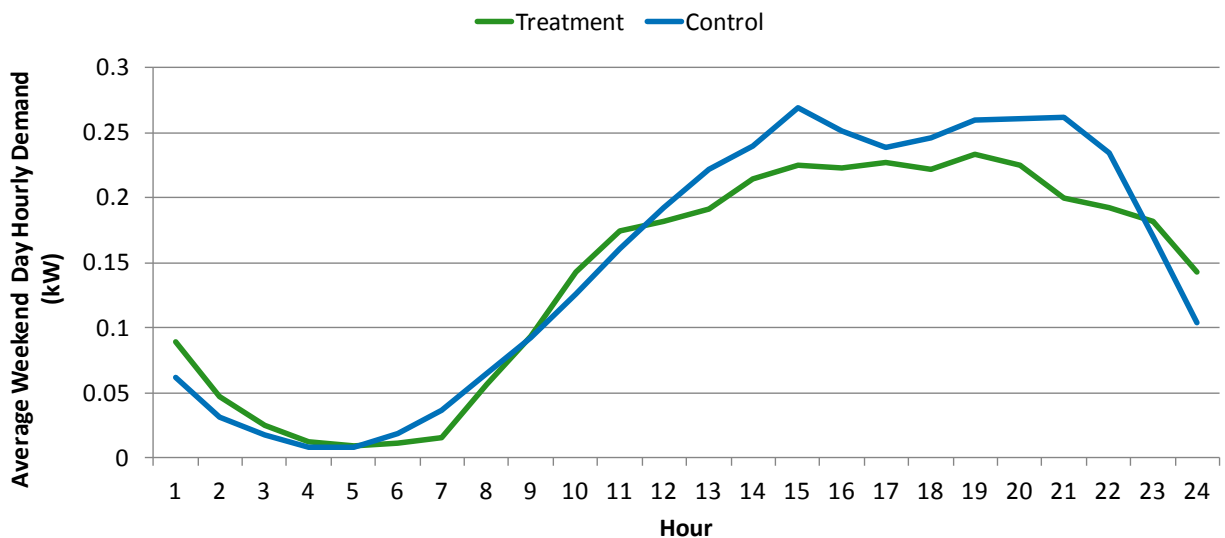
Load Shapes

In addition to energy use, the data collected allows for creation of a graphic illustrating the load shape for both weekday and weekend (see Figure 7-19 and Figure 7-20). In either case,

significant savings is not apparent. The load shapes indicate that, as expected, the majority of users operate their laundry appliances later in the day and more often on the weekend.



**Figure 7-19**  
Average Load Shape for a Weekday of a Washer and Dryer Pair for Both Control and Treatment Installations



**Figure 7-20**  
Average Load Shape for a Weekend Day of a Washer and Dryer Pair for Both Control and Treatment Installations

### Technology Assessment

The objective of the technology assessment was to determine technological drivers for energy savings, such as equipment features, control strategies, and operational features. Specific analysis includes the consumption per laundry cycle, water use, and power profiles.

### Energy per Laundry Cycle

For the purpose of this report, laundry cycle is defined as the electrical work needed to accomplish washing and drying of laundry and includes the energy for both the washer and dryer and, where noted, the energy in the hot water. Clothes washer cycles were assumed to take no less than ten minutes and run no longer than two hours. Any cycles that did not consume water were also removed. Clothes dryer cycles were assumed to take no less than five minutes and no longer than two hours. It was also assumed that dryer cycles could take no less than ten watts.

Table 7-10 lists the average energy per laundry cycle for all sites separated by washer/dryer machine energy and energy content of the water supplied to the washer from either a resistive element water heater or a heat pump water heater. Table 7-11 is similar but restricts the data to only those sites that used a pre/post control method, which means the same family for both the control and treatment appliances. The results for the all-data installations show almost no savings in washer/dryer machine energy and an increase in average cycle time of 4.6%. However, the data shows a 17% savings in the amount of energy needed to heat water for an average laundry cycle. The actual energy savings depends on the technology used to heat the water. In the case of the less-efficient resistive water heater, the savings per laundry cycle was 0.15 kWh. For heat pump water heaters, which are more efficient, the savings are 0.08 kWh per laundry cycle or roughly half the energy of the resistive heater.

In Table 7-11, which provides results for the pre/post sites, the treatment washer and dryer machine energy was greater than the control and thus had a negative savings. In terms of time, the treatment equipment operated on average 5.1 minutes or 12% longer than the control. For water energy, the savings closely agreed with the all-data installations with 16% savings or 0.15 kWh for resistive water heater and 0.07 kWh for heat pump water heater.

**Table 7-10**  
**Average Energy per Laundry Cycle for All Installations**

Data for All Installations	Average Energy per Laundry Cycle*			
	Washer/Dryer Machine Energy		Energy Content of the Hot Water**	
	kWh	minutes	Resistive Water Heater (kWh)	Heat Pump Water Heater (kWh)
Treatment Washer/Dryer	2.47	108.5	0.94	0.46
Control Washer/Dryer	2.50	103.9	0.78	0.38
Savings	0.03 (1%)	-4.6 (-4%)	0.15 (17%)	0.08 (17%)

\* Average energy per laundry cycle combines weekdays and weekend days.

\*\* The coefficient of performance (COP) used for resistive water heater is 0.83, and for heat pump water heater is 1.69. The water savings between treatment and control was 0.70 gallons per laundry cycle. The water temperatures were taken from the Demonstration results and are 50°F (10°C) and hot temperature 125°F (52°C) for hot water.

**Table 7-11**  
**Average Energy per Laundry Cycle for Pre/Post Installations**

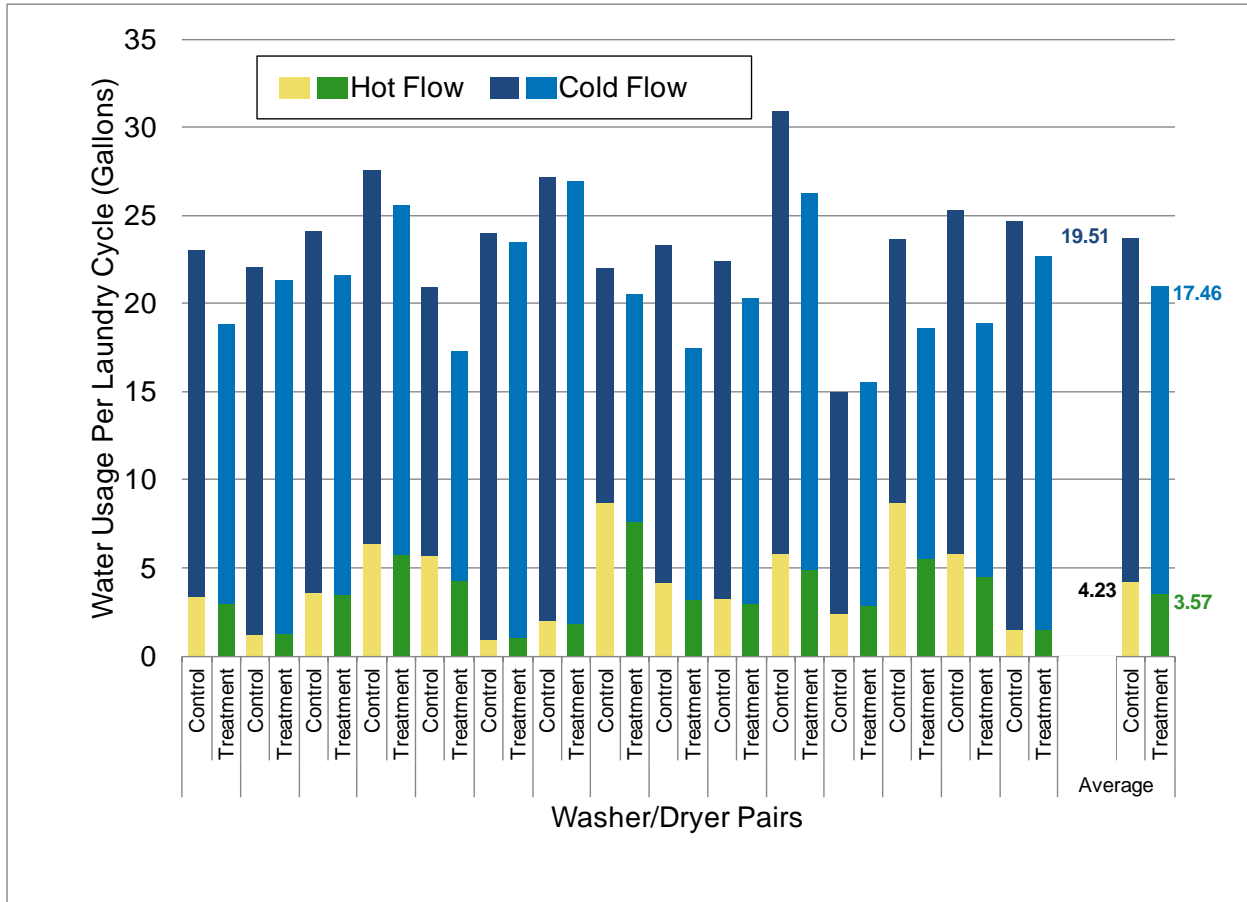
Data for Pre/Post Installations	Average Energy per Laundry Cycle*			
	Washer/Dryer Machine Energy		Energy Content of the Hot Water**	
	kWh	minutes	Resistive Water Heater (kWh)	Heat Pump Water Heater (kWh)
Treatment Washer/Dryer	2.21	100.6	0.93	0.46
Control Washer/Dryer	2.10	95.3	0.79	0.39
Savings	-0.12 (-6%)	-5.3 (-5.6%)	0.15 (16%)	0.07 (16%)

\* Average energy per laundry cycle combines weekdays and weekend days.  
\*\* The coefficient of performance (COP) used for resistive water heater is 0.83, and for heat pump water heater is 1.69. The water savings between treatment and control was 0.66 gallons per laundry cycle. The water temperatures were taken from the Demonstration results and are 50°F (10°C) and hot temperature 125°F (52°C) for hot water.

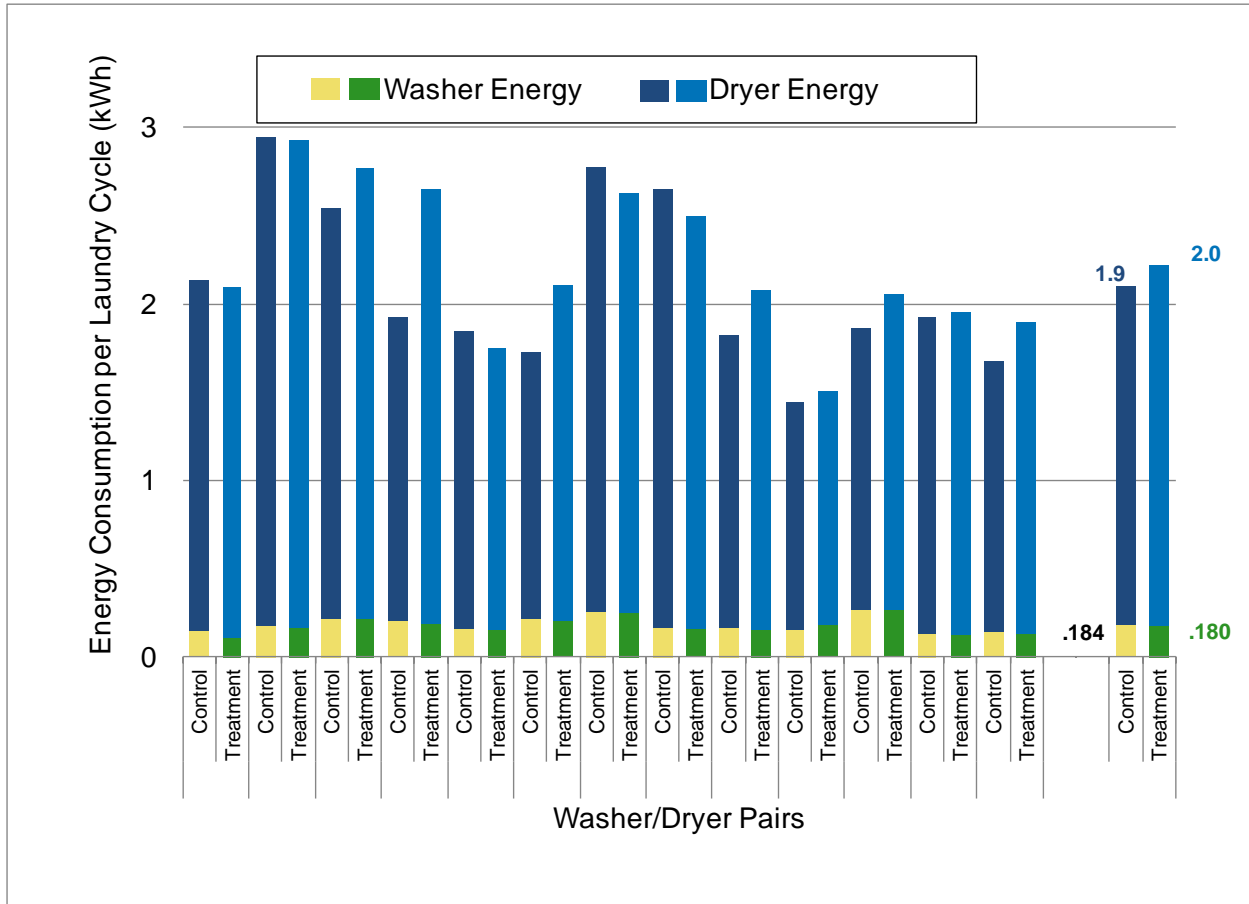
Figure 7-21 is a stacked bar chart showing *water usage* per laundry cycle for fifteen installations from the pre/post control group plus an overall average of the fifteen installations. The data from the pre/post control group is used in the following paragraphs as it allows for a comparison of the previously installed washer/dryer pair to the new treatment while reducing the influence of changes to household demographics. However, it was not verified whether changes occurred in the home or with respect to the occupants over the course of the demonstration. Water use is given for both cold and hot water. Treatment washing machines were expected to use less water, which is supported by the data. However, the data suggests that the majority of the water savings is cold water, with an average savings of 2.05 gallons of cold water and 0.66 gallons of hot water.

Figure 7-22 is a stacked bar chart showing the *energy per laundry cycle* for fifteen installations from the pre/post control group plus an overall average of the fifteen installations. Energy is given for both the washer and the dryer. The energy data includes only electricity use and excludes the energy needed to heat water. The data suggests that the dryer dominated the overall energy use, with the treatment installations using 0.1 kWh more energy than the control for an average laundry cycle. The data suggests that the advanced washing machines did not produce savings in dryer energy compared to the control group.

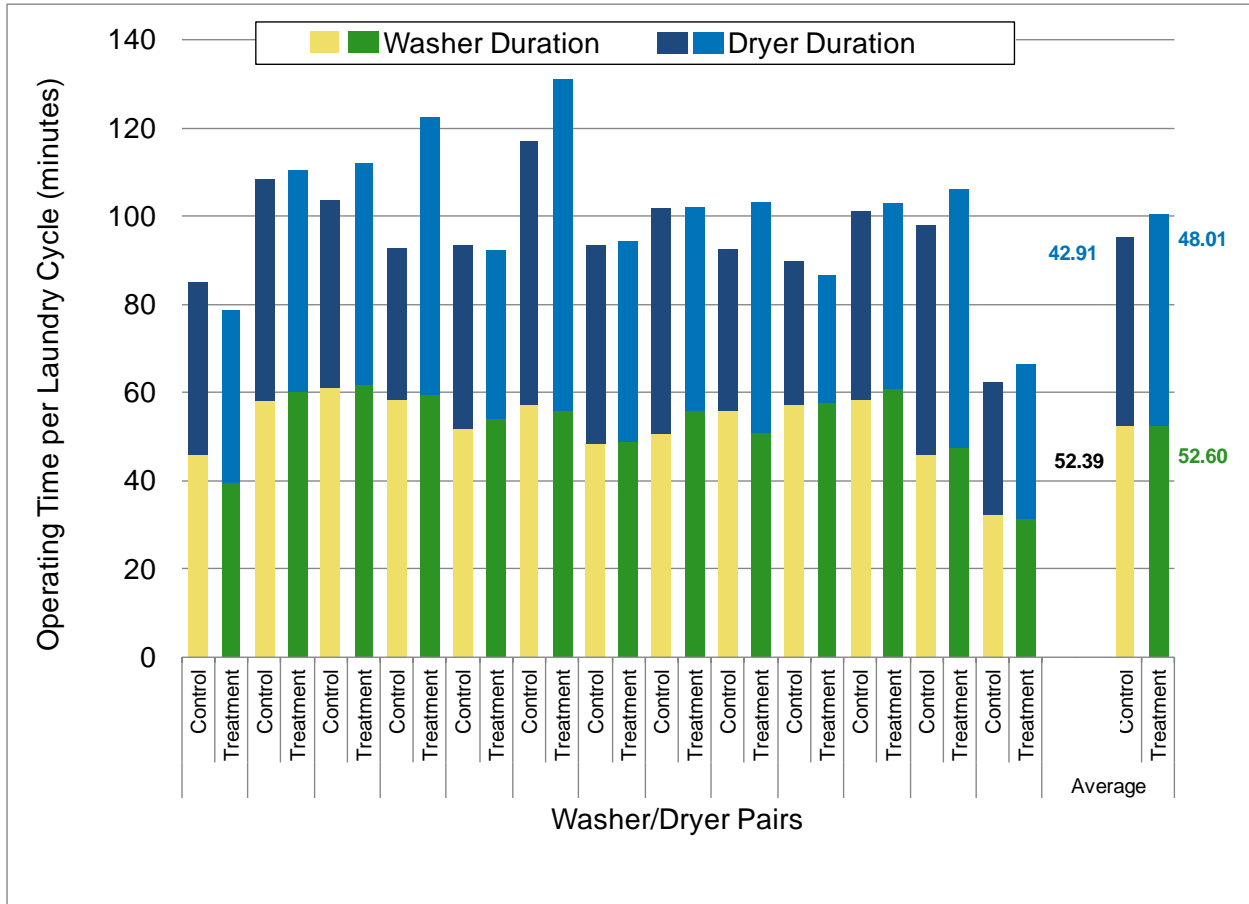
Figure 7-23 is stacked bar chart showing *operating time per laundry cycle* for fifteen installations from the pre/post control group plus an overall average of the fifteen installations. The data suggests that on average the control and treatment washer operates a similar length of time. However, the data shows the treatment dryer operated on average 5.1 minutes longer than the control. The average data is listed in Table 7-12.



**Figure 7-21**  
**Average Water Usage per Laundry Cycle for Fifteen Sites with Pre/Post Control Configuration**



**Figure 7-22**  
**Average Energy per Laundry Cycle Excluding Energy Content of the Hot Water for Fifteen Installations with Pre/Post Configuration**



**Figure 7-23**  
Average Operating Time per Laundry Cycle for Fifteen Installations with Pre/Post Configuration

**Table 7-12**  
Average Time per Laundry Cycle of a Washer and Dryer Pair for Both Control and Treatment Installations

	Average Time per Wash Cycle (minute)	Average Time per Dryer Cycle (minute)	Average Time per Laundry Cycle (minute)
Control	52.4	42.9	95.3
Treatment	52.6	48.0	100.6
Difference	-0.2	-5.1	-5.3

*Power Profiles*

The power profile for each washer and dryer is not constant but varies depending on the selected settings on the front panel by the operator. Figure 7-24 through Figure 7-30 are representative examples of the various power profiles from the thousands of cycles collected over the course of the Demonstration.

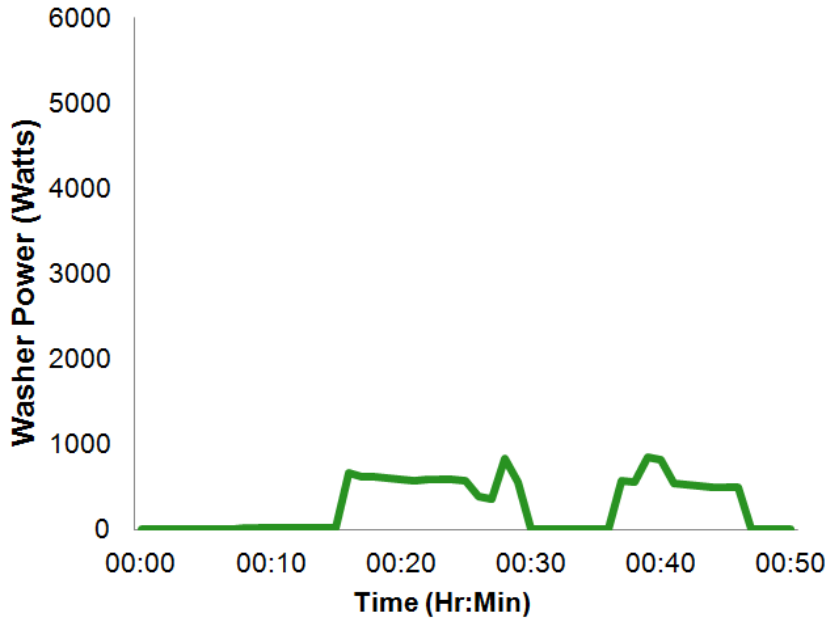


Figure 7-24  
Representative Power Profile for a Control Clothes Washer

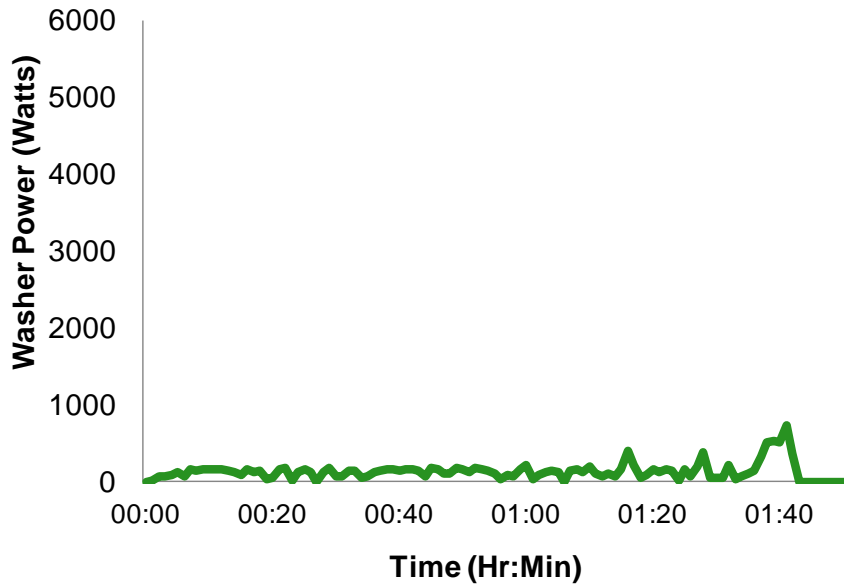


Figure 7-25  
Representative Power Profile for a Treatment Clothes Washer

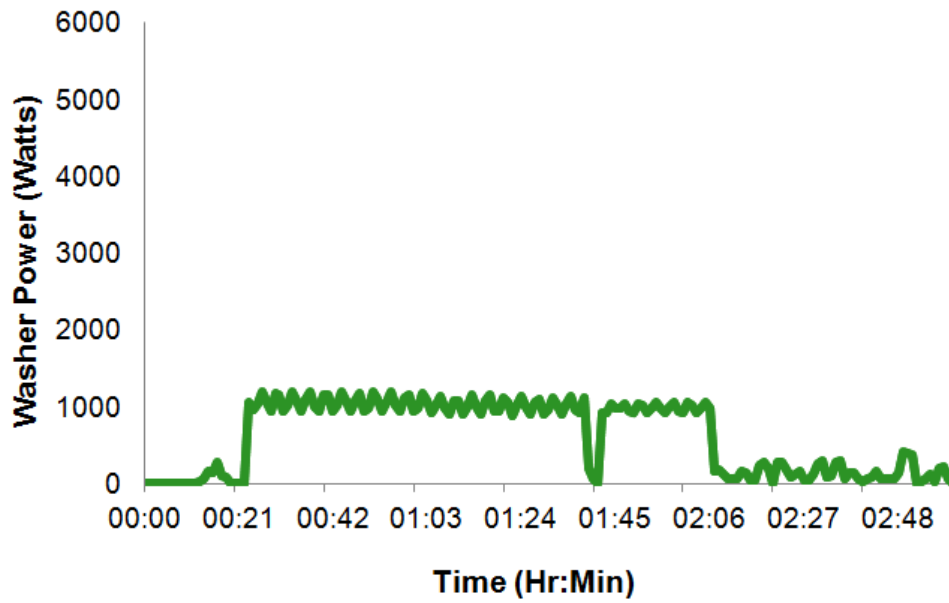


Figure 7-26  
Representative Power Profile for a Treatment Washing Machine Configured for Steam Cycle

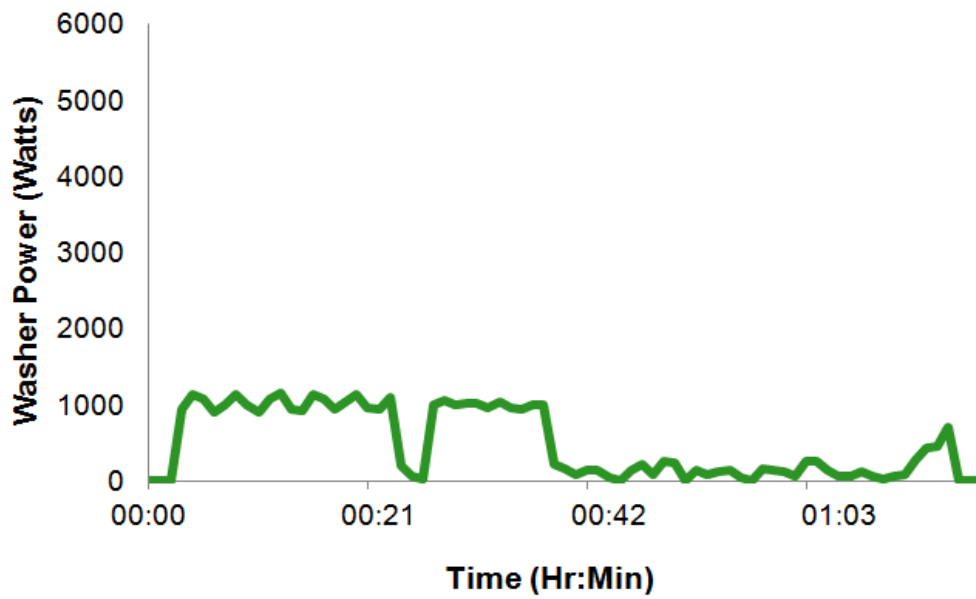


Figure 7-27  
Representative Power Profile for a Treatment Washing Machine Configured for Sanitize and Steam Cycle

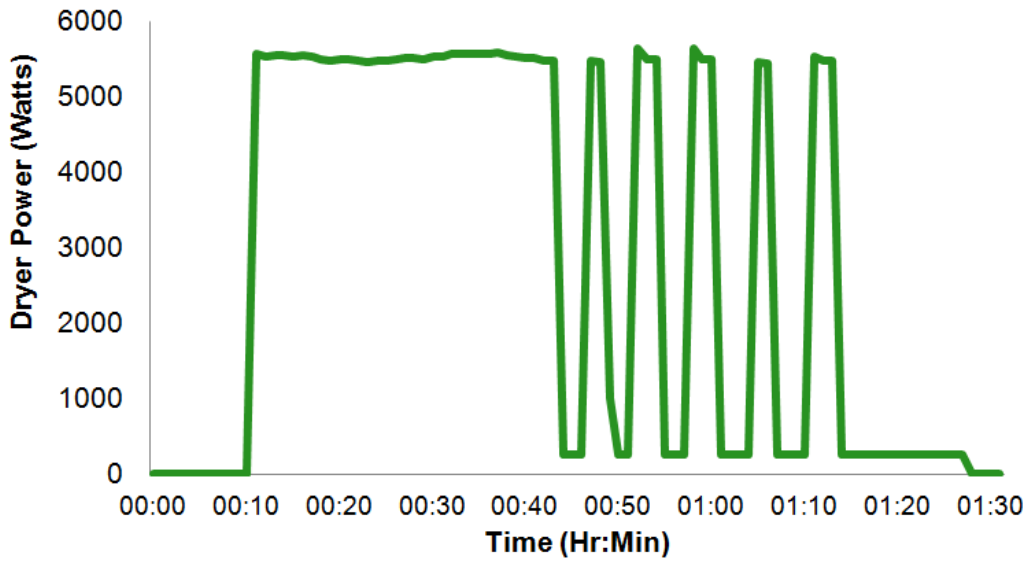


Figure 7-28  
Representative Power Profile for a Control Dryer

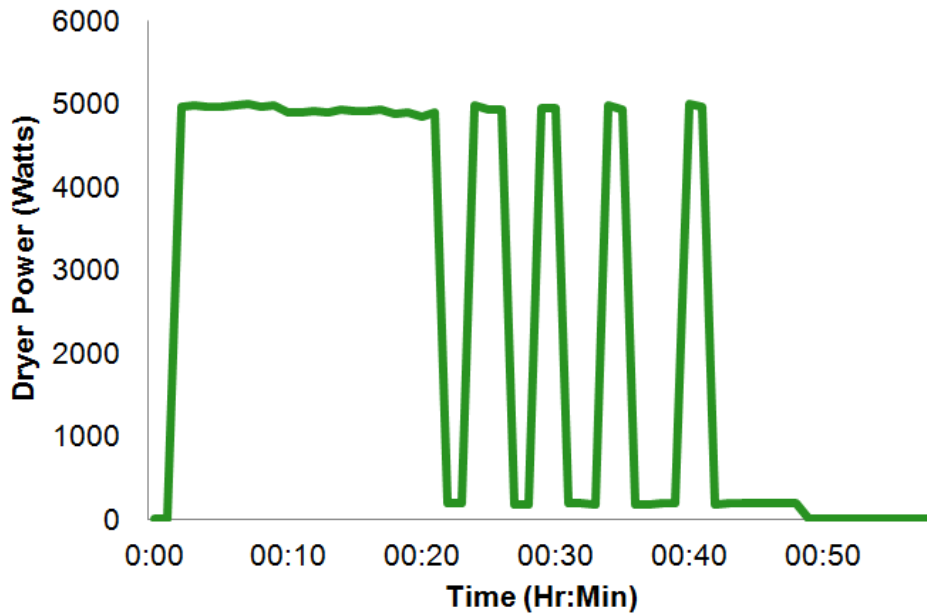
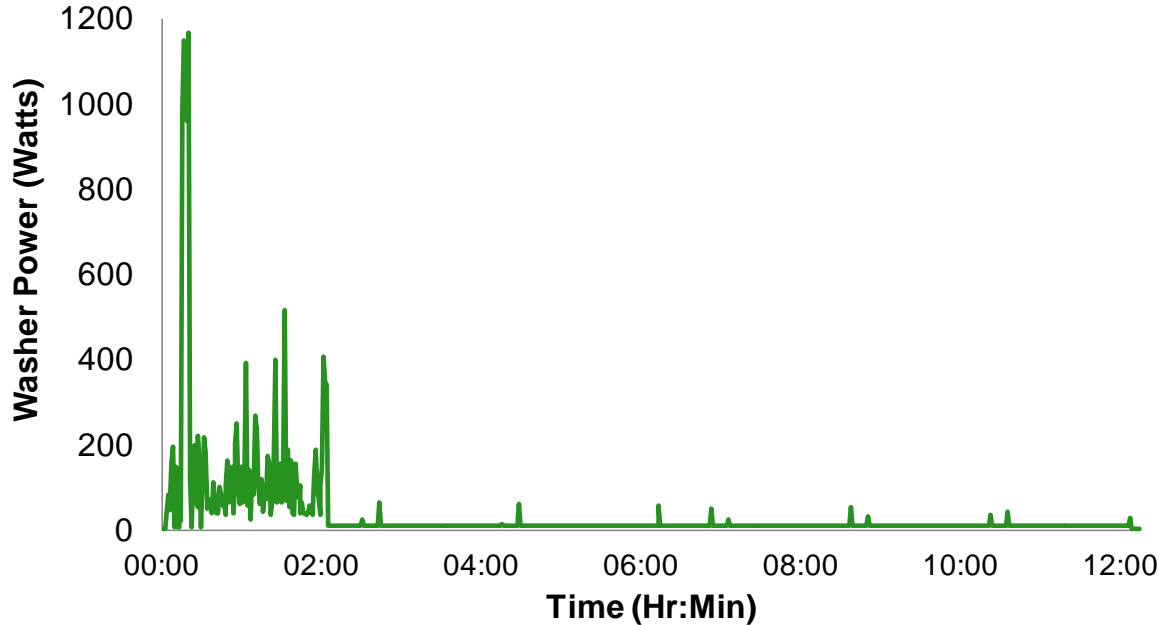


Figure 7-29  
Representative Power Profile for a Treatment Dryer



**Figure 7-30**  
**Representative Power Profile for a Treatment Washing Machine Using the Refresh Setting**

## Refrigerators

### Data Description

Table 7-13 lists the number of control installations and treatment installations by utility and provides a total for each utility and the overall total of installations included within the analysis. The analysis consisted of 12,851 days of treatment data and 6,311 days of control data. The refrigerator from manufacturer 1 consisted of three installations accounting for 1,705 days, manufacturer 2 consisted of 25 installations and 7,287 days of data, and manufacturer 3 consisted of 12 installations and 3,859 days of data. Manufacturer and model information was not retrieved for control installations.

Some utilities chose to have separate control and treatment installations. Utility 4 is unique with a pre-post configuration. This means that the existing appliances were monitored for a period of time (typically sixty days), then the refrigerators were replaced with the treatment equipment. The pre-post configuration has the advantage of maintaining the same household demographic compared to the control-treatment installations, which did not control for household demographics.

**Table 7-13  
Number of Refrigerator Installations by Manufacturer and Utility**

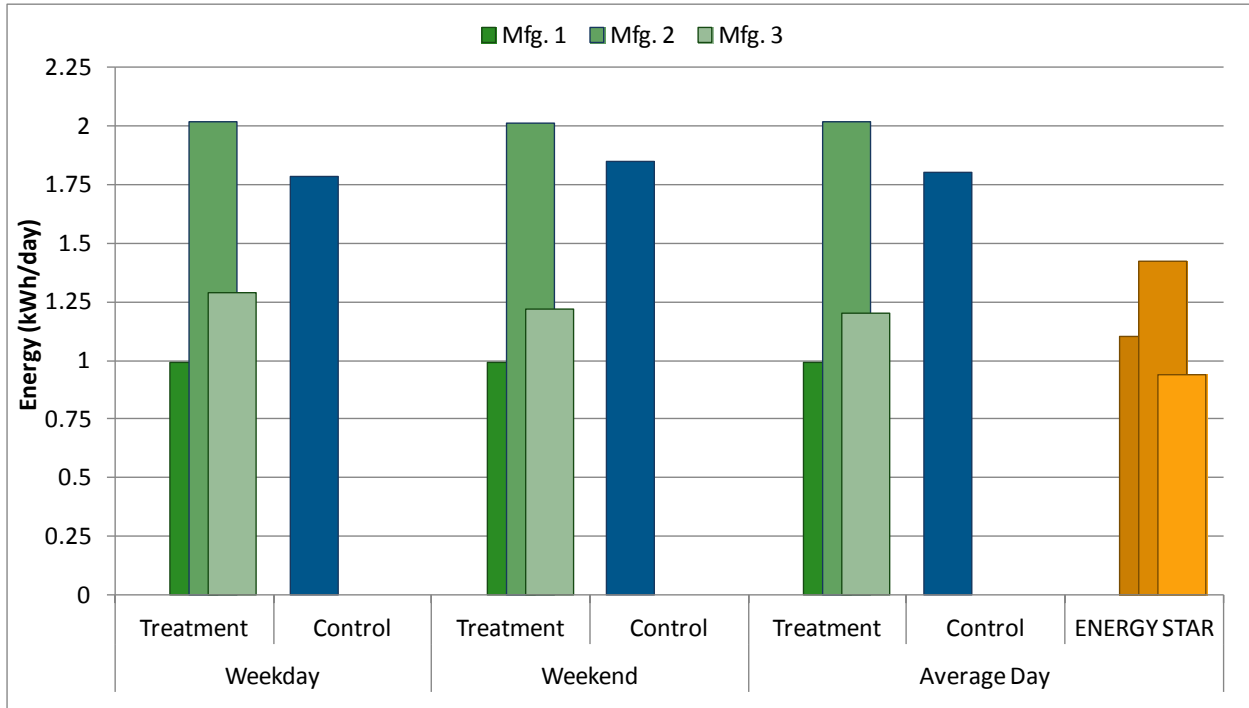
	Treatment				Control	Combined Total
	Mfg 1	Mfg 2	Mfg 3	Treatment Total	Control Total	
Utility 3	0	2+5*	1*	2+6*	6*	14
Utility 4	0	3+9*	2*	3+11*	11*	25
Utility 5	3	4	5	12	2	14
Utility 6	0	0	7	7	12	19
Total	3	23	15	41	31	72

\* Pre/Post Control

### System Impact

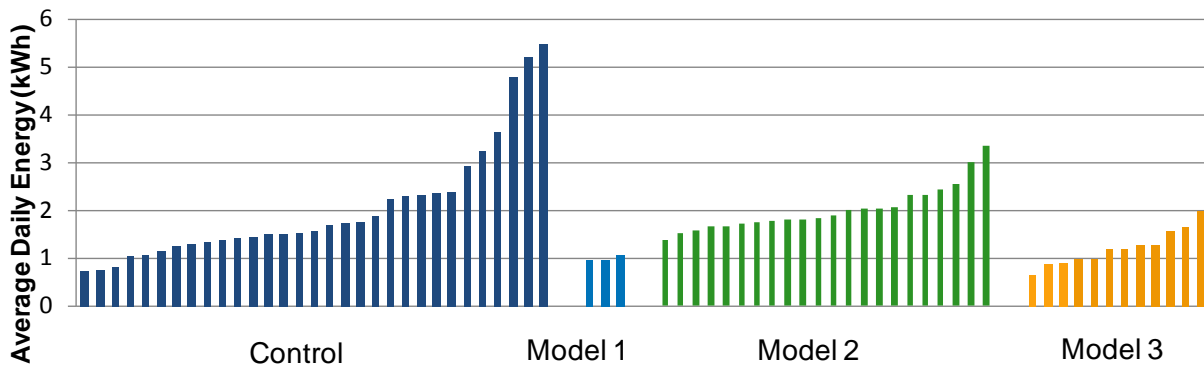
#### Energy

Figure 7-31 is a bar chart showing the energy use of treatment refrigerators by type of day (weekday, weekend, average) compared to both the control installations and the ENERGY STAR rating. Because the energy consumption of the refrigerator provided by manufacturer 2 is high compared to manufacturers 1 and 3, rather than show an average, data is provided for each manufacturer. The data does not show a significant difference between weekday, weekend day, and average. Compared to the control, the average savings by model number is: 45% (0.81 kWh) for manufacturer 1, -6% (-0.11 kWh) for manufacturer 2, and 33% (0.60 kWh) for manufacturer 3. The refrigerator supplied by manufacturer two significantly exceeded the rating provided by ENERGY STAR.



**Figure 7-31**  
**Energy of Treatment Refrigerators by Type of Day (Weekday, Weekend, Average)**  
**Compared to Both the Control Installations and the ENERGY STAR Rating**

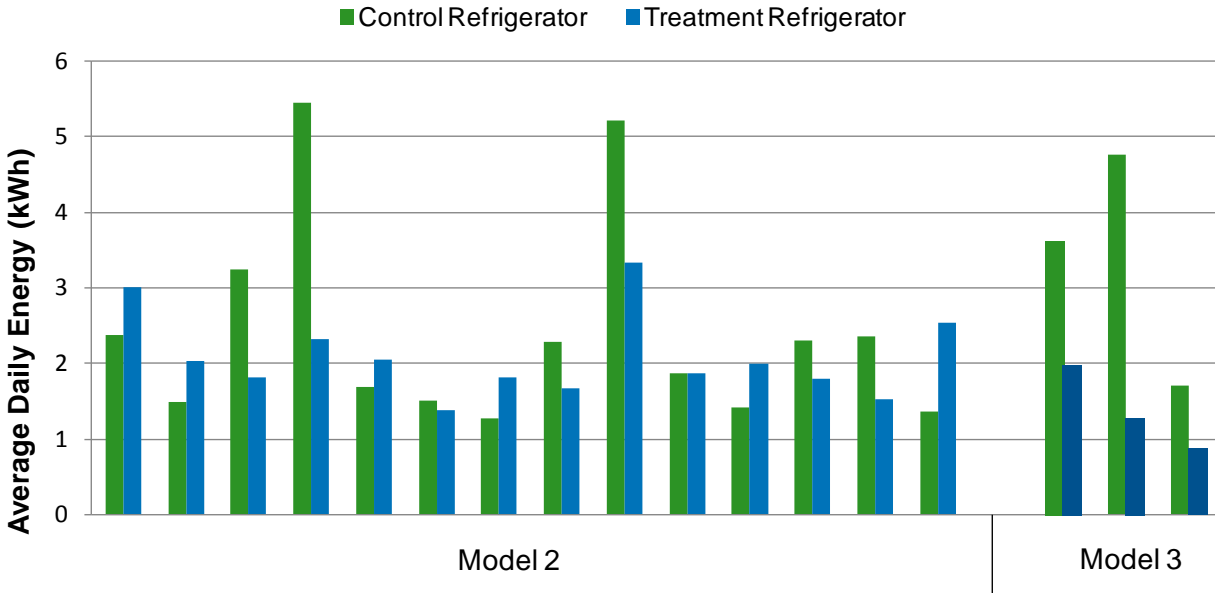
Figure 7-33 shows the average of the daily energy for each installation type (both control and treatment). The installations are sorted by energy use (least to most). The data shows a fairly high range of energy consumption for installations using the control and manufacturer 2.



**Figure 7-32**  
**Average Daily Energy for Each Installation by Control and Treatment (Models 1 – 3)**

Figure 7-33 is a bar chart showing the average daily energy of treatment refrigerators from the pre/post configuration, which had installation of both models by manufacturer 2 (model 2) and manufacturer 3 (model 3). The pre/post configuration provides a degree of control over the

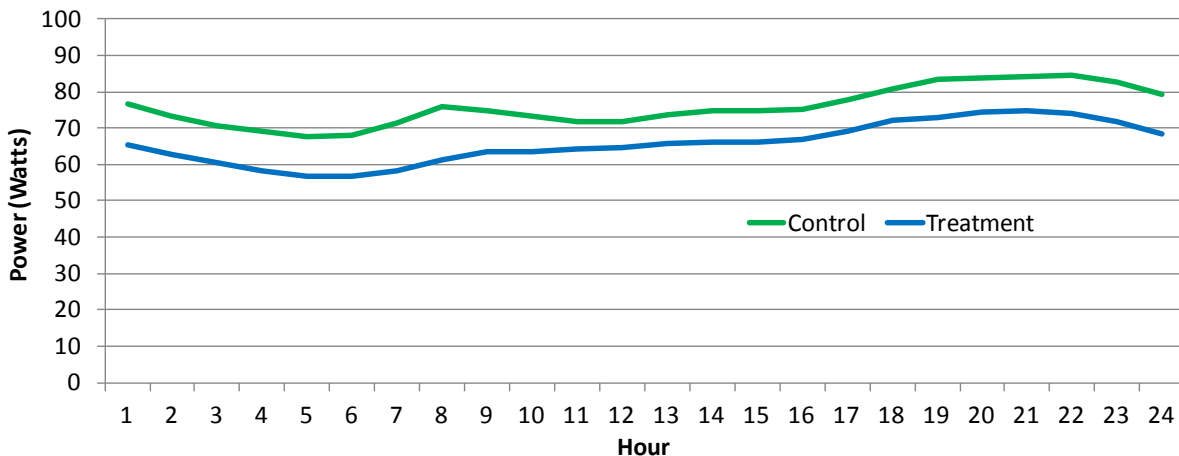
household demographics. The chart shows that even for model 2, which is the highest energy user, energy savings is possible. Model 3 shows significant savings for all three installations.



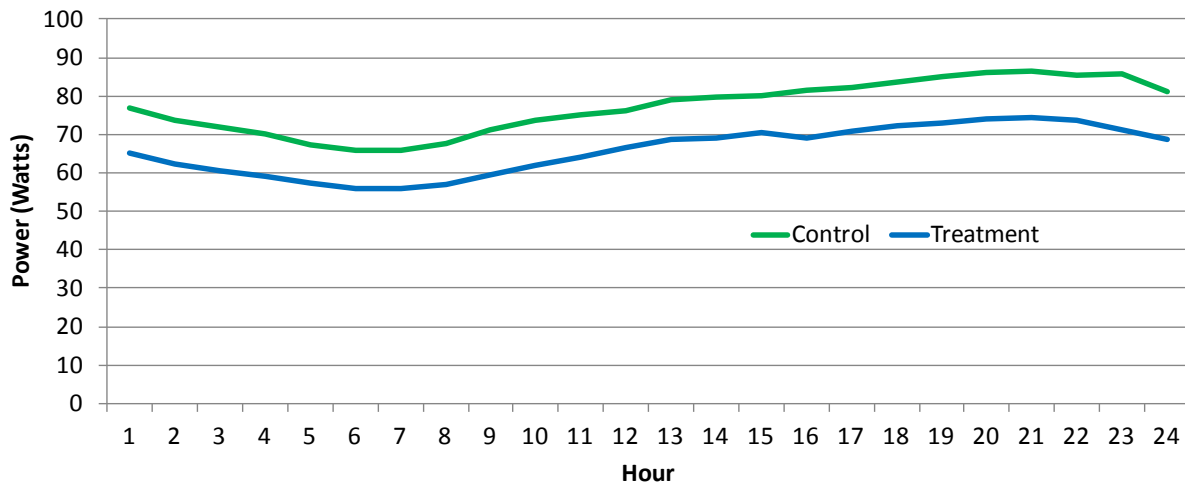
**Figure 7-33**  
Average Daily Energy of Treatment Refrigerators for Pre/Post Control Configuration

*Load Shapes*

The data collected allows for creation of a graphic illustrating the hourly load shape for both weekday (Figure 7-34) and weekend (Figure 7-35) for the refrigerators. In general the load shape is flat. Table 7-14 lists the maximum and minimum values for the load shape as well as the average hourly savings, which were approximately the same for both week day and weekend day at 11.30 and 10.05 W, respectively.



**Figure 7-34**  
Average Load Shape for a Weekday for Both Control and Treatment Refrigerators



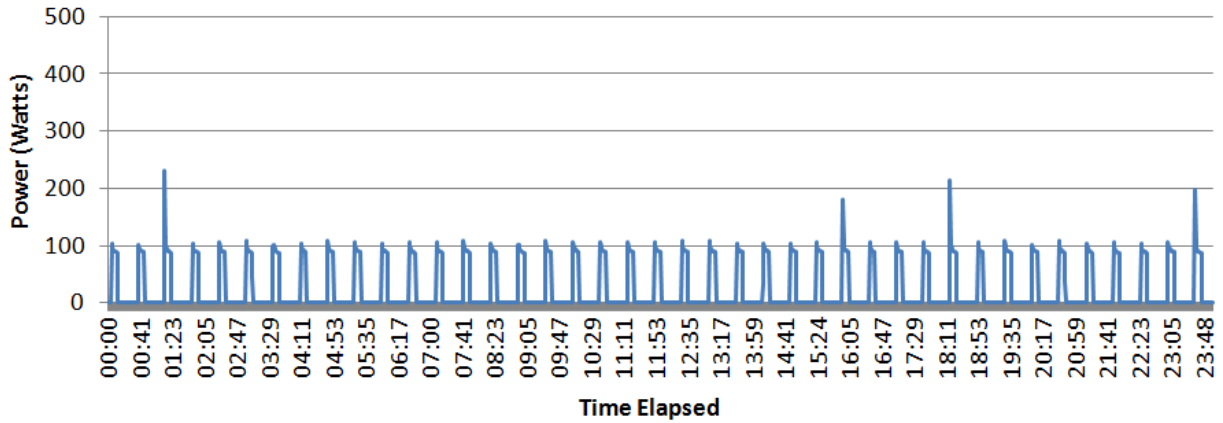
**Figure 7-35**  
Average Load Shape for a Weekend Day for Both Control and Treatment Refrigerators

**Table 7-14**  
Table Showing the Minimum, Maximum, and Average Values of the Average Load Shape for Both the Refrigerator Week Day and Weekend Day

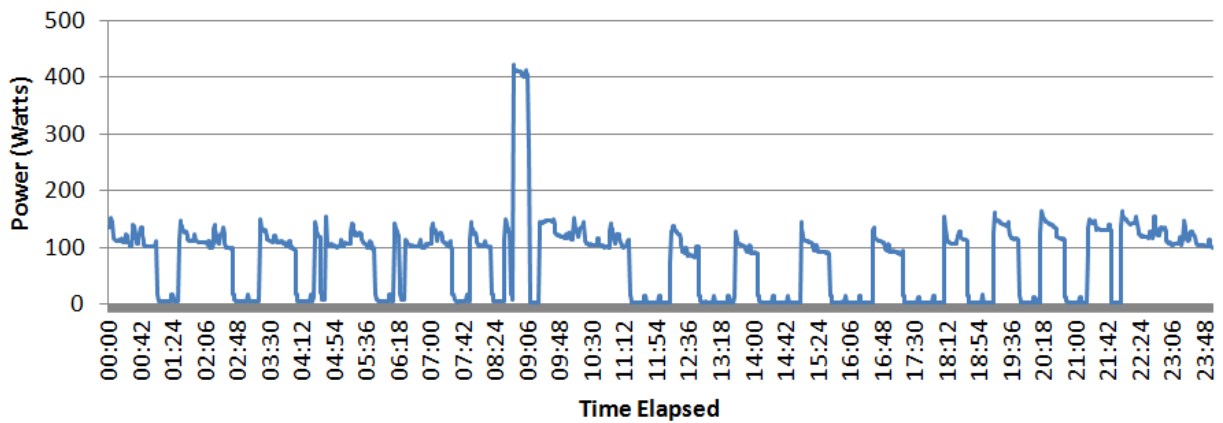
	Week Day		Weekend Day	
	Control	Treatment	Control	Treatment
Maximum (Watts)	84.63	74.63	86.58	74.24
Minimum (Watts)	67.71	56.82	65.98	55.88
Average Savings (Watts)		11.30		10.05

### Technology Assessment

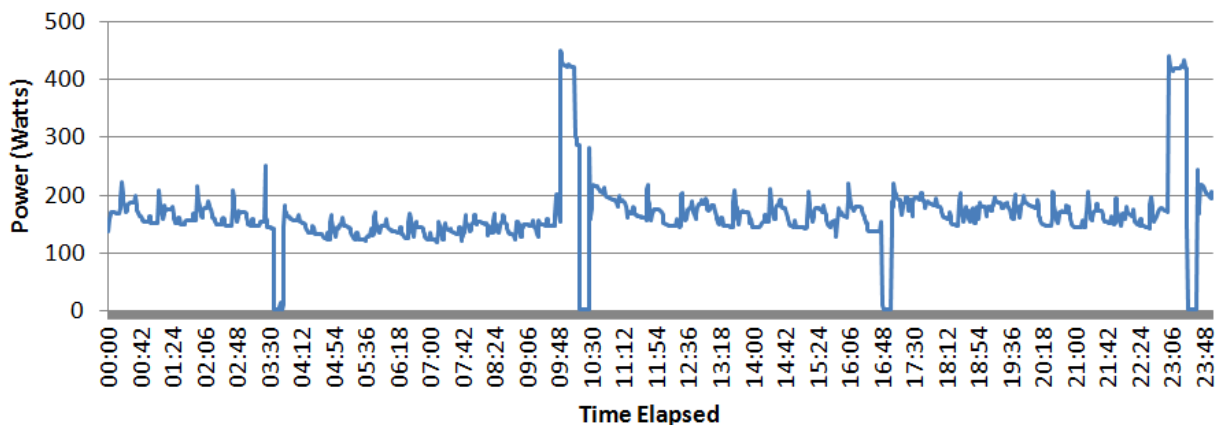
The data suggests a significant variation in energy use independent of refrigerator technology. Other drivers such as demographics and behavior affect energy use. Figure 7-36, Figure 7-37, and Figure 7-38 provide typical low, medium- and high use patterns observed over the course of the demonstration. Each plot shows power use by the same make and model of refrigerator, but in three different locations. Figure 7-38 is particularly interesting because the data suggests that the compressor of the refrigerator rarely turned off.



**Figure 7-36**  
Power Use of Model 3 for One 24-Hour Period on a Day with Low Energy Use



**Figure 7-37**  
Power Use of Model 3 for One 24-Hour Period on a Day with Medium Energy Use



**Figure 7-38**  
Power Use of Model 3 for One 24-Hour Period on a Day with High Energy Use

## **Summary**

### **Washer/Dryers**

The demonstration considered the combined energy (machine and water) of the washer and dryer pair as one laundry cycle and analyzed over ten-thousand laundry cycles including both treatment and control laundry cycles. The treatment group consisted of front loading washers with high spin speed and dryers with dryness control. The control group was a mixture of vintage, fill volume, spin speed, and dryness control. The intent of the study was to compare in aggregate the performance of new washer/dryer pairs to a sample of installed stock. Because of the aggregate comparison, no particular criteria were given to the type of washer/dryer pairs used as the control.

The aggregate results of the demonstration do not show a significant difference in energy use between the control and treatment washer/dryer pairs. Furthermore, inclusion of the energy content of water did not impact the outcome, regardless of the assumed heating source: resistive or heat pump. The data shows that the treatment washer and dryer increased the average laundry cycle time by approximately five minutes.

Because energy savings in the laundry cycle is directly related to the spin speed in the washer and because no significant energy savings were seen between aggregated control and treatment groups, it is likely that the control group in this study included a significant number of washers with a high spin speed feature. Because of the mix of washers in the control group, it is not a result of the study that that high efficiency (high spin speed, low water fill) washers have the same efficiency as conventional (low spin speed, deep water fill) washers.

The treatment washer did save water and the energy needed to heat the water. Specifically, the treatment washer decreased cold water use by 2.05 gallons and hot water use by 0.66 gallons, which resulted in an energy savings for hot water of approximately 17%. However, the overall energy savings from the hot water was offset by increased energy use in other parts of the cycle.

The load shape exhibited a steady increase in laundry use throughout the day, with a peak occurring around 9 PM on weekdays and 2 PM on weekend days. However, the field data shows that the load shapes for both the control and treatment washer and dryer are similar, with no significant difference in demand savings.

While not conclusive, this demonstration suggests that a utility program cannot expect to achieve energy savings by simply offering a new washer and dryer. Focus is needed with respect to the type of equipment being replaced. More work is needed to quantify the energy savings possible from specific measures such as spin speed and dryness control and consumer behavior.

### **Refrigerators**

Two of the treatment refrigerator models showed significant average energy savings (33% and 45%) compared to the control. One treatment refrigerator used 6% more energy than the control.

Of the three refrigerator models selected for use in the Demonstration, two closely agreed with the published ENERGY STAR data, but one greatly exceeded the published value.

The field data shows a variation of approximately 5:1 for the average daily energy use of control refrigerators and a slightly smaller ratio of approximately 3:1 for treatment refrigerators. The ratio suggests that using an average value for calculation of energy use could lead to significant

difference in estimated versus actual savings. Secondary drivers, such as lifestyle, number of occupants, and economics, may need to be taken into account in order to increase the accuracy and validity of the savings calculation.

The field data shows that the load shapes for both the control and treatment refrigerators are flat with no significant difference between week day and weekend days. Also, the data suggests that the time of highest energy use (defrost) does not occur at the same time of day for all refrigerators. The defrost cycle occurs randomly rather than at a similar time each day. A flat load shape and random defrost cycle suggest that system planners can consider refrigerators a base load and do not need special plans to accommodate a peak during a specific part of the day.

In conclusion, the demonstration shows that estimated energy savings cannot be assumed to indicate actual energy savings for the high-efficiency refrigerators tested.

### ***Readiness for Program***

This Demonstration suggests that utilities consider specifically defining the technical features of washers and dryers before inclusion in a utility program. Special attention should be taken with regard to spin speed and dryness control settings, both manual and automatic, of the washer/dryer pair being replaced. Further research is needed to understand energy savings as a function of washer/dryer cycle choice and how best to provide guidance to the consumers on the energy impacts of their choices. Regarding refrigerators, of the three models of refrigerators tested, two models had consistent energy savings. Refrigerators should be screened using the program-readiness criteria of the Coordinated Early Deployment Project to determine if refrigerators are ready for utility program inclusion.

# 8

## SUMMARY

---

The Energy Efficiency Demonstration was a field-performance assessment of emerging, efficient end-use technologies, deployed with extensive measurement instrumentation at multiple sites throughout the United States. In all, EPRI and host utilities installed about 600 units of new technology. Additionally, host utilities found participants willing to allow instrumentation of existing equipment to serve as a control (baseline) for comparison.

Having complex instrumentation inside a residence or place of business is intrusive. During site selection, practical tradeoffs necessitated compromises, such as the use of utility employees' homes and non-random selection of participants, who in many cases are not typical of the general population. The selected sites are not ideal, so the results are not immediately extensible to the general population. However, the data set is valid from the point of view that real people are using the equipment to create real data.

For each of the technologies, the report documents measured potential savings, applicable standards, laboratory work, and the field demonstration. The key findings for each technology are summarized below:

### **Light Emitting Diode for Street and Area Lighting**

1. Measured energy savings ranged from 20 to 70% and depended on the location and lighting design.
2. Energy savings in the field were the result of less light being delivered. This outcome was a result of conservation (using less light) rather than energy efficiency (using less energy to achieve the same light).
3. Despite delivering less light than the control fixtures, the opinion of survey respondents with regard to performance was favorable. Most indicated that the performance of the LED fixtures (how well they worked) were equivalent if not better than the existing design.
4. LED technology is sensitive to temperature, and fixtures use more energy when cold.
5. For some manufacturers, additional energy savings are possible from improvements in temperature and driver performance.

### **Efficient Data Centers**

1. Test results show server energy savings of 17 to 20% as a result of retrofitting with 80PLUS-compliant power supplies. There will also be an attendant reduction in cooling energy associated with the lower heat load.
2. With automated airflow management, test results show up to a 77% reduction in fan power, and between 8% and 17% total energy reduction

3. With automated airflow management, data center operators were willing to raise the operating temperature from 72 °F (22 °C) to 77° F (25°C) because they could see the impacts on equipment using thermal information from the system. This overcomes a major market barrier and will also reduce chiller energy use.
4. Distributing power in a data center using direct current (DC) resulted in 15% energy savings compared to the existing alternating current (AC) power system.

### **Variable Flow Refrigerant**

1. The annual savings in energy ranged from 20 to 45% at the four sites monitored during the Demonstration.
2. At a southeastern U.S. site with a side-by-side comparison, energy savings for the 2011 calendar year was 45%.
3. At the same southeastern U.S. site on a typical hot September day, there was an approximate 40% reduction in both system peak and billing demand.
4. Customers generally expressed satisfaction with VRF performance and improved comfort.

### **Ductless Heat Pump**

1. The ability to quantify energy savings was depended highly on specifics of home construction and occupant preferences.
2. Summer 2011 energy savings ranged from 18 to 44% at a southeastern U.S. site of three ductless heat pumps (DHPs) side-by-side with three baseline systems.
3. In the Midwest, 5 of 7 DHP sites used less energy per square foot than the baseline site (Utility B).
4. Most customers were satisfied with DHP system performance, reliability, controllability, comfort, and savings.

### **Hyper-Efficient Appliances**

#### ***Washer/Dryer***

The demonstration considered the combined energy (machine and water) of the washer and dryer pair as one laundry cycle and analyzed over ten-thousand laundry cycles aggregated from both treatment and control groups. The treatment group consisted of front loading washers with high spin speed and dryers with dryness control. The control group was a mixture of vintage, fill volume, spin speed, and dryness control. The intent of the study was to compare in aggregate the performance of new washer/dryer pairs to a sample of installed stock. Because of the aggregate comparison, no particular criteria were given to the type of washer/dryer pairs used as the control.

1. Because energy savings in the laundry cycle is directly related to the spin speed in the washer and because no significant energy savings were seen between aggregated control and treatment groups, it is likely that the control group within this study included a significant number of washers with a high spin speed feature.

It is not a result of this study that high efficiency (high spin speed, low water fill) washers have the same efficiency as conventional (low spin speed, deep water fill) washers.

2. While not conclusive, this demonstration suggests that a utility program cannot expect to achieve energy savings by simply offering a new washer and dryer. Focus is needed with respect to the type of equipment being replaced. More work is needed to quantify the energy savings possible from specific measures such as spin speed, dryness control and consumer behavior.

### **Refrigerator**

1. Two of the treatment refrigerator models showed significant average energy savings (33% and 45%) compared to the control. One treatment refrigerator used 6% more energy than the control.
2. Of the three refrigerator models selected for use in the Demonstration, two closely agreed with the published ENERGY STAR data, but one greatly exceeded the published value.
3. The field data shows a variation of approximately 5:1 for the average energy use per day of control refrigerators and a slightly smaller ratio of approximately 3:1 for treatment refrigerators. The ratio suggests that using an average value for calculation of energy use could lead to a significant difference in estimated versus actual savings. Secondary drivers, such as lifestyle, number of occupants, and economics, may need to be taken into account in order to increase the accuracy and validity of the savings calculation.
4. The field data shows that the load shapes for both the control and treatment refrigerators are flat, with no significant difference between week day and weekend days. Also, the data suggests that the time of highest energy use (defrost) does not occur at the same time of day for all refrigerators. The defrost cycle occurs randomly rather than at a similar time each day. A flat load shape and defrost cycle that is random suggests that system planners can consider refrigerators a base load and do not need special plans to accommodate a peak during a specific part of the day.
5. In conclusion, the demonstration shows that estimated energy savings cannot be assumed to indicate actual energy savings for the high-efficiency refrigerators tested.

### **Heat Pump Water Heater**

1. Well-performing models reduced energy consumption by 52% compared with simple electric water heaters.
2. Efficiency was best in warm ambient conditions, but most climates may be viable. HPWHs installed in cold climates used 34% less energy than the baseline.
3. Coincident demand reduction was moderate in summer (10 to 23%) and lower in winter (2 to 11%). Cold ambient temperatures lead to more electric resistance heat.
4. All HPWHs operated reliably; the project team did not notice any technical issues with the operation of the HPWHs throughout the period of the project.
5. Customer satisfaction was generally high overall, but surveys indicate that the pricing of heat pump water heaters may be a significant obstacle.



# 9

## REFERENCES

---

- 3-1. “Saving Energy at Data Centers,” Fact Sheet, U.S. Department of Energy, Energy Efficiency and Renewable Energy, October 15, 2007, [http://www1.eere.energy.gov/industry/saveenergynow/pdfs/data\\_center.pdf](http://www1.eere.energy.gov/industry/saveenergynow/pdfs/data_center.pdf)
- 3-2. William Tschudi and Dale Sartor, “Data Center Efficiency,” Lawrence Berkeley National Laboratory, November 30, 2008, <http://hightech.lbl.gov/presentations/Austin-Nov08-Part1.pdf>
- 3-3. Kenneth Uhlman and James Underpas, “Out of Power, Out of Cooling,” *Mission Critical, Data Center and Emergency Backup Solutions*, pp 26–29, March/April, 2009, <http://www.missioncriticalmagazine.com/digitalmagazine/SWF/MC/0409/index.html>
- 3-4. Dennis Shouldice, “Extending the Useful Life of Your Data Center,” APC by Schneider Electric, Datacenter Dynamics, San Francisco, July 17, 2009, [http://www.datacenterdynamics.com/Media/WebPages/SF09%20H1%201230%20Dennis%20Shouldice%20-%20APC%20by%20Schneider%20Electric\\_0.pdf](http://www.datacenterdynamics.com/Media/WebPages/SF09%20H1%201230%20Dennis%20Shouldice%20-%20APC%20by%20Schneider%20Electric_0.pdf)
- 3-5. Roger Schmidt et al., “Increasing Energy Efficiency in Data Centers, Designing Better Data Centers,” *ASHRAE Journal*, Volume 49, Number 12, pp 18–25, December 2007, [http://findarticles.com/p/articles/mi\\_m5PRB/is\\_12\\_49/ai\\_n25125554?tag=content;coll](http://findarticles.com/p/articles/mi_m5PRB/is_12_49/ai_n25125554?tag=content;coll)
- 3-6. Arshad Mansoor and Peter May-Ostendorp, *Generalized Test Protocol for Calculating the Energy Efficiency of Internal AC-DC and DC-DC Power Supplies*. Revision 6.4.3. October 22, 2009, [http://efficientpowersupplies.epri.com/pages/Latest\\_Protocol/Generalized\\_Internal\\_Power\\_Supply\\_Efficiency\\_Test\\_Protocol\\_R6.4.3.pdf](http://efficientpowersupplies.epri.com/pages/Latest_Protocol/Generalized_Internal_Power_Supply_Efficiency_Test_Protocol_R6.4.3.pdf)
- 4-1. *Performance Assessment of a Variable Refrigerant Flow Heat Pump Air Conditioning System*, EPRI, Palo Alto, CA: 2008. 1018446.
- 4-2. U.S. Department of Energy, “Buildings Energy Data Book,” [Online], Available <http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=3.1.4> ). [Accessed August 2012].
- 6-1. *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications*, U.S. Department of Energy, September 2008.
- 6-2. U.S. Department of Energy, “Solid State Lighting,” [Online]. Available: <http://www1.eere.energy.gov/buildings/ssl/>. [Accessed August 2012].
- 6-3. *Coordinated Early Deployments of Efficient End-Use Technologies: Phase 1 Final Report*. EPRI, Palo Alto, CA: 2011. 1024626.
- 7-1. National Academy of Engineering, “Air Conditioning and Refrigeration Timeline,” 15 August 2012. [Online]. Available: <http://www.greatachievements.org/?id=3854>.

---

References

- 7-2. EIA, "U.S. Energy Information Administration (EIA)," 2009. [Online]. Available: <http://www.eia.gov/consumption/residential/data/2009>. [Accessed August 2012].
- 7-3. U.S. Department of Energy, "Opportunities for Energy Savings in the Residential and Commercial Sectors with High Efficiency Electric Motors," Arthur D. Little, Inc., Washington DC, 1999.
- 7-4. T. R. Colling and D. DuMolin, "Higher Efficiency by Means of Variable Speed Technology in Domestic Refrigeration Appliances," *ASHRAE Transactions*, vol. 104, Pt. 2, 1998.
- 7-5. Consortium for Energy Efficiency, "Super Efficient Home Appliances Initiative (SEHA)," [Online]. Available: <http://www.cee1.org/resid/seha/seha-main.php3>. [Accessed August 2011].
- 7-6. P. Heath, "Using Field-Weakening Motor Control in Washing Machines," *Appliance Magazine*, October 2009.
- 7-7. U.S. Environmental Protection Agency, "State of the Science Literature Review: Everything Nanosilver and More," EPA/600/R-10/084, Washington, DC, 2010.
- 7-8. P. Bendt, "Are We Missing Energy Savings in Clothes Dryers?" in *ACEEE Summer Study on Energy Efficiency in Buildings*, Pacific Grove, CA, 2010.
- 7-9. U.S. Department of Energy, "2009 Sales Data – National, State, and Regional," September 2011. [Online]. Available: [http://www.energystar.gov/index.cfm?c=manuf\\_res.pt\\_appliances](http://www.energystar.gov/index.cfm?c=manuf_res.pt_appliances).
- 7-10. U.S. Department of Energy, "Technical Report: Analysis of Amended Energy Conservation Standards for Residential Refrigerator-Freezers," Washington, DC, 2005.
- 7-11. Association of Home Appliance Manufacturers, "AHAM Energy Efficiency and Consumption Trends," 2009. [Online]. Available: <http://www.aham.org/>. [Accessed August 2011].
- 7-12. U.S. Department of Energy, "DOE Proposes Higher Efficiency Standards for Refrigerators," 28 September 2010. [Online]. Available: [http://apps1.eere.energy.gov/news/progress\\_alerts.cfm/pa\\_id=413](http://apps1.eere.energy.gov/news/progress_alerts.cfm/pa_id=413). [Accessed August 2012].
- 7-13. U.S. Department of Energy, "Preliminary Technical Report Document: Energy Efficiency Program for Consumer Products: Refrigerators, Refrigerators-Freezers, and Freezers," Navigant Consulting and Lawrence Berkeley National Laboratory, Washington, DC, 2009.
- 7-14. U.S. Department of Energy, "Refrigerator Market Profile 2009: New Opportunities Multiply Savings," December 2009. [Online]. Available: [http://apps1.eere.energy.gov/states/pdfs/ref\\_market\\_profile.pdf](http://apps1.eere.energy.gov/states/pdfs/ref_market_profile.pdf). [Accessed August 2012].
- 7-15. California Energy Commission, "Consumer Energy Center," 2012. [Online]. Available: <http://www.consumerenergycenter.org/home/appliances/washers.html>.

- 7-16. U.S. Environmental Protection Agency, "Clothes Washers for Consumers," [Online]. Available:  
[http://www.energystar.gov/index.cfm?fuseaction=find\\_a\\_product.showProductGroup&pgw\\_code=CW](http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=CW). [Accessed August 2012].



# 10

## GLOSSARY

---

### Adjusted Volume

Adjusted volume is a measure of internal volume in cubic feet. Adjustments account for the ratio of freezer to fresh food storage space: The fresh food internal volume is a direct measurement, but the freezer volume is multiplied by 1.63 and added to the fresh food volume to get the adjusted volume (AV).

### Coefficient of Performance (COP)

The efficiency of heat pumps is measured by calculating a coefficient of performance (COP), which is a ratio of useful output (hot water, in this case) to the amount of work or energy input (electrical power). The COP values presented here were calculated according to the following equation:

$$COP = \frac{\dot{V} * C_p * \rho * (T_{out} - T_{in})}{\dot{P}}$$

Where,

$\dot{V}$  = Water Volume (lb<sup>3</sup>/hour)

$C_p$  = W/lb \* °F

$\rho$  = ft<sup>3</sup>/hour

$T_{out}$  = Output Temperature (°F)

$T_{in}$  = Input Temperature (°F)

$P$  = Electric Power (W)

### Cooling Capacity

Cooling capacity provided by an air conditioner is a measure of the sensible cooling (actual change in degrees) and latent cooling (removal of moisture) provided by an air conditioner, in BTU/h.

### COP Interval

The interval over which COP is calculated (over a 15-minute period or a 24-hour period).

### Data Center Infrastructure Efficiency (DCiE)

The reciprocal of Power Usage Effectiveness. It is expressed as a percentage.

### Energy Efficiency Ratio (EER)

The ratio of the input electrical power (W) to the cooling output (Btu/hr) at a specific operating point at maximum load.

### Energy Efficiency

The energy ratio of the useful output compared to the input. Increasing energy efficiency involves providing the same result while consuming less energy.

### **Energy Factor**

Various home appliances are measured with energy factor to show the overall energy efficiency of the device. It is determined with a ratio of input energy to useful output energy. A higher energy factor indicates that a higher percentage of the energy consumed is transformed into a useful energy. For heat pump water heaters, a prescribed test is performed according to protocol set by the Department of Energy to approximate the annual efficiency of the water heater. The test is designed to incorporate recovery efficiency (how efficient the actual heating process is), standby efficiency (the relative loss of heat while not operating), and cycling losses (other heat losses that might occur during operation).

### **Flow Totalizer**

The volume of liquid passing through an area is measured by the counter in the flow meter, which produces a series of pulses. These pulses are counted by the flow totalizer to give the total flow through a specific point in a system.

### **Load Shape**

The visually interpreted definition of the total power demand with regard to the time of occurrence.

### **Modified Energy Factor (MEF)**

This is a combination of energy factor and remaining moisture content and represents how many cubic feet of laundry can be washed and dried with one kilowatt hour. (The remaining moisture content affects the energy use of the dryer). The higher the number, the greater the efficiency.

### **Performance**

A qualitative and quantitative assessment of the useful work performed by a device given the amount of time and resources provided.

### **Power Usage Effectiveness (PUE)**

A measurement of the amount of power used by computers in a data center facility compared to the power consumed by supplemental equipment (cooling, lighting, and so on). It is calculated using the following equation:

$$PUE = \frac{\textit{Total Facility Power}}{\textit{IT Equipment Power}}$$

### **Seasonal Energy Efficiency Ratio (SEER)**

The SEER rating is provided by manufactures based on results of a test whose protocol is prescribed by AHRI. The rating attempts to provide a comparison of systems based on performance across a variety of indoor and outdoor conditions.

### **Sensible Heat Ratio (SHR)**

The ratio of sensible cooling capacity to total cooling capacity.

**System Peak**

The point within a time interval of the highest load demand is the system peak for that interval.

**System Peak Day**

The date with the highest load demand over a period of time is the system peak day for that date range.

**Water Factor**

Number of gallons of water needed for each cubic foot of laundry. The lower the number, the more efficient use of water.

**VAV (Variable Air Volume) Systems**

An HVAC air-delivery system where modulation of delivered capacity is accomplished by changing the rate of delivery of conditioned air. The supply air temperature is maintained at a relatively constant temperature, and the flow to different spaces is varied to provide different levels of cooling/heating.



# A

## HEAT PUMP WATER HEATER

**Table A-1**  
**Detailed Data for Comparing Performance of 60-Gallon and 80-Gallon Systems**

Flow Bin (gal)	60 Gal	80 Gal	60 Gal	80 Gal	60 Gal	80 Gal	60 Gal	80 Gal	60 Gal	80 Gal	60 Gal	80 Gal	60 Gal	80 Gal
	COP		Avg. Daily Draw		Avg. Daily Energy		Avg. Supply Temp		Avg. Ambient Temp.		Avg. Ambient RH		Avg. Inlet Water Temp	
	-		gal		kWh		deg. F		deg. F		%		deg. F	
25–40	2.25	1.58	33	32.3	2.13	3.88	117.4	120.8	70.2	66.7	46.1	47.5	62.4	62.7
40–55	2.31	1.94	47.2	47.6	2.9	4.01	118	120.8	70	67.7	45.8	49.8	62.5	62.8
55–70	2.34	2.21	62.3	62.4	3.77	4.34	118.2	120.6	70	66.9	47.6	54.1	62.5	62.6
70–85	2.5	2.12	76.6	76.7	4.33	5.72	118.6	119.7	70	67.2	49.1	52.6	62.2	62.7
85–100	2.6	2.18	91.7	91.2	5.02	6.99	118.6	119.8	69.7	67.1	48.8	53.3	62	62.6
100–115	2.57	2.34	107.7	107.4	6.32	6.89	119	119.9	69.1	66.5	49.2	59.6	61.7	62.4
115–130	2.84	2.27	120.2	123.1	5.88	8.41	118.5	119.7	69.5	65.5	49	57.5	62.5	63.2

**Table A-2  
Detailed Data for Comparing Performance vs. Ambient Temperature**

Entering Air Temp. Bin (°F)	Average COP (Model #)			Average Ambient Air Temp. °F (Model #)			Daily Water Draw (g) (Model #)			Entering Water Temp. °F (Model #)		
	A	B	C	A	B	C	A	B	C	A	B	C
40–50	0.98	1.47	0.95	47.3	47.1	47.1	66.2	67.1	67.1	49.2	49.0	52.3
50–60	1.37	1.93	1.05	55.0	55.7	56.2	65.9	66.3	65.5	52.3	53.1	57.6
60–70	1.81	2.06	1.27	65.4	65.4	65.0	66.1	66.4	65.9	57.1	59.0	61.7
70–80	1.97	2.21	1.49	74.1	73.7	74.1	65.7	65.7	65.0	69.5	69.8	72.4
80–90	1.98	2.58	1.83	84.0	83.9	84.4	66.0	65.8	65.9	79.3	75.5	80.5
90–100	2.24	2.52	1.95	93.6	92.2	93.2	66.6	67.1	65.0	84.0	82.6	83.9

**Table A-3**  
**Detailed Data for Comparing Performance vs. Daily Water Use**

<b>Model A</b>						
Water Draw, Gal	COP	Ambient Air Temp	Entering Water Temp	Outlet Water Temp	Avg. Daily Draw	Count
<10	0.56	65.5	65.0	111.7	4.9	282
10–25	1.50	65.3	60.0	117.2	18.3	954
25–40	1.80	65.2	59.0	117.5	32.5	1188
40–55	1.81	65.3	58.8	116.7	47.2	2574
55–70	1.85	65.1	57.3	116.3	62.1	986
70–85	1.75	64.9	56.3	115.8	76.6	645
85–100	1.68	64.8	56.8	115.0	92.0	308
100–115	1.72	64.5	57.2	113.8	106.6	173
115–130	1.73	64.0	57.9	113.6	121.4	102
130–145	2.11	64.2	58.7	110.8	137.3	57
145–160	2.56	64.1	57.4	110.8	152.3	35
>160	2.74	64.0	58.6	105.7	184.3	73
<b>Model B</b>						
Water Draw, Gal	COP	Ambient Air Temp	Entering Water Temp	Outlet Water Temp	Avg. Daily Draw	Count
<10	0.39	66.1	70.6	115.9	4.9	143
10–25	1.12	65.9	61.5	119.6	18.4	559
25–40	1.61	65.7	60.2	119.4	32.5	672
40–55	1.94	65.7	59.3	119.5	47.4	657
55–70	2.11	65.6	58.7	119.5	62.3	644
70–85	2.16	65.4	58.0	119.2	77.0	493
85–100	2.27	65.2	60.0	119.1	91.7	466
100–115	2.26	64.9	58.2	119.7	107.2	180
115–130	2.23	64.7	58.9	119.0	122.0	102
130–145	2.28	65.0	59.4	120.2	137.7	59
145–160	2.49	64.8	63.4	118.7	151.8	36
>160	2.76	64.9	71.7	117.6	204.1	90

---

18BHeat Pump Water Heater

	<b>Model C</b>					
Water Draw, Gal	COP	Ambient Air Temp	Entering Water Temp	Outlet Water Temp	Avg. Daily Draw	Count
<10	0.22	65.7	70.1	115.9	4.5	98
10–25	0.73	65.8	63.9	117.5	19.1	298
25–40	1.01	65.3	63.2	117.4	32.8	515
40–55	1.21	65.0	63.8	118.0	47.1	515
55–70	1.34	65.0	64.1	118.0	61.8	308
70–85	1.43	65.1	63.3	117.5	76.7	207
85–100	1.52	65.0	63.7	117.2	92.6	107
100–115	1.56	65.3	63.3	116.9	106.3	69
115–130	1.61	64.6	61.1	116.5	122.7	46
130–145	1.49	64.1	58.9	114.7	136.1	26
145–160	1.63	64.9	62.8	115.5	152.9	16
>160	1.81	64.0	64.1	111.6	208.4	23

# B

## WORKSHEET FOR SCOTTY SITE VISIT

---

### Overview

The purpose of the worksheet is to document the steps needed to perform onsite measurements of street-light performance using EPRI's Mobile Light Measurement System, also known as the Scotty and to provide a convenient place to record site data. The steps outline the actions needed starting approximately thirty days before testing and continuing a day or two after testing and detail the high-level testing procedure. For specific instructions on Scotty setup and operation see [User Manual: Mobile Light Measurement System](#). The worksheet is designed for one fixture (grid), one fixture power measurement, and spot measurements on other site fixtures. In the case of variations to the protocol, adjust accordingly and indicate procedure changes/additions with the appropriate sections and within the comments section of the LMS software.

### Site Information

Site Number:	Utility:
State (Site):	City (Site):
Address (Site):	Utility Engineer:
Email:	Phone Number:

### Steps

(Place a check next to each step after completion.)

#### **Approximately 30 days or more before testing:**

- Schedule shipment of Scotty with EPRI (email: [eedemosupport@epri.com](mailto:eedemosupport@epri.com), or call 1-865-218-8041).
- As needed, make travel arrangements.
- Coordinate visit with all vested parties (Host, police/security/city (for road block and personal security), EPRI, other stakeholders).
- Determine start time by checking time of sunset ([http://www.sunrisesunset.com/custom\\_srss\\_calendar.asp](http://www.sunrisesunset.com/custom_srss_calendar.asp)) add ½ hour for warm-up of fixtures.
- If initial site visit, coordinate re-lamping of existing fixtures (consult EPRI as needed).
- If needed, schedule an electrician to assist with instantaneous power measurement.

#### **The day of Scotty receipt:**

Unpack and assemble Scotty system. Check/Charge the following equipment batteries:

- Scotty GPS (internal rechargeable)
- Base GPS (internal rechargeable)

**Remember:** Press "Reset" in order to charge the Scotty GPS and base GPS).

- Scotty Transmitter (internal rechargeable)
- Walkie-Talkies (2) (internal rechargeable)
- Net Book (internal rechargeable)

- Control Battery (1 main, 1 spare)
- Drive Train Battery (1 main, 1 spare)
- Flashlight (2) (non-rechargeable)

**Three days before site measurements:**

- Check weather at site location (the Scotty is not rated for rain/snow, but will operate with a wet/frozen roadway). Site measurements are not recommended during conditions of high wind (because of fixture movement) or fog (because of light scattering). Regarding moonlight, the second measurement with the fixture off is used to null readings from external light sources.
- As needed, coordinate security briefing, camera pass, and on site personal to assist with measurements (access to electrical room to inspect energy monitor, access to roof for overhead photos)
- Contact EPRI for the project file (contains site details such as: base GPS physical position and coordinates – screen capture, fixture details, circuit details, etc.; email: [eedemosupport@epri.com](mailto:eedemosupport@epri.com), or call 1-865-218-8041).
- Contact EPRI to verify operation of energy monitor (email: [eedemosupport@epri.com](mailto:eedemosupport@epri.com), or call 1-865-218-8041).
- Contact EPRI for the previous site measurement file. This file contains GPS and information needed by the LMS software application to automatically position the Scotty to the previously defined grid. At some point, the file must be downloaded to the Net Book before measurements begin. The software allows for navigation to the file location.

**The day of site measurements (daylight hours):**

- Travel to treatment site.
- Record:

Test Engineer(s): \_\_\_\_\_

Date: \_\_\_\_\_

Site Name/Description: \_\_\_\_\_

Brief Description of Measurement Plan: \_\_\_\_\_

\_\_\_\_\_  
 \_\_\_\_\_

- Visually inspect and record (photograph as necessary) the condition of all fixtures for abnormalities (dirt, bird or insect infestation, damage, encroachment of vegetation or other factors that would impact the overall performance of the treatment fixtures).



5. If needed, select a fixture for measurement.

Record fixture number or description:

6. If needed, determine grid size.

Record grid dimensions and description:

7. If needed, select and place base GPS.

Record location description:

8. Using the camera provided (Canon SD970) photograph the physical location of the base GPS. Set camera to manual mode (see user manual).

9. Configure base and Scotty GPS for the local area by clearing the nonvolatile random access memory (NVRAM), pushing the configuration “script” files, and allowing twelve minutes for almanac and ephemeris tables to update. Note, if this step was performed in at a location within fifty miles it is not necessary to repeat.

10. For a first time measurement, after acquiring coordinates using “Get from receiver”, record a screen capture (Alt+PrtSC, then paste into Microsoft Works: Word Processor, save file). For a return measurement, place the base GPS at the reference location and use PCCDU to manually input base coordinates from initial visit (see project file). Caution: Do not use “Get from Receiver” for a repeat visit). See user manual.

11. When lights have operated for greater than ½ hour, configure the Wireless Local Area Network (WLAN) between the Net Book and the Scotty.

12. If needed, copy the previous site .csv file to the Net Book. It is recommended to create a folder to simplify later transfer and deletion of files.

13. Use LMS Scotty software on Net Book to operate Scotty and capture photometric data from the test fixture. Use the comment section within the site data screen to provide additional site/measurement details (i.e. pole-to-pole, second try, other variable or comment the will help document the work performed and aid in post analysis of the data).

14. Using the Yokagawa power meter, test leads, and inverter (if necessary), measure and record fixture voltage, current, power factor, volt-amps reactive (VARs), and wattage. Strive to limit the off time of the fixture while making connections.

Voltage \_\_\_\_\_

Current \_\_\_\_\_

Power Factor \_\_\_\_\_

Volt-Amp Reactive \_\_\_\_\_

Wattage \_\_\_\_\_

15. Turn off the fixture under test, use LMS software to operate Scotty and capture photometric data (Note, dataset is used to null moonlight and external light sources).
16. Turn fixture back on.
17. Use the provided camera (Canon SD970) to take a wide-angle photograph of the grid area surrounding the test fixture. The photograph is compared with the Scotty data as a sanity check. Note, set camera to manual mode (see user manual)
18. If possible, use the provided camera (Canon SD970) to take a photograph from a higher elevation (top of building, boom of trouble truck – use trained lineman). The photograph is compared with the Scotty data as a sanity check and looks good in presentations and reports. Note, set camera to manual mode (see user manual)
19. Use the provided camera (Canon SD970) to take a photograph for before/after comparison. Make a note of camera position. Note, set camera to manual mode (see user manual).

Description of camera position:

Using the Scotty, measure and manually record spot measurements for each fixture (two locations; under light and near middle of street or approximately 25 feet from fixture – use an easy to identify marker on the pavement such as an expansion joint or center line). At the same time visually inspect each fixture for failed LEDs using the inspection goggles. If a fixture has a failed LED, photograph the LED fixture with the inspection goggles over the camera lens.

Fixture #	Spot Measurement Location Description	Photopic	Scotopic
1a			
1b			
2a			
2b			
3a			
3b			
4a			
4b			
5a			
5b			
6a			
6b			
7a			
7b			
8a			
8b			
9a			
9b			
10a			
10b			

Fixture #	Spot Measurement Location Description	Photopic	Scotopic
11a			
11b			
12a			
12b			

20. Record any comments about the site (see table). For example, excessive foliage, physical changes to site, new light sources, and obstacles.

Comments (general):

- 21. Copy the measurement files to the provided flash drive. Verify transfer of data. Delete files from computer.
- 22. Connect the supplied camera to the Net Book, copy site photographs to the flash drive. Disconnect the camera. Verify transfer of photographs. Delete photos from camera.
- 23. Pack equipment cases.

***The day following the site measurement:***

- Copy the site electronic data from the flash drive to a personal computer. Verify transfer of data. Delete files from flash drive. If convenient, put the flash drive back in the Scotty Equipment case or, if not convenient, keep it.
- Put the measurement worksheet into electronic form (scan). If not able to create a .pdf, fax to EPRI: Attention: Larry Burnette, 865-218-8001. Notify Larry that a fax is on the way (email: [eedemosupport@epri.com](mailto:eedemosupport@epri.com), or call 1-865-218-8041)
- Create a photo album of all site photos. Compress. See user manual.
- Send all site data (Scotty file, photo album, screen capture of base GPS coordinates, and electronic version of the measurement worksheet – if not faxed) to [eedemosupport@epri.com](mailto:eedemosupport@epri.com).
- Receive confirmation from EPRI that all measurement data is in order.

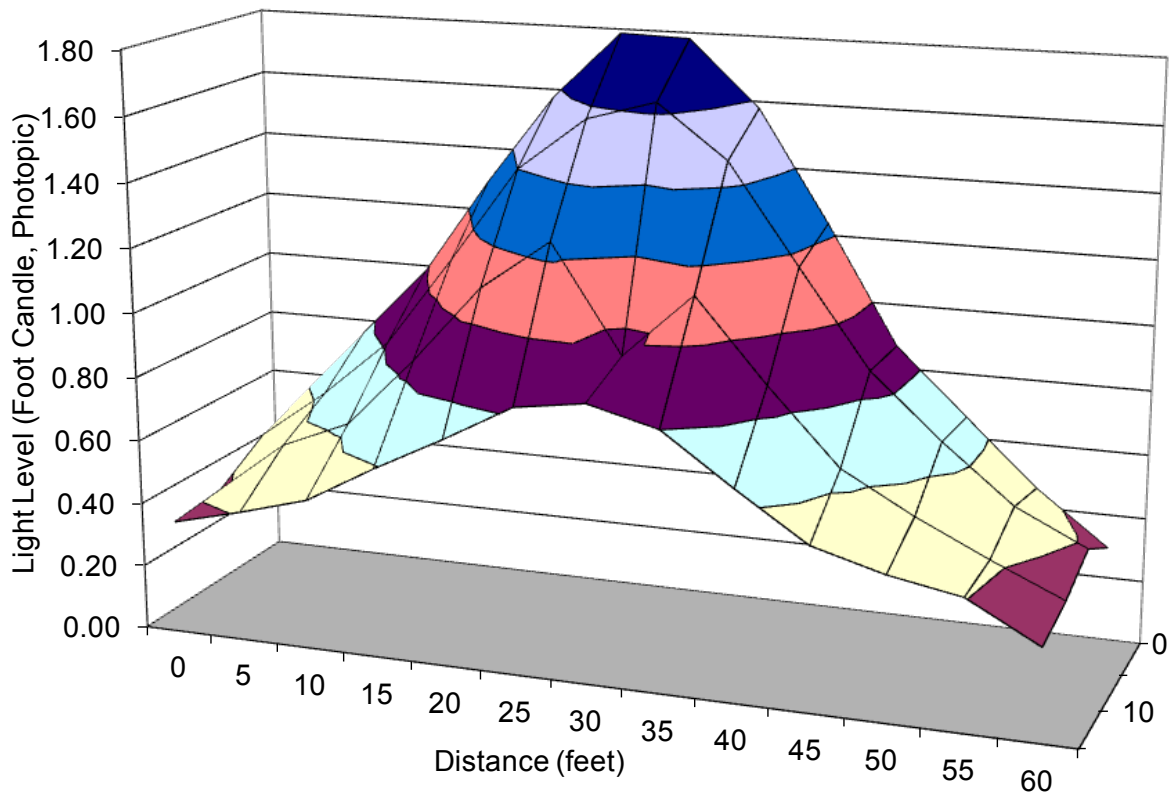
***One day or more after the site measurement:***

- Ship Scotty (call EPRI for shipping instructions – either back to EPRI or to another site).

# C

## INDUCTION LIGHT LEVELS

---



**Figure C-1**  
Light levels Produced by an Induction Fixture



# D

## U.S. FEDERAL STANDARDS STATUS AND SCHEDULE FOR RESIDENTIAL APPLIANCES

Product Category	Current Standard	Status of Updates or New Standards	Final Action Date	Effective Date	Comment
Refrigerators* and Freezers	Standards in effect as of 2011 became effective in 2001 and are based on maximum allowable energy use in kWh/yr based on adjusted volume (AV) in cubic feet for each product type and configuration (e.g., top, bottom, or side-mounted freezer, through-the-door ice-making).	EISA 2007 requires that DOE consider strengthened standards per the timetable to right.	Dec 2010	2014	Proposed standard requires a ~ 25% reduction for most models. A DOE Technical Support Document for the rulemaking was published by DOE in November 2009. See <a href="http://www1.eere.energy.gov/buildings/appliance_standards/residential/refrigerators_freezers_prelim_tsd_mtg.html/">http://www1.eere.energy.gov/buildings/appliance_standards/residential/refrigerators_freezers_prelim_tsd_mtg.html/</a>
Clothes Dryer*	Electric standard clothes dryers (≥4.4 cu. ft. capacity) manufactured on or before May 14, 1994, and before January 1, 2015, shall have an energy factor no less than 3.01 (lbs/kWh). For gas dryers, pilot lights in gas dryers have been banned since 1987.	DOE rulemaking for a new standard began in 2007 and was published in the Federal Register, Vol. 76, No. 164, August 24, 2011, Rules and Regulations. Standard (≥4.4 cu. ft. capacity) vented electric clothes dryers must have a combined energy factor (EF) of no less than 3.73. Compact (<4.4 cu. ft. capacity) vented electric an EF of 3.61 and compact ventless electric an EF of 2.55. Vented gas dryers require an EF of 3.30.	August 2011	January 1, 2015	

*U.S. Federal Standards Status and Schedule for Residential Appliances*

<b>Product Category</b>	<b>Current Standard</b>	<b>Status of Updates or New Standards</b>	<b>Final Action Date</b>	<b>Effective Date</b>	<b>Comment</b>
Clothes Washers*	Current standards require a modified energy factor <sup>a</sup> (MEF) of at least 1.26	EISA 2007 required water efficiency standards for the first time (a water factor <sup>b</sup> [WF] of 9.5 or less by 2011); energy efficiency standards were left the same. Rulemaking to assess stronger standards.	2011	2015	

a Modified energy factor (MEF): A combination of energy factor and remaining moisture content. This is a measurement of how many cubic feet of laundry can be washed and dried with one kilowatt hour. (The remaining moisture content affects the energy use of the dryer.) The higher the number, the greater the efficiency.

b Water factor (WF): Number of gallons of water needed for each cubic foot of laundry. The lower the number, the more efficient use of water.



## **Export Control Restrictions**

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

**The Electric Power Research Institute Inc.**, (EPRI, [www.epri.com](http://www.epri.com)) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent approximately 90 percent of the electricity generated and delivered in the United States, and international participation extends to more than 30 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together...Shaping the Future of Electricity

© 2012 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and TOGETHER...SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

1025437

## **Electric Power Research Institute**

3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA  
800.313.3774 • 650.855.2121 • [askepri@epri.com](mailto:askepri@epri.com) • [www.epri.com](http://www.epri.com)