I would consider changing the times we shower or bathe to save money. (Circle one)

34% - Yes — 239 – Sample size
37% - No
29% - Not sure

Our water heater has a timer that turns it off when we're not home (Circle one)

3% - Yes — 239 – Sample size
79% - No
18% - Not sure

The amount of hot water I have is (Check one)

91% - Usually sufficient — 234 – Sample size
6% - Sometimes sufficient
3% - Not usually sufficient

My water heater is set (Check one)

7% - As hot as possible (160°F or more) — 230 – Sample size
45% - For the dishwasher/clothes washer (about 140°F)
45% - To prevent scalding (about 120°F)
3% - To wash hands comfortably (less than 120°F)

How many water heaters do you have in your home? (Check one)

94% - 1 — 234 – Sample size
6% - 2
0% - more than 2

Where is the location of your water heater(s)? (Garage, basement, *etc.*)

Answers to this open-ended question varied greatly.

Including yourself, how many people have lived in the household at least half of the last 12 months? (Age No. Person)

7% - 0-11 — 571 – Sample population
12% - 12-18
8% - 18-25
9% - 26-35
12% - 36-45
25% - 46-55
15% - 55-65
13% - 66 or older

What is the total combined income for your household before taxes? (Check one)

2% - Up to $19,000 — 216 – Sample size
14% - $20,000 to $39,999
25% - $40,000 to $59,999
28% - $60,000 to $79,999
13% - $80,000 to $99,999
17% - $100,000 or more

The last questions refer to the occupant responsible for participating in the demonstration program:
(Check one)

43% - Female	238 – Sample size
57% - Male	

Age (Check one)

0% - 18-25	238 – Sample size
8% - 26-35	
18% - 36-45	
33% - 46-55	
22% - 55-65	
18% - 66 or older	

Highest level of education completed (Check one)

0% - Never attended	238 – Sample size
0% - Elementary school	
0% - Junior high school	
3% - Some high school	
6% - High school	
6% - Trade or technical school	
30% - Some college	
32% - Graduated college	
24% - Graduate college/professional school	

Comfort level using the Internet (Check one)

0% - Never use it	237 – Sample size
1% - Not comfortable	
14% - A little comfortable	
85% - Very comfortable	

Table A.3. Final Survey Summary

I received sufficient information to understand the project goals and my part in the GridWise Testbed Program.

36% - Strongly agree	103 - Sample size
55% - Agree	4.2 - Average on scale of 5
35% - Neutral	0.71 - Standard deviation on scale of 5
4% - Disagree	
0% - Strongly disagree	

Regarding your personal experience with the new clothes dryer, how satisfied were you with the installation of your dryer?

80% - Very satisfied	51 - Sample size
14% - Somewhat satisfied	4.7 - Average on scale of 5
2% - Neither satisfied nor dissatisfied	0.69 - Standard deviation on scale of 5
4% - Somewhat dissatisfied	
0% - Very dissatisfied	

How acceptable was it to have your clothes dryer cycle run a few minutes longer, occasionally, in response to power grid needs?

84% - Very acceptable, we didn't notice any change	51 – Sample size
10% - Somewhat acceptable	4.8 – Average on scale of 5
6% - Acceptable	0.54 – Standard deviation on scale of 5
0% - Somewhat unacceptable	
0% - Unacceptable	

Which of these conditions, if any, did you observe on your clothes dryer? (Check all that apply)

39% - "Pr" (Price Response) signal on appliance	94 – Sample size (total responses)
33% - Had to push start button twice to start the dryer	
28% - Audible signal (beep) with the "Pr" (Price Response)	

Assume you are planning to purchase a new clothes dryer. Which of the following would most strongly influence your decision to purchase a Grid Friendly clothes dryer instead of a standard model? (Check all that apply)

26% - Help the environment	127 – Sample size (total responses)
37% - Reduce my electrical costs	
22% - Help the electric power grid	
13% - Price	
2% - Other (please explain)	

What is the likelihood that you would purchase a Grid Friendly clothes dryer?

39% - Definitely would	51 – Sample size
43% - Probably would	4.2 – Average on scale of 5
14% - Might or might not	0.87 – Standard deviation on scale of 5
2% - Probably would not	
2% - Definitely would not	

What do you believe would be a reasonable purchase price increase or reduction for a Grid Friendly clothes dryer? How much more (positive) or less (negative) would you expect to pay for a Grid Friendly clothes dryer?

10% - ($100)
2% - ($50)
0% - ($25)
0% - ($10)
0% - ($5)
25% - $0
0% - $5
2% - $10
20% - $25
29% - $50
12% - $100

51 – Sample size
$21 - Average

Which of the following organizations, if any, do you believe would provide you the most reliable information about a Grid Friendly clothes dryer?

51% - Utility company
6% - Appliance manufacturer
4% - Government
6% - Retail store
0% - Local service organizations
14% - Environmental organizations
12% - None
8% - Other (please explain)

51 – Sample size

How much did your participation in the GridWise Testbed Program impact your loyalty toward the dryer manufacturer?

24% - Increased greatly
31% - Increased some what
45% - Did not make a difference
0% - Decreased some what
0% - Decreased greatly

151 – Sample size
3.8 – Average on scale of 5
0.80 – Standard deviation on scale of 5

In your opinion, how should the Grid Friendly feature be added to a clothes dryer?

24% - Added option at time of purchase
0% - Added option after purchase
69% - Standard on all appliances
0% - Should not be offered for clothes dryers
2% - Other (please explain)
6% - Don't know

51 – Sample size

Occasionally, there are hours of the day when cost increases because energy demand exceeds available lower-cost energy supply. This is referred to as "on-peak" demand. In the future, home devices or appliances could be modified to respond to "on peak" demand to reduce costs and to respond to help the grid during a grid emergency. Assume you incur no installation cost, and the cost of your appliance remains the same. Also assume your benefits for participation are relative to the extent of control you permit or exercise. In which one of the following programs would you most likely participate?

- 28% - The utility occasionally sends control signals directly to certain appliances; no action is needed on my part. 103 – Sample size
- 17% - The utility sends me an alert message when electric prices are high; I will be responsible for reducing electric usage as I see appropriate.
- 72% - The utility sends a price signal directly to my appliances; my appliances reduce my electrical energy costs for me; no action is needed on my part, but I may override the appliance's decision at anytime.
- 1% - The utility sends no signals; no action is needed on my part, because I elect to pay a premium for electricity (~10% more) for the right to use electricity whenever I choose.

How likely are you to participate in a program like this again if it were offered by your local electric company?

48% - Extremely likely	102 – Sample size
34% - Very likely	5.3 – Average on scale of 6
13% - Likely	0.89 – Standard deviation on scale of 6
4% - Unlikely	
1% - Very unlikely	
0% - Extremely	

How satisfied were you with the installation of your Invensys GoodWatts (load control modules, thermostats & Internet connection) equipment?

51% - Very satisfied	103 – Sample size
29% - Somewhat satisfied	4.1 – Average on scale of 5
5% - Neither satisfied nor dissatisfied	1.15 – Standard deviation on scale of 5
11% - Somewhat dissatisfied	
4% - Very dissatisfied	

Did you experience any technical issues or problems with GoodWatts equipment?

64% - Yes	103 – Sample size
36% - No	
0% - Do not remember	

My home temperature in the winter is:

1% - Too warm	102 – Sample size
72% - Just right	1.7 – Average on scale of 3
27% - Too cool	0.46 – Standard deviation on scale of 3

My home temperature in the summer is:

2615% - Too warm	102 – Sample size
84% - Just right	2.1 – Average on scale of 3
1% - Too cool	0.37 – Standard deviation on scale of 3

How willing are you to consider changing the times you use each of the appliances listed below if you knew it would reduce your energy costs? 102 – Sample size

Dishwasher	93% - Yes 1% - No 6% - Maybe	Computer	19% - Yes 56% - No 25% - Maybe
Washer	87% - Yes 1% - No 12% - Maybe	Large TV	30% - Yes 38% - No 31% - Maybe
Dryer	88% - Yes 1% - No 11% - Maybe	Small TV	36% - Yes 38% - No 25% - Maybe
Dehumidifier	46% - Yes 17% - No 37% - Maybe	Pool (pool heater or pump)	44% - Yes 18% - No 38% - Maybe
range or Oven	30% - Yes 39% - No 30% - Maybe	Hot tub	46% - Yes 18% - No 36% - Maybe
Microwave	23% - Yes 50% - No 27% - Maybe		

What is the likelihood that you would consider changing your laundry schedule to save money on energy costs?

44% - Definitely would	102 – Sample size
47% - Probably would	4.4 – Average on scale of 5 (w/o last response)
4% - Might or might not	0.71 – Standard deviation on scale of 5
1% - Probably would not	
1% - Definitely would not	
3% - We already changed schedules to save energy	

What is the likelihood that you would consider changing the times you shower or bathe to save money on energy cost?

13% - Definitely would	102 – Sample size
29% - Probably would	3.2 – Average on scale of 5 (w/o last response)
28% - Might or might not	1.14 – Standard deviation on scale of 5
19% - Probably would not	
8% - Definitely would not	
3% - We already changed schedules to save energy	

The amount of hot water I have available for household use is:

94% - Usually sufficient	102 – Sample size
5% - Sometimes sufficient	2.9 – Average on scale of 3
1% - Not usually sufficient	0.29 – Standard deviation on scale of 3

How acceptable was it to you when the water heater turned off for a few minutes in response to power grid needs?

83% - Very acceptable, we didn't notice when the water heater turned off
0% - Somewhat acceptable
13% - Acceptable
0%- Somewhat unacceptable
4% - Unacceptable

24 – Sample size
4.6 – Average on scale of 5
1.00 – Standard deviation on scale of 5

How much more (positive) or less (negative) would you expect to pay for a Grid Friendly water heater?

4% - ($100)
13% - ($50)
0% - ($25)
0% - ($10)
0% - ($5)
29% - $0
0% - $5
8% - $10
13% - $25
25% - $50
8% - $100

24 – Sample size
$14 - Average

In your opinion, how should the Grid Friendly feature be added to a water heater?

29% - Added option at time of purchase
4% - Added option after purchase
58% - Standard on all water heaters
0% - Should not be offered for water heaters
0% - Other (please explain)
8% - Don't know

24 – Sample size

Which of the following organizations, if any, do you believe would give you reliable information about a Grid Friendly water heater?

0% - Government
0% - Retail store
54% - Utility company
4% - Local service organizations
13% - Environmental organizations
8% - Water heater manufacturer
13% - Plumber / Builder / Installer
0% - None
8% - Other (please explain)

24 – Sample size

How satisfied were you with the installation of the Grid Friendly control device on your water heater?

63% - Very satisfied
25% - Somewhat satisfied
8% - Neither satisfied nor dissatisfied
4% - Somewhat dissatisfied
0% - Very dissatisfied

24 – Sample size
4.5 – Average on scale of 5
0.82 – Standard deviation on scale of 5

Approximately how many times over the course of the program did you log into the GoodWatts Web site to review or modify your comfort settings?

0% - Never
0% - 1
19% - 2-5
19% - 6-10
25% - 11-20
38% - More than 20

97 – Sample size

How many times over the course of the program did you log into the program Web site to review your program account?

0% - Never
3% - 1
20% - 2-5
18% - 6-10
21% - 11-20
37% - More than 20

89 – Sample size

To what degree did the Project incentive money influence your energy consumption habits?

5% - To a great degree
11% - To a significant degree
31% - To some degree
28% - Just a little bit
25% - Not at all

103 – Sample size
2.4 – Average on scale of 5
1.12 – Standard deviation on scale of 5

To which type of contract were you assigned as part of the GridWise Testbed Program?

22% - Control
7% - Fixed
7% - Time of use (TOU)
9% - Real-time pricing (RTP)
55% - Do not remember

103 – Sample size

If you were to participate again, which contract would you prefer to be part of?

17% - Control
10% - Fixed
35% - Time of use (TOU)
38% - Real-time pricing (RTP)

103 – Sample size

With respect to the money you earned during this experiment, which of the following most closely represents your experience?

27% - The money I received was well worth the effort — 103 – Sample size
24% - The money I received was worth the effort
30% - The money I received was about right for the effort.
6% - The money I received was not worth the effort.
13% - I have no idea how much money I made.

What is the current thermostat configuration setting for your home?

2% - No Price Reaction — 102 – Sample size
2% - Maximum comfort
10% - Balanced comfort
31% - Economical comfort
11% - Comfortable economy
13% - Balanced economy
5% - Maximum economy
26% - Do not know

How well did you like using your home computer to control energy consumption?

48% - I really liked it. — 102 – Sample size
28% - I liked it. — 4.2 – Average on scale of 5
21% - I neither liked nor disliked it. — 0.87 – Standard deviation on scale of 5
3% - I disliked it.
0% - I really disliked it

Pacific Northwest
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Operated by Battelle for the
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Pacific Northwest GridWise™ Testbed Demonstration Projects

Part II. Grid Friendly™ Appliance Project

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Abstract

Fifty residential electric water heaters and 150 new residential clothes dryers were modified to respond to signals received from underfrequency, load-shedding appliance controllers. Each controller monitored the power-grid voltage signal and requested that electrical load be shed by its appliance whenever electric power-grid frequency fell below 59.95 Hz. The controllers and their appliances were installed and monitored for more than a year at residential sites at three locations in Washington and Oregon. The controllers and their appliances responded reliably to each shallow underfrequency event—an average of one event per day—and shed their loads for the durations of these events. Appliance owners reported that the appliance responses were unnoticed and caused little or no inconvenience for the homes' occupants.

Executive Summary

From early 2006 through March 2007, Pacific Northwest National Laboratory (PNNL) managed the Grid Friendly™(a) Appliance Project, a field demonstration of an autonomous, grid-responsive controller called the Grid Friendly™ appliance (GFA) controller. This device is a small electronic controller board that autonomously detects underfrequency events and requests that load be shed by the appliance that it serves. The Grid Friendly Appliance Project was one of two field-demonstration projects of the encompassing Pacific Northwest GridWise™(b) Testbed Demonstration.

For the Grid Friendly appliance demonstration, the GFA controller was configured to observe the nominally 60-Hz ac voltage signal, which is available at any residential wall plug receptacle, to recognize instances when the measured grid frequency fell below a 59.95-Hz threshold and to promptly alert the controlled appliance about the impending underfrequency event. Grid frequency is a grid-wide indicator of any mismatch between generation and load on the grid. The sudden loss of a large generator on the grid will result in a sudden drop in grid frequency that cannot be immediately counteracted by the existing resource-side controllers and available spinning reserves. The resulting underfrequency condition will continue until generation and load again become matched.

The study used 150 new residential clothes dryers that were manufactured for the project by Whirlpool Corporation and 50 retrofitted residential water heaters. The appliances were modified to shed major portions of their electrical loads when they received signals from their GFA controllers. These modified appliances were distributed among residences in several communities in the Pacific Northwest—Gresham, Oregon; and Yakima, Port Angeles and Sequim, Washington. The GFA controllers' output signals and corresponding appliance responses were monitored at the participating residences for more than a year using commercial energy-management systems.

Autonomous underfrequency load shedding. The Grid Friendly Appliance Project tested the hypothesis that the GFA controller could directly contribute to frequency protection on the electric power grid. It performed a function similar to what is now practiced at some substations where underfrequency relays autonomously react to shed the load of entire feeders when low-frequency thresholds are crossed—essentially leaving whole neighborhoods in the dark to prevent even more widespread outages.

Substation frequency protection is seldom activated, but the frequency threshold of the GFA controller was set high enough so it would recognize frequent, shallow frequency excursions. Indeed, 358 GFA underfrequency events were observed and analyzed during the field demonstration using the selected threshold of 59.95 Hz. This report shows that these events were reliably detected in the field by GFA controllers and that the appliances responded to the signals as designed by shedding portions of their loads.

Based on laboratory test observations, the GFA controller supplied a signal to shed its appliance's load within about ¼ second after a sudden drop in frequency. The underfrequency events observed in the field lasted from several seconds to 10 minutes—short enough that residential customers, when later

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(a) "Grid Friendly" is a registered trademark of Battelle Memorial Institute.

(b) "GridWise" is a registered trademark of Battelle Memorial Institute.

surveyed, responded that they had neither observed nor been inconvenienced by the curtailments of their appliances. The appliances received virtually the same frequency signal and responded to the signal similarly, despite the distribution of controllers over a wide geographic region. Every appliance responded when the frequency dipped 0.003 Hz or more below the control threshold as measured by a frequency monitor in eastern Washington State.

While the results were promising, the sum of the load resources controlled by the 200 controllers was admittedly small. Therefore, the hypotheses that an army of such controllers could protect the system frequency, prevent actuation of substation underfrequency relays, and displace much of the need for spinning reserves remain to be definitively proven by simulation and by larger field demonstrations.

It is interesting to consider that the service provided by demand-side controllers might be superior in many ways to the underfrequency protection currently provided at substations. First, the frequency threshold of the GFA controller was set relatively high compared to the thresholds for substation underfrequency relays. The response of the GFA controller will, therefore, anticipate and precede that of the substation relays. Protection performed with GFAs results in little or no inconvenience for the appliance owner, whereas the substation relay action creates outages for many customers on entire feeder circuits. The loads shed by large substation relays represent large bulk load reductions; the curtailment of a vast number of loads controlled by GFA controllers could be intentionally staggered by imposing a distribution of frequency-response thresholds, resulting in a smoother abatement of system deceleration. Furthermore, if widely adopted throughout distribution systems within a power grid, GFA appliances might better prevent the propagation of disturbances by mitigating them near their source, which is not as feasible using more centrally located substation protection devices.

Autonomy and communication. Among the important attributes of a GFA controller is that it performs its duties autonomously. The only communication that it requires is the ac voltage signal that is available at any appliance's wall-plug receptacle. For the purposes of this demonstration, however, components of the Invensys Controls GoodWatts™ energy-management system monitored the performance of each controller and its appliance and communicated observations of the controller and appliance actions. This energy-management system further allowed the traditional demand response to be successfully applied from a central location to the controlled appliance. A fully communicating controller could offer benefits such as permitting the controller to be temporarily disabled, or its performance to be modified, as might be requested by system operators. However, communication to otherwise autonomous demand-side controllers like the GFA controller incurs additional costs. Those who invest in GFAs and their services must weigh whether additional functions and additional flexibility warrant the additional costs for external communications.

Traditional demand response applied to GFA controllers. Several times during this field demonstration, traditional peak-shaving demand-response requests were submitted to the appliance loads for intervals from 2 to 4 hours. While not as innovative as other aspects of the project, performing this curtailment successfully demonstrated that loads controlled by the GFA controller could also receive and react to other demand-response requests. The affected water heaters fully curtailed their loads in response to this prolonged signal; the dryers simply alerted their operators to the request audibly and visually via a front panel light-emitting diode indicator. If the dryer owners wanted to use the appliance during this time, they would have to push the start button a second time to acknowledge the curtailment request. This is one of the first demonstrations wherein an interactive appliance like the clothes dryer has been equipped to announce a utility's curtailment request for voluntary curtailment.

Correlation of underfrequency events and load shapes. Persistent monitoring of the controlled water heaters and dryers gathered extensive data as to how consumers used these appliances. Most important, the likelihood that these appliance loads will be active and available for curtailment at various times of the day was determined. This information permitted a strong statistical argument to be established about the capacity value of the autonomous regulation and protection services available from this experimental appliance population for utilities and the entire grid.

Between 0.02 and 0.2 kW per controlled clothes dryer were available to be shed, depending on time of day, day of week, and season. Between 0.1- and 0.7-kW average load per controlled water heater was observed. The water-heater peak consumption corresponded closely with Pacific Northwest grid electric-load peaks. The clothes dryer load, in contrast, was relatively flat throughout the daytime hours.

No relevant pattern was observed for the occurrences of underfrequency events for the specific threshold exercised in the Grid Friendly Appliance Project, meaning that the likelihood of such frequency excursions was quite random and unpredictable. The statistical argument that accompanies these observations will be instrumental to utilities as they evaluate and develop programs to apply autonomous grid-responsive controllers.

The authors contend that there will be value in controlling multiple appliance types over a broad geographical area to benefit from the diversity of such diverse load populations. While the onset and release of underfrequency appliance responses in this project were applied uniformly, it is recognized that frequency threshold distributions should be imposed, and event releases should be randomized to maintain and re-create load diversity in the populations of appliances.

Cold load pickup. Any time the controlled appliances were energized, the GFA controllers initialized themselves in their triggered, curtailed states. A short delay therefore occurred before controlled appliances were permitted to operate. Such a cold-load-pickup capability is obtained at no cost with smart appliance load controllers like the GFA controller. The delay may be designed to ease the introduction of loads onto feeders as they energize.

Cost effectiveness of controlling small loads. Part of the vision for GFA controllers is to inexpensively employ numerous distributed controllers to perform needed demand-side control that will, ultimately, support and improve the operation and reliability of a power grid. Two load-control options presently exist for large and small loads: large industrial loads may be controlled by applying unique engineering site-by-site. Smaller and appliance loads may be controlled by applying external load-control switches placed between the loads and their electric service. The cost of controlling a single large commercial or industrial load is great, but the one large control point controls much capacity. The electric-power industry has not yet fully investigated whether a superior application model might exist for numerous smaller, perhaps even residential, loads that are designed once and manufactured literally by the millions, ready to respond to demand-response signals or other grid needs. A goal for developing GFA controllers would be to have such control eventually installed by the appliance manufacturers at their manufacturing facilities where labor is most economical.

The "friendly" part of GFAs. The model for applying demand-side controllers is also greatly affected by the "friendliness" with which demand-side control or ancillary services are performed. The resource pool is very restricted if the goal is only to control the largest commercial and industrial loads. Utilities that request commercial and industrial loads to be curtailed must pay their customers well for inhibiting profitable endeavors. Indeed, anyone's willingness to supply demand-side responsiveness will be influenced by the inconvenience they must endure to supply the response. If, for example, a circuit is interrupted even briefly while a clothes dryer is being used, it must be restarted and reset. In contrast, the "grid-friendly" dryer used in this demonstration simply stopped powering the heating elements, leaving the dryer drum to tumble until the heating elements could come back online. Significant power was thereby shed without an observable inconvenience to the dryer owner.

The authors contend that many such opportunities exist to perform similar innocuous and "friendly" demand-side functions on millions of residential and small commercial appliance loads. These opportunities are further enhanced if they are designed in close cooperation with the manufacturers of such appliances to achieve such grid benefits while incurring only minimal customer inconvenience.

Participants surveyed. A unique aspect of this report is the inclusion of several essays from project participants representing the perspectives of utilities, appliance manufacturers, and appliance owners. When surveyed at the conclusion of the project, residential participants confirmed that they had not been inconvenienced by the autonomous underfrequency control of their appliances, and most would purchase an appliance configured with such a grid-responsive control.

Conclusions and recommendations. Based on the conclusions drawn from the Grid Friendly Appliance Project, technical feasibility is not standing in the way of applying distributed, frequency-responsive appliance load controllers. The project's controllers reliably recognized and responded to underfrequency events on the electric power grid. Appliance owners accepted and were not inconvenienced by such control applied to their home appliances. More work is needed, however, in developing a viable business case that is acceptable for utilities, appliance manufacturers, and appliance owners. More work also is needed to verify the grid-wide benefits and the advisability of applying such distributed load control.

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PacficCorp provided counsel from conception through the conclusion of this project. Their contributions included financial resources, research design, technical guidance, customer recruitment, issue resolution, and recommendations for the customer questionnaire. Jeff Baumgarner, Dean Miller, and especially Bill Marek provided their useful insights and participation.

Port Angeles was kind enough to help the project recruit residents from among their electric utility customers. The project acknowledges the valuable participation of Bob Kajfasz and his coworkers.

Portland General Electric Company provided counsel from conception through the conclusion of this project. Their contributions included financial resources, research design, technical guidance, customer recruitment, issue resolution, and recommendations for the customer questionnaire. The contributions of Joe Barra, Laura Rooke, and Conrad Eustis helped make this project successful.

PUD #1 of Clallam County kindly helped the project recruit participants from among its electric utility customers. The project acknowledges especially Mattias Järvegren and Bronna Hankoff for their enthusiastic participation.

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Whirlpool Corporation has made significant research investments in smart appliances and made significant in-kind investments in this project. Project dryers were supplied to the project by Whirlpool at a deeply discounted rate. The project especially recognizes Andrew Sinclair, Jiannong Zhang, and Gale Horst for their efforts on behalf of the project.

Acronyms

AMI	advanced metering infrastructure
ASIC	application-specific integrated circuit
BPA	Bonneville Power Administration
DOE	U.S. Department of Energy
DSL	digital subscriber line
FPGA	field programmable gate array
GFA	Grid Friendly™ appliance
HVAC	heating, ventilation and air conditioning
ISO	independent system operator
LCM	load control module
LED	light-emitting diode
NERC	National Electric Reliability Council
OEM	original equipment manufacturer
PGE	Portland General Electric
PLL	phase lock loop
PNNL	Pacific Northwest National Laboratory
PUC	public utility commission
PUD	public utility district
RTO	regional transmission organization
RTP	real-time price
TOU	time-of-use
VPN	virtual private network
WECC	Western Electricity Coordinating Council

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1.0 Introduction

The Grid Friendly Appliance Project was part of the Pacific Northwest GridWise Testbed Demonstration Project managed for the U.S. Department of Energy by Pacific Northwest National Laboratory (PNNL) from 2005 through 2007. This project was intended to demonstrate a toolset to manage the emerging smart grid. PNNL and the U.S. Department of Energy at times use the word *GridWise* for these smart grid tools and their programmatic application. This report describes the field demonstration of the Grid Friendly appliance (GFA) controller, an underfrequency load-shed controller applied to 50 water heaters and 150 clothes dryers in the Pacific Northwest. A companion report describes the Olympic Peninsula Project in which energy price controls were experimentally applied (Hammerstrom et al. 2007).

This chapter introduces the GFA controller hardware and its functions. After a brief overview, the function of the controller will be introduced, including its potential benefits to various stakeholders. The specific capabilities of the controller will be stated. Then an attempt will be made to describe the state of the controller's commercialization, including its present cost.

The next chapter will address the integration process by which the GFA controller was placed in homes with water heaters and clothes dryers for the field project. Chapter 3 will address how the project recruited and interacted with homeowners in whose homes the frequency-responsive appliances were placed and monitored. In Chapter 4, collected field data concerning the performance of the appliance controllers are analyzed and discussed. Chapter 5 includes essays from several utility, manufacturer, and appliance owners describing their unique project perspectives. The last chapter summarizes the project's findings, list lessons learned during the project, and suggests possible future research directions. The report also includes a list of references and an appendix containing detailed information on GFA responses, participation criteria, and participant survey results.

1.1 Introduction to the GFA Controller

The ultimate purpose of the GFA controller is for it to reside within an electrical appliance load, observe the ac voltage signal available to the appliance at its wall plug, autonomously detect grid problems, and alert its appliance when the appliance load can react to help the electrical power grid. In this specific field demonstration, the GFA controller observed only grid frequency and advised its appliance to shed portions of its load whenever an underfrequency threshold was matched. This action, when carried out by numerous appliances, could help protect the power grid frequency, enhance regulation, and perhaps also avoid excitation of oscillatory modes within the power grid.

One could foresee many other future opportunities for the GFA controller to also respond to voltage and, with communications, to price signals and more traditional demand-response program signals.

1.2 Potential Benefits for Various Stakeholders

Even after the technical performance of grid-responsive load controllers like the GFA controller has been proven, business cases must be made to each stakeholder to convince them to move forward to build and apply such controllers. Consider the benefits available to each stakeholder:

1.2.1 Appliance Owner

The appliance owner potentially benefits in both indirect and direct ways. First, the appliance owner could benefit from a more-reliable electric grid if many appliances on the grid were responsive. This benefit is indirect and relies on the altruism of numerous appliance owners. The case may be hard to make, especially for the electric customer who has become accustomed to adequately reliable power at moderate electricity costs. The argument might be easier to make for one who has recently experienced rolling blackouts or other power quality hindrances. On a more positive note, altruism itself might be enough to convince some appliance buyers to pay more for a global benefit. Indeed, some utility customers now buy premium "green" power that is, other than by price, indistinguishable from the power received by non-green customers.

Also, appliance life might be increased for appliances that anticipate and respond to electric grid problems. An appliance could place itself in safe mode, for example, during an underfrequency or under-voltage event, thus preventing premature failure of the appliance. Again, this argument may be weak for an electric customer who now trusts his utility to indefinitely supply reliable electric power. Appliance owners may also expect appliance manufacturers to warrantee that their appliances will work regardless of poor power quality.

Finally, appliance purchasers have increasingly smart appliances from which to choose. It may be easier to justify grid-responsive functions in appliances that are already "smart." Some additional functionality in processor-based appliances may be had through changes in software alone. Some customers already pay premiums for smart, processor-based appliances.

More direct economic benefits derived from improved system efficiencies might be passed along to an appliance owner as rebates, program participation payments, or pay-per-response rewards from the utility, state, or federal governments. Ideally, an appliance owner should share economic benefits received by his utility or another party.

For his/her willingness to participate, each appliance owner incurs a small cost—the inconvenience of having his/her appliance respond and operate in a curtailed mode. Inconveniences borne by the appliance owner should be minimized. This study will show that such inconvenience was small for appliances responding to short underfrequency events.

1.2.2 Utility Grid Operator

While all utilities desire stable, regulated grid frequency, the responsibility for these services is distributed among utilities and are not wholly attributable to a single utility or region. Programmatically, the investment of utilities in Grid Friendly underfrequency appliances duplicates the functions now provided by substation underfrequency relays and by generator regulation. Utilities realistically need to invest no more than their share in the correction and regulation of grid frequency, the benefits of which might be received by their neighbors instead.

A cost perspective, however, will drive utilities and other grid entities to value grid-responsive technologies if they can cost-effectively displace their need for costly spinning reserves. Utilities must use their resources efficiently. Therefore, the potentially off-set costs of spinning reserves maintained for frequency regulation and other contingencies will enhance the value of GFAs from the utility perspective.

1.2.3 Appliance Manufacturer

The appliance manufacturer may not benefit directly from its decision to include grid-responsive controller technologies in its appliances, but appliance manufacturers constantly seek ways to differentiate their products in the marketplace and better serve their customers. For example, grid-responsive controllers might help an appliance last longer by avoiding stalled motors or by anticipating and performing graceful recoveries from grid problems. An appliance manufacturer's GFA might better satisfy the needs of emerging utility programs and thereby become the preferred appliance for a utility program. Through competition, the manufacturer's appliance earns participation in even more utility programs if his appliance is more responsive to program needs than those appliances offered by competitors.

The appliance manufacturer can also differentiate itself from competitors by the "friendly" way in which the appliance interacts with its owner. This means the appliance manufacturer will avoid unnecessarily inconveniencing customers while its appliances help the grid. Those appliances that inconvenience their owners unnecessarily will compete poorly.

Ultimately, the appliance manufacturer participates in a competitive market and has limitations because of the challenges of manufacturing. Even minor manufacturing costs incurred by appliance manufacturers must be recovered from their customers or from others. The appliance manufacturer must anticipate and react to mandatory programs and standards to which it might become subjected. Also modifications to existing product assembly lines are prohibitively expensive. An appliance manufacturer cannot easily and economically modify its product uniquely region-by-region or program-by-program.

1.3 Function of the GFA Controller

The GFA controller used in this field demonstration is a small electronic control board that calculates the electrical ac fundamental frequency of a grid voltage signal and asserts one of its output signals whenever the measured frequency falls below a threshold frequency. Once asserted, the signal remains asserted until the measured frequency rises above another higher threshold. This higher threshold provides some response hysteresis that will prevent the output signal from oscillating should the measured frequency hover near the underfrequency threshold. After the higher frequency has been exceeded, a timer is initiated, and a predetermined time duration must be exceeded before the output signal will be released. If the frequency falls below the higher frequency again at any time during this count, the count is restarted. This delay, too, prevents oscillatory responses and verifies that system frequency is acceptable and stable before the controlled appliance load is permitted to restart.

No claim is made that the thresholds and delays used in this project are optimal. The underfrequency threshold was chosen instead to guarantee that numerous underfrequency events would be observed at least once per week. The recovery delay was set long enough to verify that the event would be captured by the event logging equipment used by the project. Eventually, the instantiation of thresholds and delays should be determined in coordination with appliance manufacturers and utilities according to the needs and capabilities of each. Single, specific values for the thresholds and delays were chosen, but the thresholds and delays should eventually be assigned as distributions to promote smooth responses and to quickly re-establish the diversity of cycling loads after each grid event.

1.4 Underfrequency Load Shedding

The nominally 60-Hz power grid frequency is ordinarily controlled by a combination of automated generation controllers and human oversight. Mismatched system generation and load cause deviations from nominal grid frequency. Automatic generator controls respond to such mismatches within tens of seconds; humans further respond within tens of minutes. Active loads can rapidly shed portions of their loads in response to sudden generation deficits—underfrequency events—and can respond faster than either generation or humans. Autonomous underfrequency controllers could become an important tool for the management of grid frequency.

A histogram of the likelihood of grid frequencies on the Western Electricity Coordinating Council (WECC) system was shown by Lu and Hammerstrom (2006) and is reproduced here in Figure 1.1. Note that the likelihood axis is a log scale, demonstrating the remarkably narrow region within which the grid frequency is managed about its nominal value.

Project staff desired to observe underfrequency events in the field with intermittency between once per week and once per day. This design criterion was chosen to achieve numerous observable underfrequency events during the experiment. Ultimately, the underfrequency threshold would be established lower than this for permanently installed frequency-responsive resources at frequencies perhaps midway between nominal and those frequencies at which substation underfrequency relays now respond. Fewer events would then become recognized and cause load responses. However, appliance owners were apparently not inconvenienced even by the high experimental threshold and by the consequent high number of appliance responses during this field experiment.

Lu and Hammerstrom (2006) thoroughly analyzed historic WECC data from which an acceptable underfrequency threshold was selected. Simulation studies were performed on historic WECC frequency data to predict the effects, in general, of using various underfrequency thresholds, triggering response delays, t_t, and reset delays, t_r (see Table 1.1).

The triggering response delay (the delay from the time the system frequency signal goes below the threshold and the response of the appliance) is a function of both the GFA hardware and its firmware. The minimum duration is limited by hardware, hardware configuration, sensing algorithm, and by any intentionally imposed filtering that is performed on the raw data. The appliance hardware also can intentionally or unintentionally increase the triggering-response delay. While actually a function of event depth and frequency deceleration rate, the controller's triggering-response delay can be approximated well enough as being 0.2 second. The maximum allowable value for this delay should be specified by industry to avoid harmful excitation of grid dynamic system modes.

The reset delay (the delay between the frequency recovery and the release of the appliance response) can be designed to protect the appliance without incurring unnecessary numbers of, or oscillatory, control actions. Field monitoring equipment used in this experiment had been specified during a request for proposals to capture events 15 seconds and longer in duration. Therefore, the reset delay was set at 16 seconds for the project.

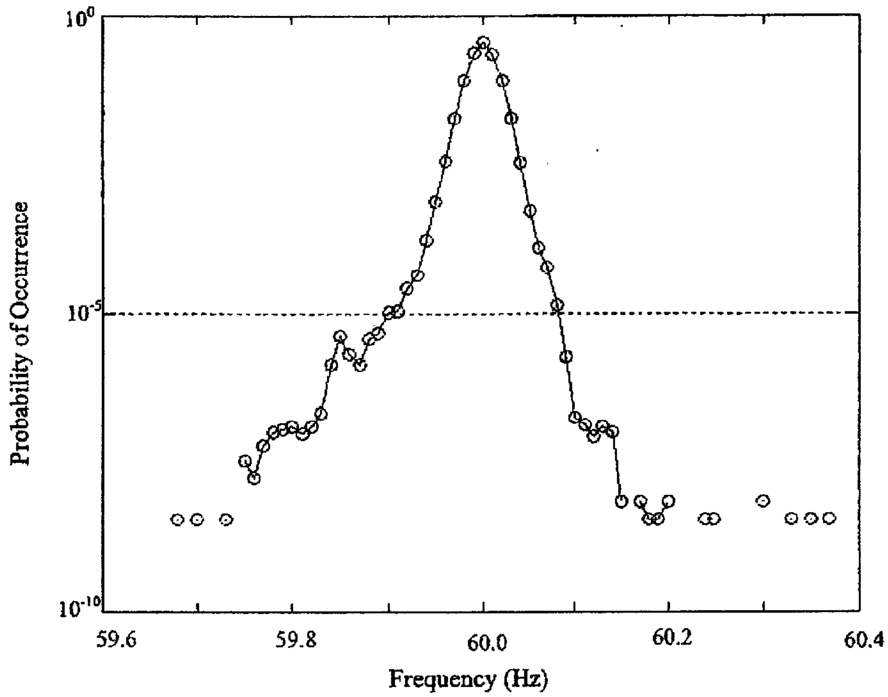

Figure 1.1. WECC Frequency Histogram Using Data Collected by PNNL from 2002 to 2005

Table 1.1. Likelihood of Underfrequency Events (Events/Day) (Lu and Hammerstrom 2006)

	t_1 = 0.2 s			1.0 s			4.0 s		
f (Hz)	t_r = 1 s	10 s	100 s	1 s	10 s	100 s	1 s	10 s	100 s
59.90	0.03	0.01	0.01	0.03	0.01	0.01	0.020	0.00	0.00
59.91	0.06	0.01	0.01	0.05	0.01	0.01	0.03	0.01	0.01
59.92	0.09	0.02	0.01	0.08	0.01	0.01	0.06	0.01	0.01
59.93	0.26	0.05	0.02	0.21	0.03	0.01	0.14	0.03	0.01
59.94	0.69	0.10	0.03	0.61	0.10	0.03	0.51	0.07	0.02
59.95	2.0	0.34	0.11	1.6	0.26	0.09	1.2	0.20	0.06
59.96	10	1.7	0.54	8.1	1.3	0.41	6.3	0.99	0.30
59.97	56	9.0	2.6	44	7.1	2.1	34	5.4	1.6
59.98	270	42	10.	230	35	8.4	180	27	6.8
59.99	1000	150	28	870	130	25	720	100	21

Using these known values for triggering and reset delays and using the simulation results summarized in Table 1.1, an acceptable underfrequency threshold was estimated to be 59.95 Hz to achieve more than one response per week but not more than one response per day. Not included in this analysis was a response hysteresis parameter designed to avoid multiple triggers for each event. By design, after a frequency event was recognized at 59.95 Hz, the frequency must then exceed 59.96 Hz for 16 seconds before the event would become released and the controller reset.

1.4.1 Related Research

Ongoing research can be found for underfrequency load shedding at substations, but research at the feeder level need not be addressed here. The use of distributed loads to enhance the frequency stability of electrical power is being addressed by Dr. Trudnowski at Montana Tech, University of Montana (Trudnowski, Donnelly, and Lightner 2006). Virginia Tech researchers have focused on studying the propagation of frequency disturbances through a power grid (Virginia Tech 2007). Researchers at the Technical University of Denmark have been among the first to investigate the modulation of set points on small thermostatically controlled loads for provision of frequency reserve (Xu et al. 2007). Cannon Technologies, Inc. (2005) has provided and installed underfrequency load-control devices on loads on the island of Oahu, Hawaii, which is served by the Hawaiian Electric Company, Inc.

1.4.2 Response Time

The response of the GFA controller was observed in a laboratory setting before its application in the field. The controller-frequency measurement includes the effects of a low-pass digital filter, which smoothes the data and prevents false responses to spurious inputs and noise. Therefore, the triggering response time of the controller is best defined by a formal *response time*, the time needed for a measurement to transition between 10% and 90% of its response to a step input that is being tracked.

A step change in frequency was applied to the controller, the threshold of which had been set at 10% of the range between the final frequency value and the initial. The GFA controller consistently responded to this step 0.4 seconds after the start of the step change (Figure 1.2). Note that a consequence of the logarithmic response is that deep events will be responded to faster than shallow ones. This is a desirable ramification.

The applied low-pass filter could have been designed for faster responses, but faster responses were found to permit spurious events to become recognized as the large dryer and water heater loads became energized. These spurious events are believed to be caused by the interactions of the phase-lock-loop, the digital filter, and a real phase shift that will occur in the load circuit upon the startup of a large household load.

1.4.3 Cold-Load Pickup and Release of Curtailment

The GFA controller used in this field experiment automatically performs cold-load pickup. That is, when it is first energized, it initiates a curtailment. The curtailment is released after 16 seconds, providing the grid frequency exceeds 59.96 Hz throughout those 16 seconds. A cold-load pickup feature is useful for utilities because it holds off startup transients for controlled appliances until the grid can become stabilized. Cold-load pickup is easily performed on processor-based controllers by establishing appropriate initialization conditions that will enact the cold-load pickup. The cold-load pickup delay can be assigned identically to those of the underfrequency delay. The permissible delay would be short for many appliances, longer for others.

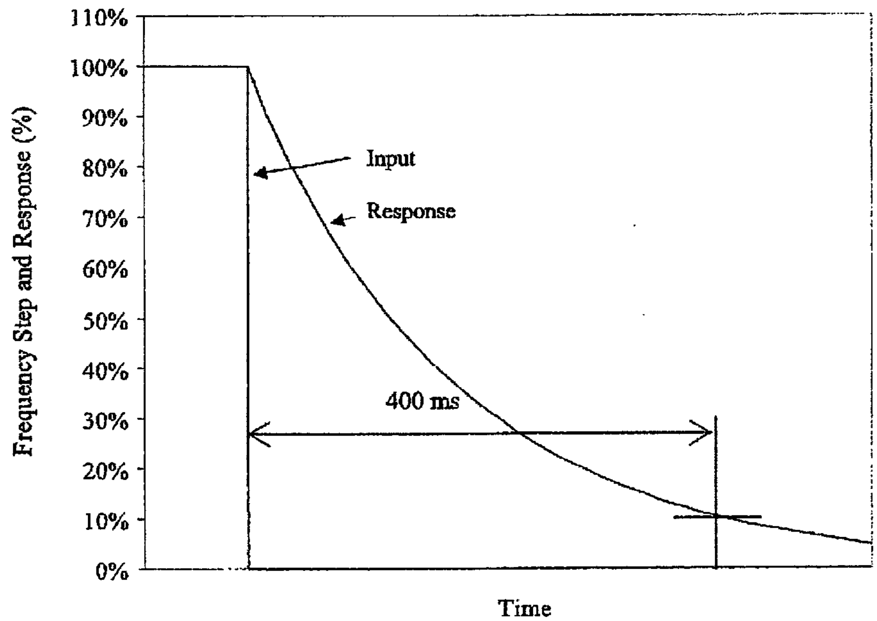

Figure 1.2. Response Time of the GFA Controller

1.5 GFA Controller Hardware

The GFA controller used in the field project is a 5-cm × 7.5-cm (2-in. × 3-in.) digital electronic controller board. The digital intelligence is based on an Altera field programmable gate array (FPGA) (Figure 1.3).

Inputs to the controller board include 5 V dc, which is used to power the board, and a 24-V ac voltage-sensing input from a voltage transformer that is used to sense grid frequency of the appliance's 120- or 240-Vac electric service. The exact ac voltage magnitude applied to the 24-Vac input is not critical. The ac signal is conditioned by a series of comparators that convert the ac sinusoid into a square-wave signal having fast rise and fall times. The period of the resulting 60-Hz square wave is measured using the pulse count from a 7.2-MHz crystal oscillator reference. The details of the calculation will be more fully described in the firmware section that follows this section.

Outputs of the controller board consist of several digital outputs, the characteristics and meanings of which can be assigned by firmware. Only the "relay control" signal was passed along to the controlled appliance. This signal was pulled to its low logic state while a curtailment response was being requested from the controlled appliance. Remaining output pins were assigned to facilitate testing and troubleshooting, but these additional signals were not used for appliance control.

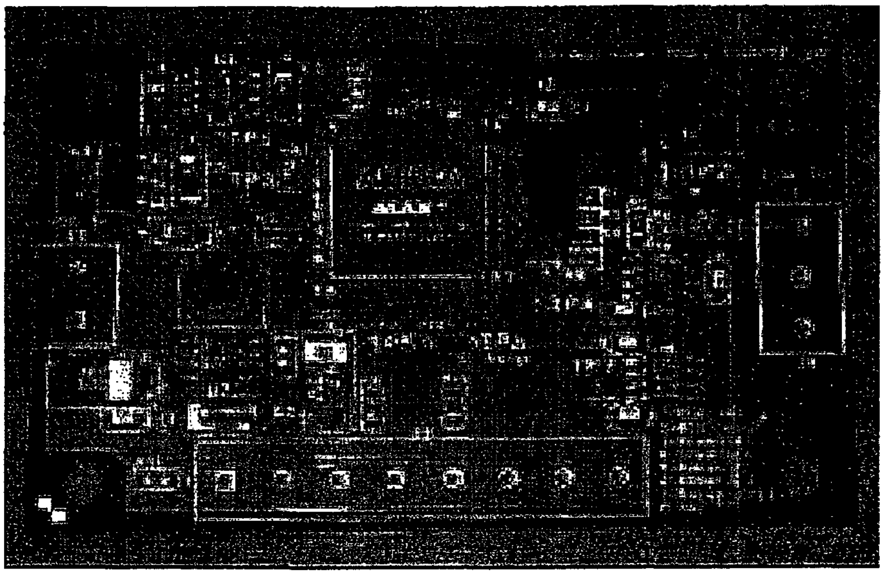

Figure 1.3. GFA Controller Board used in the Grid Friendly Appliance Project

The output of the GFA controller is simply a binary signal. Appliance load current did not flow through any part of the controller board. The binary output signals were used to control the relay switches in the control modules for water-heater loads. For the dryers, optically isolated versions of the controllers' output signals were sent to Whirlpool's communication processors, where they were then translated into Whirlpool's proprietary serial protocol and sent to and understood by the dryers' microcontrollers.

1.6 GFA Controller Firmware

The firmware operation of the GFA controller was designed and implemented on the equivalent of an Altera EPM7128BTC100-10 FPGA. A hardware gate design approach was used to achieve an efficient implementation using the limited number of FPGA macrocells. The block diagram of the FPGA firmware is shown in Figure 1.4.

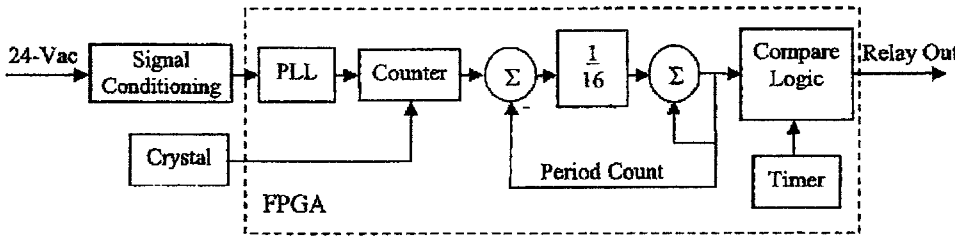

Figure 1.4. Simplified FPGA Firmware Logic-Block Control Diagram

It is stated at some places in this report that the GFA controller measures frequency, but it is more correct to state that it measures the period of the input signal. A period is, of course, the reciprocal of the signal's frequency.

The conditioned 60-Hz square wave from the power grid is an input to the phase lock loop (PLL) that is implemented on the FPGA. The PLL removes jitter from the period measurement. It also prevents logic confusions that can occur when multiple zero crossings occur in noisy appliance electrical environments. A difference is taken between the period measured by the PLL and the present reported period of the GFA controller. This difference is an error signal. The error signal is then divided by an integer to create a low-pass filtered tracking of the actual frequency. PNNL found the divisor 16 to be best for the project's combination of appliances and controller hardware. This divisor removes the responses to high-frequency noise, but it also slows the response to legitimate changes, as is typical for low-pass filtering. The result of this division (an attenuated error signal) is then added to the reported period. The reported period is then digitally compared against thresholds to determine the state of the device's output-control signal. If the reported period fell below the threshold frequency of 59.95 Hz, the relay output signal was activated. Thereafter, the controller waited until it encountered periods corresponding to a frequency exceeding 59.96 Hz. The frequency had to then remain above 59.96 Hz for 16 seconds before the relay output signal would become released.

The response parameters chosen and used in the GFA controller firmware are summarized in Table 1.2. Although the PLL was effective at conditioning the 60-Hz signal, it contributed to undesirable wind-up integration behaviors for the controller. Alternative, improved approaches will be used in future controller firmware algorithms.

Table 1.2. Field Settings of the GFA Controller

Underfrequency threshold	59.95 Hz
Measured response time (from 0 to 90% of step value)	0.4 s
Recovery threshold (starts delay timer)	59.96 Hz
Minimum delay imposed before release of control	16 s

1.7 Controller and Implementation Costs

The purpose of this section is to discuss the hardware and installation costs incurred in applying the GFAs used in the field demonstration. The challenges of accurately stating implementation costs are as follows:

- The field demonstration was small in scale and proved none of the benefits anticipated for large-scale implementation.
- The degree of integration of the controller into the appliances was also low. The resulting costs, therefore, exceed what should be expected for full integration of the controller into appliances by appliance manufacturers in their factories where labor and manufacturing efficiencies can eventually be realized.
- The experimental design mandated that monitoring and control were included, but ultimate cost effectiveness of the implementation might not bear the additional costs of communication.
- The form of the GFA controller itself has not yet been reduced to an application-specific integrated circuit (ASIC) where its final cost effectiveness can be proven.

The cost of the GFA controller board used in this project was approximately 44 U.S. dollars. This cost is based on the delivery price at which a commercial board manufacturer purchased components for and populated 300 controller boards for this project. This estimate does not include initial engineering costs for the board, which was replicated from PNNL designs. The estimate does, however, include the non-recurring engineering charges incurred for setting up automated pick-and-place board population and other purchasing, manufacturing, and testing charges to the project by the commercial board manufacturer. The additional costs borne by the project for each appliance included approximately $290 for both a modified load control box, which monitored the performance of the controller, and for a home gateway that relayed the information back via a broadband internet connection.

Both the dryer and water heater also incurred installation charges from skilled electricians for installing monitoring equipment in the homes. The costs of these installations were approximately $110 for the water heaters and dryers and another $40 for installing communications equipment.

For both appliances, the load-control monitoring boxes were required by code to be directly spliced into the 220-V ac circuit. Each installation, therefore, also incurred Washington state electrical inspection fees. The initial fee per installation was $50. Fortunately, this fee was later reduced to $10 thanks to actions taken by the Bonneville Power Administration (BPA) as it was able to negotiate a preferred bulk inspection fee applicable to both this and another BPA project.

Broadband connectivity was provided by various cable and Internet providers at the expense of the appliance owners, but the project paid a small fee of approximately $1 per month for each home to maintain a back-end server for all the monitoring services.

Research labor is not included in these estimates. Also not stated are labor costs for removing equipment at the end of the project. One can see that many of these incurred costs are directly attributable to the research nature of the project. Others may have been incurred by communication equipment, which may be desirable, but not essential, to the function of the GFA controller. Ultimately, PNNL's goal is to have the GFA controller installed by an appliance manufacturer at an incremental cost under $2, ready to provide grid supportive services at the time it is plugged in by its new owner.

2.0 Appliance Integration Process for the Grid Friendly Controller

This section describes the methods used to integrate the GFA controller with clothes-dryer and water-heater appliances for this field demonstration. This section also describes the methods used to monitor the performances of both the controller itself and the controlled appliances.

The long-term objective for GFA controllers has been to achieve close integration of the controller with appliances. Ideally, appliances would incorporate grid-responsive controllers at the time of the appliances' manufacture. In practice, only a small degree of integration could be practiced and demonstrated. These are contributing factors:

- Appliance manufacturers are unwilling to significantly modify production lines for the needs of the small number of appliances used in pilot-scale demonstrations. Even minor modifications of manufacturing lines require major planning and investments.
- Participating utilities had a limited tolerance for experimental, non-commercial-grade equipment as a result of their potential liabilities.
- PNNL also wished to limit liabilities that might be incurred by placing experimental equipment permanently in residences. Ultimately, a decision was made to remove all non-commercial-grade and test equipment from homes at the conclusion of the experiment.
- Safety certifications were more readily obtained for modifying an existing piece of equipment—the load-control modules of the chosen energy-management system. This approach allowed state inspectors to review a single, fully packaged solution for their approval processes.

2.1 General Grid Friendly Controller Integration

PNNL selected and solicited five vendors of energy-management systems to request equipment that would house the GFA controller and would monitor both the controller and its controlled appliance. The responsive device was to recognize and report events no less frequently than daily concerning any controller or appliance event that was at least 15 seconds in duration. An appliance event was defined as a change in load of at least 1200 Watts. Time-stamped data logs were requested from the vendors to track events and verify controller performance for the project. Three vendors submitted complete responses to the solicitation. The winner, Invensys Controls, met the solicitation requirement at the lowest price.

The components of the Invensys Controls GoodWatts™ system (Figure 2.1) used for the Grid Friendly Appliance Project included:

- Load control modules—The load-control module monitored the GFA controller and water heater or dryer load.
- Home gateway—The home gateway wirelessly communicated with the load-control modules and relayed the information to the back-end server via the appliance owner's broadband cable modem or digital subscriber line (DSL) connection.
- Back-end server—The back-end server received periodic data from each home's gateway and stored and organized the data for the project.

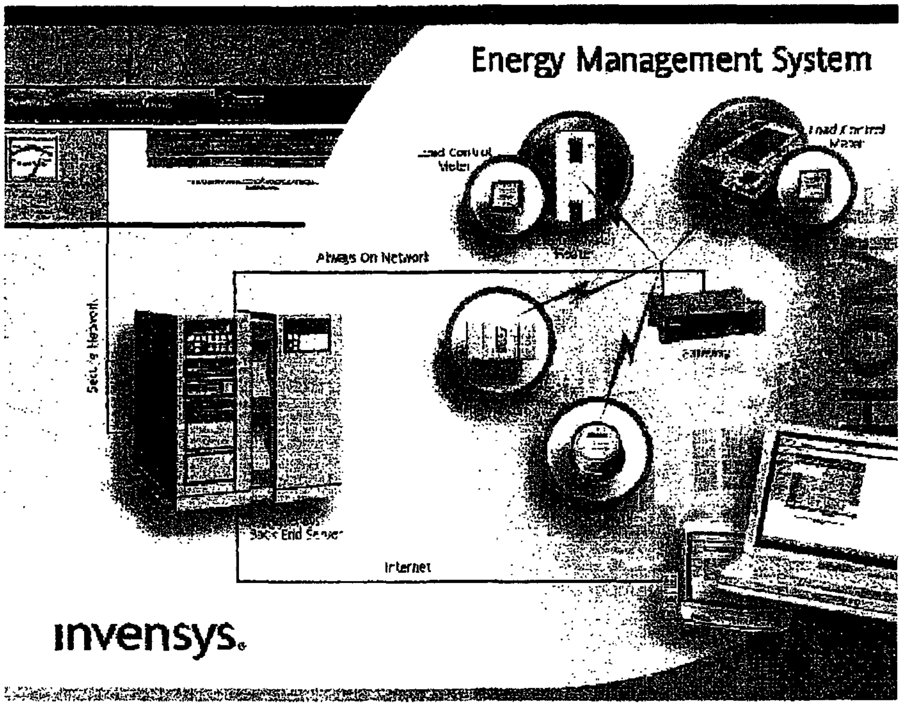

Figure 2.1. Invensys GoodWatts System (Courtesy of Invensys Controls)

During design, Invensys Controls and the project elected to also include a second box that would be attached to the load-control module to house the GFA controller. This modification was suggested and accepted because doing so hastened the design and approval processes.

It was observed early in the project but after the initial equipment installations that the premise radio communications at times failed to fully link radio-system components in some homes. This was especially true when unusual building materials or long distances were encountered within homes. Regardless of the reason, GoodWatts communications thermostats were sometimes used as radio-communication relays within homes to link the load-control modules and home gateways. This need and limitation had not been anticipated.

The chosen energy-management system's home gateway was also found to not communicate with some of the broadband communications available at responding homes. The existing system worked well where cable modems existed, but an additional virtual private network (VPN) router box was necessary where homes had DSL Internet connectivity. The router box supplied by Invensys Controls looked identical to their home gateway except for its nameplate. This also had not been anticipated.

2.1.1 Load-Control-Module Description

The load-control module of the Invensys's GoodWatts system had been designed to control water heaters and pool pumps to facilitate occupancy scheduling and traditional time-of-use demand response. Each load-control module has a 240-V ac switch, and each load-control module can wirelessly exchange information with its home gateway. The project had requested some modifications be made to the load-control module to suit project requirements.

Invensys and project staff elected to attach a second box adjacent to the load-control module to accommodate project functions because doing so hastened the design and approval processes. Figure 2.2 shows the load-control module and attached second box that housed the controller. The second box also housed one of Whirlpool Corporation's processors that interpreted their proprietary serial communication protocol for the project dryer.

The project required that the load-control module collect time-stamped event data whenever the state of the GFA controller's output changed. In the case of the water heater, the load-control module opened the 240-V ac circuit immediately whenever an underfrequency event was recognized by the controller. For the dryer, the load-control module was only to pass the GFA controller signal onward to the dryer, but it was never to open the circuit. The GFA controller was powered from the load-control module's existing 5-V ac power supply.

An additional 24-V ac transformer was provided in the extra second box to provide the ac signal, which was monitored by the controller for its frequency signal. It may be acceptable for the frequency sensor to share a transformer with its power supply, but PNNL chose not to do so to avoid possibly confounding noise problems that can occur on the loaded secondary of a power-supply transformer.

The load-control module was also to monitor and report any time its appliance significantly changed its load. As noted above, "significant" changes were defined as changes of approximately 1200 W or more. The accuracy of these measurements was not critical, but the measurements should have clearly indicated the appliances' operational state. Each such event was to be time stamped to the nearest second, and every event 15 seconds or more in duration was to be logged. Therefore, important information about each load's usage was logged, regardless of whether the changes in operation were attributable to underfrequency events. The event log captured by the load-control module was periodically relayed to the home gateway via wireless by radio communication.

Safety was always a priority while designing and installing project equipment. Invensys Controls sought and received Underwriter Laboratory certification for their modified load-control module and second box. They also submitted the modified load-control module for rigorous testing by a Whirlpool Corporation approvals process that was perhaps more restrictive than the national certification process.

The State of Washington initially demanded that a $50 inspection fee be paid for each dryer and water heater installation because each installation required modifying an existing 240-V ac home circuit. After negotiations led on the project's behalf by the Bonneville Power Administration, Washington State eventually agreed to bulk permitting of the project installations for $10 each, a great cost savings for the project.

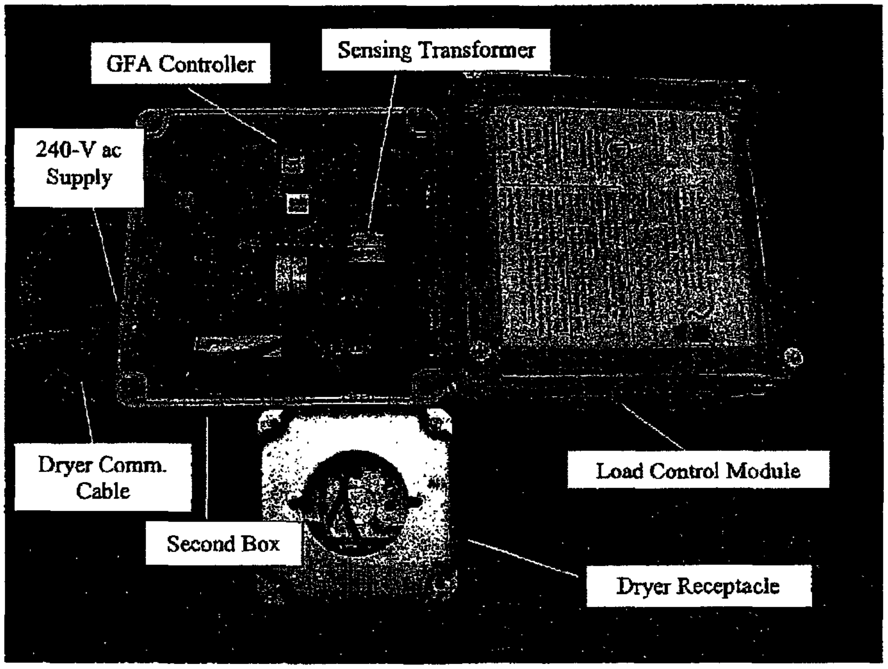

Figure 2.2. Invensys GoodWatts Load Control Module and Extra Second Box

2.1.2 Home Gateway

The Invensys Controls GoodWatts system included a communications home gateway that communicated with other premise system components using a proprietary wireless radio communication. The home gateway communicated outside the premise using broadband cable or DSL (Figure 2.3).

After it is plugged in, the home gateway identifies the communicating load-control modules within its premise and establishes a persistent broadband link to Invensys Control's back-end servers. Light-emitting diode (LED) indicators on the gateway's front panel show the home gateway's status. The home gateway required an additional VPN router to communicate with its back-end server via DSL broadband connections. The need for this device had not been anticipated at the start of the project.

The reliability of home gateway communication was a persistent challenge during the field experiment. While the underfrequency event log data were collected and maintained at the load-control modules, intermittent home gateway communications at times delayed the communication of that logged data back to the back-end server. Severe winter weather interrupted connectivity at least twice. Project staff then needed to request that reboot procedures be conducted for all non-communicating home gateways in participating homes.

Figure 2.3. Invensys Controls GoodWatts Home Gateway

Wireless communication distance and material obstructions also affected data collection within homes. Where wireless communication quality was insufficient, the vendor supplied and positioned wireless communication relays between load-control modules and the home gateway until adequate communication quality could be achieved.

2.1.3 Local Monitoring Provided by the Load-Control Module

The water heaters turned on and off according to the needs of their thermostatically controlled loads. The dryer heating elements also cycled on and off frequently during each laundry load. The load-control modules calculated power consumption just before and just after such load changes.

Unfortunately, these measurements and calculations occurred during transients and were sometimes difficult to interpret as either ongoing or off-going appliance events without intelligent human intervention and interpretation. The project was, therefore, unable to find an efficient means to determine exactly how much aggregate load was curtailed by each underfrequency event. Furthermore, data from early in the experiment failed to reliably pair off-going events with every ongoing event, making it appear that some appliances remained on indefinitely. The data, especially early in the field demonstration, were therefore useful only for anecdotal observations of individual appliance, not aggregated, events. A series of gateway firmware updates progressively improved data quality, but never fully rectified these stated limitations.

The project relied instead on a statistical argument based on each appliance type's daily load shape, as was measured in 15-minute intervals for appliances by the GoodWatts system, to evaluate the GFA controllers for their statistical likelihood of shedding water heater and clothes dryer loads.

2.1.4 Remote Communications Provided by the Energy Management System

The event data were maintained at the back-end servers of Invensys Controls and were made available to PNNL in a series of daily logs. Eventually, the process of retrieving the daily logs from Invensys to mirrored databanks at PNNL was automated. An example series of event data entries is shown in Table 2.1. The definitions of column headings are given in Table 2.2.

Table 2.1. Example Event Data Set as Maintained at and Retrieved from the Back-End Server

ACCOUNTID	DEVICETYPEID	METERID	EVENTTYPE	READTIME	READING	METERSTATUS	DEMAND	QOS	CONTROLLEVEL	OVERRIDETYPE	SCHEDULEDSTATE	ALARMSTATUS	DEVICEREADING	PRICECONTROLLED	UNITPRICE	LOCATION
431	3	553	128	03/06/2006 1:02:08	1282782	0	0	100	2	0	1	4	0	0	0	Richmond
431	3	553	2	03/06/2006 1:03:04	1282782	7648	2	100	16	0	1	0	0	0	0	Richmond
431	3	553	128	03/06/2006 11:04:46	1282782	-32768	0	100	16	0	1	5	0	0	0	Richmond

2.2 Integration of Grid Friendly Controller with Appliance Loads

Interfacing between several vendors' products requires extraordinary cooperation to achieve successful product integration. If a technically skilled visionary were able to author a flawless specification, there would still be errors in implementing the specification. Because there were neither existing designs nor a flawless specification, the approach in this project was regularly scheduled phone discussions between design engineering staff of the participating organizations—Invensys Controls, PNNL, and Whirlpool. These phone meetings were supplemented by numerous e-mailed concepts and drawings. With few comparable efforts to emulate, various issues and approaches were discussed. Note that these were technical discussions between hands-on engineers to rapidly uncover and resolve technical concerns.

The design was prefaced with some technical issues. For example, would the GFA controller reside in or at each device (dryer, water heater) or only at a single central location in the home? With the desire of a sub-second response time, discussions of the central GFA placement were abandoned in favor of guaranteed faster control responses at each appliance, avoiding potential communication latency issues. In the end, the equipment was proven to respond faster than the project's capability to measure and report the response back to the central servers.

Table 2.2. Definitions of Data Column Headers Used for GFA Event Data Logs

ACCOUNTID	Unique participant identification number for project	
DEVICETYPEID	3	water heater
	5	clothes dryer
METERID	Not used for Grid Friendly Appliance Project.	
EVENTTYPE	-32768	Startup of LCM
	2	Control Level has been changed
	4	An override occurred that did not change the control level
	6	An override occurred that caused a change in the control
	34	Curtailments caused a change in the control level
	38	The curtailment was overridden
	64	The clock between lcm and gateway synced
	128	Entry came from an internal lcm log
READTIME	Time stamp date and time as applied by the load-control module.	
READING	Revenue meter reading, where GoodWatts revenue meter was used. Most Grid Friendly Appliance Project homes did not have GoodWatts revenue meters installed.	
METERSTATUS	Not used for Grid Friendly Appliance Project.	
DEMAND	For certain event types, calculated load power demand. Calculated for second before and second immediately following significant load change.	
QOS	Quality of service indicator from poor (0) to good (100)	
CONTROLLEVEL	1	Operating as scheduled
	2	Recovering from curtailment
	7	Schedule curtailment
	9	Override
	16	GFA frequency event
OVERRIDETYPE	0	Override cancel
	1	Override temporary
	2	Override hold
SCHEDULEDSTATE		Scheduled by occupancy modes to be
	0	Off
	1	On
ALARMSTATUS	4	Underfrequency start
	5	Underfrequency release
DEVICEREADING	Not used for Grid Friendly Appliance Project.	
PRICECONTROLLED	Not used for Grid Friendly Appliance Project.	
UNITPRICE	Not used for Grid Friendly Appliance Project.	
LOCATION	Premise location (Yakima, Gresham, Sequim, or Port Angeles)	

Several alternate approaches were considered. The fact that a GFA controller signal (and also the price alert signal that was opportunistically designed into those dryers that would overlap with the co-located Olympic Peninsula Project) were Boolean (True/False or On/Off) suggested a simple design. To facilitate parallel development of the custom load-control module and the custom dryer interface with minimal risk of interoperability issues, the hardware interface was simplified to a concise Boolean format.

The format consisted simply of three logic-level Boolean bits, as are defined in Table 2.3. The state of the GFA signal was to immediately curtail either the water-heater or dryer-heater loads. The dryer drum motor was not to be affected. With minimal additional expense, a demand response signal was provided for the receipt of external signals from the utility. On receipt of the demand response signal, the dryer would display an "En" signal on its front panel and would require the operator to depress the start button a second time to acknowledge and override the signal. The water heater could be directed to curtail for demand-response signals via other means provided through the load-control module—an existing feature of the Invensys Controls system. The price signal was to elicit a similar response from the appliances, except the dryer would display "Pr" in response to the price signal.

Table 2.3. Designed GFA Signals and Corresponding Appliance Responses.

bit name	water heater response	dryer response
GFA	Underfrequency shed: 0 – Curtail entire load 1– Release load	0 - Immediately turn off heating elements for up to 10 minutes. Drum motor is not affected. 1 – Release heating element load
Pr	High price response: 0– No action 1– No action	0 – Display "Pr" on panel front. User must push start twice to override. 1 – No action
En	Demand response: 0 – No action (existing GoodWatts LCM response possible) 1 – No action	0 - Display "En" on panel front. Must push start twice to override. 1 – No action

2.2.1 Water-Heater Control Integration

Local electricians were contracted by the project to insert the modified load-control modules into the 240-V ac circuits between each home's electrical service and water-heater appliance. Except for the presence of the extra second box, installing the water-heater load-control module was identical to the installation that would have been performed otherwise for the commercial load-control module. No unique electrical installation challenges were anticipated or found (Figure 2.4).

Installers were to apply labels to the load-control modules at the time of their installation. These labels advised appliance owners to phone the project phone numbers if they had questions or concerns about the performance of their modified water heaters.

2.2.2 Integration of the GFA Controller with the Clothes Dryer

As has been stated, the modified load-control module with a Grid Friendly response had to communicate with the existing serial communication protocol of the Whirlpool dryer. Selecting a simple Boolean interface resolved some issues, but other issues persisted unique to the dryer:

- Testing and debugging an interface reliant upon a proprietary data payload can be difficult and time consuming. This was especially true because the design center for the dryer and the communication hardware were located in different regions of the country.
- The dryer vendor was hesitant to disclose enough protocol and security information to allow including their interface into a load control module (LCM) provided by another vendor. Obtaining permission within Whirlpool to share this information would have taken a prohibitively long time.

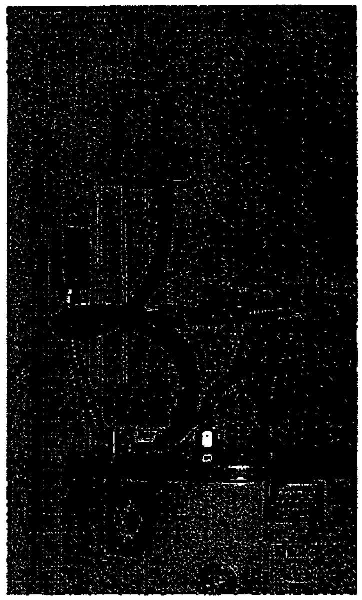

Figure 2.4. Load-Control Module Installed on Water Heater in a Project Home

This last issue was resolved for the demonstration project by providing an interpretative layer programmed into an external microprocessor developed by and provided by the dryer vendor. The inputs from the load-control module into this microprocessor are simply the three Boolean inputs that indicated an underfrequency event, pricing event, or demand-response event. These signals were then translated within the microprocessor into serial communication protocols that could be interpreted by the dryer. The project thus avoided the need to share any part of proprietary protocols between the cooperating vendors.

Whirlpool engineers opted to provide optical isolation between the external load-control module boxes and their microprocessor and communication pathway. This step was prudent to avoid possibilities of conflicts between the various systems or their housings.

Although the target of the project was the Grid Friendly demonstration, Whirlpool implemented extensions to the interface. For a demand-response event, the dryer was capable of functioning as a consumer notification point. The special energy-conservation display code "En" was implemented and would appear on the display of the dryer when a corresponding signal was received via the modified load-control module. It indicates that the utility company has issued a request that the consumer use less electrical power for several hours. Upon receipt of this signal, the dryer will temporarily wake up (for several minutes) and provide both an audible and visual indication of the curtailment event. After a short time, the dryer will return to the off state. However, if the event is still active when the consumer presses the START button, "En" reappears on the display, and an audible notification is sounded. If the consumer needs to proceed with the drying cycle, he/she may press START again, and the dryer will start and operate normally. This feature provided a consumer-override capability at the appliance control panel.

The concise interface definition simplified testing and debugging as intended. The project team was able to use a very simple test to determine if a signal arrived at the dryer. The custom Whirlpool microprocessor chip in the load-control module then converted the concise signal to the appropriate proprietary serial signal for the dryer. The project collaborators submit that this simple interface model could successfully accommodate both advanced microprocessor-controlled devices and simpler analogue and electromechanical devices.

In retrospect, the project should have implanted a verification of connectivity. With the demonstrated configuration, it was difficult to determine if, for example, the interface cable between the load-control module and dryer had been disconnected from the dryer. It would have been very helpful to have had a return "handshake" signal to verify that end-to-end communications were intact. This could also have been done in a concise manner, although it was not designed into the demonstrated system.

Disadvantages of the selected concise design were also identified. The simple Boolean interface limits future expansion in the type of energy signals that can be transmitted and received. A more complex serial interface could always add messages in the protocols transmitted. This luxury is not possible with limited binary messages. Perhaps the vision for the future should be to move ahead with an interface specification that includes both the concise interface as well as accommodations for a more advanced interface to enable future expansion. It must be realized that the appliance manufacturer might envision other uses for an external interface and will not want their interface port captured exclusively for the purpose of energy management.

This was the first time (to our knowledge) that a research modification for a product manufacturing line has been accommodated in an existing product line for the purposes of conducting energy appliance research. The 150 dryers modified by the project took less than 1 hour to manufacture on the existing Whirlpool production lines. The planning for this short run of appliances took months.

2.3 Observed Load Effects on Frequency Measurement

The GFA controller was first implemented with a faster response time near 200 ms. Upon appliance testing, it was observed that introducing the large appliance loads could trigger false underfrequency events for the integrated GFA controllers. This result was likely caused by 1) a real shift in the relative phase caused by drawing power over long premise distribution lines and 2) the PLL filter that was designed into the controller. The PLL is an effective integrator that can cause windup error and overshoot of the frequency that was to be tracked.

An adequate engineering solution was found by doubling the response time of the controller without otherwise changing the design. The response remained fast, but most false triggers could be avoided with this solution. The PLL will not be used as a filter component in later controller solutions because of this windup behavior.

3.0 Recruitment Activities and Project Interactions with Appliance Owners

This chapter describes the project's interactions with appliance owners in three main areas—recruitment, routine interactions during the project, and project decommissioning activities.

3.1 Recruitment Activities

The project identified, qualified, contracted, and supplied the experimental project equipment to residential participants. With the help of collaborating utilities, the project recruited homeowners who would agree to house and operate project appliances for the project.

3.1.1 Recruitment of Potential Participants

Three target populations in Washington and Oregon were made available to recruit residential participants by four collaborating project utilities:

1. PacifiCorp recruited for the placement of 50 dryers and 25 water heaters in Yakima, Washington.
2. Portland General Electric (PGE) supported 50 research sites for the placement of 50 dryers in Gresham, Oregon.
3. PUD #1 of Clallam County and Port Angeles together recruited sites for the placement of 50 dyers and 25 water heaters in and near Sequim and Port Angeles, Washington.

These regions recruited accordingly. Applicants were required to own their residences and have high-speed, broadband Internet access.

Participants were offered a new Sears Kenmore HE^2 dryer, manufactured by Whirlpool Corporation, as their principal participation incentive. Project staff had anticipated that this significant incentive would cause the project to become overwhelmed by applicants, but that was not the case. The stringent list of additional participation criteria greatly reduced the number of eligible homes available to the project. Staff had to conduct creative recruitment activities and contacted increasingly more potential participants to finally identify and sign up between 150 and 200 applicants to participate in the Grid Friendly Appliance Project.

The following are examples of some of the special recruitment activities:

- January 2006, in Port Angeles and Sequim, PNNL staff led two town hall meetings to inform and recruit participants, answer questions, and assist applicants with completing their applications.
- During January 2006, a radio advertisement was purchased and aired in Sequim and Port Angeles. The text for the advertisement read

  Pacific Northwest National Laboratory, in cooperation with Clallam County PUD and the City of Port Angeles, need your help testing smart energy technologies. As demand for electricity goes up, progressive utilities are looking for ways to avoid building additional transmission lines while keeping your rates low. You can actually earn money, and maybe even a new dryer, by testing technologies to control how and when you use electricity. There will be two Town Meetings on Thursday, January 26, where you can learn more about this innovative program and how you can earn money for volunteering. The meetings will be at 1 in the afternoon and 6:30 in the evening on Thursday, at the Vern Burton Meeting Room, 321 5th Street, Port Angeles. If you own your home, have high-speed Internet and electric water and heat, you may qualify. To sign up for the program today, call 1-866-528-1882 or apply online at www.gridwise.pnl.gov/testbed.

- A particularly enthusiastic recruit in Sequim single-handedly recruited at least five additional participants by phone calls and by demonstrating his installed project equipment to others in his home.

- Newspaper advertisements were run during January 2006 on the Olympic Peninsula. One example read

  Power to the People! Come learn how you can earn money by testing smart energy technologies in your home; Pacific Northwest GridWise™ Demonstration Project; Town Meetings; Thursday, January 26, 2006 1:00 and 6:30 p.m.; Vern Burton Meeting Room, 321 5th Street, Port Angeles. Find out how you can be part of this program if you: * own your home * have electric hot water and heat * have high speed Internet *(cable modem, fiber optic or DSL, not dial-up);* www.gridwise.pnl.gov/testbed; 1-866-528-1882; This project is funded by the U.S. Department of Energy and is being conducted by Pacific Northwest National Laboratory in collaboration with Clallam County PUD and the City of Port Angeles."

- Rob Pratt and Don Hammerstrom, both of PNNL, and Bronna Hankoff, Clallam County PUD, were interviewed on November 1, 2005, by KNOP radio talk show from Port Angeles, Washington. This exposure generated several more sign-ups on the project's GridWise Testbed Web site.

- PacifiCorp provided its own recruiter, who at one point canvassed neighborhoods of Yakima, Washington, door-to-door to invite project participation.

3.1.2 Qualification of Participants

A tiered approach was used to qualify applicants for project participation. First, the project targeted recruitment where it would likely be successful in finding qualified applicants. The recruitment advertisements themselves listed many of the most important qualifications. Applicants were then directed to an automated Web site, where the applicants' qualifications were further tested. The action of accessing the Web site itself was part of the selection test because applicants were required to have (broadband) connectivity. The project preferred applicants who were Internet savvy and able to participate in a final survey by Internet. Finally, all remaining applicants were further interviewed by telephone to confirm that they were indeed qualified to participate.

The main recruitment qualifications consisted of

- having high-speed Internet service, either cable or DSL
- ownership of the home occupied by the applicant
- having electric water heater and dryer services, not gas, to the home.

Several calls were received from potential applicants during recruitment asking whether "high-speed" dial up service would qualify for the program. High-speed Internet consisted of a home having access to either cable or DSL service. One participant having satellite Internet service was disqualified after having program equipment installed because the satellite signal in this particular application was not strong enough to communicate with the project's Invensys equipment.

An example logic flow diagram (Figure A.1), according to which the automated Web site qualification processes were designed, may be found in Appendix A. Care must be used to accurately assess whether respondents are truly eligible to participate. Even after automated qualification had been conducted, the follow-up interviews revealed misunderstandings. Some applicants perhaps answered the questions to intentionally avoid disqualification and receive project incentives. Others were unable to answer basic questions about their appliances and their Internet connections. For example, those applicants who did not know whether they had electric or gas water heaters required further interview by the project.

3.1.3 Initial Project Survey

Participants were provided by mail and were asked to complete and return an initial project survey before their further project participation. The purpose of this survey was to assess characteristics of the participant population and detect biases that might influence the project's findings. The text of this survey has been included in the appendix of this report (Table A.3).

The same survey was sent to all participants. Questions that could affect the Grid Friendly Appliance Project perhaps fall into these several categories:

- home quality and age
- appliance owner's present likelihood to perform certain energy practices within the home
- appliance owner's laundry practices
- appliance owner's hot water consumption practices
- home's occupancy.

The survey results suggest that participants were a roughly even mix of males and females who were typically late, middle-aged. Most participants owned a single water heater that they kept between 120 and 140°F. They used their dryers about 4 to 6 times per week and claimed to do their clothes washing at various times of the day.

3.1.4 Participant Contracts and Initial Education Process

Each applicant was required to sign and return to the project a participation contract and access agreement. The participation contract educated applicants about their and the project's respective responsibilities and formalized their agreements to participate through the duration of the project. The access agreement addressed the liability faced by the presence of project equipment and contracted project personnel who would access participating homes.

In general, PNNL had greater interest in the participation contract, which confirmed its education of participants pertaining to their rights and responsibilities; the utilities tended to be more interested in the access agreements, which addressed the liabilities incurred by the presence of equipment and personnel in their customers' homes.

Participants committed by contract to

- participate for the duration of the experiment
- not modify or remove project equipment
- provide reasonable access to project personnel for the installation, repair, and removal of project equipment
- participate in both opening and closing surveys.

While the project had an obligation to inform participants about the experiment, it tried to do so without greatly influencing their perceptions of the Grid Friendly function that was to be tested. For example, it was stated that some parts of their appliances might momentarily curtail operation, but it was not explicitly stated that the project would do so for the purpose of underfrequency protection. It was also not explicitly stated what changes in appliance performance that appliance owners might observe during such an event. By avoiding these specifics, the project was able to ask and assess at the end of the experiment whether appliance owners had observed project appliance behaviors without improperly influencing their answers to these questions.

The placement of project stickers on project equipment too was an effort to educate the participants and others who might encounter the modified appliances during the project. Stickers advised appliance owners to phone a project phone number if they had further questions.

3.1.5 Equipment Installations

Three electrician contractors were hired to make appointments with residential participants and install modified load-control modules and home gateways in selected homes. Fifty dryers were installed in each of the cities of Gresham, Yakima, and on the Olympic Peninsula. A schematic of the dryer installation is shown in Figure 3.1, and a picture of a dryer installation is shown in Figure 3.2. Because the project was recruiting over 50 participants in the Olympic Peninsula (coincident with recruitment for the Olympic Peninsula Project [Hammerstrom 2007]), the project team decided to distribute the 50 dryers there on a first come, first serve basis to those applicants who met all the required qualifications and submitted their paperwork.

The modified load-control modules were to be installed on the wall behind dryers and water heaters. See Figure 3.1 concerning a schematic for the dryer installation. This installation required that several screw holes be placed in the wall. The project accepted responsibility to fill the screw holes after removing the equipment but accepted no additional responsibility for cosmetic damages.

Dryer installers were contracted by the project through Whirlpool Corporation authorized factory service to install and connect project dryers. This effort required coordination with the project's contracted electricians, who installed the project's dryer load-control modules to make sure the dryers had the proper pronged plugs and were functional after the installers' visits. The Whirlpool appliance installers were also qualified to confirm that the homes' dryer venting was adequate for the new dryers. These same dryer installers would provide any warrantee service on the dryers during the project.

The project had offered to remove existing dyers from participating homes, but few individuals took advantage of this service, choosing instead either to store their dryers or to donate the dryers to relatives and friends.

Installing project water-heater controllers required only a visit from an electrician to install the water-heater load-control module and home gateway. See Figure 2.4 for a typical water-heater installation. Only one mishap occurred during these installations: A copper pipe was pierced accidentally as a contractor drilled a hole through sheet rock, which resulted in a slow leak and minor water damage in an appliance owner's garage. This damage was corrected to the owner's satisfaction by the same contractor. No other reports of significant damage occurred during equipment installations.

The home gateways were positioned near the participants' personal computers, and communication was established between the home gateways and the homes' broadband service. During some of the first gateway installations, it was determined that some computer configurations would not automatically allow for plug-and-play operation of the home gateways. The vendor's product worked seamlessly with cable connectivity, but the systems needed a VPN router on most computers having a DSL type of broadband connectivity. Additional routers were provided, as needed, by the project to achieve the needed broadband connectivity.

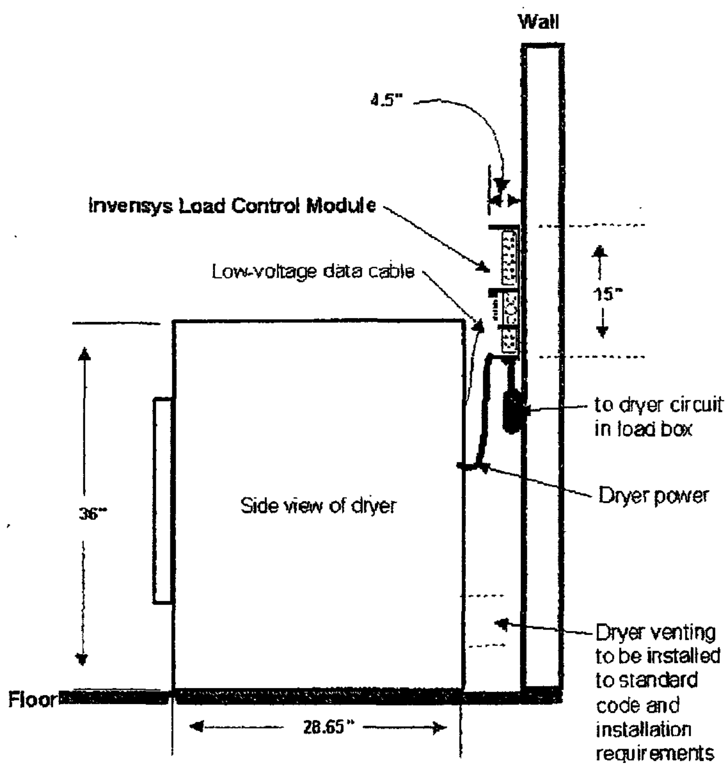

Figure 3.1. Dryer Installation Schematic