PNNL-25082 Draft 1

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Draft Plan to Develop Non-Intrusive Load Monitoring Test Protocols

September 2015

ET Mayhorn
GP Sullivan
JM Petersen
MC Baechler

U.S. DEPARTMENT OF
ENERGY

Prepared for the U.S. Department of Energy
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Pacific Northwest National Laboratory
Richland, Washington 99352

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1.0 Scope

To decide whether a non-intrusive load monitoring (NILM) product is suitable for particular use cases, potential users are interested in understanding key NILM characteristics, i.e. performance in terms of event detection, estimating energy use, and correctly identifying individual appliances, as well as reporting frequency, ease of use, ease of installation, etc. The protocols under development will focus on providing a consistent method that can be used to evaluate, describe and compare the performance characteristics of NILM products. In particular, the protocols will include a set of metrics, test conditions, instrumentation, appliances to be used, and a procedure to establish a schedule for appliance operation during tests.

These protocols will be vetted by the project's NILM Protocol Development Advisory Group and through broader industry and stakeholder engagement. Members of the advisory group have already been identified. Advisory group meetings will be held quarterly. Broader stakeholder involvement will be gained from annual webinars and through the NILM User Group established by Mira Vowles, the Bonneville Power Administration project manager.

2.0 Develop Method to Evaluate Performance

The plan to develop a method to evaluate NILM performance can be divided into 4 steps:

1. Develop a list of performance characteristics that are important to communicate to prospective users

2. Select metrics to evaluate performance characteristics, create a taxonomy that clearly defines terms that are important to understand when applying metrics to data, and establish a common framework for summarizing NILM performance.

3. Develop and validate protocols to schedule appliances and select appropriate test conditions for appliances that will encourage realistic behavior during experiments.

4. Specify instrumentation for experiments

Each step represents part of the agenda for the NILM Protocol Development Advisory Group. Quarterly meetings, consisting of facilitated discussions, will be held with the advisory group. Prior to the first meeting, this document will be distributed. As a plan for protocol development, this document contains the discussion topics and questions that will form the agenda for each of the group meetings. In the first meeting, the group's response to the plan will help to form the process for protocol development and establish the criteria used to evaluate iterations of the protocol. PNNL will refine the plan based on feedback in and following the first meeting.

After the first meeting, PNNL will develop a first draft of the protocol informed by responses to the questions outlined in this document, and begin conducting tests in the PNNL Lab Homes (see Appendix A for information on capabilities of the Lab Homes) to verify that results obtained from executing the draft protocol are representative of NILM performance and gather additional information. Metrics will also be defined and justified via examples created using realistic data.

In successive meetings, results of the experiments will be presented to the advisory group for inputs. Responses to the questions included in this plan will establish the criteria by which the iterations are discussed and evaluated. Up to three iterations of candidate metrics and draft protocols, tested in the PNNL Lab Homes, will be presented to the advisory group over four quarterly meetings. A more detailed description of each step is discussed in the following sections of chapter 2.

2.1 Define Important Performance Characteristics

Before the protocols are developed and metrics are selected, industry and other researchers in the field must first converge on a list of clear performance expectations for NILM devices. This is critical because any defined metric should be used evaluate the NILM device performance against an ideal or expected outcome. By designing test protocols based on user expectations, prospective users can make educated decisions about whether a NILM product is suitable for their particular needs. In addition, results of testing could reveal opportunities to improve the products to increase market adoption.

Simply saying that NILM devices are expected to disaggregate appliances is not specific enough when deciding which elements should be included in a standard test protocol to evaluate performance. For example, appliances that are most important to include in the test should be understood. For many use cases, the energy load of individual appliances with a rated power draw that is less than 60 W may not be important to most users. Therefore, reporting the ability of the NILM to estimate the energy use of low power load types would not be important information to relay to potential users and should not be included in the test protocol. It might be important that NILM products be capable of properly labeling and disaggregating energy use of “major” appliances and that these types of appliances should be considered when testing and evaluating performance.

In the first meeting, PNNL plans to involve the NILM protocol development advisory group to develop a list of expectations, which will then be translated into a list of important performance characteristics to evaluate. This list of performance characteristics will then be used to specify the types of appliances to be considered, select the appropriate metrics, and develop a test protocol to assess NILM performance. An initial list of performance characteristics is given in Table 2.1, to which the advisory committee and/or stakeholders will be invited to provide input.

Table 2.1. Initial List of Important Performance Characteristics

☐ **Types of appliances that can be recognized**
○ Power/energy consumption above a specified threshold ○ Major appliances ○ Common appliances ○ Energy Star labeled/non-Energy Star labeled ○ Emergent high efficiency appliances ○ Other ____
☐ **Accuracy in labeling appliances**
○ May not recognize all modes of multi-state appliances (i.e. only the compressor operation is recognized and labeled as a refrigerator but not the defroster operation is not picked up at all) ○ May recognize the many modes of an appliance but may not label each mode with the correct appliance (i.e. an air handler and a compressor labeled as different appliances even though considered part of a HVAC system) ○ May label single mode appliance as another appliance (i.e. dryer operation is labeled as a furnace) ○ Other ____
☐ **Accuracy in detecting events**
○ Any event ○ Single events ○ Simultaneous events by different appliances ○ Multiple events in one appliance occurring at the same time ○ Other ____
☐ **Accuracy in disaggregating energy use per appliance**
○ Different time scales (minutes, hourly, daily, weekly, etc.) ○ One time scale (5 minutes) ○ Other ____
☐ **Overall accuracy**
○ Comprehensive assessment that considers both event detection and energy use estimation accuracy ○ Other ____

Advisory Committee questions to consider:

1. What do potential users want to know about NILM when deciding whether or not to use NILM for their needs?
2. What capabilities are NILM devices expected to have?
3. Are there any other performance characteristics that should be considered? Why?
4. Are any of the performance characteristics listed in Table 2.1 not important to consider?

5. Please rank the listed performance characteristics, along with any others you have identified, in order of importance

2.2 Select Metrics, Taxonomy and Framework to Summarize Performance

Research to date (Butner et al. 2013a, Mayhorn et al. 2015) has found that the industry has not yet developed a comprehensive set of metrics to allow for performance verification of these devices. The research also revealed some of the unique challenges with metric development and evaluation as they relate to the diverse spectrum of electricity end-uses, multi-state load profiles, and short-interval cycle times. The outcome of the initial research was that there are many factors that should be considered when defining the "accuracy" of a NILM, and multiple metrics may be required to evaluate performance.

To start, the set of existing and proposed NILM evaluation metrics have been assembled. These metrics include those previously researched (Butner et al. 2013a) and newer metrics recently identified (Pecan Street 2015, Holmes 2014, Mayhorn et al. 2015). Metrics for consideration include:

- Relative error by appliance/end use – used to determine the accuracy of NILM energy estimates compared to actual/metered use.
- Relative error compared to total home use – presents a normalized error over the total home energy use to assess relative error magnitudes.
- Event detection accuracy – a measure of the detection accuracy which includes wrongfully detected events.
- Traditional statistics – developed mean and standard deviation of error.
- Average measurement accuracy by appliance/end use – average prediction accuracy using root-mean-square deviation via average actual energy measurement.
- Percent standard deviation explained – presents the fraction by which the standard deviation of the error between predicted and metered is less than the standard deviation of the metered value.
- Normalized root mean squared deviation

Since not all of these metrics are necessarily meaningful or appropriate, this process will provide an evaluation, via real-world data application, to determine metric effectiveness. The metric evaluation will include a systematic application of actual residential end-use appliance/equipment data and its companion metered data. These metrics will be applied to the data in a step-wise process whereby discrepancies will be introduced in the data to see how each metric responds. The discrepancies are intended to model the typical faults or errors encountered with NILMs and are based on findings of the NEEA RBSA field study (Mayhorn et al. 2015). With the request of input from the advisory group, some of the faults/errors to consider include:

- Consistently lower energy reading – NILM estimates a nominal percentage lower than actual appliance energy use

- False positives/negatives – data are adjusted to include false positive/negative events
- Offsets in start/stop times – data are shifted by one or more time intervals.

Figure 2.1 below presents a single day of actual NILM and metered refrigerator energy use data from previous research. Of interest is the consistently lower energy reading detected by the NILM and the missed events related to the refrigerator defrost cycle occurring at about 6:00 AM. Data such as this, with its discrepancies, will be used (and modified) in the metric evaluation. The evaluation plan is designed to apply the data sets in a consistent manner across all proposed metrics and then evaluate their performance by data-fault type. It is anticipated that the output will be presented in a matrix form whereby each metric will be reported to allow comparisons by metric and data-fault type.

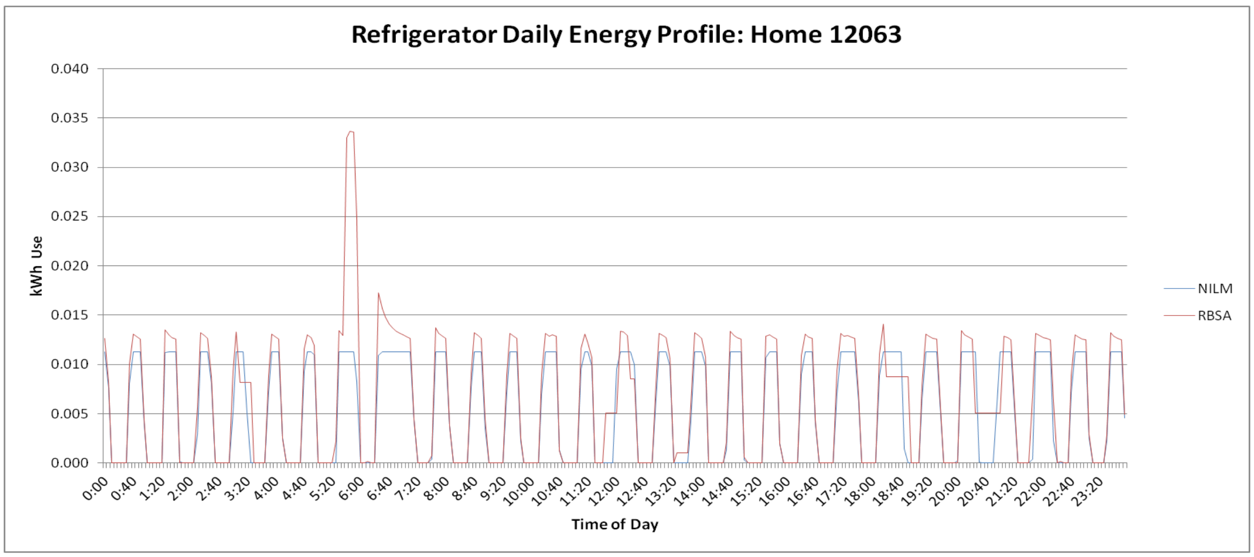

Figure 2.1. Single Day of NILM and Metered Refrigerator Energy Use

In a parallel effort to the taxonomy development, this plan proposes the development (with input from the advisory group) of a NILM taxonomy that becomes the working language the industry can use when discussing, developing, testing, and ultimately evaluating NILM devices. This taxonomy will be well defined and relevant to NILM metric development. The taxonomy is expected to clearly define, amongst others, the following terms:

- Event – There may be many ways to interpret an event. For example, and event can be identified by: (1) the occurrence of any INCREASE in power/energy consumption of an appliance, above a specified threshold, at any time interval relative to the lowest consumption recorded just before the increase, (2) any time interval where an appliance is ON or (3) any time interval where an individual component of an appliance is ON
- Actual event – occurs when sub-metered appliance data indicates event actually took place
- Missed event – indicated by and event that took actually place but was missed by the NILM

- False event – event that did not take place but registered with the NILM
- Correctly-detected event – event that took place and were correctly registered and identified
- Correctly-classified appliance – how it is determined that the NILM has correctly identified, classified or labeled an appliance
- Total events – determining the total number of events that took place
- Disaggregation Accuracy – define meaning of this metric in combination with the advisory group
- Overall Accuracy – define meaning of this metric in combination with the advisory group

As appropriate, the taxonomy will distinguish between generic and end-use-specific terms.

This plan will engage the advisory committee on aspects of taxonomy development and metric selection. Also, using the important performance characteristics identified and the corresponding metrics chosen, a framework will be developed to summarize NILM performance. After testing the NILM products in the PNNL lab homes, the using the protocols being developed (see section 2.3 for more details), performance results will be presented to the advisory group according to this framework.

Advisory Committee questions to consider:

1. Does the taxonomy capture the relevant terms that should be clearly defined? What should be added/removed?
2. Are the listed metrics relevant (note - we will need to expand these and provide taxonomy and formulas)? Are some not appropriate? Why?
3. What additional metrics should be considered? Why?
4. What are the NILM most common deficiencies/errors?
5. What are the most relevant NILM applications available today?
6. Of those applications, what are the required accuracy levels?
7. What are the most relevant future (near-term, 3-5 years) NILM applications?
8. Of those applications, what are the required accuracy levels?
9. Are there requirements on the data intervals a NILM should be capable of, e.g., at least 5-minute or 1-hour?
10. How is NILM measurement accuracy defined, i.e., how do the manufacturers define this for their respective products?

2.3 Develop and Validate Protocols

In 2013, PNNL developed a first round of protocols (Butner et. al 2013b) that were designed to test the limits of the NILM technologies in a number of different dimensions: (1) Ability to discern loads of varying magnitudes, (2) Ability to detect loads of varying duration, (3) Ability to correctly identify individual loads, and (4) Accuracy of overall energy use estimates. The protocols consisted of seven day experiments in the PNNL Lab Homes. Simultaneous and sequential loads are scheduled to cycle ON/OFF several times, over fixed durations that get progressively longer after a few cycles (starting from 1 min to 10 min to 1 hour per load type). Different sized and types of loads were considered, such as, a 25 W table lamp, 240 W set of 4 hardwired light fixtures, 2 kW electric resistance water heater.

The 2013 NILM test protocols do not consider real world load behavior and the set of loads included are not representative of the various types of loads that typically exist in a home. From evaluating NILM based on the first round of protocols developed, it was concluded that the following issues should be considered when developing a protocol:

- NILM algorithms are typically proprietary algorithms and therefore disaggregation approaches may be unknown
- NILM approaches may require a training/learning period
- There may be limitations on NILM energy outputs and data resolution
- Approaches may be based on load pattern library or behavioral cues
- Some NILM are hardware/software and others are software only solutions
- Software solutions can be compatible with different whole house meters with different measurement accuracies
- Overly prescribed test conditions and instrumentation may burden the industry

PNNL plans to design appropriate schedules and/or settings for each appliance that consider the aforementioned issues identified and capture the important performance characteristics defined. Because of the nature of many NILM algorithms, NILM should be evaluated based on realistic patterns. Thermal loads, such as refrigerators, HVACS, and water heaters, typically operate automatically based on setpoints and changes in temperature. Other appliances typically have several modes and require a resident to initiate an event or cycle (e.g. clothes washer, dryer, oven, dishwasher).

For thermal loads, appropriate temperature settings and test conditions (i.e. water usage for water heaters, and food stored in a refrigerator, building occupancy for HVACs, etc.) will be selected to encourage normal operation. Sensitivity tests will be performed in the PNNL Lab Homes on these settings and test conditions to decide how strict the test conditions should be. National/regional surveys, field study data and/or DOE appliance standards will be leveraged to specify test conditions and appliance settings as needed.

For other appliances, the intent is to use statistical analysis of the Northwest Energy Efficiency Alliance (NEEA) Residential Building Stock Assessment (RBSA) metering study data will be used to generate realistic schedules. PNNL proposes to use the following approach to obtain the typical use schedules for these appliances:

1. Identify key factors that are impacted by behavioral patterns and appliance type

    a. Start time of first event in each day

    b. Duration of the events

    c. Interval between successive events

2. Empirically determine probability distributions of each key factor based on dependent variables selected, such as, type of day

    a. Weekday

    b. Weekend

    c. Any day

    Example probability distributions of first event start times, duration of events, and intervals between successive events are given for clothes washers, in Figure 2.2-Figure 2.5, based on the types of days considered.

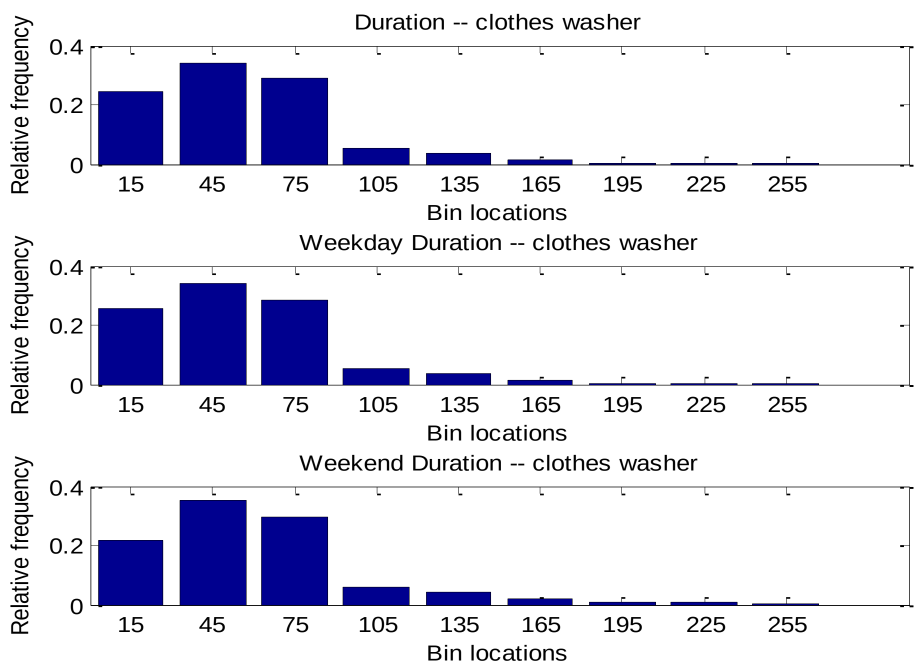

Figure 2.2. Distribution of the first event's start time of the day for the detected events without the abnormal events

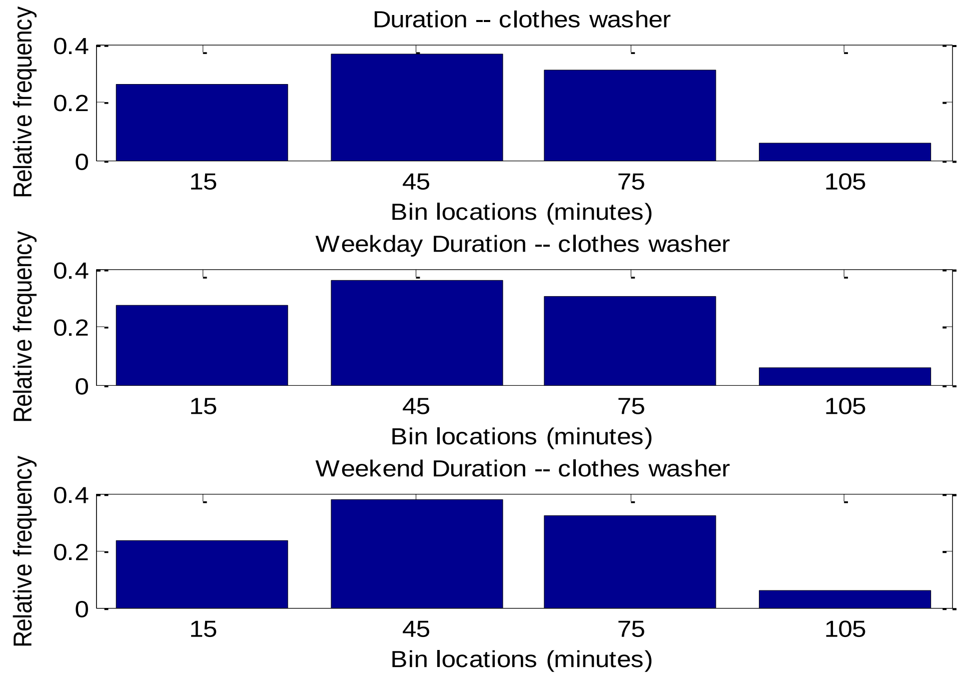

Figure 2.3. Distribution of event duration of the detected events without the abnormal events

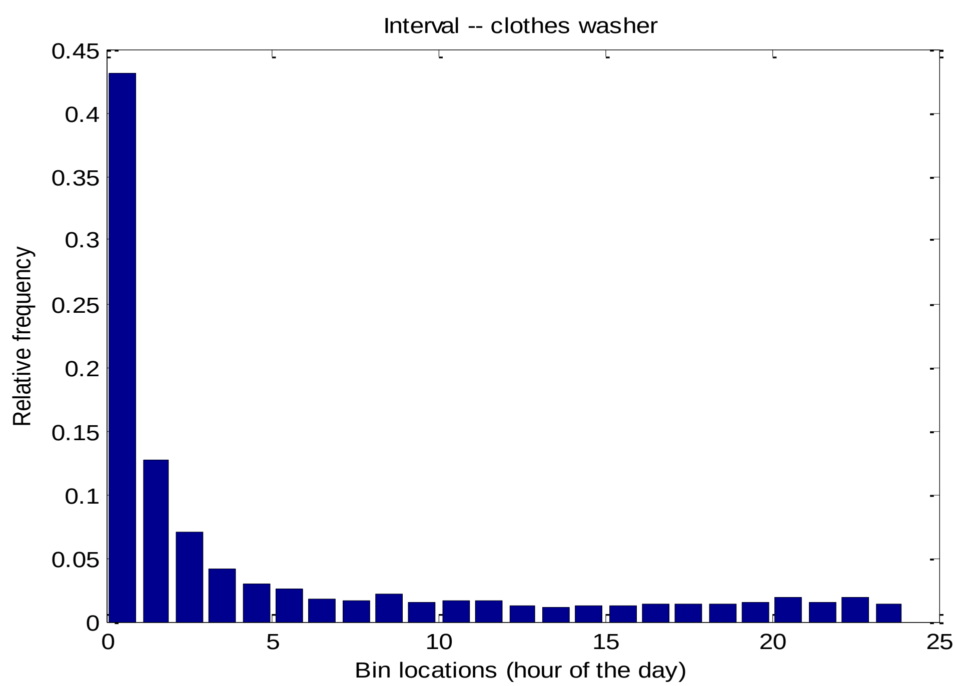

Figure 2.4. Distribution of the time interval between the detected events without the abnormal events

3. Sample the distributions of each key factor based on the dependent variables selected. Figure 2.5 illustrates the process of generating the schedules by sampling the distributions of each the key factor, based on dependent variable (e.g. type of day desired). Example weekday and weekend schedules were generated for clothes washers, dryers, dishwashers, and ovens, using this process and are shown in Figure 2.6 and Figure 2.7.

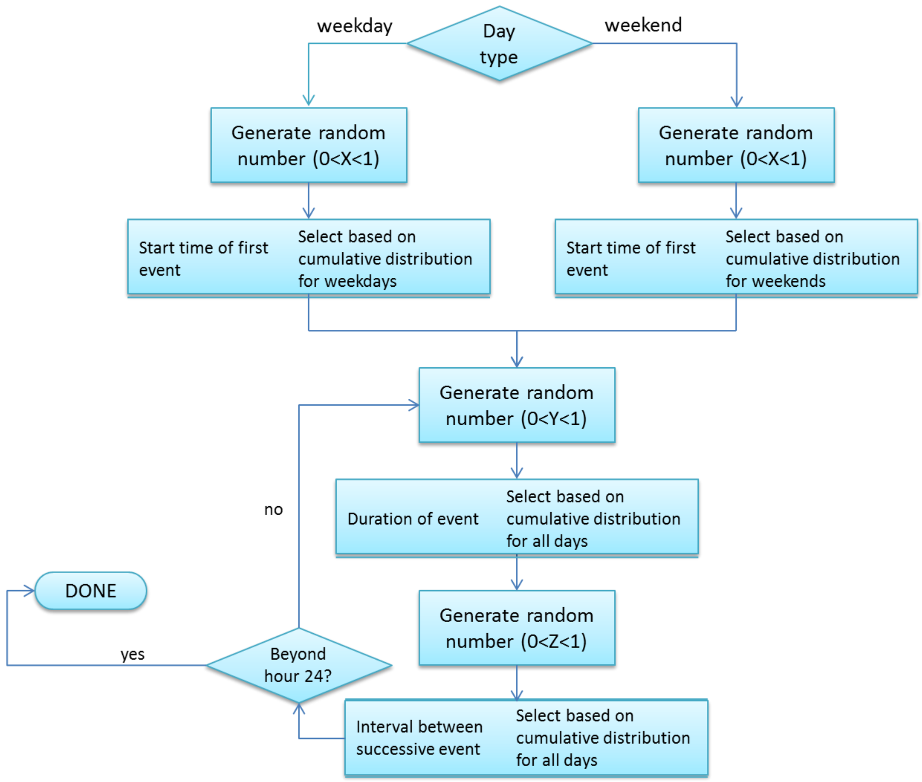

Figure 2.5. Decision tree for determining key factors to generate appliance schedules

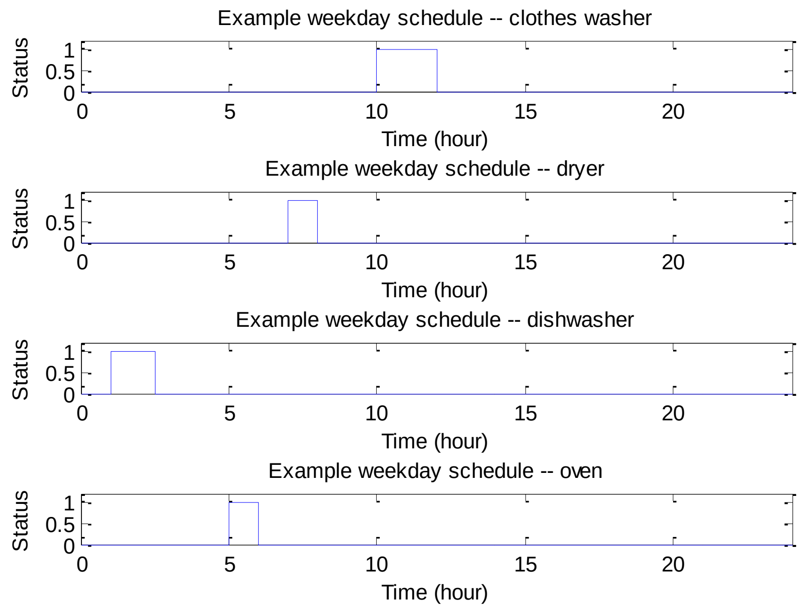

Figure 2.6. Example schedules for weekdays

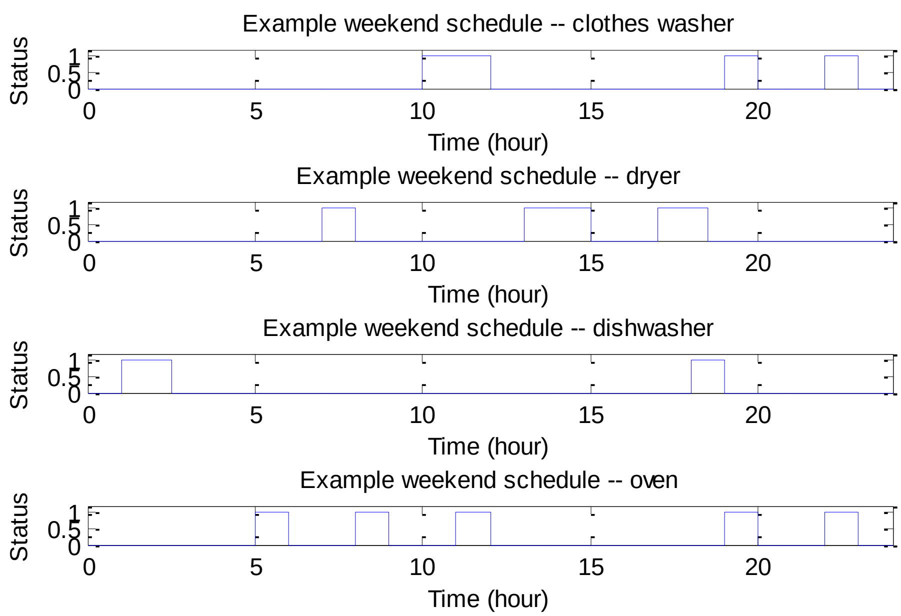

Figure 2.7. Example schedules for weekends

4. Map prevalent event durations to particular cycle settings or modes of each appliance. For example, four durations were found to be highly probable for clothes washers (~30 min, 1 hr, 1.5 hr, and 2 hr), as shown in Figure 2.3. The "super cycle" setting last for 1.5 hr, so this cycle could be chosen every time an event is generated that lasts for 1.5 hr. The "short cycle" setting may last for ~30 min, this cycle could be scheduled whenever a 30 min event is generated.

In addition to the test conditions and appliance schedules, the appropriate length of the experiments and the number of times an experiment should be repeated should be settled on. The PNNL Lab Homes will be used to perform several tests with various test conditions and appliance schedules to examine NILM performance sensitivity and validate whether the protocols are suitable. The intent is to demonstrate repeatability of performance. Results will be presented to the advisory committee to get feedback and inputs. The protocols will then be revised as needed.

Advisory Group questions to consider:

1. Should stressed test conditions be considered in addition to typical test conditions? Why?
2. What ability do NILM vendor labs have to control thermal mass of a conditioned space or simulate outdoor temperature?
3. Should one schedule or several sample schedules be used to evaluate NILM performance?
4. What should the maximum length of an experiment to evaluate the NILM performance be?
5. Is the approach to generate appliance schedules appropriate for appliances that are not classified thermal loads?
6. Should several sample appliance schedules be considered in experiment and evaluation of NILM products? If so, how many?

2.4 Develop Specifications for Instrumentation

To specify instrumentation requirements, DOE appliance and/or ANSI metering standards will be leveraged.

3.0 Performance Requirements

PNNL also plans to develop and prioritize a list of use cases. This final list of use cases will be considered to develop performance requirements for up to three specific uses of NILM. An initial list of performance requirements and use cases are given below in Table 3.1. Results of the experiments will be presented to the advisory group to allow them to provide inputs on justify performance requirements

Table 3.1. List of Use Cases

☐	Low cost verification of savings obtained as a result of energy efficiency measures
☐	Self-learning control systems to manage building energy use using whole house energy monitoring and disaggregated device level monitoring from meter data
☐	Self-learning control systems to manage building energy use using whole house energy monitoring and disaggregated device level monitoring from meter data
☐	Enabling advanced data analytics for recommending actions to be taken and sending maintenance alerts to improve building operational efficiency
☐	M&V for utility demand response programs
☐	Development of automated auditing processes to replace the expensive, inconvenient, and time consuming early step required by most efficiency programs that has proven to be terribly inaccurate

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Advisory Committee questions to consider:

1. Are there any other important use cases to consider now? Why?
2. Are any of the use cases, listed in Table 3.1, not important to consider?
3. Please rank the use case in order of importance.

4.0 References

Butner RS, DJ Reid, M Hoffman, et al. 2013a. *Non-Intrusive Load Monitoring Assessment: Literature Review and Laboratory Protocol*. PNNL-22635, Pacific Northwest National Laboratory, Richland, Washington.

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Holmes, Chris. 2014. "Non-Intrusive Load Monitoring (Nilms) Research Activity: End-Use Energy Efficiency & Demand Response." URL: http://publications.aeic.org/lrc/2014_Workshop_NonInstrusiveApplianceLoadMonitoring.pdf

Mayhorn ET, GP Sullivan, RS Butner, et. al. 2015. *Characteristics and Performance of Existing Load Disaggregation Technologies*. PNNL-24230, Pacific Northwest National Laboratory, Richland, WA.

Pecan Street. 2015 (accessed). "Setting the Benchmark for Non-Intrusive Load Monitoring: A Comprehensive Assessment of AMI-based Load Disaggregation." URL: http://www.energyefficiency.me/

Appendix A

PNNL Lab Homes

The PNNL Lab Homes are a unique platform in the Pacific Northwest region for conducting experiments on residential sector technologies. These electrically heated and cooled 1500 square-foot homes are sited adjacent to one another on the PNNL campus in Richland, Washington. They are fully instrumented with end-use metering (via a 42-circuit panel), indoor and outdoor environmental sensors, and remote data collection. The homes can be operated to simulate occupancy (controllable breaker panels) and, thus, can evaluate and manage any occupant effects on equipment performance using the control features in the homes. The unique nature of this side-by-side comparison means the homes experience the same weather at any given time. This allows for comparison of efficient measures in the experimental home with baseline equipment in the baseline home under identical environmental (indoor and outdoor) conditions and water supply temperatures over the same time period. In addition to providing accurate calculation of the energy consumption and savings associated with a specific technology, the independence of the data from weather allows weather-related factors, such as outdoor air temperature and wind speed and their effects on savings, to be evaluated as independent variables rather than confounding variables.

During the cooling season, an exterior heat pump, A-coil, and house fan supply conditioned air to the lab homes. The whole house fan can operate in differing modes to supply conditioned air to the homes as needed, cycling on an off with the air conditioning system, or constantly as an air circulation fan. The internet enable Venstar ColorTouch T7850 thermostat can increase or decrease the internal set point of the lab homes via an HTML remote application or onsite. In general, the set point remains at about 71F throughout the year.

During the heating season, the lab homes have differing capabilities that allow for conditioned air to be generated in differing methods. During normal operation, the exterior heat pump supplies conditioned warm air into the interior space via the whole house fan. Equipped with a forced air furnace, resistive elements can supply emergency heat to the space if the heat pump operation cannot maintain the required internal set point. Additionally, each room within the homes is equipped with a cadet wall mount space heater. These electric resistance heaters have a set point that can be manually set based on occupant preference.

Incandescent 60W lighting technology is implemented throughout the homes. This outdated lighting infrastructure is used to better represent the typical home within the Pacific Northwest. As lighting technology moves toward LEDs, the lab homes can be retrofit to accommodate and help model this transition. Operational lighting schedules are programed into the electrical panel to simulate occupancy throughout the lab space.

The envelope of the lab homes is typical of a standard manufactured home except for the larger than normal window area. This was altered to be more to be more representative of the Pacific Northwest. The double pane windows make up an estimated 221 ft^2 of the total 1284 ft^2 wall area. R-11 wall insulation is concealed behind wood trim on the exterior of each home.

Internal plug load of the homes vary between homes. The larger appliances within the homes include clothes washer, clothes dryer, water heater, range, dish washer, and refrigerator. The type and efficiency of appliances vary between homes. Table A.1 and Table A.2 details the specific appliance within each home. Implementation of standard and high efficiency appliances increases the capabilities of the lab homes to more accurately model the typical residential home. In general, appliances and plug load that draw large amounts of power remain unplugged during experiments where they are not being specifically tested. This minimizes any possible effect of the appliance on the whole house load during each experiment.

Table A.1. Lab Home B Appliances

Appliance	Lab Home B Appliance Brand	Lab Home B Appliance Model Number	Lab Home B Appliance Serial Number
Furnace	Intertherm	E3EB-015H	E3E110602596
Wall Heaters	Cadet Manufacturing Company	RM151	?
Thermostat	Venstar	ColorTouch T7850	?
Refrigerator	GE Profile	PFQS5PJYASS	TS 302860
Oven	GE Profile	PB979SP5SS	MT266116Q
Dish Washer	GE Profile	PDWT585R00SS	MS752080B
Clothes Washer	GE Profile	WPDH8910K0WW	LS200097T
Clothes Dryer	GE Profile	DPVH891EKWW	MS800225C
Bathroom Fans	NuVent	050411	?

Table A.2. Lab Home A Appliances

Appliance	Lab Home A Appliance Brand	Lab Home A Appliance Model Number	Lab Home A Appliance Serial Number
Furnace	Intertherm	E3EB-015H	E3E110602597
Wall Heaters	Cadet Manufacturing Company	RM151	?
Thermostat	Venstar	ColorTouch T7850	?
Refrigerator	GE	GTS18DBPXRWW	LV509010
Oven	GE	JBS07M1WW	MV124215P
Dish Washer	GE	GSD2100V00WW	DZ787641B
Clothes Washer	GE	GHWP1000M0WW	TV164451G
Clothes Dryer	GE	GTDX100EM1WW	DZ707133A
Bathroom Fans	NuVent	050411	?

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