Non-Intrusive Load Monitoring (Nilms) Research Activity
End-Use Energy Efficiency & Demand Response

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EE&DR Analytics (EPRI)

AEIC Load Research Analytics Workshop
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About EPRI

Together…Shaping the Future of Electricity

• Founded in 1973 as an independent, nonprofit center for public interest energy and environmental research.

• Objective, tax-exempt, collaborative electricity research organization

• Technology development, integration, demonstration and applications

• Broad technology portfolio ranging from near-term solutions to long-term strategic research
Analytics Complements Technology Research

Technology Expertise

Scout  Test  Demo  Deploy  Program

Advancing the emerging technology pipeline

EE-DR-CO₂ Potential Analysis

Load Research

Contributing Loads from End-uses

Understanding Customer Behavior

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Related Supplemental: Evaluation of Alternative, Low Cost Technologies for Load Measurement & Disaggregation

Non-Invasive, Low-Cost Metering (Ind.)
- Design, development, Lab. evaluation

NILM Round 2 Lab Assessment (Res.)
- 6-7 products total
- 3-4 new market products
- Fall 2013- Spring 2014

NILM Evaluation Activities (Com.)
- Recruit host sites by building type

Adhoc Research (Potential)
- Detecting power theft (diversion) using NILM methods

High-Value NILM Applications
- Early notification, failure and remote diagnostics of electrical loads

NILM – European Product Lab Assessment (res.)
- Test bed development (proposed)

NILM Field Assessment (res.)
- TVA host sites @ Glasgow, KY “Ground truth” measurements

Other less-invasive, low cost technologies
Individual sub metering of loads (“Ground truth”) available
Laboratory Evaluation of Non-Intrusive Load Monitoring (Nilms) Technologies

**Measurement Accuracy**
- Interval Usage (1 min, 5 min, 15 min, 60 min)
- Daily Usage
- Weekly Usage

**Disaggregation Performance**
- Loads isolated (#)
- Energy Coverage (%)
- Repeatability of Isolation

**Cost**
- Initial
- Installation
- O & M
Laboratory Evaluation – Round I (Lab. Measurement vs. NILM Measurement)

Load Control & Measurement

Metered Whole Premise Load

Residential Loads

Product A

Product B

Product C

Product D

Metered End Use Loads

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Round 1 Evaluation – Basic Statistics

- Average measurement accuracy for each disaggregated load by NILM product is computed based on Root Mean Square Deviations (RMSD).
- Basic statistics (mean ($\bar{x}$), standard deviation ($\sigma$)) of the difference between NILM estimated and lab. measured values assessed for each interval resolution as supported.
- Mean ($\bar{x}$) – indicates if the NILM estimated interval value is on average over-estimated or under-estimated relative to the lab measured values.
  - A positive mean ($\bar{x}$) implies an overall higher proportion of over estimated values, negative mean ($\bar{x}$) implies a higher proportion of under estimated values.
- Standard deviation ($\sigma$) - indicates the extent of spread or dispersion of differences around the mean ($\bar{x}$) estimation.
  - A larger standard deviation implies wider dispersion of individual NILM estimated values from the mean difference, lower standard deviation implies tighter distributions.
Results: Product A Software Approach (Cloud-based Disaggregation)

Output resolution is daily and weekly.

Four (4) isolated and labeled loads.

HVAC and WH estimations are in the 84-91% accuracy range.

Refrigerator /freezer and dryer estimations are relatively lower in accuracy (69-76%)

Estimations are all over-estimated over the period assessed.

Distributions wider for clothes dryer and refrigerator.
Results: Product D
Hardware Approach (Agg. Power + Waveform Analysis)

### Product D: Average Measurement Accuracy

<table>
<thead>
<tr>
<th>Period</th>
<th>Interval</th>
<th>HVAC</th>
<th>Water Heater</th>
<th>Pool Pump</th>
<th>Clothes Dryer</th>
<th>Refrigerator</th>
<th>Freezer</th>
<th>Lights</th>
<th>Range</th>
<th>Microwave</th>
<th>Fans</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 min.</td>
<td>0.838 (\bar{x} = 3.786) (\sigma = 1.120)</td>
<td>0.858 (\bar{x} = 2.402) (\sigma = 1.583)</td>
<td>0.858 (\bar{x} = 19.833) (\sigma = 12.063)</td>
<td>0.828 (\bar{x} = 14.281) (\sigma = 42.934)</td>
<td>0.784 (\bar{x} = 12.089) (\sigma = 22.120)</td>
<td>0.802 (\bar{x} = 2.531) (\sigma = 39.939)</td>
<td>0.844 (\bar{x} = 12.192) (\sigma = 21.521)</td>
<td>0.828 (\bar{x} = 12.192) (\sigma = 36.983)</td>
<td>0.798 (\bar{x} = 9.892) (\sigma = 21.291)</td>
<td>0.845 (\bar{x} = -0.29) (\sigma = 59.241)</td>
</tr>
<tr>
<td></td>
<td>15 min.</td>
<td>0.842 (\bar{x} = 10.884) (\sigma = 7.238)</td>
<td>0.868 (\bar{x} = -6.092) (\sigma = 19.768)</td>
<td>0.867 (\bar{x} = 23.87) (\sigma = 41.278)</td>
<td>0.842 (\bar{x} = 43.761) (\sigma = 51.102)</td>
<td>0.773 (\bar{x} = 53.39) (\sigma = 36.281)</td>
<td>0.848 (\bar{x} = 26.745) (\sigma = 26.389)</td>
<td>0.866 (\bar{x} = -9.22) (\sigma = 22.945)</td>
<td>0.838 (\bar{x} = -11.961) (\sigma = 19.02)</td>
<td>0.823 (\bar{x} = 12.83) (\sigma = 62.781)</td>
<td>0.854 (\bar{x} = -3.023) (\sigma = 89.411)</td>
</tr>
<tr>
<td></td>
<td>60 min.</td>
<td>0.866 (\bar{x} = 23.892) (\sigma = 11.623)</td>
<td>0.876 (\bar{x} = 96.16) (\sigma = 18.937)</td>
<td>0.884 (\bar{x} = 98.855) (\sigma = 52.097)</td>
<td>0.804 (\bar{x} = 103.329) (\sigma = 69.077)</td>
<td>0.789 (\bar{x} = 191.62) (\sigma = 72.789)</td>
<td>0.864 (\bar{x} = 67.901) (\sigma = 76.833)</td>
<td>0.868 (\bar{x} = 107.371) (\sigma = 129.13)</td>
<td>0.848 (\bar{x} = 12.921) (\sigma = 49.065)</td>
<td>0.838 (\bar{x} = 216.873) (\sigma = 59.681)</td>
<td>0.848 (\bar{x} = -13.20) (\sigma = 62.361)</td>
</tr>
<tr>
<td></td>
<td>10/8-12/10/21/12</td>
<td>0.880 (\bar{x} = 190.239) (\sigma = 16.376)</td>
<td>0.874 (\bar{x} = 149.231) (\sigma = 56.378)</td>
<td>0.894 (\bar{x} = 1259.983) (\sigma = 60.001)</td>
<td>0.848 (\bar{x} = 1033.72) (\sigma = 91.606)</td>
<td>0.804 (\bar{x} = 496.921) (\sigma = 73.371)</td>
<td>0.878 (\bar{x} = 127.75) (\sigma = 36.11)</td>
<td>0.884 (\bar{x} = 281.184) (\sigma = 115.723)</td>
<td>0.847 (\bar{x} = 362.397) (\sigma = 68.801)</td>
<td>0.820 (\bar{x} = 301.531) (\sigma = 84.13)</td>
<td>0.842 (\bar{x} = -13.20) (\sigma = 62.361)</td>
</tr>
<tr>
<td></td>
<td>Daily</td>
<td>0.894 (\bar{x} = 620.092) (\sigma = 27.787)</td>
<td>0.881 (\bar{x} = 1082) (\sigma = 92.367)</td>
<td>0.898 (\bar{x} = 2063.980) (\sigma = 97.671)</td>
<td>0.852 (\bar{x} = 1493.33) (\sigma = 102.921)</td>
<td>0.828 (\bar{x} = 1173.1) (\sigma = 117.239)</td>
<td>0.872 (\bar{x} = 1023.20) (\sigma = 131.12)</td>
<td>0.875 (\bar{x} = 1497.82) (\sigma = 166.921)</td>
<td>0.842 (\bar{x} = 1332.152) (\sigma = 194.231)</td>
<td>0.838 (\bar{x} = 1332.152) (\sigma = 129.831)</td>
<td>0.843 (\bar{x} = 1232.152) (\sigma = 129.831)</td>
</tr>
</tbody>
</table>

Note: Values in bold represent average measurement accuracy (%). Mean \(\bar{x}\) and standard deviation \(\sigma\) of the differences between NILM estimated and actual measured values are shown in watt-hours.

- Output resolution: 5-min, 15-min, 60-min, daily and weekly
- Ten (10) loads isolated and labeled (or annotated)
- HVAC, WH, Pool pump, dryer and lighting estimations are in the 80-89% accuracy range.
- Refrigerator, freezer, microwave and fan estimations are in 77-84% accurate
- 15-minute load estimations are over and under-estimated over the period assessed. Distributions are fairly tight around the mean difference.
HVAC and WH Cost vs. Accuracy

HVAC: Accuracy vs. Cost

Water Heating: Accuracy vs. Cost

Annual cost for Product D is based on 100 installed units.
NILM Round I: Results and Conclusions

- NILM is an evolving technology
- Four(4) to eight(8) end-use loads disaggregated by evaluated products
- Best 15-minute disaggregation accuracy ~ 89%
- HVAC, WH loads relatively easier for disaggregation, more accurate than others.
- Clothes dryer, Refrigerator challenging for disaggregation, least accurate
- Hardware based, waveform approaches seem to be more accurate than others, but more expensive based on 5-year costs.
- Complex algorithms and technologies being commercialized. Disaggregation performance expected to improve.
EPRI-DOE Industry Workshop in November 2013

- DOE and EPRI conducted a NILM Industry workshop in November 2013.
- Hosted by EPRI in Palo Alto, CA. Representatives from utilities, manufacturers, government, regulators academia and EPRI
- Focus to foster utility/vendor participation and address gaps through the formulation of an interest group
- Topics discussed:
  - Standards
  - Metrics for accuracy/uncertainty/errors
  - Test/evaluation methods, protocols
  - Output definitions (time resolution, quantity)
  - Data security/privacy
  - Use-cases for NILM

Presentations available on EPRI FTP site:
ftp://NILMSWorkshop:November2013@ftp.epri.com

Interest Group Formation!
Potential Use Cases - Regulated

- Measurement & Verification (M&V)
- Energy Audits
- Appliance Diagnostics
- End-Use Load Data
- Building Controls
- Rate Options
  - Competitive Pricing
  - New Product Development
- Customer benefits – Feedback,
  - Energy Transparency
  - Bill Transparency

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NILMs Interest Group Formation

Three Sub-committees

• Performance Metrics
  ✓ Granularity ( # of end-uses identified)
  ✓ Accuracy ( comparison of actual and estimated end-use loads)
  ✓ Skew (check for systematic bias in estimations)

• Standard Data Outputs & Labeling

• Use Cases

EPRI to Facilitate and Document Interest Group Activities

Open to everyone!
Round II to Commence: EPRI NILM Projects and Current Status

EPRI is conducting two (2) NILM laboratory evaluation projects and one (1) field assessment study

• Round II Laboratory Evaluation [Apr.-Sept. 2014]
  – Market research and new vendor engagement complete
  – Testing to commence Spring 2014
  – New 3-4 products, total 7-8 Nilms products to be evaluated
  – Inclusion of stress testing, HPWH and EV, and PV

• European Evaluation
  – Supplier market segmentation and pricing
  – Acquire appliance and 50Hz inverter
  – Use case: customer acquisition and retention
NILM Field Evaluation & Study

- Field evaluation of residential Nilms to assess accuracy in the field but to also document the practical issues with a field deployment.
- TVA hosting the field trial at Glasgow, KY.
  - 30 residential sites
  - TVA paying for Nilms meters, site installations and managing data collection.
  - Sites are fully instrumented on major and some minor end-uses to serve as the “ground truth”
  - Nilms installs to begin in Spring 2014
  - Technical report and data made available in Fall 2014
Next Steps: Statistical Disaggregation Methods

• TVA-EPRI Conditional Demand Analysis (CDA) [Apr. 2014 – Sept. 2014]
  – Concomitant with NILMs Field trial the administration of a detailed survey instrument will be made and used in a CDA exercise
  – Comparison of three major methods of disaggregation – Direct metering, NILMs, CDA/AMI metering
  – Comprehensive assessment of cost versus accuracy of load disaggregation methods
  – Inform National Campaign Phase I?
Questions?
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