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Is disaggregation the holy grail of energy efficiency? The case of electricity ☆

K. Carrie Armel [a,*], Abhay Gupta [b], Gireesh Shrimali [c], Adrian Albert [d]

[a] Precourt Energy Efficiency Center, Jerry Yang & Akiko Yamazaki Environment & Energy Building, 473 Via Ortega, Room 385, Stanford University, Stanford, CA 94305-4205; 650-380-1965, USA
[b] Bidgely Inc, 440 North Wolfe Rd, Sunnyvale, CA 94085, USA
[c] Indian School of Business, and Program on Energy and Sustainable Development at Stanford University, Stanford, CA 94305, USA
[d] Electrical Engineering Department, Stanford University, CA 94305, USA

HIGHLIGHTS

- Appliance energy use data can produce many consumer, industry, and policy benefits.
- Disaggregating smart meter data is the most cost-effective and scalable solution.
- We review algorithm requirements, and ability of smart meters to meet those.
- Current technology identifies ~10 appliances; minor upgrades could identify more.
- Research, technology, and policy recommendations for moving forward are outlined.

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ABSTRACT

This paper aims to address two timely energy problems. First, significant low-cost energy reductions can be made in the residential and commercial sectors, but these savings have not been achievable to date. Second, billions of dollars are being spent to install smart meters, yet the energy saving and financial benefits of this infrastructure – without careful consideration of the human element – will not reach its full potential. We believe that we can address these problems by strategically marrying them, using disaggregation. Disaggregation refers to a set of statistical approaches for extracting end-use and/or appliance level data from an aggregate, or whole-building, energy signal. In this paper, we explain how appliance level data affords numerous benefits, and why using the algorithms in conjunction with smart meters is the most cost-effective and scalable solution for getting this data. We review disaggregation algorithms and their requirements, and evaluate the extent to which smart meters can meet those requirements. Research, technology, and policy recommendations are also outlined.

1. Introduction

We face several looming energy problems at this junction in history, yet taken together they may offer a unique opportunity for resolution. The first problem relates to the fact that significant low-cost energy reductions can be made in the residential and commercial sectors, but these savings have not been achievable to date. In the United States, the residential and commercial sectors account for much of the demand: buildings in these sectors contribute roughly equally to 40% of U.S. energy consumed and greenhouse gases emitted (Energy Information Administration, 2008; U.S. Environmental Protection Agency, 2008; Vandenbergh and Barkenbus, 2008). It is estimated that about 20% of this, or 8% of all U.S. energy use and emissions, could be avoided with efficiency improvements to these buildings (McKinsey & Company, 2007; Creyts et al., 2007; Gardner and Stern, 2008; Laitner et al., 2009).[1] Further, this estimate is derived from changes that can be achieved with little or even negative cost[2], making savings here particularly attractive (Creyts et al., 2007). Importantly, experts believe that a major reason why reductions have not yet been achieved in these sectors involves behavioral barriers (IPCC, 2007; American Physical Society, 2008).

☆ "If you cannot measure it, you cannot improve it."—Derived from Lord Kelvin.
* Corresponding author.
E-mail addresses: kcarmel@stanford.edu (K. Carrie Armel), abhay@bidgely.com (A. Gupta), gireesh_shrimali@isb.edu (G. Shrimali), adalbert@stanford.edu (A. Albert).

[1] For comparison, 10% of the total U.S. energy consumption is roughly equivalent to the total yearly energy consumption in Brazil or the UK, or the quantity of fossil fuels that would be saved and greenhouse gas emissions reduced in the U.S. by a 25-fold increase in wind plus solar power, or a doubling of nuclear power (Energy Information Administration, 2009; Sweeney, 2007).

[2] Assuming a cost of \$50 per ton of CO_2e.

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Table 1
A summary of the benefits of appliance specific energy information.

Benefits	Domain	Explanation
Consumer	Residential energy use	Greater energy reductions from this type of feedback (a) Automated personalized recommendations (through auto-commissioning, fault detection, elucidating behavioral patterns, analysis of when and what type of new appliance to purchase based on current use, etc.), (b) personalized recommendations allow for personalized information to reduce barriers to energy efficient actions (e.g., mapped recommendations on where to purchase recommended items); enabling of additional/ enhanced behavioral techniques (feedback, competition, visualizations, markets, incentives, etc.)
	Commercial energy use	Similar application to residential; large untapped savings here
Research and development	Appliance innovation	Better data to (a) redesign appliances for energy efficiency, (b) improved standards, and (c) back up appliance energy efficiency marketing
	Building research and design	Improved building simulation models to increase design and operational efficiency (commissioning and auto-commissioning)
Utility and policy	Segmentation for energy efficiency marketing	Strategic, specific, energy efficiency marketing
	Program evaluation	(a) Improved objectivity, sensitivity, and causal inference in program evaluation; secondary benefits of (b) improved program design from improved evaluation learnings, and (c) diversification of program types, because these can be quantified, and utilities in many states are incentivized when program savings can be quantified
	Building and contractor ratings and Incentives	Affords performance based metrics, ratings, and incentives of buildings which could impact real estate value, and evaluation of contractor performance
	Economic modeling and policy recommendations	(a) Improved load forecasting; (b) Improved economic models to better inform policies and funding allocations

The second problem we face is that billions of dollars are being spent to install smart meters yet the energy saving and financial benefits of this infrastructure – without careful consideration of the human element – will not reach its full potential. Business cases justify ratepayer expenditures with reduced labor costs (e.g., meter readers), as well as the avoided generation capacity and lower consumer energy bills that are expected from shifting and reducing energy use (e.g., California Public Utilities Commission, 2006; Faruqui et al., 2011).[3] It is estimated that the energy shifting and conserving benefits from consumer activities will, respectively be about 10% (Hledik, 2009) and between 1% and 8% (Electric Power Research Institute (EPRI), 2009; Hledik, 2009; Pratt et al., 2010). Estimates to break even on smart grid costs and to attain net positive benefits depend upon consumers achieving these benefits[4], and it is further hoped that consumer benefits are achieved beyond those estimated (Faruqui et al., 2011; NARUC, 2011). However, some public utility commissions and public interest groups have questioned the benefit (e.g., initial decisions regarding smart meter expenditures in Maryland and Florida; National Association of State Utility Consumer Advocates, 2010). Clearly the ultimate cost or benefit rests to a large degree on facilitating consumer behavior with the meters. Furthermore, the window for realizing the potential of smart meters is closing, if greater hardware capabilities are required.[5]

How can we address both of these problems simultaneously? Can we leverage smart infrastructure to maximize energy savings and peak shifting in the residential and commercial sectors? We believe that the answer is yes—contingent upon the infrastructure's ability to support disaggregation. Energy disaggregation[6] refers to a set of statistical approaches for extracting end-use and/or "appliance level"[7] data from an aggregate, or whole-building, energy signal. This information affords numerous consumer, R&D, utility, and policy benefits, as detailed below. Leveraging data from smart meters to perform disaggregation is crucial because other approaches are more costly and labor intensive, and do not provide opportunities for scale.

This paper provides a detailed justification for these ideas. It discusses the benefits of appliance level data, reviews disaggregation algorithms and their requirements, and evaluates whether the technical specifications of smart meters are adequate to support the algorithm requirements.[8] We close with a set of specific recommendations for realizing the potential of disaggregation.

2. Benefits of appliance-specific information

There are numerous benefits of appliance-specific over whole-home data, summarized in Table 1. These fall into three

[3] Business cases are mostly based on those factors (in California, estimates of avoided capacity and reduced energy bills are mostly from demand response). Additional benefits may include: CO2 reductions and other environmental benefits (from reducing energy use, and also load shifting in states where the base load is cleaner than the peaking plants); improved operational efficiency; automatic outage notification, avoidance, and faster recovery; faster transactions and customer service; remote connection and disconnection service; prepayment capability; meter tampering alert; acceleration of electric vehicle adoption; and others (Faruqui et al., 2011; Electric Power Research Institute (EPRI), 2009; Hledik, 2009; Pratt et al., 2010).

[4] This group estimated that costs per million households are likely to be $198–272M, while operational savings are likely $77–208M, and consumer-driven savings are likely $100–150M. The reader is directed to Faruqui et al. (2011) for specific scenarios from which these figures are derived.

[5] As of June 2011, approximately 20 million smart meters had been deployed in the U.S. It is estimated the number will rise to approximately 65 million meters by 2015, or about 50% of all U.S. households, and that by the end of this decade

(*footnote continued*)
smart meters may be deployed to almost all U.S. households (Faruqui et al., 2011; Institute for Electric Efficiency, 2010). The window for change is even narrower when one considers the contractual and manufacturing timelines that precede installations.

[6] Also referred to as disambiguation, non-invasive load monitoring (NILM), or cognitive metering.

[7] Referred to simply as "appliance level" from here forward. Note this includes anything that draws electricity, such as appliances, electronics, air conditioning and heating, pumps and motors, and water heating loads. This paper focuses on electricity, but similar disaggregation approaches are under development for gas, water, and transportation.

[8] The work presented here grew out of a workshop held at Stanford University in May of 2010. The workshop included a diverse set of stakeholders including disaggregation algorithm developers (both start-ups and large companies), solid state meter companies, smart meter networking companies, home area network companies, academic researchers, investors, utilities, and government representatives.