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Non-intrusive load monitoring through home energy management systems: A comprehensive review

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ABSTRACT

The enhanced utilization of Appliance Load Monitoring (ALM) in customer sites enabled by Home Energy Management Systems (HEMS) technologies, offers customized services and enables demand side flexibility in power systems. The significant integration of advanced electrical and computer engineering tools makes the nonintrusive approach of ALM a technically feasible solution to improve demand side energy utilization in the context of HEMS. This paper presents a comprehensive study conducted to reveal significant inevitabilities of a well organized Non-intrusive Load Monitoring (NILM) that aids Smart Home (SH) idea to be implemented. In fact, the viewpoint of this study is to discuss critical issues related to NILM prerequisite necessities, hindered the practical implication of this approach despite improvements during over 30 years. Accordingly, this work presents actual analyses in order to elucidate some arguments using state of the art procedures and results of a semi-synthetic data generator tool. In addition, with the aim of an achievable NILM, we analyze NILM applications from the stakeholders' perspective to assist the choice of employed techniques. Consequently, by investigating crucial intentions of an effective NILM considering current standstill and future progression, the authors propose the Advanced NILM (ANILM) concept and describe its properties to provide an enhanced energy usage system in demand side. In order to meet its ambition, the paper uses a realistic point of view to pinpoint major obstacles toward NILM and elaborate various factors that will make it effectively feasible.

1. Introduction

Smart grid, as an inevitable solution toward innovative energy management systems, is a key enabler for smart energy consumption in the future [1,2]. The significant interest in deploying effective energy management in demand side, due to national security concerns and social and economic benefits has its root in smart grid development, carbon dioxide emission reduction purposes, renewable energy resources integration, limited conventional energy resources, and growing trend of energy prices [3,4]. For instance, United States (US) primary energy, and electricity consumption in buildings is more than 38% and 76% respectively, which can be reduced up to 15–40% using a whole building energy management system [5].

Smart Home (SH) is the main conceptual archetype for demand side smart energy usage enabled by deriving the creation of a Home Energy Management System (HEMS) [1,3]. HEMS technologies can provide a mutual satisfaction between customers by realizing their comfort preferences and the utility by assisting energy saving strategies [6,7]. The emergence of an automation network offered by HEMS yields an advanced deployment of Appliance Load Monitoring (ALM) as the primary requirement to realize the SH platform [4]. It is noted that Department of Energy (DOE) defines SH on the edge of technologies with wider deployment and cost reduction in the coming years [8].

ALM can be executed using both intrusive and non-intrusive techniques. However, due to costly sub-metering installations, difficult upgrades settings, and customer privacy issues from one side, which hinder the former, as well as the integration of enhanced electrical and computer engineering tools from other side, which facilitates the latter; the non-intrusive approach is favored from both academic and industrial perspectives [9–11]. Non-intrusive Load Monitoring (NILM) technology is the practice of disaggregating household total electrical load measured at a single point into individual appliances signals, using the combination of an electrical acquisition system and signal processing algorithms [11,12]. NILM is considered as a high tech viable solution to achieve an improved demand side energy usage by contributing energy consumption feedbacks and progressive diagnosis mechanisms [4,7].

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NILM concept proposed by Hart [12] in 1992, has been studying for a long time however; it requires more progression to be regarded as a solved problem. NILM methods analyze the total signal through a routine process including event detection and feature extraction, as well as appliance classification and energy consumption estimation [4]. However, the proficiency in NILM techniques is one of the issues, which proves that more advanced disaggregating algorithms are required. From the standpoint of different approaches to the NILM procedures and mathematical algorithms, NILM has been already reported in literature. Zeifman and Roth [4] studied NILM with the focus of interest in signature examination for feature extraction as the first step of the general process. Tabatabaei et al. probed NILM mainly by concentrating on computational algorithms consisting of machine learning techniques for load disaggregation and classification as the second step of the common practice [13]. Zoha et al. reviewed NILM whole process presenting the same viewpoint as [4] regarding feature extraction step and moreover, discussing mathematical developments toward load disaggregation phase [14]. Without surveying NILM process, Alahakoon and Yu [1] investigated smart meter technologies to establish a data intelligence system in order to primarily realize utility concerns. Their study is regarded due to smart meters importance, as the hardware framework unavoidable for executing a part or entire NILM process. As a matter of fact, the revealed studies analyze technical and mathematical advances applied to the NILM common methods with different focuses. It is deduced that conducting an investigation intended to compare NILM methods and mathematical solutions where they are all case-specific and lack a standard evaluation process, is fruitless. However, the need for more efficient algorithms remains as a critical subject in order to design NILM systems that aim to recognize a wide range of household appliances with different electrical characteristics.

On the other side, there are other issues vital to achieve an adequate accuracy in order to design a practical NILM application, which have been neither studied nor fairly discussed in literature. Accordingly, in this study, we present a comprehensive survey with the aim of thoroughly evaluating these issues as significant factors toward realizing a feasible NILM. Unlike the prior arts, focusing on the methods analysis, the origin of this study is based on first, investigating the prerequisite necessities of an operative NILM and second, examining NILM applications as the fruits of its process to assist the choice of techniques. The analysis of these initial and final steps, which have been neglected by previous studies, result in comprehension of achievable NILM properties, contributed by authors in terms of Advanced NILM (ANILM).

Accordingly, this paper discusses major primary steps required for a successful NILM considering both technical and environmental concerns. Particularly, authors' discussion on the multi-faceted nature of NILM provides practical analyses to clarify the viewpoints on some related matters. The analyses are the results of a semi-synthetic dataset creator tool recently developed by authors, and NILM contemporary algorithms based on probabilistic methods. The semi-synthetic data generator platform is capable of deriving appliances probabilistic schedules and subsequently, simulating power demands of household heating/cooling systems and electric water heater in a modeled building [7]. Moreover, the probabilistic technique for NILM analysis is developed using Hidden Markov Models (HMM) as a concrete mathematical solution for recurrent pattern recognition and load classification [15–17]. Additionally, NILM applications as the end products of the NILM task are investigated from the participants i.e. the household customers and the system operator outlooks. NILM aspect is classified concerning the mutual priorities and interests of the stakeholders in order to examine practical approaches and represent an accurate detailed view on its applications with various intentions. Additionally, through a realistic vision, the authors thoroughly discuss noteworthy points regarding NILM to define future progresses. Correspondingly, this work prepares remarks, which will make NILM practically feasible by presenting the idea of ANILM and its features.

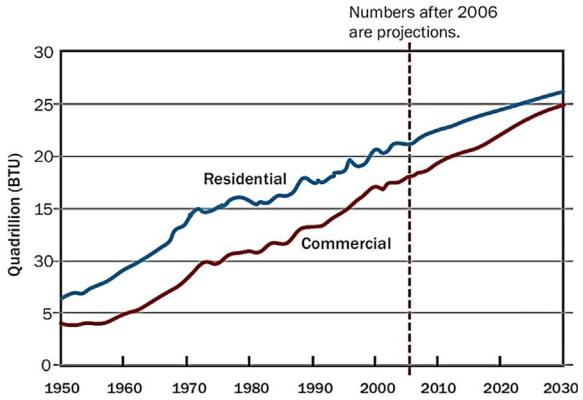

Fig. 1. Total primary energy consumption for building in US; Key: BTU=British Thermal Unit [19].

The rest of this study is organized as follows: Section 2 introduces NILM aspect and discusses critical issues toward an actual NILM using a detailed categorization. Section 3 provides the classification of NILM applications from the perspective of customer facilities and system operator interests. Section 4 analyzes the opportunities and challenges regarding the future of non-intrusive essence of ALM systems. The ANILM approach is presented in Section 5 followed by the concluding remarks in Section 6.

2. NILM concept

Population growth and increased standards of living are the main driving forces, which have caused an unavoidable growth of energy consumption [18,19]. The graph in Fig. 1 indicates the primary energy use (including that associates with electric use) of US residential and commercial sectors projected out to 2030 [19]. Therefore, the growing trend of energy usage necessitates the development of infrastructures for energy saving which is reinforced by government incentives and goals such as [19–22]:

- US federal government goal of using no more primary energy in 2030 than it does in 2008 by implementing a set of governments' policies and programs;
- US DOE goal of market-ready net-zero energy residential and commercial buildings in 2020 and 2025 by investing sufficient fund in R & D for next generation of building technologies;
- Canada's CamnetENERGY idea of Net Zero Energy (NZE) housing on the time horizon of 4 year research by the goal of drastically reducing the cost and risk of NZE technologies, and becoming readily available in market place.
- Canada's Energy Efficiency Regulation program of EnerGuide to reduce energy cost and emission by rating the energy efficiency of household appliances, heating and cooling equipment, new homes and vehicles, and making related information available to the public.

Accordingly, NILM as the promised type of ALM procedure receives a significant interest due to its capability to manage the energy consumption in demand side including residential and commercial buildings. Information collected from appliances' monitoring also assists to cope with more integration of fluctuating energy resources [23–25]. Moreover, NILM allows diagnosis and control of different loads connected to the grid and aids [24]:

- Customers to have valuable information of their individual appliances' energy consumption;
- System operators to analyze the energy flow in electric networks;