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Design criteria for visualization of energy consumption: A systematic literature review

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ABSTRACT

Visualizing energy consumption is widely considered an important way to motivate end-users to conserve energy. Designing effective visualizations, however, is a non-trivial software design challenge. In particular, there are no clear criteria for designing visualizations of energy consumption for end-users. This paper presents systematic literature review findings from a total of 22 primary studies selected after applying quality and relevance filters. The results were synthesized using Grounded Theory's open coding and constant comparison procedures and led to the emergence of *design criteria for visualization* as the central theme across all primary studies. The key categories comprising this central theme include: (a) *functional criteria*, which include information displayed in the visualization, modes of visualization, and visualization techniques, and (b) *non-functional criteria*, which include hardware and software considerations such as integrality, extensibility and portability. Together, these criteria provide clear guidelines based on research evidence for software engineers and researchers designing visualizations of energy consumption for end-users.

1. Introduction

Visualization of energy consumption is a cross-disciplinary research area spanning software, electrical, and mechanical engineering. While visualization is widely considered an important way to motivate end-users (consumers in residential spaces) to conserve energy, designing visualization of energy consumption is a non-trivial design challenge from a software engineering perspective. In particular, there are no clear criteria to guide visualization design for this critical application domain.

At the global level, depleting energy resources, increasing global warming [S1–3] and its adverse consequences such as rising temperatures [S3–7], extreme weather patterns, and pollution are some key motivators driving research in this area. On the ground level, motivating end-users to conserve energy is imperative to the success of any efforts toward resolving the worsening energy crisis.

Despite theoretically motivating factors such as economic and environmental benefit, practically it is challenging to motivate end-users to conserve energy [S1]. This is primarily due to lack of awareness and knowledge of their precise energy consumptions; inability to discern concrete steps to be taken to conserve energy; and also due to their unwillingness to sacrifice living comforts for the sake of energy consumption [S2].

Visualization has long been considered as a viable way to motivate end-users to converse energy by empowering them with the ability to monitor and consequently control energy consumption. Optimal design of such visualizations is considered critical to achieving this aim and generating savings for maximum end-users (Atzori, Iera, & Morabito, 2010).

Despite growing interest and endeavor in this area, no thorough survey exists which assesses the current state-of-affairs and provides clear criteria to guide the design of effective visualizations [S2]. Responding to this need, we conducted a systematic literature review to understand the design strategies and techniques for visualization in this critical application domain. A total of 22 primary studies were selected from 232 initial finds after applying quality and relevance filters. The results were synthesized using Grounded Theory's open coding and constant comparison procedures (Glaser, 1992; Glaser & Strauss, 2009). In this paper, we present the central theme that emerged across all primary studies: *design criteria for visualization of energy consumption*.

The rest of this paper is organized as follows: Section 2 describes the background and related works in this research area. Section 3 describes the review method used for systematic literature review including synthesis using Grounded Theory. Section 4 presents the review results and Section 5 presents a discussion of the results followed by the conclusion.

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2. Background

The visualization of energy consumption has immense potential to assist end-users with energy conservation. Visualization of energy consumption could be useful in: (a) providing the ability to monitor and control power usage [S3], (b) analyzing and predicting energy consumption [S2] (c) providing real time feedback [S2], (d) increasing sustainability through energy conservation [S1,2,4,5], (e) imparting information in an innovative, understandable and legible way [S6], (f) being publicly accessible [S4], and (g) providing unambiguous and interesting visualization [S7].

Efforts in visualization of energy consumption for end-users dates back to early 1970s when a psychologist Ronald Bittle and his team placed daily feedback post cards to inform the daily energy consumption for household, leading to a cut down in energy consumption by 1–9% (Dobson & Griffin, 1992).

In 1978, a research used large posters to display energy consumption in a medical institution (Bittle, Valesano, & Thaler, 1978), which also cut down energy charge. Later in 1992, visualizations migrated to the next level with the use of computer-based monitor 'Residential Electricity Cost Speedometer (RECS)', which claimed that the energy consumption was reduced by 12.9% (Seligman & Darley, 1977).

Later in late 1990s, the energy consumption data was visualized on the personal computers (McCalley & Midden, 1998) [S2]. Although the continuous in-home feedback emerged in 1979 (Cook, 1979), computer-based real time feedback was not introduced until late 1990s (e.g., stock market visualization, Wattenberg, 1999).

More recently, real time visualizations were presented both in 2D and 3D, and were made available on mobile phones [S1,2], tablet PCs, Internet-based applications [S2], touch-based displays [S2], in-home displays [S2], energy monitoring dashboards [S2,6,8], etc. enhancing easy accessibility [S5].

Another area of interest has been the art and technology into visualization for better understandability [S1,4,6]. Some research involved psychologists to harness aspects of human psychological behavior to increase the sustainability of energy conservation [S1,2,4,5]. In another research, visualizations were linked to human psychological factors through environmental impact to enhance energy conservation [S4,6,8].

The latest trend in this area is the introduction of Smart Grids which focus on intense use of technology to tackle the energy consumption and conservations challenges. One of the seven domains in NIST Smart Grid conceptual model (Metke & Ekl, 2010) is customer domain and one of the responsibilities of that domain is to inform the end-users and to conserve household energy. While Smart Grids' customer domain cover the complete energy cycle, research on the use of visualization for energy consumption for end-users is in its infancy and is a clear area for future work.

3. Review method

The systematic literature review (SLR) is the process of identifying the literature, extracting the relevant papers based on study selection criteria, and synthesizing the extracted studies to answer selected research questions (Kitchenham, 2004). This review process, in turn, helps to understand the literature in any specific area; consequently, it helps in yielding an effective summary for the future researchers (Petticrew & Roberts, 2008). Fig. 1 explains the SLR procedure (Khan, Kunz, Kleijnen, & Antes, 2003; Kitchenham, 2004) as we applied it.

3.1. Scope of the review

The major research in this area is driven by various visualization techniques, surveys for understanding the best visualization, psychological survey for understanding human behaviors, and so on. But, there is no concrete description for designing the visualization tool. The goal of this review is to understand the current evidences and challenges in the visualization of energy consumption. The main objective of this review is to provide comprehensive solution to the following research questions:

RQ1. What are the current visualization techniques for energy consumption?

RQ2. What are the information displayed in the visualization to motivate users to conserve energy?

3.2. Identification of the literature

The initial step in the SLR is to structure the search terms. First, we identified the subject terms or headings from several databases using keywords from RQ1 to 2. Next, the search terms were written by following simple rules (Mendes, 2005): (a) using the Boolean operator '*OR*' to use synonyms and alternate spellings (Salleh, Mendes, & Grundy, 2011) and, (ii) using the Boolean

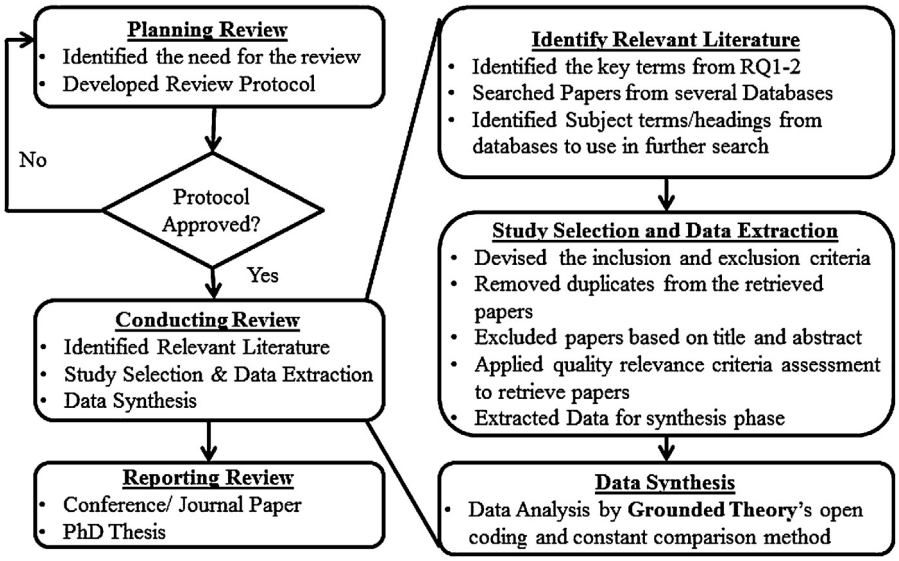

Fig. 1. Systematic literature review – procedure.