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

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A B S T R A C T

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 integrity, 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.

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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 [1–3] and its adverse consequences such as rising temperatures [3–7], 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 [1]. This is primarily due to lack of awareness and knowledge of their precise energy consumption; 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 [2].

Visualization has long been considered as a viable way to motivate end-users to conserve 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, Jera, & 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 [2]. 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.
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.
operator ‘AND’ to link major terms from identified subject terms or headings (Salleh et al., 2011), which is depicted in Table 1.

Table 1 shows some sample search terms that were identified through the above-mentioned strategy and were used to access published papers and technical reports from various databases, journals, conference proceedings and research websites. Other search terms included, but were not limited to: electricity consumption, energy reduction, household energy, home electricity. We collected a total of 232 papers from the resources such as Scopus, ScienceDirect, IEEE Xplore, ACM Digital Library, SpringerLink, and INSPEC. The papers’ information such as author, title, source, year of publication, abstract, keywords, DOI are stored in spreadsheet. Along with those, two other columns ‘included (I)/excluded (E)’ (i.e., to show whether the paper is included or excluded for data synthesis) and ‘inclusion/exclusion criteria’ (i.e., to show the criteria number from Table 2 for inclusion or exclusion). Once the information was entered, we removed the duplicates which left 218 papers. Fig. 2 shows the overview of the study selection process.

3.3. Study selection and data extraction

The study selection criteria were used to extract the papers for the data synthesis. It is classified into two categories as the inclusion and exclusion criteria and they are further classified as quality and relevance criteria and are expected to be satisfied by the primary studies to enter data synthesis phase. The inclusion criteria and the exclusion criteria are shown in Table 2. The criteria were applied at the title and abstract level which excluded several papers that satisfied the exclusion criteria. The spreadsheet with column ‘included (I)/excluded (E)’ (with ‘I’ or ‘E’) and ‘inclusion/exclusion criteria’ (with QI#, RI#, QE#, RE#) was updated. Only 11% (25 studies) of the primary studies were included from the data extraction at title and abstract level. Fig. 3(b) depicts the proportion of papers excluded.

Criteria assessment was applied for data extraction based on paper’s full text. It was done by means of a marking scale to include a paper for data synthesis, which depended on the answer to the inclusion criteria questions. Inclusion criteria have the marking scale as Yes – 1, No – 0. Partially – 0.5. The papers were included for the data synthesis only if the criteria rating were more than the acceptability threshold. The acceptability threshold was calculated as the mean of the quality scores (Moher, Jadad, & Tugwell, 1996), which was approximately 5.9. To avoid removing lot of studies, the acceptability threshold was set at 5 out of 7.

Fig. 3(a) represents the criteria assessment for study selection. The quality score for the selected studies (25 studies) were calculated. Only 22 out of 25 studies satisfied the acceptability threshold. Three studies were excluded because they exhibited major flaws such as ambiguous outcomes. Hence a total of 22 studies entered the data synthesis phase.

3.4. Data synthesis

Data synthesis is the process of summarizing the extracted data in an effective and understandable format. We employed Grounded Theory (GT) (Glaser, 1992) as a bottom up approach for discovering the patterns within datasets (Hoda, Noble, & Marshall, 2012). We employed GT’s data analysis and synthesis procedures, i.e., open coding and constant comparison method to synthesize data. To explain this process, we present an example of working from raw data (primary studies’ texts) to results for one of the categories, techniques in visualization here (see graphical depiction in Fig. 4).

First, we obtained the key points from the qualitative data in the primary studies. Key points are the texts from the primary study that answer the research questions, e.g. bar chart, box chart, line chart (answered RQ1). We then assigned a code to key point. A code is a phrase that summarizes the key point in 2 or 3 words (Glaser, 1992; Glaser & Strauss, 2009).

Key point: Bar chart [S1,7,9–11]  
Code: Traditional visualization

The codes arising out of each study were constantly compared against codes of the same study, and those from other studies. This is GT’s constant comparison method (Glaser, 1992). In this example, other similar code identified was “modern visualization”. Using the

<table>
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<th>Sample search terms.</th>
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<td>Search terms</td>
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<td>Synonyms or different spellings</td>
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| Q1. Is the article peer reviewed? (Yes/No) (Leedy & Ormrod, 2005)  
| Q2. Does the article report unambiguous findings based on evidence and argument? (Yes/No) (Cruzes & Dybå, 2011)  
| Q3. Is the article based on research (or is it merely a “lesson learned” report based on expert opinion)? (Yes/No) (Dybå & Dingsøyr, 2008)  
| Q4. Are the limitations of the study discussed explicitly? (Yes/No) (Dobson & Griffin, 1992)  
| Q5. Does the article discuss the implication for research and practice? (Yes/No)  
| Relevance criteria |  
| R1. Does the article provide information on both energy consumption and visualization? (Yes/No)  
| R2. Does the article revolve around the applications such as home, workplace, study place, and public buildings? (Yes/No) (Partially) |

| Exclusion criteria |  
| Q1. Is the article an editorial, preface, article summary, interview, news, review, correspondence, technical discussion, comments, reader’s letter, summary of tutorial, workshop, panel or poster session? (Dybå & Dingsøyr, 2008)  
| Q2. Does the article claim without any supporting evidence? (Greenhalgh, 2010)  
| Q3. Is the article in consideration a duplicate (i.e., same article from various databases)?  
| Q4. Is the article not written in English?  
| R1. Does the article center on both energy cost and visualization, but as non-digital means (e.g., capacitors, circuits, and other analog means)?  
| R2. Does the article concentrate on energy efficiency for wireless sensor networks or adhoc networks?  
| R3. Does the article speak about the visualization of energy translation of atoms, mobile data mining?  
| R4. Does the article provide visualization on energy optimization, energy monitoring, energy analysis, energy modeling, energy scheduling, and load balancing? |
constant comparison method we grouped these codes to produce a higher level of abstraction, called concepts.

Concept: 2D visualization
Other concept that emerged include ‘3D Visualization’. Finally, we repeated the constant comparison method on concepts to produce a third level of abstraction called Categories (Glaser, 1992; Glaser & Strauss, 2009).

Category: Techniques in visualization
Similarly, information displayed in visualization was the other category identified (see Appendix).

Implementing a systematic literature review enables focus on well-defined research question(s), research identification from comprehensive sources and explicit search strategy, unbiased criterion-based research selection, qualitative and or quantitative synthesis, etc. Similarly, the use of Grounded Theory for data analysis and synthesis enables qualitative sampling, data collection, and data analysis, which results in higher order themes and interpretations (Cruzes & Dybå, 2011).

3.5. Limitations of this SLR
A limitation of this review is the bias in the data extraction process typically associated with SLRs. To avoid the bias, we designed the review protocol carefully and conducted criteria assessment to ensure selection of quality papers for review. We have also tried to avoid the bias by cross-verifying the SLR process and resolved as and when the need arose. Since the research’s main objective was to understand software solution for visualizing household energy consumption, ‘wireless and ad-hoc networks’ were applied as exclusion criteria as this article concentrates only on the software solution to visualize the household energy data. Although, the search terms used to retrieve papers were based on the research
questions in the review protocol, some of the studies may be omitted due to specific visualization terms used in place of more general search terms (Dybå & Dingsøyr, 2008).

4. Results: design criteria for visualization of energy consumption

The contribution of this paper – the results of our SLR – is that we identified the key design criteria for visualization of energy consumption for end-users. These are classified under two main areas: functional criteria and non-functional criteria as in Rainardi (2008). The functional criteria comprise of these categories: information displayed in the visualization, modes of visualization, and techniques in visualization and the non-functional criteria comprise of hardware and software considerations. In this section, we present these categories, which together form the design criteria for visualization of energy consumption, also summarized in Table 3, and depicted in Fig. 5. In doing so, we answer the initial research questions set for conducting the SLR.

4.1. Functional criteria

4.1.1. Information displayed in the visualization

This section describes the information displayed in the visualization tool as identified from the primary studies. There are a total of 18 studies (out of 22, 82%) [S1–4.6–9,11–20] which focus on this aspect. Information displayed in visualization is aimed at two main user groups: (a) end-users, who are consumers in residential spaces, and (b) energy managers, who are trained professionals who understand the information displayed in the visualization very effectively and monitor energy consumption at universities, public buildings, workplace, and manufacturing units. In both cases, the aim is to assist users in decision making regarding the energy consumption, which in turn, leads to energy conservation. It is quite important to categorize the information based on energy consumption analyzers to enable effective utilization of visualization.

Information appropriate for end-users: Residents or end-users constitute a major decision making group for energy consumption in residential spaces. The appropriateness of the information displayed in visualization varies from one user to the other based on their level of education, analytical ability, cognition on technology, psychological behavior, esthetic sense, etc.

A total of 12 studies (67%) [S1–3,11–19] focused on describing the information appropriate for end-users. Of these, almost 11 studies [S1–3,11–13,15–19] describe information on energy consumption in particular. End-users were provided real-time energy and water consumption information for immediate decision making and effective energy conservation [S1,2,11,18,19]. This included software application receiving the information on energy consumption from various appliances through Internet within a fraction of a second to provide immediate suggestions through visualization. In addition, peak energy consumption in a day or month or year was visualized [S1], which helped people in shifting the loads (e.g. washing or drying) to avoid peak-time energy pricing. In particular, one of the studies [S21] described visualization of the amount of unnecessary energy consumption when the resident is not at home.
which helped the user to switch off certain appliances through mobile-based user interface of the application.

Four studies [S1,12,16,17] described the visualization of a comparison of energy consumption. For example, some studies [S1,12,17] compared and visualized the energy consumption among the homologous periods, i.e., hours, days, months, years, etc. in the form of graphs, charts or user interfaces. This kind of visualization helped the users in identifying peak energy consumption. To motivate the end-users, comparison of energy consumption among the people in the neighborhood buildings or homes was also visualized [S12,17]. Furthermore, some studies visualized the position or rank of the end-user in their social networking circles [S16], with the aim to motivate them to conserve energy.

Four studies [S1,3,12,15] visualized some of the supplementary information on energy consumption. For example, Dominguez et al. [S12] researched the prediction of energy consumption, i.e., prediction of monthly bills, and verification of energy bills, i.e., by validating it with the stored historic energy details. Based on the amount of power and water consumption, some tools provided energy saving recommendations [S1,3,15], aimed at minimizing the gap between end-users’ cognition of energy consumption and effective energy conservation.

Some other studies [S1,11,14,19] dealt with information based on sensors and equipment. One of these studies [S14] investigated appliance information and visualized the energy consumption based on environmental conditions by means of the information acquired by sensors [S14]. For example, suggestion was made to switch off the light when the light intensity was sensed to be high. The other three studies [S1,11,19] explained the visualization of energy consumption based on equipment. The basic visualization depicted the energy consumed by each equipment [S11] either in the form of graph or chart on the user interface. Quintal et al. displayed the power states which depicted the change in energy consumption during ON/OFF transition [S1]. Later, there was another research effort, which explained the importance of customization by means of annotating the energy consumption states [S19] (refer to Fig. 7g).

Information appropriate for energy managers: In addition to residential spaces, a significant amount of electrical energy is consumed in public spaces such as at universities, public buildings, workplace, and manufacturing units. However, unlike at home, these spaces are monitored by well-qualified energy managers to keep the energy consumption under control. Energy managers are efficient, trained professionals, who understand the information displayed in the visualization very effectively. Only very few studies (3 out of 18, 17%) [S9,12,20] examined the information appropriate for energy managers. The studies [S9,20] explored the use of energy consumption patterns for managers which helped them in efficient decision making. Another research study presented an understanding of the power profiles and voltage peaks; moreover,
the energy managers were trained to understand the fault detection and voltage drops from the information in the visualization [S12].

**Information appropriate for both end-users and energy managers:** Around 61% (11 out of 18) [S3,4,6–9,13,14,16,17,20] of the papers that examined the information based on energy consumption, were appropriate for both average end-users and qualified energy managers. The first and foremost step taken to reduce the energy consumption was to provide the daily energy feedback in the form of post cards to each residence [S4,7]. Later in the research, history of the energy consumption was made available to the residence, where the end-users could compare their energy consumption with previous homologous periods [S1,2,12,15,19]. In addition, the maximum and minimum energy consumption was made available to understand their energy consumption patterns [S12].

Three studies [S6,8,18] concentrated on the information based on energy equipment for both user groups. Couple of studies [S6,8] depicted the amount of idle time or standby time of the equipment in the visualization tool for better understanding of the equipment. In addition, modern web-based mobile and PC technology was employed to remotely control the equipment/appliances at home [S18].

### 4.1.2. Modes of visualization

The primary role of visualization is to provide the energy consumption feedback to the end-users. To avoid ‘One-for-all’ scenario, various modes of visualizations can be used. The modes of visualization are classified based on granularity with respect to: (a) time, (b) scale, (c) information, and (d) visualization techniques. The modes of visualization based on information of energy consumption could be in the form of Watt-hour (Wh) [S10], energy charge ($), kilo joule (kJ), amount of CO₂ emission, number of trees planted for amount of CO₂ emission (seven trees have to be planted for one pound of CO₂ emission [S4]), user interface (interactive visualization), etc. to visualize and control energy conservation [S1,2,4,14,16,18].

The modes of visualization could be toggled based on time periods such as month, year, day, or hour [S1,10,11,14,15,19] and based on scales such as per appliance [S1,10,11,17,19], room by room [S19], or overall energy consumption [S10,11,15]. The visualizations were represented in the form of bar charts and line charts to depict the above mentioned information.

The modes of visualization based on visualization techniques could be flexible in toggling between various techniques described in the next section.

### 4.1.3. Techniques in visualization of energy consumption

Around 95% (21 out of 22) of the studies listed various techniques in visualization of energy consumption. The techniques in visualization comprise of: (a) 2D visualization and, (b) 3D visualization, both of which included samples of traditional and modern approaches.

**2D visualization:** Two dimensional (2D) visualization is the classic way of representing quantitative data for better understandability. For example, graph and chart are common 2D visualizations. Out of the 22 reviewed papers, 20 (90%) studies, described 2D visualizations. 2D visualization is further classified into traditional (or chart-based) visualization and modern visualization.

Traditional 2D visualization includes chart visualization which comprises of bar chart, line chart, box chart, pie chart, whereas the advanced chart visualization require special tools to create charts like geo chart (Google maps), time chart, running race chart, time log, spiral display, cluster maps and component planes.

Most studies (15 studies) dealt with traditional 2D visualization [S1,3,6,7,9–16,18–20]. Almost 86% of the studies (13 out of 15) referred to basic chart visualization [S1,3,7,9–15,18–20], whereas, 33% (5 out of 15) of the studies referred to advanced chart visualization [S3,6,13,15,16], and 20% (3 out of 15) of the primary studies discussed on both [S3,13,15].

**Fig. 6** represents the different techniques in traditional 2D visualization, along with references to the primary studies they appeared in.

Modern visualization includes visualization which is interactive, artistic, esthetic and informative. Modern visualization emerges from the major design requirements of visualization.

![Fig. 6](image)

Source: primary studies represented by S#. 

Design requirements which make a visualization effective include pragmatic (comprehensibility), ambient (peripherality), ecological (environment-friendly) and esthetic (attractiveness) factors [S21]. These requirements lead to visualizing energy consumption in the form of artistic [S21], illustrative [S3], interactive [S1,2,4,14,17], and environmental visualization [S4,6,8]: all of which are types of modern 2D visualization (Fig. 7). A total of 9 studies (45%) dealt with modern visualization [S1–4,6,8,14,17,21].

The artistic visualization technique combines art and technology to visualize energy consumption, i.e., visualization based on dispersion and contraction of the objects in the art, e.g. phyllotaxis design, pin-wheel design, and hive design (Fig. 7d–f). The illustrative visualization technique combines the floor-plan of the home with the electricity consumption, e.g. red spots visualization shows the current use of electricity in different parts of the home (Fig. 7b). The interactive visualization uses the graphical user interface (GUI) to visualize the energy consumption (Fig. 7a and c) uses the ‘environmental impact of energy consumption’ as theme, e.g. corolag depicts the impact of sea lives in visualization, whereas tree plantation visualization calculates the number of trees to be planted for CO₂ emission (1 pound CO₂ ≈ 7 trees).

3D visualization: 3D visualization is more realistic and psychologically appealing for the human brain. 3D technology originated as far back as in 1870s when a photographer demonstrated his ability to take a 3D photograph. However, it was not until 1980s that 3D technology was popularized on a global scale. In the primary studies, 3D visualization was less commonly used than 2D visualization for the energy consumption (only 3 studies) [S18,20,22].

The two major classification of 3D visualization are same as 2D, i.e., traditional [S18,20] and modern visualization [S18,22] and [S18] centered on both traditional and modern visualization. Fig. 8 represents some 3D visualization and their classifications as found in the primary studies. Traditional visualization includes 3D chart visualization, i.e., they could be drawn using the spreadsheet application, e.g. hit maps and choropleth maps, whereas the 3D modern visualization includes the visualization of the energy consumption in the form of any 3D objects, e.g. 3D mapping and user interface (Fig. 8).

4.1.4. Effect of visualization in motivating end-users

According to Bartram et al. [S2], there are various factors motivating end-users or residents to save electricity. Some of the important motivating factors in visualization are social interaction (i.e., information sharing on energy conservation in social media), personal milestones (e.g. goal setting for a week/month) and community involvement (e.g. competition in Facebook, Twitter) on top of the basic motivating factors such as display units (kWh, cost, CO₂ emission, etc.), display method (numeric or diagrammatic), and time scale. The study [S8] explained that the commitment to conserve is far more successful than monetary incentives in motivating the end-users. It is important to include some of the above information, namely energy consumed by each appliance in kWh/$, energy goal setting for a week or month, etc. in the visualization to effectively conserve energy.

4.1.5. Challenges in visualization of energy consumption

The primary challenge is to identify and understand the effective visualization which helps users in conserving energy and also to find how and where it would fit in larger dashboards to help residents to make informed decisions [S2]. Some of the other challenges are to make the visualization simple, easy to understand, easy to attract attention, easy to remember, and easy to deliver notifications close to the time of decision. Also, it is important to retain users’ attention over time [S19]. Hence, the software designed for this issue must be capable of addressing above-said issues.
4.2. Non-functional criteria

A total of 8 studies reported on the non-functional criteria in designing the visualization tool, out of which 4 studies [S2,7,12,21] described the non-functional hardware considerations and 6 studies [S2,4,5,7,12,19] described the non-functional software design considerations. Non-functional criteria would help in improving the overall performance of the application.

4.2.1. Hardware considerations

Hardware considerations illustrate the issues pertinent to the visualization display. The issues with respect to the positioning of the visualization display include the viewing distance [S2], i.e., right distance to view the visualization application effectively to make decisions. The viewing distance highly correlates with the size of the display, which was another hardware consideration.

The next criteria were the placement of the display, i.e., place at which the display was mounted [S21], for example, in kitchen walls or entry ways. The other issues include the installation of the visualization display physically (i.e., for mounting the display) and technically (i.e., for installing the software) [S7] and to balance between comfort and cost effectiveness [S2].

Some of the issues to be addressed with respect to the property of visualization display were to choose the perfect size of display [S2] for better clarity and the ability to adjust the light intensity of display [S2] for better view. The low storage capacity of the visualization display [S12] was seen to reduce the performance of the visualization.

In addition, perceptual considerations in viewing the display, e.g., when the light intensity was high or problems in understanding the visualization were highlighted. Also, ergonomic considerations of choosing the right place for mounting, understanding the time of people who spend in analyzing, impact of visualization with respect to energy use in different time periods were also relevant in designing the visualization display.

4.2.2. Software considerations

Out of 22 primary studies, 6 studies (36% studies) [S2,4,5,7,12,19] discuss software-related non-functional design considerations.

Table 4 summarizes these under the acronym PAFUSE, described below:

- **Portability**: the application’s ability to work on multiple platforms and devices, such as mobile, Internet, in-home display, iPad [S8].
- **Accessibility**: refers to the ease of finding, downloading and using the visualization application online, such as on websites or social networking sites [S5]. Accessibility could also be defined as the ease of downloading the feedback online for offline processing [S4]. It is expected that both the application and feedback data are easily accessible.
- **Flexibility**: refers to the ability to toggle between different modes of visualization [S7]. If the time taken to toggle is low, the application is considered more flexible.
- **Understandability**: the ease in recognition of information displayed in the visualization by the human mind [S2,7]. It is more likely to have a better understandability for perfect decision making.
- **Scalability**: the ability of the application to scale in order to accommodate future information in the visualization [S2]. The application is expected to be more scalable.
- **Extensibility**: the ease for the developers to extend the application. This includes avoiding the use of the proprietary software to ensure extensibility [S3].

The look and feel of the display influences the visual factors. The issues related to the look and feel of the display include the (a) right choice of the esthetic factors, i.e., the factors that describe how visualization cohere with home’s design and ambience [S2], (b) importance of designing a display which sustains user’s interest over a long period to increase sustainability, i.e., choosing appropriate visualization technique and visualization information [S7].

The major issue pertinent to human factors was to design effectively to suit the cognition of the end-users; moreover, similar visualization does not attract diverse people (one-for-all visualization) [S2,3,7] and sometimes reaching the averagely educated people is quite difficult [S19].

**Table 4** Non-functional software considerations (PAFUSE) and their descriptions.

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<th>Non-functional software criteria</th>
<th>Criteria description</th>
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<td>Portability</td>
<td>Ability to work on multiple platforms and devices</td>
<td>[S4]</td>
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<tr>
<td>Accessibility</td>
<td>Ability to download the feedback from online sources for offline processing</td>
<td>[S4]</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Ability to download the feedback from online sources for offline processing</td>
<td>[S7]</td>
</tr>
<tr>
<td>Understandability</td>
<td>Ability to toggle between different modes of visualization</td>
<td>[S2,7]</td>
</tr>
<tr>
<td>Scalability</td>
<td>The ability of the application to scale in order to accommodate future information in the visualization</td>
<td>[S2,19]</td>
</tr>
<tr>
<td>Extensibility</td>
<td>The ease for the developers to extend the application</td>
<td>[S19]</td>
</tr>
</tbody>
</table>
5. Discussion

The major theme that emerged out of the SLR as a result of Grounded Theory analysis was ‘design criteria for visualization’ for the domain of energy consumption. This section presents: (a) a summary of research and design trends found across the primary studies; (b) some recommendations based on the results for software designers and researchers; (c) recommendations for end-users; (d) implications for research and practice; and (e) ideas for future works as gathered from suggestions in the primary studies. While most of these apply to researchers and designers working in the domain of energy conservation, more generally the recommendations can also be consulted for design of visualizations for other similar domains.

5.1. Research and design trends

Modern visualizations attract people but require some initial learning to use. On the other hand, chart or traditional visualizations are simple to understand and appropriate for rapid and effective decision making. Bar chart and graphical user interfaces were the highly used visualization techniques across the primary studies reviewed.

There were several studies which proved that strong motivation for energy consumption led to sustainable behavior. Some of the motivations were: rewards and fame among the social community [S2,19], incentives [S2], competitions [S16], discussion on energy conservation [S2], comparative feedback [S2,6,12], energy saving goal setting [S19], and comparison and collaboration through social networking [S2].

Around 40–50% of the energy consumption is determined by the environmental factors such as climate (temperature) [S15], brightness (day light) [S11], but only one out of 22 studies related the environment with the energy consumption by means of sensors for visualization [S14].

The visualization display may have lot of information to be displayed on it, such as amount of energy consumption, energy prediction, ranking in the community, sensor data, but none of the studies concentrate on the organization of the information.

Customization is a vital factor in any application and it includes customizations in look and feel of the application, in selecting the type of visualization, the mode of visualization, context of the information, and selecting the display for the convenience and understanding of the user. Out of the above mentioned types of customizations, the only customizations addressed in the studies were the context of information [S18] and the look and feel of the application [S21].

5.2. Recommendations for software designers and researchers

Here we present some frequently encountered requirements and corresponding recommendations based on the SLR findings.

Requirement specification 1: Target users are residents or energy managers.

Design recommendation: When the requirement specification targets residents as users, designers can refer to Section 4.1.1 on information appropriate for end-users. In the similar manner, if the target users are energy managers, Section 4.1.1 on information appropriate for energy managers can be consulted. In both scenarios, subsection on information appropriate for both end-users and energy managers apply. Further customization of the information can be done in consultation with sample users.

Requirement specification 2: Visualization should be simple and easily understandable.

Design recommendation: In this case, it is better to select traditional 2D visualization presented in Section 4.1.3. The section presents various options within 2D visualizations to choose for simplicity.

Requirement specification 3: Visualization display to be mounted in public space.

Design recommendation: This requirement would suggest selecting an esthetic and pragmatic visualization, where the designers could use either modern 2D visualization or 3D (traditional or modern) visualizations described in Section 4.1.3. Also, these visualization techniques could also be applied to public buildings, apartment corridors in the form of infographics for effective visualization.

Requirement specification 4: Visualization must be interesting.

Design recommendation: To make the visualization interesting, customization could be done by using various modes of visualization (Section 4.1.2). A sample user interface is presented in Fig. 9 to improve customization of the user interface, so that user could select the modes of their choice.

![Multiple modes of visualization sample.](image-url)
**Requirement specification 5**: Visualization should be portable i.e. work on multiple platforms and devices like PC, mobiles, iPad, in-home displays, etc.

**Design recommendation**: Designers may look in Section 4.2.2 to resolve such non-functional software-related considerations. This section clearly explains some of the other concerns such as accessibility, understandability, flexibility and extensibility.

5.3. Recommendations for end-users

This section presents some recommendations for users based on typical end-users’ questions.

**Question**: What is the optimal size of the visualization display that could be mounted on the end-user’s wall?

**Recommendation**: The visualization display size depends on the size of the room in which the display is mounted. Fig. 10 represents the viewing distance and its corresponding screen size, i.e., if the width of the room is 6–10 feet, then the screen of size 28–32” is desirable.

5.4. Implications for research and practice

From the results presented in Section 4, it is obvious that while almost 30–40% of energy is consumed in residential areas, research focusing on visualizing energy consumption for the residential sector needs further attention.

With respect to modern visualization, only 3 out of 22 papers focused on artistic or esthetic visualization. As such several studies supported that modern visualization should be a stronger focus for research and commercial design.

Many studies undertook surveys to assess the effectiveness of visualizations, highlighting the importance of human factors in visualization. However, none of the survey provided the questionnaire used in the survey or the factors that supported the questionnaire. Also, none of the studies surveyed human expectations beforehand. Clearly, researchers and commercial designers can work toward overcoming these limitations.

One of the techniques to reduce energy consumption to a greater extent was to display continuous (real time) feedback on idle time or standby time of appliances [6,8]. In addition, it is better for the people to know the cause and effect of energy consumption [14] to act immediately; furthermore, this helps in fault detection in appliances and voltage leaks. Both these areas are ripe for further investigations.

![Fig. 10. Viewing distance and size of display. Source: Siero, Balkir, Dekker, van den Burg, and Marcel (1996).](image)

From the studies, the number of applications developed for mobile platforms (13%) and embedded display (4%) is much lower when compared to the applications developed as web pages (72%). As the mobile platform is very popular, both research and commercial design can turn focus toward it.

There are several gaps in research that are to be addressed. First of all, most of the studies used either bar chart or line chart for visualization; therefore, the upcoming research may explore different visualization based on ergonomic factors.

Most of the primary studies focus only on presentation of the energy consumption, but not on human computer interaction (HCI) aspects, i.e., interaction of users with energy visualization displays [19] to better understand relevant usability issues. Also, research on HCI issues in this context will require a detailed understanding of human psychology and thus, a cross-disciplinary research approach is recommended.

An obvious next area of research and commercial engagement is visualization of energy consumption for Smart Grid end-users (customer domain specified in NIST Conceptual model, Metke & Ekl, 2010). Based on the SLR findings, we recommend the use of modern visualization techniques (Section 4.1.2) and a deeper integration of expectations and behaviors of suppliers and end-users.

The main scope of future research is to address the above design considerations which have received little attention thus far. We also found some specific ideas for future work covered in the primary studies themselves which we cover next.

5.5. Ideas for future works from primary studies

In this digital world inundated by mobile phones, tablets, PCs, Internet, social networking, embedded displays, and in-home displays, achieving portability across multiple devices and platforms is a critical area of future work. One step forward in this direction would be to visualize electrical systems through Internet [12] (Qiu, Gooi, Liu, & Chan, 2002), i.e., Internet of things (Atzori et al., 2010). Holmes et al. proposed to attain the extensibility by means of using nonproprietary software to develop visualizations [54]. Dominguez et al. [12] proposed future work on efficient and statistical data mining techniques (Bishop & Nasrabadi, 2006) to achieve understandability and at-a-glance awareness, which are fundamental to decision making. Also, they proposed to visualize power quality information (Khan, 2001). Integrating energy consumption visualizations with social networking has also been highlighted as an important area of future work.

6. Conclusion

We conducted a systematic literature review with the aim to better comprehend the design strategies and techniques for visualization of energy consumption. A total of 232 studies were identified from the search of the literature, of which, 22 were included in the SLR based the study selection criteria pertaining of quality and relevance. Data from these 22 studies was analyzed and synthesized using Grounded Theory’s open coding and constant comparison method. This 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.

Findings of this SLR not only address our initial research questions but also present the trends and patterns in research in the area of visualization of energy consumption for end-users. The most important contribution of this paper is the description of
design criteria which serve as recommendations for designers and researchers designing visualization of energy consumption for end-users. The findings have particular significance with a focus on designing effective visualizations for end-users.

Finally, there is an immediate attention required for designing a prototype for visualization to balance between esthetic appeal and practical usefulness, to balance between accuracy and clarity, and to balance between comfort and cost effectiveness.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.scs.2015.04.009

References


