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Visualisation in energy eco-feedback systems: A systematic review of good practice

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ABSTRACT

While adopting eco-feedback systems can lead to significant energy savings, in the region of 5–20%, research has shown that the inappropriate use of visualisation patterns and techniques decreases their effectiveness. However, existing reviews on energy feedback visualisation provide little guidance on when to use them and how to enhance their effectiveness in various scenarios. The uncertainty and lack of clarity surrounding eco-feedback visualisation techniques and their impact on end-userengagement present challenges to the design of eco-feedback systems. This paper presents the first systematic review of a wide range of energy eco-feedback visualisation techniques, including, for the first time, Augmented-Reality (AR) and thermal imaging visualisation. We analysed 82 relevant studies published between 2000 and 2021 using the PRISMA protocol for systematic reviews. The visualisation techniques have been reported under five distinct categories, which we have identified: (a) *statistical visualisation*, (b) *architectural and geospatial visualisation*, (c) *game-based visualisation*, (d) *artistic visualisation*, (e) *emerging visualisation*. Furthermore, they have been analysed based on the following criteria: type of visualised information, the purpose of use, end-user perception, scholar suggestions, and potential impact. The findings show that statistical visualisation techniques are essential in any energy eco-feedback system. Furthermore, they suggested combining different visualisation techniques to accommodate different user profiles, but such combinations must be carefully planned based on usage scenarios. Following this analysis, a series of considerations and good practice guidelines are presented for each of the reviewed techniques to assist practitioners in this area (e.g., designers and researchers) while providing recommendations for future work.

1. Introduction

The built environment sector currently consumes approximately 40% of the globe's energy, translating into around 30% of the world CO_2 emissions. This figure is expected to continue rising in the future due to the rapid growth of the urban population, technological development, economic growth, and cultural development [1].

Whilst significant progress has been made in recent years due to implementing passive and retrofit energy efficiency measures; research has also shown that changing users' behaviour can result in important energy savings [2]. One of the measures that can affect ecologically responsible behaviours, leading to energy savings in the region of 5–20% is Eco-feedback [3–5]. An Eco-feedback system provides building occupants with information about their historical and current energy usage through technology (device and/or interface). Such systems aim to promote the environmental awareness of energy users and ultimately reduce their environmental impact [6]. Since research has shown that feedback alone is not enough to influence behaviour change [7], many studies on eco-feedback leverage a wide range of techniques from environmental and social psychology such as comparison, goal-setting, competition, and reward [6]. However, despite the implementation of such techniques, eco-feedback systems still suffer from a decay in their effectiveness to stimulate behavioural change over time [8]. This explains why recent studies in this area (e.g. Refs. [9,10]) are gradually shifting away from providing users with "mere" feedback to enable them act upon the provided feedback through the use of user-centred and community-based approaches [9].

Despite continuous improvements in the ability of eco-feedback systems to promote sustainable pro-environmental behaviour, a recent thematic analysis of 125 reviews on eco-feedback [11] suggested that the inappropriate adoption of visualisation remains a major obstacle to the engagement and interest of even highly motivated users. There is

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Table 1
Depicts existing reviews of eco-feedback visualisation while highlighting their focus.

Reviews	Years	Elements covered	Criteria of the review
[18]	2020	The effectiveness of different eco-feedback mediums such as mobile, tablets, web, and computer-based	Studies were analysed based on criteria such as type of feedback, eco-feedback medium, interventions to support eco-feedback (e.g., normative and community interaction), sample size, and duration of intervention.
[17]	2019	Energy consumption monitoring; energy data visualisations; behaviour change	Survey and categorise different categories of interactive energy data visualizations using the Fogg behaviour change model
[15]	2015	Ground theory; energy; visualisation	Categorise two criteria (functional and non-functional) for designing visualizations of energy consumption for end-users
[16]	2015	Information access; eco-visualisation; engagement and motivation	Review how the data, psychological factors, effort, context, and communicative scope yields in design dimensions

consensus in the literature that adequate visualisation could improve users awareness and understanding of energy-related issues, which could stimulate behavioural change when combined with actionable instructions fitting users' context [12–14]. However, despite this, only a few reviews [15–17] concentrated on the visualisation of eco-feedback. Even though these reviews represent an invaluable source of information, they provide little guidance/considerations on "when" and "how" to use different types of visualisation techniques in an eco-feedback system to enhance its effectiveness. The uncertainty and lack of clarity surrounding the acceptance, complexity, and impact of different eco-feedback visualisation techniques on the engagement of building occupants make the design of effective eco-feedback interfaces difficult [24]. This explains why eco-feedback studies often utilise qualitative and/or empirical methods (e.g., surveys, field studies, etc.) to determine such factors, which may be time-consuming and resource-intensive.

In light of the above, this paper explores the current research on eco-feedback visualisation to identify existing research challenges and analyse ongoing research efforts. The contribution of this review paper is twofold. Firstly, it provides a comprehensive review of eco-feedback visualisation techniques, including those not covered by previous reviews, such as AR (Augmented Reality) and thermal imaging. Secondly, it provides practitioners with guidelines and recommendations about effective implementation.

Specifically, the paper has the following objectives:

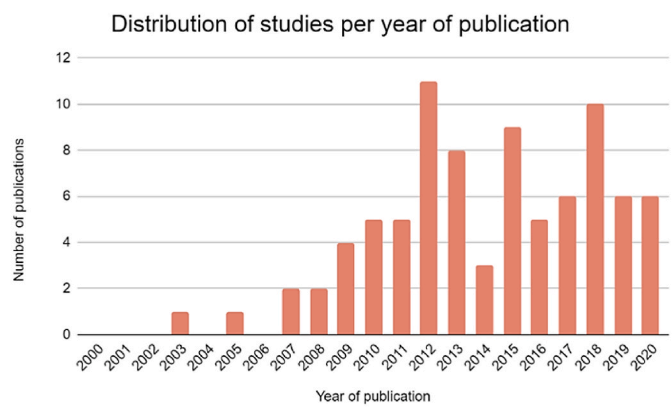

Fig. 2. The distribution of the analysed studies per year of publication.

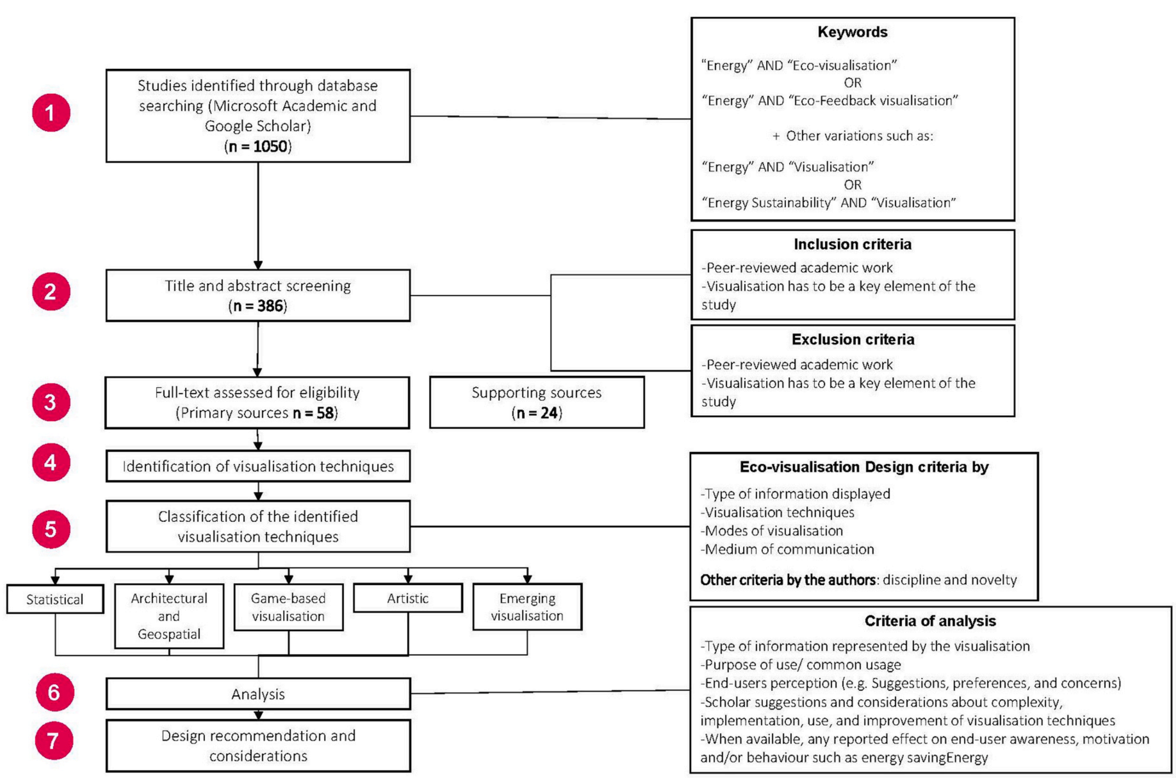

Fig. 1. Flow chart representing the methodological process of this review, including screening, selection, classification, and analysis.

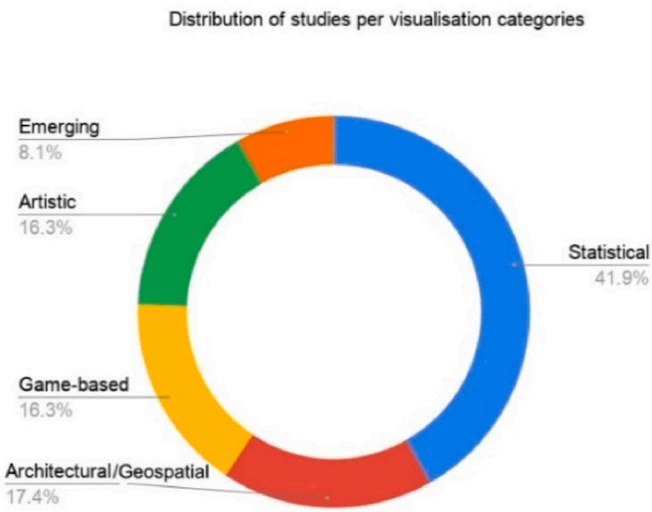

Fig. 3. Distribution of analysed studies per visualisation categories.

1. To analyse the current efforts in the field of eco-feedback visualisation (mainly reviews) in terms of domain coverage with specific attention to knowledge gaps and unexplored areas.
2. To review different eco-feedback visualisation techniques based on the type of visualised information, their purpose of use, complexity, and end-user experience (e.g. perception).
3. To develop recommendations for different visualisation techniques covering areas such as “when to use”, “how to improve them”, and “how to potentially improve their effectiveness based on various situations.
4. To provide suggestions for future research.

The remainder of the paper is structured as follows. Section 2 analyses in detail previous reviews on visualisation in eco-feedback and highlights the gaps. Section 3 discusses the research methodology. Section 4 analyses the general characteristics of the 82 reviewed studies (e.g., distribution per year, location, etc.). In Section 5, however, we present a review of different energy visualisation techniques, including statistical, architectural and geospatial, game-based visualisations, artistic, and emerging visualisation techniques. Section 6 concludes the paper by providing considerations/recommendations for each reviewed visualisation categories while discussing future research opportunities.

2. Previous reviews of eco-feedback visualisation

Table 1 shows existing studies that reviewied the visualisation aspect of eco-feedback. First [18], recently reviewed 27 eco-feedback studies to determine the effectiveness of different eco-feedback mediums, including mobile, tablet, and web-based systems. In addition to reporting the intervention outcomes of the studies, the review also analysed them based on other criteria such as type of feedback, feedback interventions (e.g., normative and community interactions), sample size, and intervention length of the analysed studies. The study concluded that feedback mediated through digital mediums such as mobile phones, computers, and tablets, is promising for energy conservation. However, the review focused largely on the impact of digital mediums of eco-feedback on energy savings and did not address the visualisation aspect of eco-feedback systems in detail.

[17], on the other hand, recently analysed different visualisation

Table 2
Applicability of line and area graphs in eco-feedback systems.

		Single line graphs	Multiple Line graphs	Area graphs
When to use	Analyse change in one dataset over time	✓	×	×
	Compare the change of multiple datasets over time	×	✓[a]	✓
	Identifying anomalies in energy consumption	✓	Possible but more evidence is needed	×
	Analysing the relationship between two or more variables	✓	✓	✓
	Conveying total amounts over time and sub-categorical breakdowns	×	×	✓

[a] Whenever possible, area line graphs should be used instead because they are easier to read and interpret than multiple line graphs.

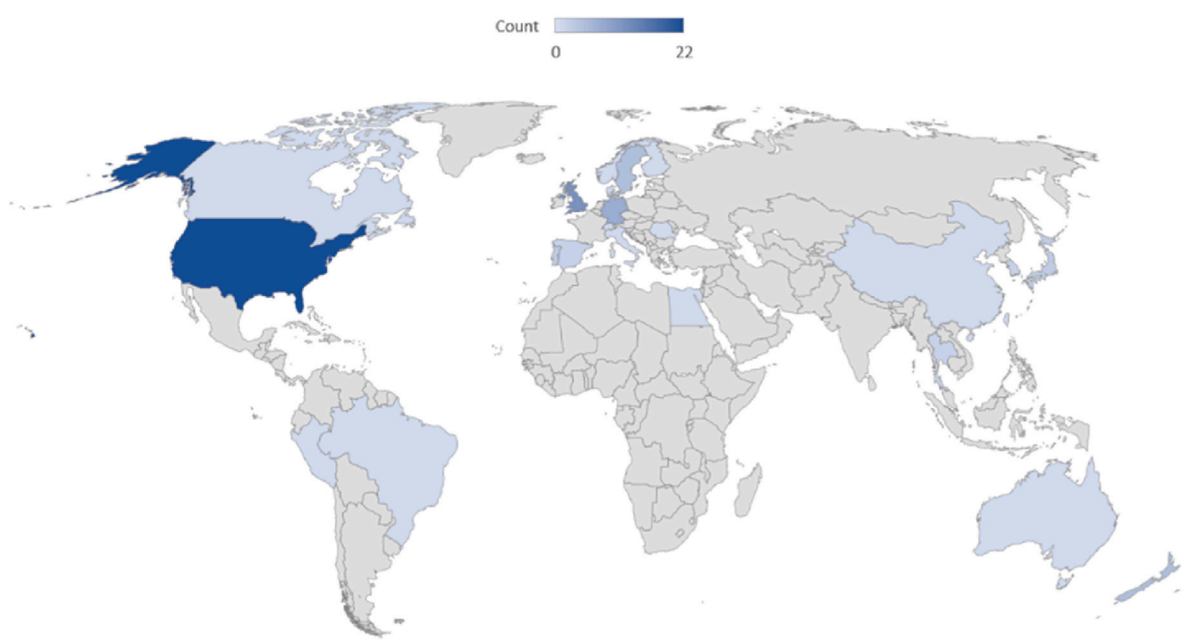

Fig. 4. The distribution of review studies by country.

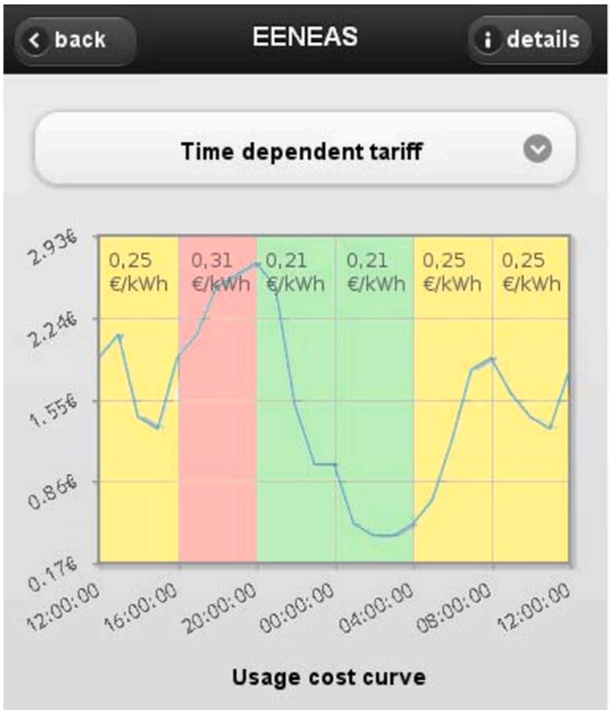

Fig. 5. A single line graph showing the change of energy tariff over the day (24 h), retrieved from [37].

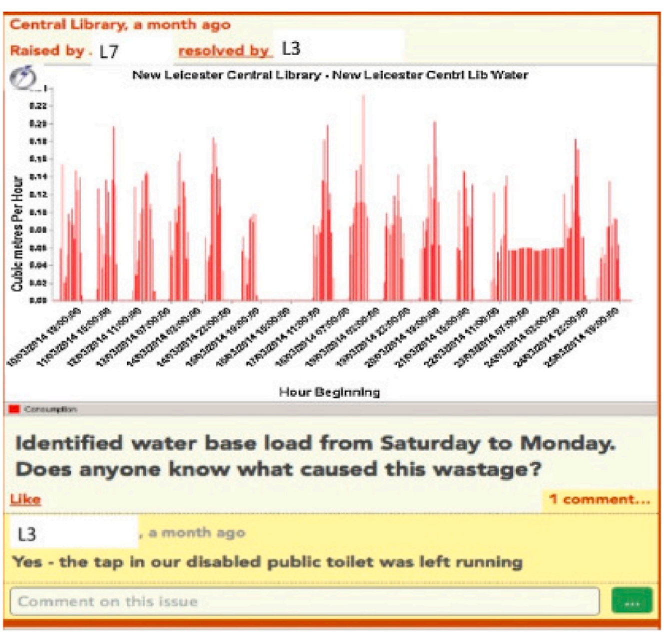

Fig. 6. Water based load of a library space in cubic meters per hour during weekends, retrieved from [35].

techniques used in digital eco-feedback systems based on criteria defined in Fogg [19] behaviour change model: motivation, trigger, and ability. The authors further classified the reviewed visualisations into five distinct categories: charts and graphs, energy gauges, eco-visualisations, visualisations for analytics, gamified and serious game visualisations, and ambient and physical visualisations. However, emerging visualisation techniques in eco-feedback, such as augmented reality and thermal imaging, were not covered in this review. This work concluded that most existing visualisations target the motivation factor of end-users while some support the ability or trigger factors. However, only a few studies, such as [20,21], dealt with the three factors together.

[16] took a different direction to Ref. [17], where they first developed their framework for designing eco-feedback. The framework contained five domains: data, psychological factors, context, effort and interaction, and communicative scope. Subsequently, they employed this framework to identify gaps related to the design of different eco-feedback systems, including dashboards, IHD, smartphone apps, and artistically inspired ones. In response to the lack of criteria for designing eco-feedback visualisation [15], conducted a comprehensive review of 22 primary studies using grounded theory open coding and constant comparisons. Their framework contained two categories of design criteria, namely, functional and non-functional. Functional criteria include elements such as visualisation techniques, type of displayed information, and modes of visualisation. Conversely, non-functional criteria comprise software and hardware considerations (e.g., size and placement of display) [15]. classified eco-feedback visualisation techniques based on the dimension of representation into 2D and 3D. The authors further sub-divided each category based on their novelty into traditional and modern. While this review provides an invaluable source of information for eco-feedback designers, it did not address emerging visualisation techniques, including AR and thermal imaging. Even though the authors provided five invaluable general design recommendations covering areas such as the type of information to target end-users and managers and visualisation requirements for public spaces, their paper did not specifically focus on generating design recommendations for each visualisation technique/category. Finally, the review did not discuss the end-users experience or level of engagement with different visualisation techniques.

While the above reviews provided new insights into eco-feedback visualisation, they excluded emerging visualisation techniques such as Augmented reality and thermal imaging. Furthermore, they presented little guidance on "when" to use existing visualisation techniques and how to possibly improve their effectiveness to "improve end-users awareness and help them develop pro-environmental behaviour concerning energy conservation.

3. Research methodology

As mentioned in section 1, the purpose of this paper is to provide a comprehensive review of existing eco-feedback visualisation techniques and develop recommendations and considerations for their effective implementation and use based on different factors. To attain this aim, we developed a review protocol (Fig. 1) that complies with the specification of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) checklist [22]. PRISMA is a rigorous, well-establish, widely adopted reporting guideline for systematic reviews. According to Ref. [23], the PRISMA checklist was proven to enhance the reporting quality and clarity of reviews while providing substantial transparency in the selection process of sources.

Firstly, an extensive literature search has been conducted, spanning 21 years from 2000 to 2021. For this, we used two different search engines, namely: Microsoft Academic and Google Scholar. While Google scholar is comprehensive in its coverage, it does not allow searching/

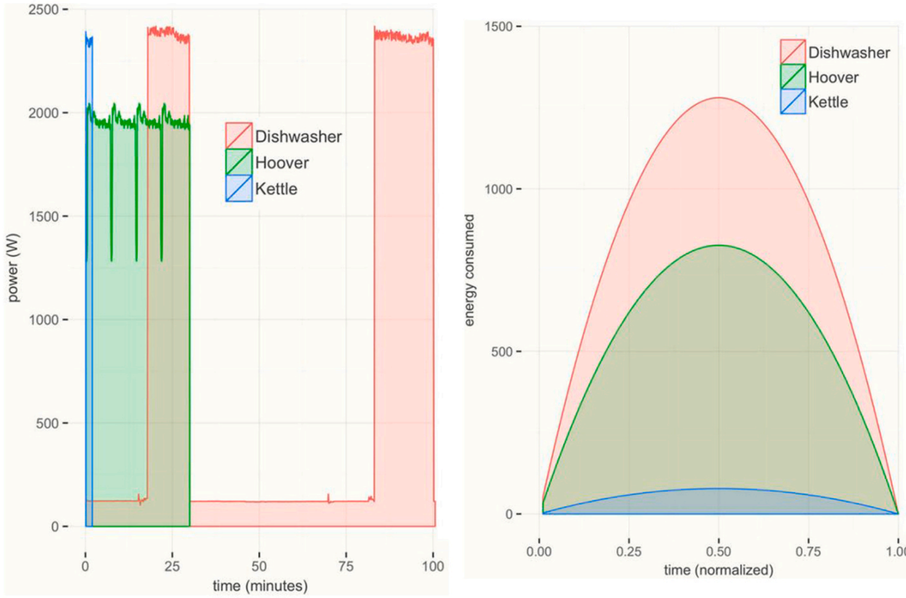

Fig. 7. The disaggregated area time-series line graph (left) and normalised disaggregated (right) visualisations used by [39].

Table 3
Applicability of bar/column graph visualisation patterns in eco-feedback systems.

		Bar/column graphs
When to use	Analyse change in one dataset or multiple datasets over time	✓[a]
	Comparing quantities in different groups/ categories	✓
	Conveying total amounts and sub-categorical breakdowns	✓[b]
	Representing a single linear progressive data value	×
	Setting goals and normative comparisons	✓[c]

[a] Column/bar graphs are not adequate for analysing small changes.
[b] Sub-categorical breakdown is possible through stack bar/column graphs.
[c] Bar/column graphs can be used to help consumers draw normative comparisons by including a green bar/column to act as a target aid.

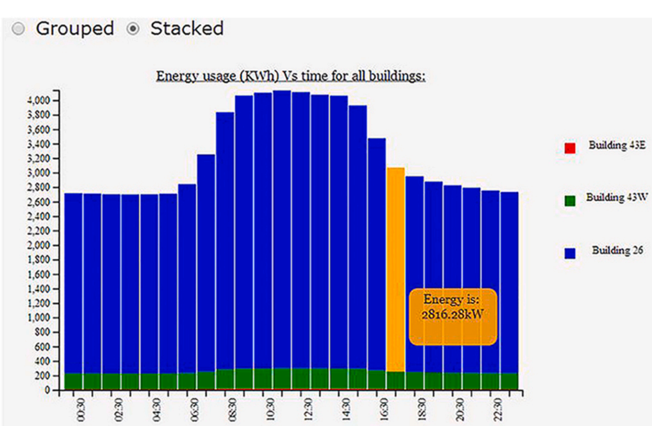

Fig. 8. The contribution of three buildings to the overall energy usage of the pilot area of [50].

sorting by specific disciplinary field. That is why we started the literature search using Microsoft Academic with a search string consisting of a combination of the following keywords ("Energy" AND "Eco-visualisation") OR ("Energy" AND "Eco-feedback Visualisation") OR ("Energy" AND "Data visualisation"). These terms were selected to capture any studies that explored the visualisation of energy feedback. However, variations to the terms "energy" and "visualisation" (e.g., energy sustainability and information visualisation) were also used to capture literature from a wide range of disciplines. This initial search returned a total of 974 sources. However, after using Google Scholar, we identified additional 76 sources resulting in a total of 1050 studies which in turn were written in English.

Second, sources were initially screened based on their title and abstract. Afterwards, the studies' full text was assessed through set inclusion criteria. In line with PRISMA guidelines and to avoid the risk of bias, the selection process was performed by three authors (MC, BM, MZ) independently, and any disagreements in the list of sources selected were solved through consensus. The inclusion criteria for publications are; 1)-peer-reviewed academic work except for very few game-based eco-feedback applications such as EnergyVille that did not have related scholarly literature; and 2)- visualisation had to be a key element or outcome of the study. Additionally, the following exclusion criteria were applied: 1)- studies that did not explicitly discuss visualisation aspects in their findings or at least related work section; and 2)-studies that did not consider end-users interaction with visualisations (e.g. studies on energy management systems); and 3)-extended abstracts, posters, and unpublished papers. Please consult Fig. 1 for a detailed breakdown of how many studies were filtered following the above criteria. A review of abstracts led to the selection of 386 studies, but the three authors consensually selected only 58 after reading the full text.

To analyse the extracted 58 publications, we have first identified different visualisation techniques by name (e.g., bar graph, AR visualisation, and 2.5D visualisations). After that, we classified the identified visualisation techniques using some of the design criteria for visualisation of energy feedback developed by Ref. [15] (see section 2). The used criteria were a)-information displayed in the visualisation; b)-visualisation techniques; c) modes of visualisation (e.g. the scale at which information is displayed); d)-medium of communication (e.g.

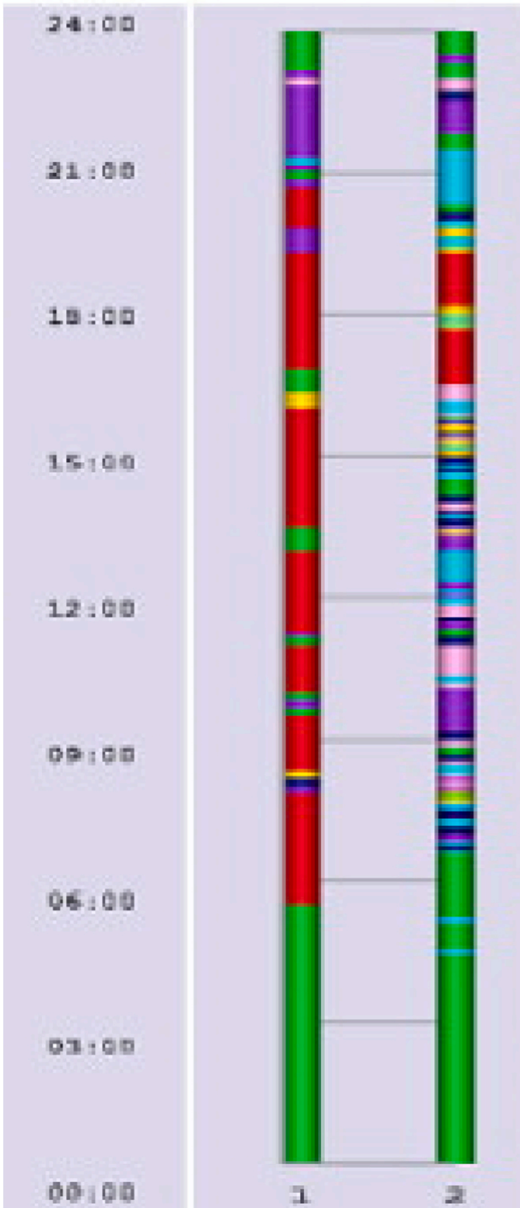

Fig. 9. The stacked column graph used by Ref. [42] to show the breakdown of participants' energy consumption by their daily activities.

software and hardware). In addition to those criteria developed by Ref. [15], we included two additional criteria in the classification process: e)-discipline and f)-novelty. This was mainly to limit the number of visualisation categories and to review emerging visualisation techniques in eco-feedback in a separate category. The resulting categories based on the above criteria and which were reviewed in section 4 are *statistical visualisation*, *architectural and Geospatial visualisation*, *game-based visualisation*, *artistic visualisation*, and *emerging visualisation*.

Once we developed the above categories, the visualisation techniques under each category were analysed based on the following criteria:

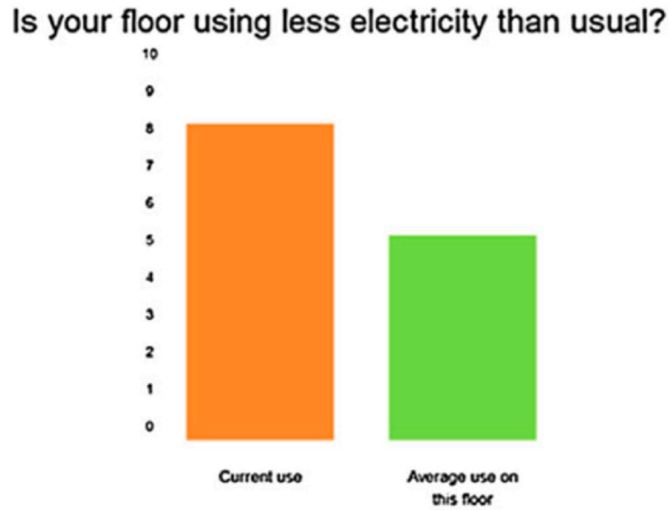

Fig. 10. The daily energy performance of a residential floor against the set average usage, retrieved from [51].

- Type of information visualised
- Purpose of use/common usage
- End-users perception and feedback about the visualisation techniques including suggestions, preferences, and concerns.
- Scholars suggestions and considerations concerning the complexity, implementation, use, and improvement of the visualisation techniques.
- When available, any reported effect on end-user awareness, motivation and/or behaviour such as energy savings reported after the implementation of the visualisation technique

Please note that not every study we analysed covered all of the above criteria. Therefore, 24 additional 24 sources were used to support the findings, which results in 82 studies in this review. For more information about the analysed studies, please refer to the attached review database excel sheet (Link). Finally, following the analysis of studies, we develop a set of recommendations/considerations for each visualisation technique under the five categories while providing recommendations for future work.

3.1. Review limitation

The review presents a set of good practice recommendations/considerations for practitioners in the area of energy feedback by analysing existing and emerging visualisation techniques in this area. Even though visualisation is an important driver of end-user awareness of energy usage and its implication on the environment [12–14,24], our work does not assume a direct or linear relationship between effective visualisation and energy conservation. In fact, visualisation provided by eco-feedback systems alone is not sufficient to create behavioural change. This is a complex issue that depends on other factors such as psychological, socio-economic, technological, methodological, and personal qualities and preferences. This is a complex issue that depends on other factors such as psychological, socio-economic, technological, methodological, and personal qualities and preferences of end-users [5,25,26]. Some of these factors, including socio-economic and psychological, are not

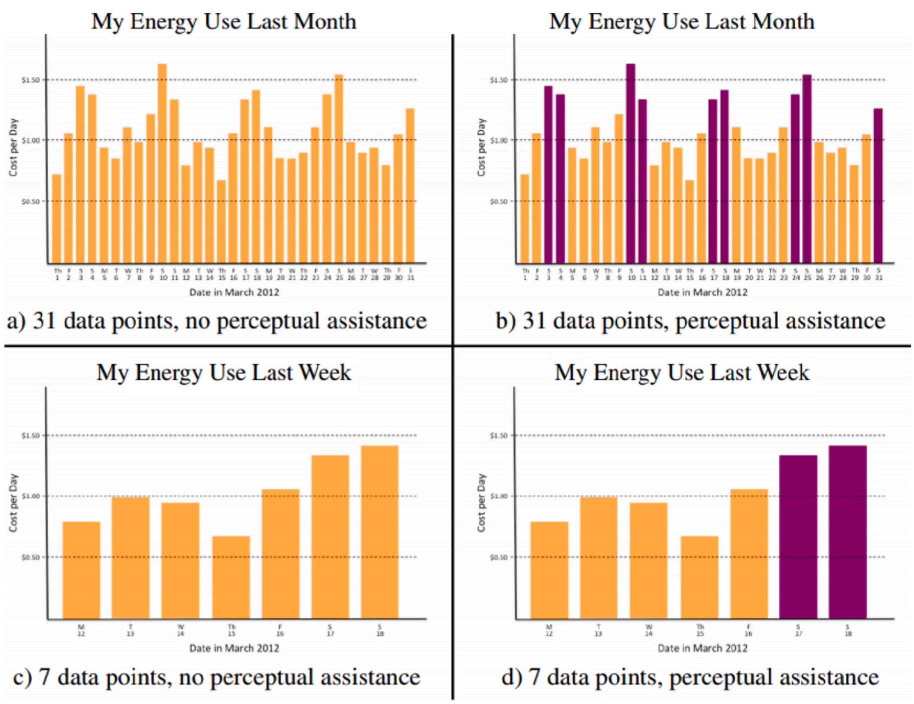

Fig. 11. The bar charts employed by Ref. [30] in their study.

Table 4
The applicability of pie, gauge, and radar charts visualisation patterns in eco-feedback systems.

		Pie charts	Gauge charts	Radar Charts
When to use	Analyse change in one dataset or multiple datasets over time	×	×	✓
	Comparing quantities in different groups/ categories	×	×	✓[d]
	Conveying total amounts and sub-categorical breakdowns	✓	×	×
	Representing a single linear progressive data value	×	✓	×
	Setting goals and normative comparisons	Not discussed in the studies, more evidence is needed	✓	Not discussed in the studies, more evidence is needed

[d] Radar charts can be used to compare variables with different scales.

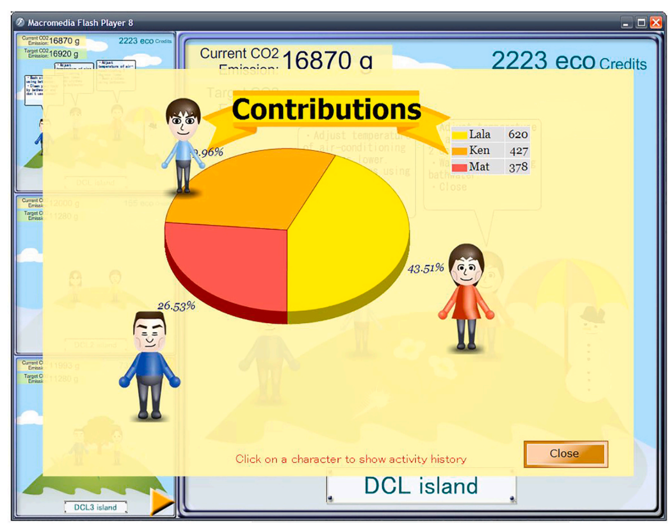

Fig. 12. Pie chart visualisation showing the contribution of each household member to the overall CO2 emission of the community in the study of [56].

covered in this review. Further research from other angles, including both quantitative and qualitative methods, is welcomed.

Additionally, as eco-feedback visualisation is often combined with other environmental and social psychology interventions, it is difficult to pinpoint the exact effect of the visualisation aspect on energy conservation. Therefore, the reported effects associated with the implementation of visualisation techniques in the reviewed studies only represent their potential and suitability and NOT an account of their effect size on energy conservation.

Finally, generalisations should be cautious because the generated recommendations/considerations correspond to a set of scenarios and contexts (e.g. certain types of end-users) which may vary from one study to another. Therefore, the suggestions/recommendation provided by the review should be used as a starting point when designing eco-feedback systems. Furthermore, designers and practitioners should evaluate their intended eco-feedback visualisation patterns in the context of their study and by using participatory approaches to reach a consensus [9,27,28].

4. General characteristics of the reviewed studies

Fig. 2 illustrates the distribution of the reviewed studies per year of publication. Overall, it is evident that attention to the area eco-feedback visualisation/eco-visualisation has risen since the year 2007. It is believed that this trend was influenced by the outcomes of the 2005 world summit on social development, which identified the education, awareness, and engagement of people in environmental sustainability as important social factors of sustainable development. This was evident in

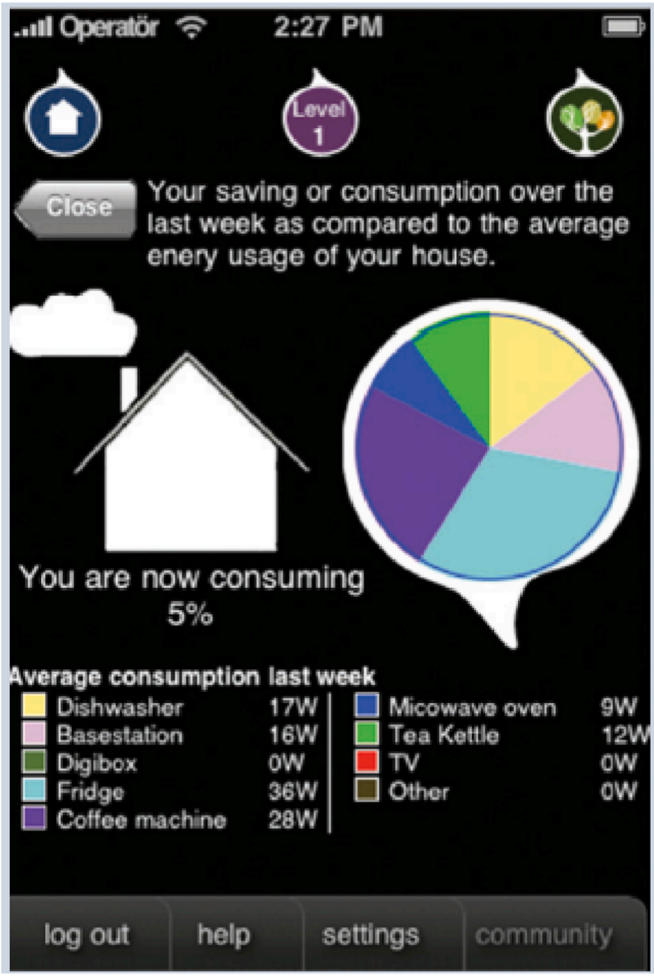

Fig. 13. A pie chart visualisation showing the breakdown of electricity usage by appliances, retrieved from [57].

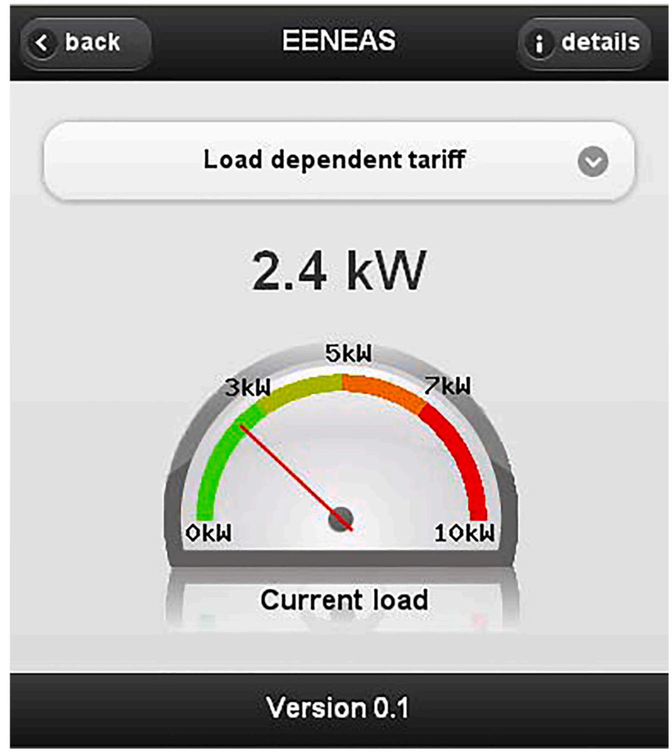

Fig. 14. The Gauge chart used by in their eco-feedback system to represent the current electricity load [37].

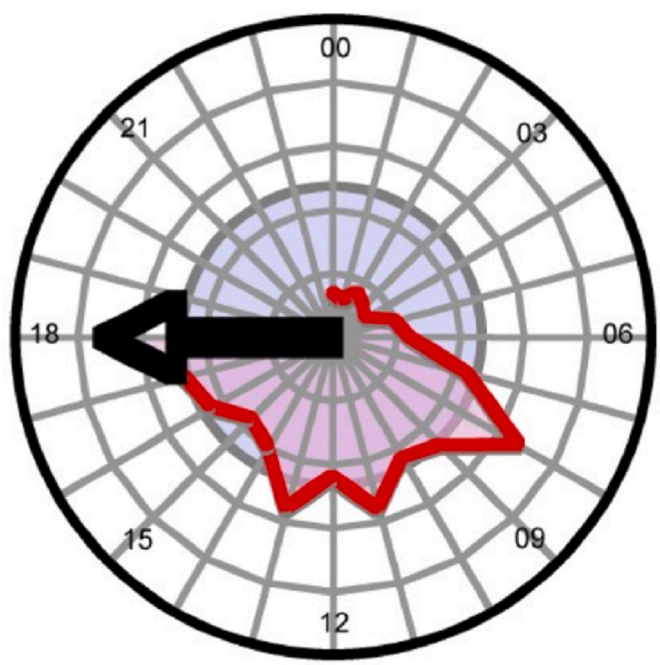

Fig. 15. Radar chart used in the study of [70].

the initiatives of artists such as Tiffany Holmes [29], who combined art techniques with technology to visualise complex/invisible environmental data in a meaningful way to raise public awareness about climate change issues and promote sustainable behaviour. In addition to the above, approximately 42% of our study sample included statistical visualisation techniques, whereas the remaining studies covered almost equally techniques belonging to artistic (16.3%), game-based (16.3%), architectural & geospatial (17.4%), and emerging visualisation (8.1%), (Fig. 3). This was expected because most existing eco-feedback systems rely predominantly on statistical visualisation patterns [30]. Considering the reviewed studies' location (Fig. 4), 26.8% were based in the United States, 14.6% in the UK, 9.7% in Germany, and 6% in Sweden. 39.25% was split across different countries in Europe, Asia, Australia, and South America. However, three studies could not be classified by location because they were European projects.

5. Review of visualisation in eco-feedback

Data, a raw and unorganized fact, becomes information when processed in a meaningful way according to the given requirement. If we place data into a relationship with other information, it can be synthesised into knowledge [31]. Thus, visualisation is considered vital for communicating information and enhancing users' knowledge in many fields. In eco-feedback, visualisation goes beyond just presenting "mere" information to the end-users to make them develop sustainable thinking, environmental awareness, and pro-environmental behaviour. As previously discussed in section 3, this section reviews different visualisation techniques under five distinct categories statistical, architectural and geospatial, game-based, artistic, and emerging visualisations.

5.1. Statistical visualisation

Statistical data visualisation, also known as statistical graphics, often relies on mathematical data as a communication medium. Techniques under this category, including charts and graphs, are based on a

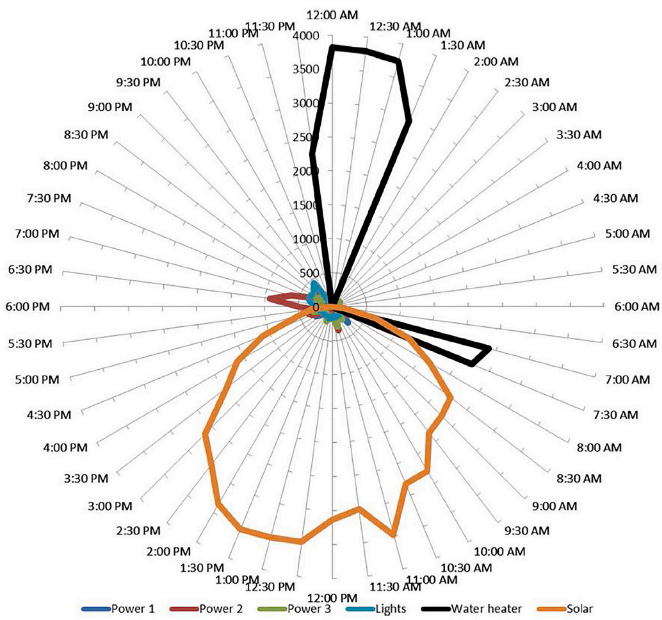

Fig. 16. A radar graph depicting the daily energy household consumption and electricity generated by PV panels, retrieved from [61].

Table 5
Applicability of Time-pie, time-stack, and time-tone visualisation patterns in eco-feedback systems.

		Time-pie charts	Time-stack graphs	Time-tone visualisations
When to use	Analyse change in one dataset or multiple datasets over time	✓[a] Limited	✓[b]	✓[c]
	Comparing quantities in different groups/ categories	✓	✓	✓[e]
	Conveying total amounts and sub-categorical breakdowns	✓[a] Limited	✓	✓[d]
	Representing a single linear progressive data value	×	×	×
	Setting goals and normative comparisons	Not discussed in the studies, more evidence is needed	Not discussed in the studies, more evidence is needed	Not discussed in the studies, more evidence is needed

[a] It is difficult to determine the exact measurement using time-pie charts because they are radial visualisations.
[b] Like bar/column graphs, it is difficult to compare the change in the overall energy usage over time if differences between the size of columns are not significant.
[c] It is advisable to utilise a larger range of tonal variations of a single hue to better represent a larger range of variation in the energy data.
[d] Possible but only if supported by text indicating the contribution of each category to the overall energy usage (e.g. lighting (20%)).
[e] Possible but only if supported by text showing the percentage of the total energy used by a given category at a given time frame.

systematic mapping between graphic marks and data value to represent "measurable data and information" [32]. Although the use of charts and graphs is common, the choice of visualisation techniques under this category should be based on two factors to help end-users make sense of data. These are a) *the type of data to be visualised*; b) *what is to be shown* [33]. [33,34] identified 50 common statistical visualisation techniques and categorised them into five distinct groups. These are:

- Temporal chart types to show trends and activities over time (e.g. line graph).
- Categorical chart types to compare categories and distributions of quantitative values (e.g. bar graphs).
- Hierarchical chart types to compare part-to-whole relationships and hierarchies (e.g., pie charts and treemaps).
- Relationship chart types to graph relationships through correlations and connections (e.g. scatter plot)
- Spatial data chart types to map spatial data (e.g. choropleth map)

Below we review some techniques from the above five categories, and which are commonly used in the area of eco-feedback.

5.1.1. *Line and area graphs*

They are the most frequently used visualisation techniques in the area of eco-feedback as they permit the presentation of how energy units or time-dependent tariff change (mapped at the Y-axis) in function of times series data at the X-axis [35,36]. There are two types of line graphs; single line graphs are used to study the change in one variable (e.g. energy usage) over time. Conversely, multiple line graphs are employed to compare the change of multiple datasets with the same value (e.g., energy used by HVAC and appliances) over time (Table 2). For example [37], developed an eco-feedback application where they employed a single line graph. The X-axis represents the past 24 h, and the Y-axis shows the KWh cost. The authors also utilised a traffic light system to help users identify periods to shift the usage of energy-intensive appliances such as washing machines (Fig. 5). Similarly [35], in their GoodDeeds project utilised a single line graph showing the water consumption in cubic meters per hour in a library facility during weekends (Fig. 6). Some participants found this technique helpful in identifying any anomalies in water consumption through spikes in the graph.

There is a consensus in the literature that multiple line graphs are difficult to read and interpret than single line graphs. However, transforming multiple line graphs into area line graphs does not only reduce their complexity but also help users make sense of total and breakdown values [38]. In this regard [39], investigated how three visualisation techniques affected 43 users' understanding of electricity consumption using lab experimentation with a quiz measuring the precision, confidence, and timing of their answers about daily domestic electricity consumption activities. The three analysed visualisation patterns were aggregated time-series area line graph, a disaggregated area time-series line graph, and a normalised disaggregated visualisation (Fig. 7). The study findings advised that participants' answers when using disaggregated area time-series line graphs were more accurate and had a higher confidence level than when using the aggregated area graph. The authors concluded that a disaggregated area line graph visualisation helped the end-users understand the energy consumption of different household appliances, which was in line with the findings of [40]. However, using a normalised time scale (from 0 to 1), which represents the overall energy consumption of an appliance over a single usage, increased participants understanding and confidence about using a disaggregated area line graph to monitor their electricity usage.

5.1.2. *Bar and column graphs*

Table 3 illustrates the suitability of bar/column graph visualisation in eco-feedback systems. Bar/column charts seem to be the second most frequently adopted visualisation technique in eco-feedback and can be found in several studies [15,37,41–48]. This group of visualisation techniques use either horizontal (bar graph) or vertical bars (column chart) and have two axes where one of the axes represent the quantity variable and the other shows discrete categories/groups (e.g. appliances). While line and area graphs are useful techniques for representing

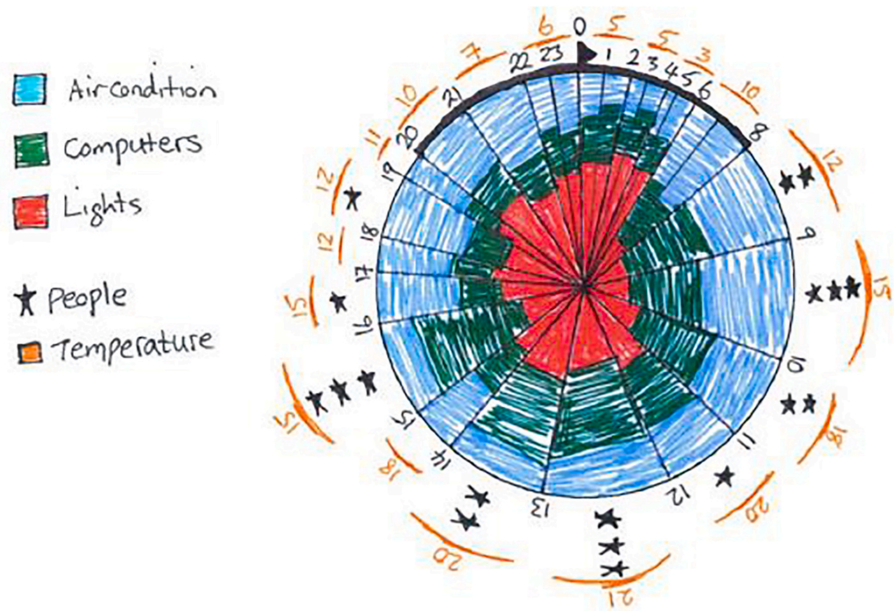

Fig. 17. The time-pie visualisation developed by, showing the total energy use in function of three appliances (lighting, computers, and air-conditioning [73].

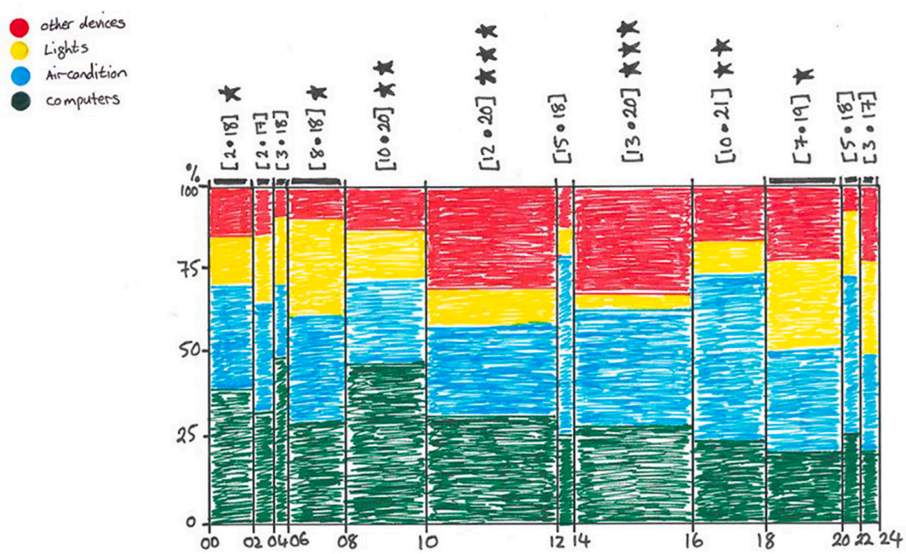

Fig. 18. An example of time-stack visualisation developed by Ref. [75] and showing the energy consumption by 4 appliances lights, computers, ai-conditioning, and other devices.

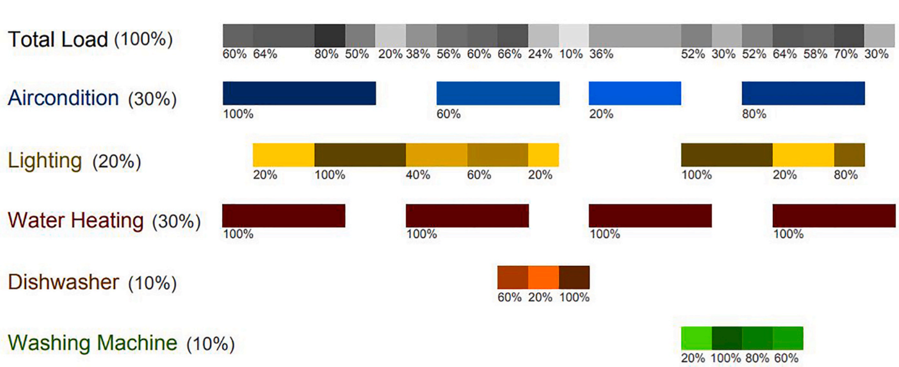

Fig. 19. A time-tone visualisation proposed by Ref. [76] illustrates the contribution of five appliances to the overall energy consumption.

Table 6
The applicability of numerical visualisation in eco-feedback systems.

		Numerical text
When to use	Analyse change in one dataset or multiple datasets over time	×
	Comparing quantities in different groups/categories	Possible[a] but more evidence is needed
	Conveying total amounts and sub-categorical breakdowns	×
	Representing aggregate data	✓[b]
	Setting goals and normative comparisons	Not discussed in the studies more evidence is needed

[a] In the study of [80], users related their total energy usage in relation to their hot water temperature.

[b] Numerical visualisation is proved effective for representing aggregate information that needs to be accessed quickly by users such as temperature, energy tariff, and overall energy usage.

trends over time, identifying anomalies, and relationships between 2 or more variables, bar graphs excel at comparing quantities in different groups/categories [49]. As a versatile visualisation technique, it can also be utilised for comparing and breaking down parts of a whole through stacked bar/column graphs. For example [50], employed a stacked column graph to represent the contribution of three different buildings to the overall energy consumption of the pilot area at different times of the day (Fig. 8). Another use of a bar/column chart is to track change over time, but these changes must be large otherwise the resulting bar/column charts would be hard to interpret (Table 3).

To enhance users perception, column/bar charts are often combined with colours. For instance Ref. [45], utilised green colour to indicate when the energy consumption is 20% lower than the seven-day average. Similarly [51], used a column graph composed of two categories, namely: current use and average use. The authors designed the average use column to be always green to act as a target for end-users to reach (Fig. 10). [42], however, utilised a stacked column graph combined with colours to show the proportion of different types of activities (e.g., travel and cooking) in the typical day of men and women participants (Fig. 9). Furthermore, they mapped the average energy usage of each activity using bar graphs [30]. conducted an interesting quantitative study on 1470 US residents who were provided with four different bar charts and were required to fill a survey questionnaire to measure the charts' perceived ease of use and interpretability. As shown in Fig. 11, two of the four charts showed the daily energy cost of a random US household for a month and a week, respectively. Conversely, the other two charts were the same as the previous ones, except the authors showed the energy cost during weekends using a different colour, referred to as data chunking a. Following a statistical analysis using ANOVA and Tukey's HSD test, the authors found that participants who received perceptual assistance for the monthly energy usage chart had better interpretation scores than those who did not. However, the ones who saw the weekly energy cost chart without perceptual assistance scored higher than those who viewed the one with perceptual assistance. Based on that, the authors concluded that the higher the number of columns/bars a bar/-column chart, the lower interoperability it has, but using perceptual assistance in the form of data chunking could enhance the interpretability of large datasets bar graphs.

Although colours are important when designing an effective bar/column chart, their incorrect and arbitrary use can confuse and distract viewers [52]. According to Ref. [53], this type of chart should employ soft colours to visualise most information, whereas dark/bright colours should be used to spotlight information that requires high attention. Additionally, they advised using consistent colours for similar groups/categories such as appliances. This is because using different colours implies differences between the types of categories, which is misleading. Since the X-axis/Y-axis is the backbone of bar/column charts, they should be clear and organised. Specifically, the axis has to always start at a value of zero because starting it at a value above zero shrinks the bars and skew the look of the data. Additionally, gaps between uneven or large bars should be minimal and consistent. Bar graphs should be used instead of column charts when labels are long as the former is proven to enhance viewers' interpretation [54]. Furthermore, visual effects (e.g. 3D effect) should be avoided. Finally, bars/columns should be ranked logically (e.g., chronologically or by their size) to facilitate their readability [55].

5.1.3. Other statistical charts

Although line graphs and column/bar charts visualisations are common in eco-feedback systems, scholars such as [36,37,44,56–61] have also used other types for different purposes, as shown in Table 4. For instance Ref. [36], incorporated a pie chart to represent the energy use of different buildings within a geographical area. A pie chart is a circular graph divided into slices where each represents the contribution of a given category of the whole [62]. [56], for instance, implemented a pie chart to depict the contribution of each household member of the total household CO2 emission levels (Fig. 12). Another common use of pie charts in eco-feedback is to represent the breakdown of energy usage per appliance [57] (Fig. 13) and activity [58]. While pie charts are simple and quick to analyse and assimilate by a uniformed audience [59], they become hard to read and interpret if they included more than 5–6 categories even with the presence of data labels [20,63]. For instance Ref. [20], analysed users' perception on several visualisation techniques including a pie chart and multiple line graph. To achieve this, the authors conducted a lab experiment with a survey questionnaire featuring Likert scale questions measuring the visualisations' usefulness. While participants found the pie chart visualisation useful, they had difficulties interpreting the information when more than five categories were visualised. In addition to that, unlike bar/column charts, pie charts are not appropriate for comparing different categories (Table 4). This is because it is difficult to compare the angle and size of non-adjacent slices [64]. Another consideration to enhance pie charts legibility is to use contrasting colour pallets, where each colour represents a category.

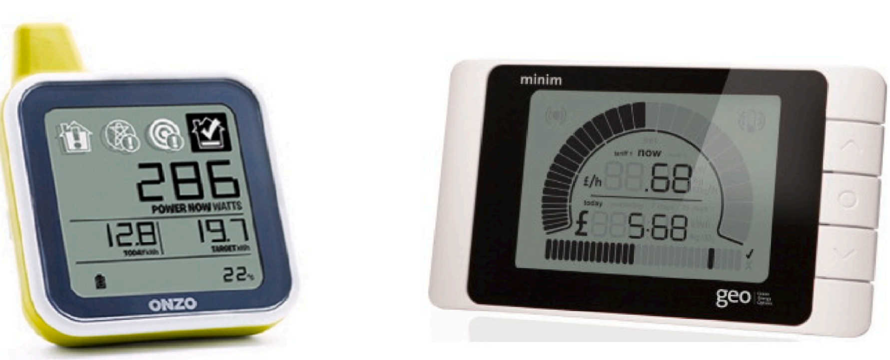

Fig. 20. Examples of Numerical displays used in the study of [24]. The one on the right was developed by Onzo [161] and the one on the left by [162].

Table 7
The applicability of 2D/3D geographic and Architectural visualisation in eco-feedback systems.

		2D/3D Geographic representations	2D/3D Architectural visualisations
When to use	Analyse change in one dataset or multiple datasets over time	✓	Not discussed in the studies, more evidence is needed
	Comparing quantities in different groups/ categories	✓	✓[d]
	Conveying total amounts and sub-categorical breakdowns	×	×
	Representing aggregate data	✓	✓[e]
	Help end-users understand the spatial dimension of their energy data	✓[a]	✓[f]
	Assist end-users in making decisions about retrofitting measures	✓	Not discussed in the studies, more evidence is needed
	Explore and compare the effect of different measures	✓[b]	Not discussed in the studies, more evidence is needed
	Setting goals and normative comparisons	✓	✓
	Promote peer-to-peer learning	✓[c]	Not discussed in the studies, more evidence is needed

[a] 2D/3D visualisations are ideal for community-based eco-feedback systems.
[b] Geographic visualisation patterns that show change over time (e.g. change in CO2 emission over time) enable end-users to explore and compare the effectiveness of different retrofitting measures.
[c] This type of visualisation can promote peer-to-peer learning opportunities when coupled with other measures such as public information campaigns and online discussion forums.
[d] Architectural visualisation patterns facilitate the comparison of the energy performance of similar/different spaces (e.g., bedroom vs living room areas).
[e] It is advisable to visualise one dataset (e.g., energy usage or temperature) because the effectivity of this type of visualisation pattern can worsen with the mapping of detailed and diverse information.
[f] Unlike geographic representations, the mapping of energy-related data is limited to the building scale.

Finally, it is advisable to sort slices based on their size and use short names for labels [65].

Another visualisation technique that appeared in eco-feedback is the gauge chart (also known as the dial chart). It is similar to pie charts but is used to represent a linear progressive value and has a needle to indicate data points. The dial uses different colours and labels to show the minimum, maximum, and current values. This makes gauge charts ideal for normative comparisons and goal setting where end-users do not only compare their energy usage to the average consumer but attempt to use less energy (Table 4). For instance Ref. [44], employed gauge charts to display the hourly, weekly, monthly, and yearly energy consumption [37,60]. used gauge charts to visualise the real-time electricity load (Fig. 14). Similarly [66], explored adult end-users response to a smart metering interface (minim GEO) that has a gauge chart showing the real-time cost and electricity consumption. Their findings suggested that gauge charts are easy to interpret even by those unfamiliar with technology which agrees with [67]. However, their major drawback lies in the large space they occupy in the interface. Another disadvantage is that they are not adequate for representing multiple variables simultaneously, especially when they have various scales [68].

In addition to gauge charts, radar charts were employed in the eco-feedback area but mainly to aid the decision-making process of building/energy managers. Radar charts (also known as web or spider charts) are two-dimensional graphics which are employed to plot three or more series of values on multiple quantitative variables. This makes this visualisation technique suitable for comparing the different attributes and across multiple categories or groups [69]. Another advantage of radar charts is that they can represent the change in multiple categories/variables over time. For example [70], employed a radar chart which shows three various types of information which are current energy consumption (using an arrow), historical daily usage (red area), and current daily consumption (blue area), (Fig. 15). Similarly [61], used a similar visualisation pattern showing the daily energy consumption and the electricity generated by PV panels (Fig. 16). The author argued that this visualisation technique helps prosumers (consumers and producers of electricity) effectively manage their consumption, production, and interaction with the grid. However, since there is a lack of evidence in the study about the effectiveness of this visualisation technique, further research is needed in that respect. Although radar charts are visually striking to viewers, they are more difficult to read than bar/column graphs. That is why it is advisable to employ them when comparing multiple variables with distinct scales, which cannot be accommodated by bar/column charts. It should be noted that the interpretability of spider diagrams decreases significantly when more than three variables/categories are included in the chart [71]. Finally, they are not adequate for the visual measurement of values because it is difficult to determine radial distances [72].

5.1.4. Emerging statistical charts

Although line graphs, pie charts, and bar/column graphs are well-established statistical visualisation techniques since their invention in the 18th century, their graphical representation has been evolving in line with the advancement in technology, data, and statistical theory [32]. This has resulted in the emergence of new visualisation techniques. In Eco-feedback, for instance Ref. [73], proposed a time-pie

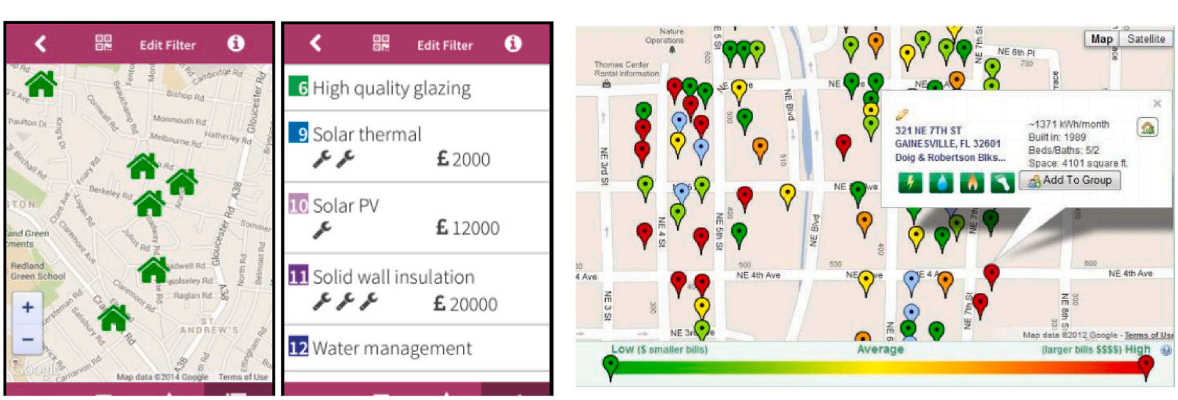

Fig. 21. An example of Eco-feedback applications that used 2D geographical representations.Figure on the left is the GreenDoors application developed by Ref. [90], whereas the application on the right (EnergyIT) was created by [91].

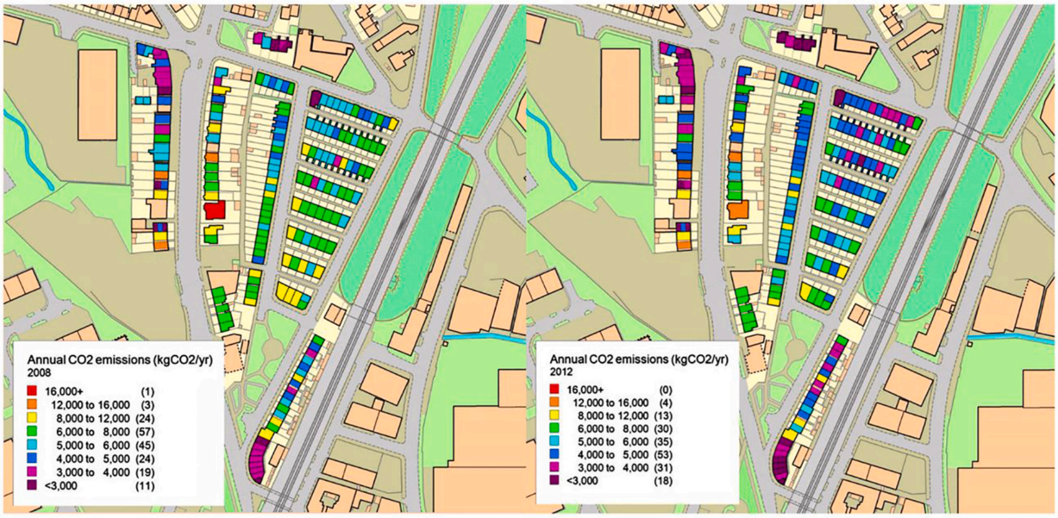

Fig. 22. A carbon energy map showing the change in the CO2 emission of an area after applying retrofitting measures [88].

Fig. 23. The community information model (CIM) developed by [93].

visualisation which combines the main features and benefits of time series with pie charts. As indicated in Table 5, this makes this visualisation technique adequate for comparing the overall energy consumption across different time slices (Fig. 17). If each slice is further broken down by category (e.g. appliances), it is possible to determine the amount of energy used by each category within individual slices. However, radial visualisation such as pie and time-pie charts are proven to be less effective than length based visualisations because comparing lengths is perceptually easier than comparing angles [74]. Thus [75], proposed an alternative visualisation to the time-pie series which is a time-stack graph (Fig. 18). This technique, similar to a stacked bar graph, shows the energy breakdown by appliances/activities over 24 h, where each bar segment represents -two hours. The width of each column represents the overall energy usage in a given 2-h time frame. Following a validation laboratory experiment on 15 participants [75], concluded that time-stack visualisation is more effective than the time-pie visualisation technique in terms of the time taken to respond to the set questions and the accuracy of responses, and the participants' number of eye gaze shifts to the visualisation techniques while performing the tasks. However, like bar/column graphs, it is difficult to compare the overall change in energy consumption if differences in the width of columns are not significant [76]. developed a bar version of the time-stack graph called time-tone visualisation, where the colour hue of each bar segment changes based on the percentage of energy consumed (Fig. 19). Following the briefing of 12 participants about the developed visualisation techniques, the authors compared the effectiveness of the time-tone and area graph visualisations using a laboratory experiment and a survey questionnaire with Likert scale questions measuring the accuracy of answers, time taken to answer the questions, and the end-users difficulty rating of the experiment tasks. The study concluded that both techniques are comparable. However, the time-tone visualisation was less effective than the area graph one when the variations in energy consumption are small over time.

5.1.5. Numerical text

Several studies suggested that numerical presentations are the quickest to interpret by different end-users (see Table 6). For instance Ref. [24], compared the effectiveness of three smart meter displays, namely: numerical, analogue, and ambient displays, on 41 participants (Fig. 20). Their results indicated that numerical displays were superior in terms of response time to questions and the accuracy of participant responses. Conversely, using an analogue display with a dial chart led to the slowest and least accurate responses. Interestingly, introducing coloured displays with numerical communication did not significantly improve participants' response time and accuracy. In another study [77], implemented a smart shower meter (Amphirio a1), which shows

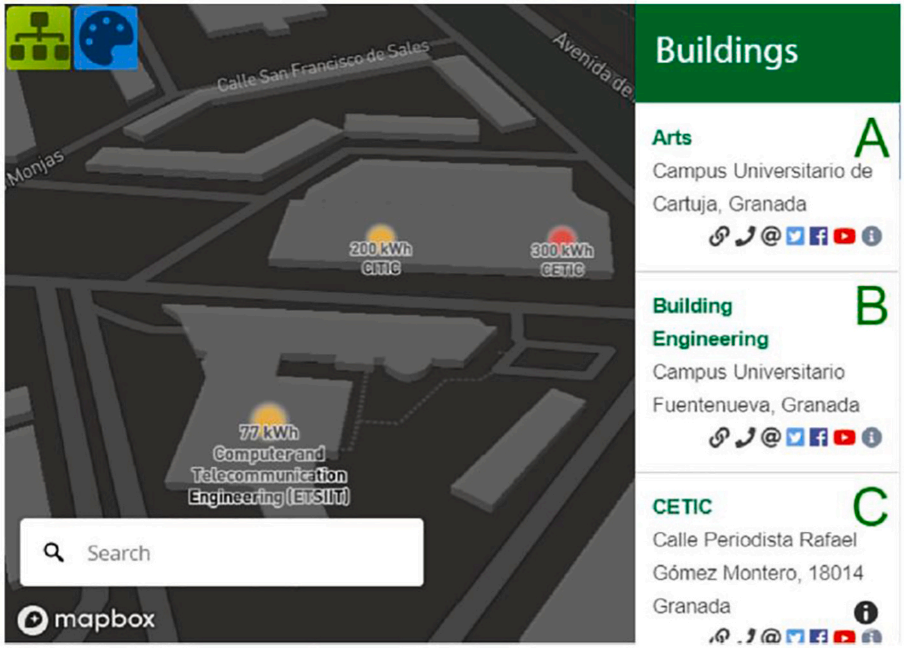

Fig. 24. The Eco-feedback application developed by using 3D geographic visualistions techniques from an open-source mapping platform (MAPBOX) [36],

the quantity of hot water and its temperature along with a polar bear animation, in 700 swiss households to help them reduce hot water electricity consumption. This study reported energy savings of 1.2 KWh per day per household.

Whilst numerical information seems very effective and fast to interpret by end-users, there is no clear evidence in the literature that one measurement type is superior to the other (e.g., cost vs quantity) [78]. Instead, research has shown that utilising a combination of energy units leads to more engagement in pro-environmental behaviour [79]. For example, in a two-year study [7], found that providing participants with cost information and energy quantity in KWh helped them save 0.5 KWh daily than when given energy quantity information only. According to Ref. [78], relying on a single unit, especially those with small magnitude, may lead to increase energy usage. For instance, if a household saves 10 KWh and the eco-feedback system only shows the equivalent CO2 reduction of 0.007 metric tons, users might lose interest in engaging in sustainable actions.

5.2. Architectural and geospatial visualisation

Visualisation techniques under this category are based on geographic and geometrical data and visual-spatial entities [81]. In the AEC (Architecture, engineering, and construction industry), such techniques are employed to invite and sustain imaginative engagement between different stakeholders through an aesthetic medium [82]. This explains why many eco-feedback initiatives incorporated architectural and geospatial visualisations. We further subdivide this category into two sub-categories into two distinct categories: 2D/3D geographic representations and 2D/3D Architectural visualisations, which are discussed in more depth in the subsequent sections.

5.2.1. 2D/3D geographic representations

Although geographic-based data in itself can sometimes be complex to analyse, using graphical displays to represent it can help retrieve knowledge and insights [83]. Geographic visualisations employ maps and different mapping techniques such as thematic mapping to overlay and geolocate a wide range of datasets. This, in turn, permits users to understand the spatial dimension of their data [84]. Conventionally, geographic representations, mainly 2D, have long been utilised in different areas of urban planning, including land use, transportation, and energy planning to solve various problems and develop new strategies [85]. However, the advancement in 3D computer graphics has gradually shifted the focus from 2D to 3D geographical representations, which provide more details such as building/infrastructure geometry (with various levels of detail) and topography. This makes them more suitable for certain complex tasks such as access to sunlight/daylight planning and shadow analysis than 2D representations [86]. Nevertheless, many scholars stress the importance of utilising both 2D and 3D geographical representations since each category is suitable for different purposes [87].

The emergence of open-access mapping platforms in 2011 (e.g. open-street-map (OSM)) encouraged the development of a wide range of location-based applications in different areas such as tourism and eco-feedback [89]. In Eco-feedback, 2D and 3D geographic representations were mainly employed in community-based applications, as depicted in Table 7. For instance Ref. [90], developed a smartphone eco-feedback application (Green Doors) where they employed a combination of 2D maps and pin mapping techniques to geolocate dwellings that adopted retrofitting measures in a given area (Fig. 21). In this way, end-users can access information related to the nature of retrofitting measures, their cost and impact on energy demand, and the level of disruption caused by installing each measure. The provided information helped end-users

Fig. 25. A screenshot of the community-based Eco-feedback system we previously developed [9].

make informed decisions about the type of retrofitting measures to implement in their dwellings based on their circumstances [91]. developed a similar application (Energy IT) but they concentrated on representing the energy performance of dwellings supplied by the energy company Gainsville in relation to their annual running cost and CO2 emissions (Fig. 21). The application utilises a 2D map and colour-coded pins to show the efficiency of 2000 dwellings. [88]; on the other hand, used 2D choropleth maps to visualise carbon emission of 1800 households across the UK (Fig. 22). While the implementation of such maps did not necessarily lead to significant energy savings, the authors concluded that this type of visualisation (coupled with dialogue and discussion features) promoted peer-to-peer learning opportunities amongst community members. Additionally, they found that providing carbon maps of an area from different periods did not only help participants to compare the change in CO2 emission over time but also encouraged them to find out about the nature of the implemented energy reduction measures.

In comparison to 2D geographic representations, the 3D ones are less common in the area of eco-feedback since they are costly, complex, and time-consuming to integrate and process [36]. This also explains why they are utilised mainly by energy experts, planners, and policymakers [92]. An example of eco-feedback initiatives using this type of visualisation is the community information model (CIM) of [93], Fig. 23. CIM is a multi-touch screen eco-feedback system that visualises the real-time energy data (e.g., energy demand and green energy) of the project buildings on a 3D mass model using thematic mapping. Although the CIM was not implemented yet, the authors recommended combining physical with digital media (e.g., energy community room and online discussion forum) to enhance interactions with and engagement in energy-saving activities. In response to the high cost of 3D detailed models [36], utilised an open-source mapping platform (MAPBOX) to visualise their energy predictions of a set of geographically distributed buildings (Fig. 24).

While 2D and 3D geographic visualisation techniques seem to positively affect end-user engagement in pro-environmental through encouraging normative comparisons, our recent study [9] indicated that they can be a source of privacy concerns amongst community members if the data is visualised at the building level. Thus, we advised representing data at the block level (Fig. 25). Finally, the perception of the public and their preferences of 2D vs 3D representations is varied [94]. Thus, eco-feedback application developers should consider this aspect by giving users a choice between 2D and 3D geographic visualisations.

5.2.2. 2D/3D architectural visualisations

2D/3D architectural visualisations are less common in the area of eco-feedback because the accessibility to detailed 2D/3D architectural drawings is still limited to the general public. As a result, producing and integrating detailed 2D and 3D architectural data into eco-feedback applications might not be the preferred option because it is costly, time-consuming, and requires the involvement of advanced technologies such as 3D laser scanning [95]. Although this category includes a wide range of visualisation techniques, we noticed that 2D floor plans

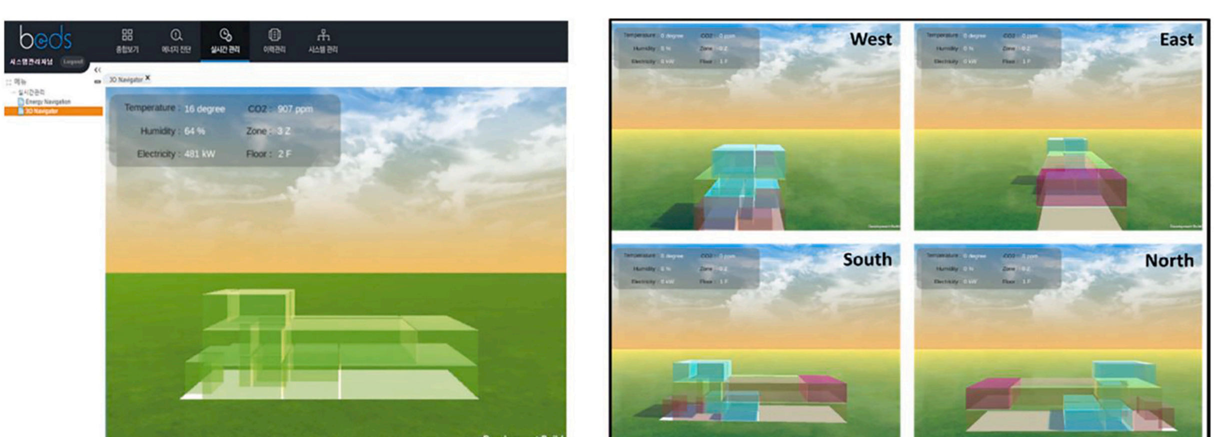

Fig. 26. The 3D Architectural visualisation used by Ref. [97] in their eco-feedback system.

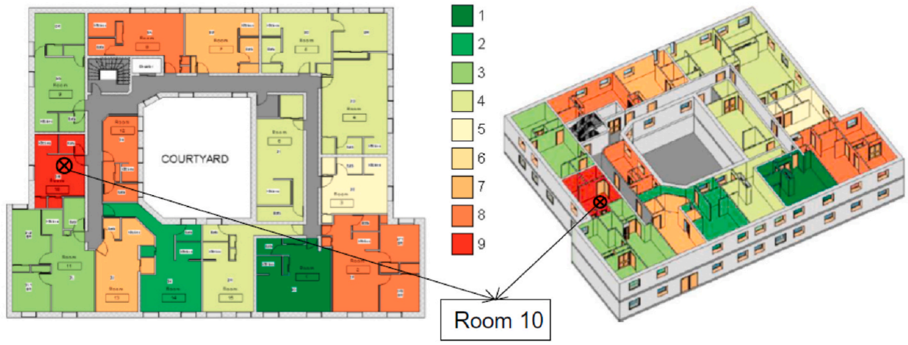

Fig. 27. The Architectural visualisation techniques used in the eco-feedback system of [98] (2D floor plan on the left and axonometric plan on the right).

[96], 3D mass models [97], axonometric floor plans [98], and 3D sections [99] were the only techniques used in relevant eco-feedback studies.

Similar to 2D/3D geographic representations, integrating architectural visualisation techniques in eco-feedback systems permits the spatial mapping of a given dataset(s). However, in the case of 2D/3D architectural visualisations, the mapping occurs at the building level as opposed to the urban scale for geographic representations. In this way, architectural visualisation techniques (e.g. floor plans) facilitate the identification of differences between one location (e.g. bedroom) and similar/different neighbours (e.g. common areas) [100]. For this reason, they provide visually intuitive normative comparisons, which could lead to an ameliorated interpretation of eco-feedback and increased engagement in pro-environmental behaviour [98]. For example [97], achieved 30% energy savings by implementing a 3D based eco-feedback application in a commercial building in Seoul, Korea (Fig. 26). A considerable proportion of their eco-feedback interface visualises the energy demand of different spaces on a building 3D mass model constructed using close-range photogrammetry.

2D plans and axonometric plans were common in eco-feedback systems implemented in commercial [97], and residential buildings [98] (Fig. 27). Usually, the visualisation of data on such 2D and axonometric plans is attained through thematic mapping. However, combining thematic mapping with a colour spectrum legend was proven effective. For example, in a study by Ref. [96], 71.77% of participants believed that thematic mapping with a traffic light system helped them better understand their energy consumption. Furthermore, most of them argued that 2D architectural visualisation combined with goal-setting measures helped them better save energy than the one without.

Since data is thematically visualised at the building scale, 2D/3D architectural visualisations are better suited for representing aggregate data (often the energy demand) of various spaces. In fact, including detailed and diverse information in architectural drawings worsens the end-users' perceptions, especially the non-experts [101]. In this respect [102], analysed the understandability, level of engagement, intuitiveness, and perceived engagement of 2D floor plans, axonometric plans, and bar graphs visualisations. Although many studies, including [103, 104], advised that Architectural 3D drawings are easier to interpret than the 2D ones, the analysis of participants' responses in Ref. [102], interestingly, revealed that information mapped onto 2D plans were easier to understand compared to information included in 3D plans. However, this could be because the 3D plan used in this study was more detailed than the 2D one (I.e. building contains many small spaces) which reinforces the fact that architectural visualisations should contain minimal information to be effective. Another interesting finding in Ref. [102] was that participants found 2D and 3D plans more engaging and motivating to reduce energy than bar chart representations. This is even though there was no difference between how intuitive participants perceived 2D, 3D plans and bar charts. These findings were in line with the work of [105].

Apart from the 2D/3D floor plans and 3D mass models, our analysis indicated that 3D sections appeared mainly in game-based eco-feedback systems [99,106]. This could be attributed to their purpose where the focus is to reduce the electricity usage through various activities such as replacing/improving the usage of appliances and lighting fixtures, adjusting room temperature and frequency of window opening, etc. Certainly, using a section visualisation permits the representation of the above activities as opposed to floor plans. This was evident in the study of [99], which advised that section views are more useful than floor plans when comparing how energy is consumed across multi-storey building spaces than 2D or 3D floor plans.

5.3. *Game-based visualisation techniques*

While conventional eco-feedback systems were proven to effectively engage end-users in pro-environmental behaviour, they struggle to adapt to the learning, communication style, and social routines of young people [107]. Although game-based visualisations include aspects of 2D/3D architectural and geospatial visualisation, they are predominantly based on animation, storytelling, and communication. Thus, gamification is considered a powerful technique to educate young people about environmental issues and engage them in eco-friendly activities [108]. This explains the emergence of gamified eco-feedback systems in recent years.

In general, game visualisation is broadly classified into three distinct visual styles: abstract, stylised, and realistic. First, abstract game visualisation focuses on simplifying game objects (e.g. people) using geometry [109]. Nintendo Tetris is an example of games that employ abstract visualisations. On the other hand, stylised visualisation (sometimes referred to as caricaturism) concentrates on presenting game objects artistically and emphasising their most important feature. Super Mario and Zelda represent games that utilise a stylised game visualisation style. Finally, realistic game visualisation is based on the principle of emulating reality through realistic 3D modelling, photo-realistic texturing, lighting, rendering, and animation. Examples of realistic games include Battlefield and Forza Horizon. Although realistic visuals received increasing attention after introducing three-dimensional games in the 1990s, stylised game visualisations are more flexible and versatile. Specifically, they can be customised to target different audiences, fit different purposes, and require less computational resources to process (high portability) [110]. That is why the majority of eco-feedback game-based applications use stylised visualisation.

Following the above classification and based on our analysis of various game-based eco-feedback applications, we further classify stylised visualisation into 2.5D stylised visualisation, 3D stylised visualisation, and 2D stylised visualisation. Table 8, further summarises the applicability of different game-based visualisation patterns in eco-feedback systems. We found that many studies on eco-feedback game applications present the outcomes of implementing their systems from

Table 8
The applicability of game-based visualisation patterns in eco-feedback systems.

		2D game-based visualisation	2.5D game-based visualisation	3D game-based visualisation
When to use	Analyse change in one dataset or multiple datasets over time	✓[a] Limited	✓[a] Limited	✓[a] Limited
	Comparing quantities in different groups/categories/spaces	✓[b]	Not discussed in the studies, more evidence is needed	Not discussed in the studies, more evidence is needed
	Conveying total amounts and sub-categorical breakdowns	×	×	×
	Representing aggregate data	✓	✓	✓
	Help end-users understand the spatial dimension of their energy data	✓[c]	✓	Not discussed in the studies, more evidence is needed
	Assist end-users in making decisions to reduce their carbon footprint	✓	Not discussed in the studies, more evidence is needed	✓
	Raising awareness about the impact of energy usage on the environment	✓[d]	✓	×
	Educating occupants about electricity usage	✓[e]	×	✓
	Setting goals and normative comparisons	✓	✓	✓
	Promote peer-to-peer learning	✓	✓	Not discussed in the studies, more evidence is needed
	Accepted by a wide range of users	✓	✓	Not discussed in the studies, more evidence is needed
	Encourage a sense of community	✓	✓	Not discussed in the studies, more evidence is needed

[a] The analysed eco-feedback studies using game-based visualisation techniques provided real-time or near real-time feedback to users, allowing them to assess the change in their energy usage during game play. However, other visualisation techniques such as line graphs are more effective for this purpose.
[b] 2D section visualisation patterns were proven adequate for promoting comparisons between the electricity usage of different/similar appliances and across different building spaces.
[c] It is possible if building section visualisation patterns are used.
[d] Only when 2D landscape scenes are employed.
[e] Only when 2D building scenes are included.

user-experience or behavioural perspectives (e.g., positive correlation between self-assessed future behaviour change and usefulness of the application). This could be attributed to the fact that a considerable proportion of these studies sought to understand the complexity of responses of those who dislike serious gaming based on different social factors [111].

5.3.1. 2D stylised visualisation

As illustrated in Table 20 (appendix), 2D stylised visualisations appeared in various eco-feedback game genres, including Idle, platform, and role-playing. Regardless of the game genre, this visualisation category incorporated elements such as 2D avatars, statistical visualisations (e.g., pie charts, line graphs, gauge charts), 2D internal scenes of building spaces, 2D landscape scenes, interactive tables, and numerical and textual information. However, we noticed that the use of 2D landscape scenes appeared in games whose focus was on making end-users aware of the implications of their actions (e.g. energy consumption) on the environment (see Table 8). For example, in the Eco Island game [112] (Fig. 30), if the CO_2 emissions of players exceeded the set target, the water around their island starts to rise until their possessions are swept away, resulting in a game-over. The implementation of EcoIsland resulted in a 6% reduction in the daily CO_2 emission of the six involved households. However, it was not clear whether this figure was sustained post experimentation. Similarly, the implementation of games with similar visualisation techniques such as *Power Explorer* [113] *(*Fig. 28) achieved a 14% reduction in energy usage during the project. The game authors noticed an improvement in the participants' attitude to energy saving and their willingness to promote energy conservation measures to their social circle, which indicates a change in their self-perception. However, games adopting internal building scenes as their main visualisation pattern (e.g. Powerhouse) concentrate on educating end-users about aspects related to their electrical energy usage such as appliances rating and frequency of usage and enable them to take better decisions to save energy in real-life situations. In certain role-playing 2D-stylised eco-feedback games such as Power House [114] (Fig. 31), players have to collaborate with other individuals during gameplay. This helps both promote sharing ecological values across end-users with different interests and level of awareness but also help them maintain sustainable actions in various social contexts [115]. In Refs. [114,116], the authors found that participants maintained some level of engagement in pro-environmental behaviour even during the post-game period. Finally, as discussed at an earlier stage, 2D stylised visualisations can be used to target different age groups due to their flexibility and versatility (see Fig. 29).

5.3.2. 2.5D stylised visualisation

First, eco-feedback applications using 2.5D stylised visualisation patterns are usually web-based simulation or strategy game genres such as Enercities (Fig. 32), EnergyVille (Fig. 33), and ElectroEnergy, some of which are integrated into social media platforms (e.g. Facebook). As shown in Table 21 (appendix), they mainly rely on 2.5D maps, which are convenient and efficient for representing large 3D city models when there is limited computational power and bandwidth [117]. That is why 2.5D visualisation is convenient for educating end-users and raising their awareness about various environmental/urban sustainability-related matters and measures such as energy grid supply and demand, pollution, energy shortage, and renewable energy sources (see Table 8). Although there is a lack of studies that evaluated the effectiveness of 2.5D eco-feedback games, several sources such as [107,118] have shown that the implementation of eco-feedback games using 2.5D visualisation in schools and universities curricula helped foster a sense of community, especially when combined with social techniques such as social sharing and competition. Another advantage of 2.5D visualisation is that it can be accepted by a wide range of age groups (e.g., pupils, students, educators).

5.3.3. 3D stylised visualisation

In contrast to eco-feedback applications using 2.5D stylised visualisation, the ones using 3D stylised visualisation are rare. According to Ref. [120], 2D serious games are popular than 3D ones because of their ease of programming and the minimal computational they require in their development and processing. Two out of three of the eco-feedback games using 3D stylised visualisations were idle games genres that are based on minimal player interaction (mainly clicks) [121]. As shown in the example illustrated in Fig. 34, Fig. 35, and Figs. 36 and 3D stylised visualisation in idle games can be composed of 3D internal scenes of residential spaces (e.g. kitchen) with more emphasis on appliances,

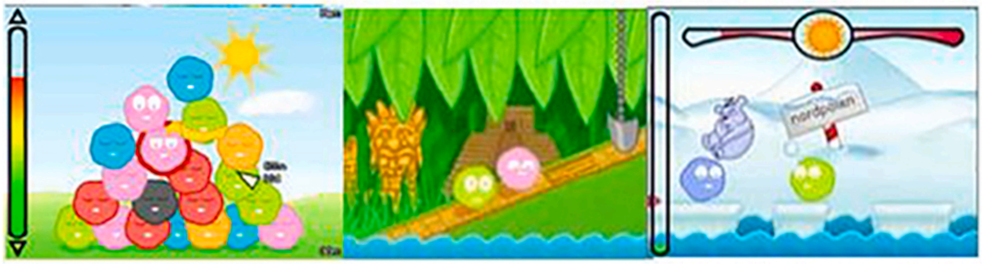

Fig. 28. Power Explorer, an eco-feedback game-based application that employs stylised 2D visualisation, developed by [113].

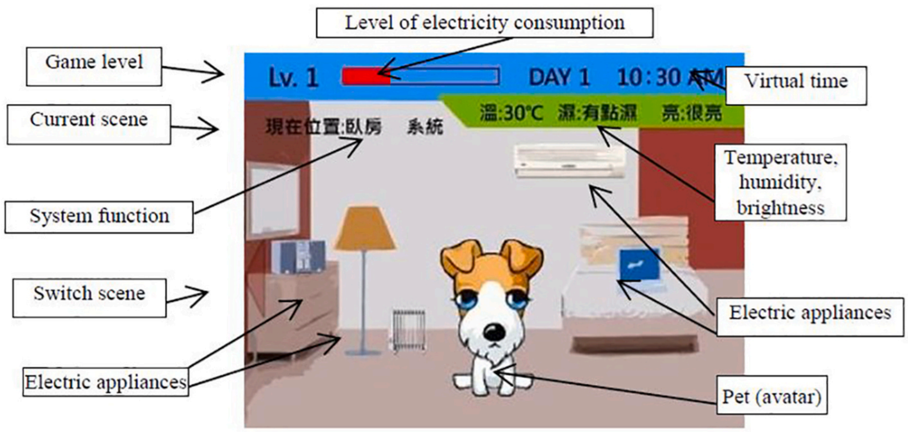

Fig. 29. The eco-feedback system developed by Ref. [115] (ECOPET) incorporates 2D stylised game-based visualisation techniques.

Fig. 30. The interface of EcoIsland, a game-based eco-feedback application using 2D stylised visualisation [112].

numerical information, and texts (e.g., the wattage of appliances, scores/credits, and tips/hints). If carefully designed, they can effectively enable end-users, especially children (see Table 22 in appendix), to make prudent decisions in real situations based on the knowledge they acquire during the gameplay [122]. These include: upgrading appliances, improving the thermal properties of building components (e.g., external walls and roofs) and changing behaviour such as frequency of opening windows and duration of showers.

Fig. 31. Screenshot of Power House game-based eco-feedback application developed by [114].

For example, in the RES (residence energy saving) battle game [123], players are given a particular budget and are required to collect hidden coins by clicking on efficient appliances, some of which have their wattage tag displayed briefly. After 30 s, a graph of energy usage will be displayed. If the cost of used energy is less than the income, the player will proceed to the next and more challenging level. Finally, one of the game-based eco-feedback applications using 3D stylised visualisation was a role-playing game (Super Delivery). Although Super Delivery focused mainly on educating sixth-grade students (11–12 years) about home electricity-saving, interestingly, the visualisation elements incorporated in the game, such as 3D avatars, 3D street views, 2D schematic

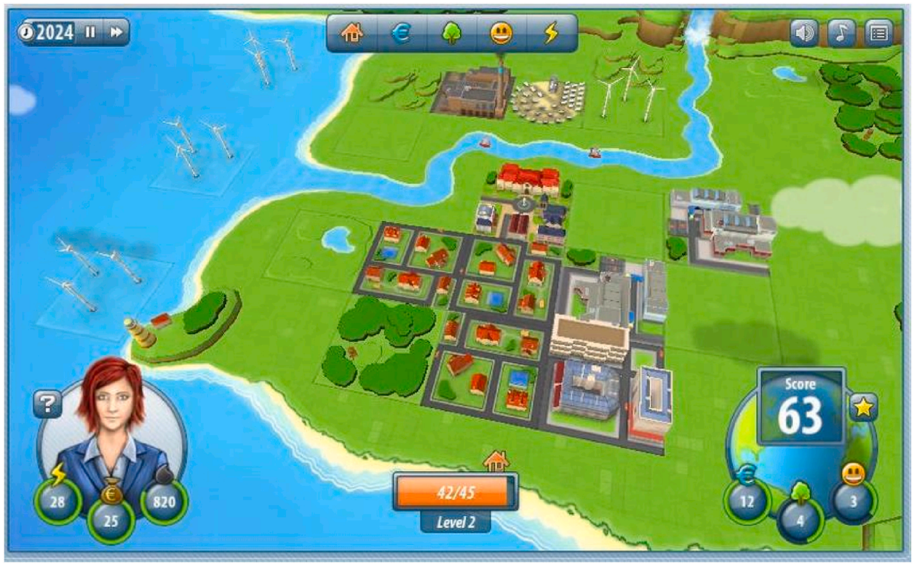

Fig. 32. A screenshot of Enercities; a game-based eco-feedback system developed by [107].

Fig. 33. EnergyVille, an eco-feedback system developed by Ref. [119] that utilised 2.5D visualisation.

maps, were irrelevant to home energy saving. In fact, the only relevant visualisations to the game's purpose were home energy saving quizzes and energy cost calculations that interrupt the game at several stages. The reason behind this rationale could be to offer an engaging and fun experience for this age group; knowing that racing games are the most popular among 10 to 14-year-old children [124]. For more information on the applicability of 3D game-based visualisation patterns consult Table 8.

5.4. Artistic visualisation techniques

Unlike statistical visualisation, the artistic one is utilised to communicate a concern rather than to show data. In fact, it is adequate for transforming data into something interesting and visible but without compromising its readability [127]. In eco-feedback, this visualisation category is mainly confined to creating an emotional connection between end-users and the natural environment (Table 9). The design of artistic visualisations for eco-feedback applications often links to persuasion, which, in turn, is a form of attempted influence in the sense that it seeks to alter the way others think, feel, or act with autonomous judgements [128]. Following an analysis of various sources, we identified two types of artistic visualisations namely: digital and physical. However, studies such as [129,130] combined both categories.

5.4.1. Digital-based artistic visualisation

The digital category employs, mainly, nature-inspired artistic visualisations [131]. Unlike other visualisations, the persuasive use of nature-inspired artistic visualisation (e.g. trees) was proven effective at exposing environmental issues to end-users. Subsequently, this helps them develop a sense of sustainable thinking and self-awareness about climate change and its consequences [132–134]. While eco-feedback systems adopting nature-inspired artistic visualisation might share

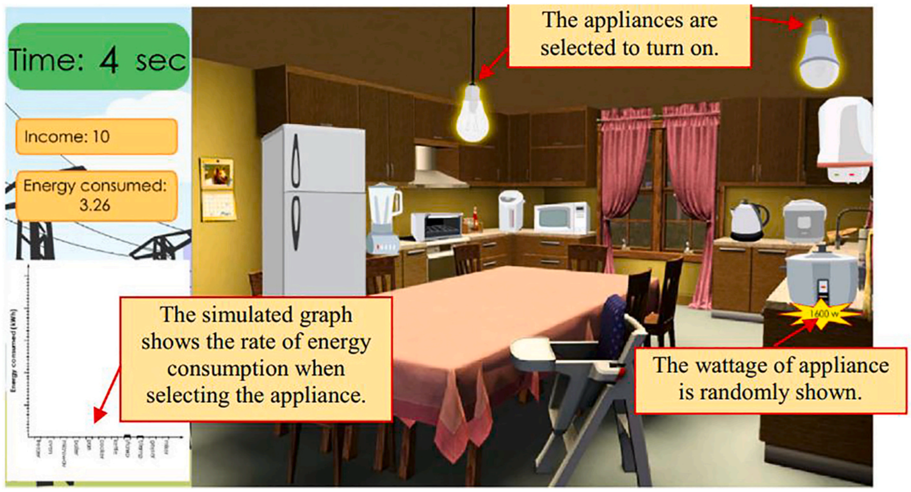

Fig. 34. A screenshot of an eco-feedback application (Residence Energy Saving Battle (RES)) [123] that utilises 3D stylised game visualisation.

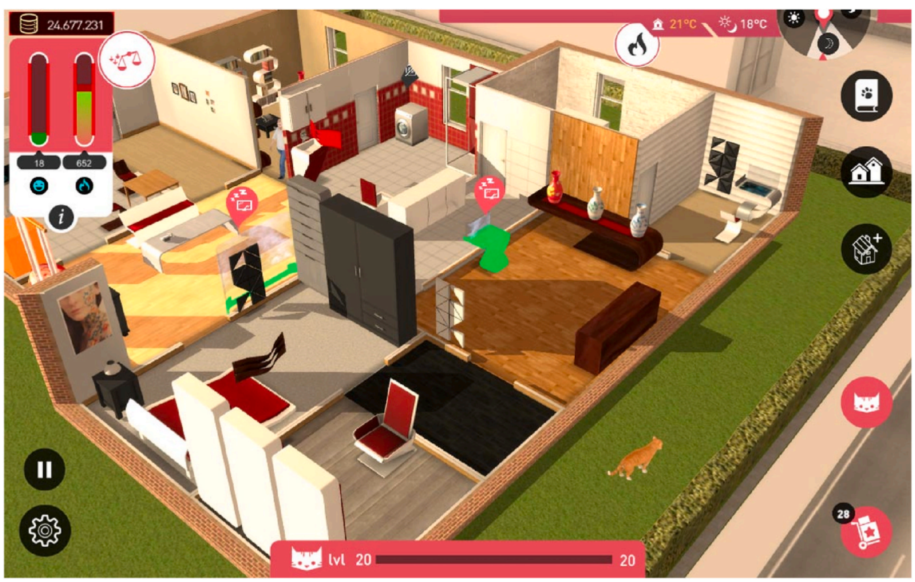

Fig. 35. An example of a game-based eco-feedback application (Energy Cat) using 3D stylised visualisation, developed by [125].

Fig. 36. Super Delivery; a game-based eco-feedback application employing 3D stylised visualisation [126].

similar representations (e.g., landscape scenes, polar bear, fog, etc.), they can be utilised in various ways depending on the eco-feedback system itself and its context of implementation. For example [44], included an energy awareness mode in their eco-feedback system, which consists of a digital illustration of a local endemic forest that is triggered when end-users have not engaged with the system for 2 min. To simulate end-users motivation and engagement in energy-saving activities [21], utilised a digital living tree animation pattern in their Eco-feedback

Table 9
The applicability of physical and digital-based artistic visualisations in eco-feedback.

		Digital-based artistic visualisation	Physical-based artistic visualisation
When to use	Analyse change in one dataset or multiple datasets over time	✓[a] Limited	×
	Comparing quantities in different groups/ categories/spaces	Not discussed in the studies, more evidence is needed	✓
	Conveying total amounts and sub-categorical breakdowns	×	×
	Representing aggregate data	✓	✓[c]
	Help end-users understand the spatial dimension of their energy data	×	×
	Help to trigger immediate sustainable decisions	Not discussed in the studies, more evidence is needed	✓[d]
	Raising awareness about the impact of energy usage on the environment	✓	Not discussed in the studies, more evidence is needed
	Help end-users develop an emotional connection with the environment	✓	✓
	Make end-users curious about their energy consumption	✓[b]	✓
	Setting goals and normative comparisons	✓	✓
	Encourage a sense of community	Not discussed in the studies, more evidence is needed	✓[e]

[a] Systems using this visualisation use animations to show the user real-time energy consumption but unless embeded in the eco-feedback system, it is difficult to retrieve the historical energy usage. Thus, other visualisation techniques such as line graphs are more effective in that respect.
[b] This is possible when abstract visualisation patterns are utilised. However, these should be combined with other visualisation techniques because they do not suit everyone.
[c] It is also possible to include disaggregated information such as minimum and maximum energy usage.
[d] It is possible but feedback needs to be delivered to end-users in the periphery of their attention.
[e] Sharing data from eco-feedback systems on social media helps build a community sense.

application (ChArGED) as an emotional inceptive. The tree grows and prospers based on the end-users energy-saving scores (Fig. 37) [135]. used a 2D tree fill gauge visualisation combined with a traffic light colour coding system where the filling level and its colour change based on the community energy score as illustrated in Fig. 38. Although their eco-feedback interface was not implemented, feedback from experts during the design stage advised that this visualisation pattern was attractive and intuitive.

[136] used a flowering garden visualisation pattern where the garden starts flourishing if the energy consumption is below average and withered when it is above the mean (Fig. 39) [137]. incorporated a polar bear visualisation pattern to draw end-users attention to their real-time energy usage. Specifically, when the usage is high, the interface shows a single polar bear on a block of ice, whereas a family of polar bears are visualised if the consumption is low. The authors found that participants who were emotionally attached to the polar bear visualisation showed great concern for the environment [138]. investigated the impact of different digital-based artistic visualisation patterns, including environmental, metaphorical, and literal, on the emotion and empathy of 14 primary school children in Portugal. Interestingly, the literal polar bear visualisation pattern evoked less empathy and was less engaging for children than the pet metaphorical visualisation. Considering that most children in the study had pets, the authors advised that designers of eco-feedback for children need to connect the implications and causes of climate change to tangible and concrete actions that relate to the personal experience of children [139]. developed an eco-feedback application to make MAC book users aware of the implication of their idle time on their energy usage. The interface includes a bar graph and animation of coral reefs whose colour and size changes based on the participants idle time (Fig. 40). The study concluded that 87.5% of bar graph users did not report any willingness to shut down their MAC book when not in use as opposed to the ones relying on the coral reefs animation. The analysis of the participants responses also suggested that the use of artistic visualisation helped them make an emotional connection between the visualised information and the real world. However, certain users expressed concerns about the feeling of guilt when their consumption is high, which could potentially lead to a rejection of the eco-feedback visualisation as suggested by Ref. [140]. In response to this issue [141], developed three abstract visualisations, namely: Phyllotaxis, Pinwheel and Hive (Fig. 41). Moreover, studied their comprehension and degree of acceptance by 23 participants. While the study findings advised that the ambiguity of abstract representation encouraged participants' curiosity and engaged them to some degree, they do not suit everyone. Notably, the authors discovered that some participants preferred other forms of visualisation such as graphs. Moreover, they acknowledged that abstract visualisation patterns undermined the comprehension of other contributors. For these reasons, they advised using traditional visualisation patterns, including statistical along with artistic ones, to accommodate the end-user preferences and maximise the effectiveness of eco-feedback. In another study conducted by Ref. [131], it was found that participants did not intuitively perceive some visualisation patterns such as a change in the cloud speed in function of end-users real-time energy usage levels and grass becoming dry when the energy consumption is high. Based on that, the authors concluded that artistic visualisation patterns such as landscapes need to be carefully chosen and tested by the users themselves before implementing the eco-feedback system to ensure a more effective emotional connection.

5.4.2. Physical-based artistic visualisation

In contrast to digital-based artistic visualisation, physical-based visualisation (often called ambient visualisation) relies on the pre-attentive processing of information through the use of elements such as lighting, colour change, and kinetics. Their aim is not only to provide feedback to end-users in the periphery of their attention but also to encourage them to take immediate sustainable actions [142]. For instance Ref. [143], made an extension lead prototype (Fig. 43) which has an LED power cable and whose light pattern changes in function of the end-user electricity load (e.g., static, pulsing, and flowing intensity blue light). Although the study sample was not representative, participants believed that blue light better represents electrical current. Furthermore, the majority found that constant light glow with varying intensities is calming and visually pleasing, whereas the flow and pulse animations were the most informative. However, pulsing and flowing lighting patterns were perceived as irritating when their electricity usage is high. Similarly [144], developed a prototype composed of three light spots to visualise the real-time, minimum, and maximum daily electricity usage of a factory. As shown in Fig. 42, the size of the light beam projected indicate the amount of electricity usage and the colour of light to distinguish between real-time, min, and max consumption. Although the Watt-Lite system was developed using discursive design principles to better engage factory workers, some wrote down additional information (e.g. time) and took pictures when interacting with the system. This suggests that relying just on the size and colour of light beams is not enough and should be supported by other visualisation techniques (e.g. numerical) to make end-users fully aware of the change

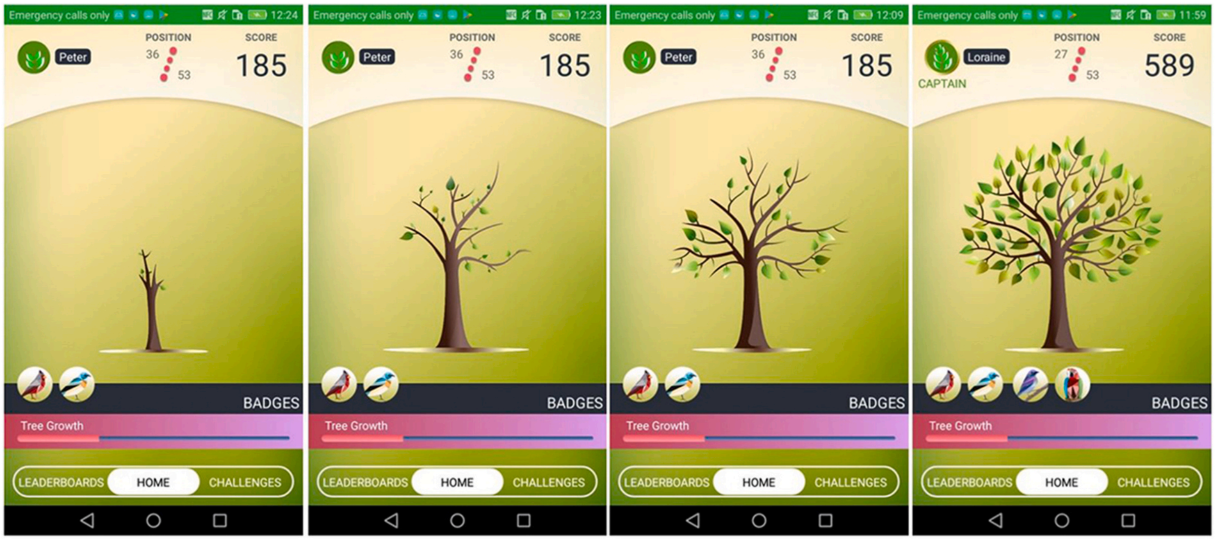

Fig. 37. A digital living tree animation pattern used by Ref. [21] in their Eco-feedback application (ChArGED). The tree grows and prospers based on the end-users energy-saving scores.

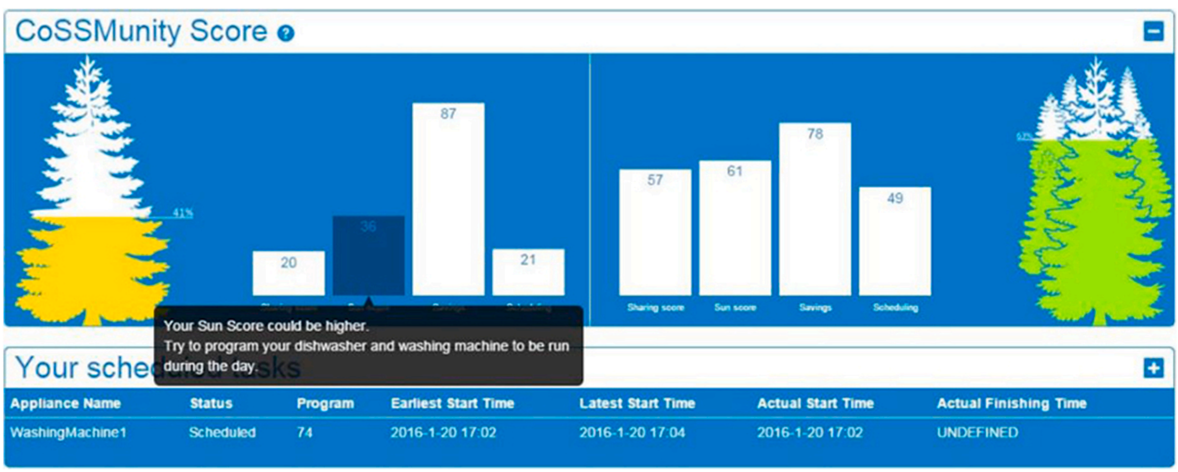

Fig. 38. The artistic visualisation pattern used by Ref. [135] in their community based eco-feedback system.

Fig. 39. The digital artistic visualisation pattern used by Ref. [136]. If the users' consumption is below average, they will see the image on the left. However, if their usage is above average the image on the right will show.

in their energy usage and its impact. The study concluded that placing Watt-Lite in social spaces such as canteens resulted in a high engagement with the system [145]. created a low-cost ambient display prototype that utilised an LED light strip to visualise end-users real-time energy consumption. The scholars employed a VU meter visualisation pattern (Fig. 44) where a few green lights show at the bottom when energy usage is low and a completely red strip following a high consumption.

[146] developed an interesting artistic visualisation prototype composed of 4 glass cylinders (Fig. 45). The cylinders were filled with distilled water combined and liquid paraffin to create different colour

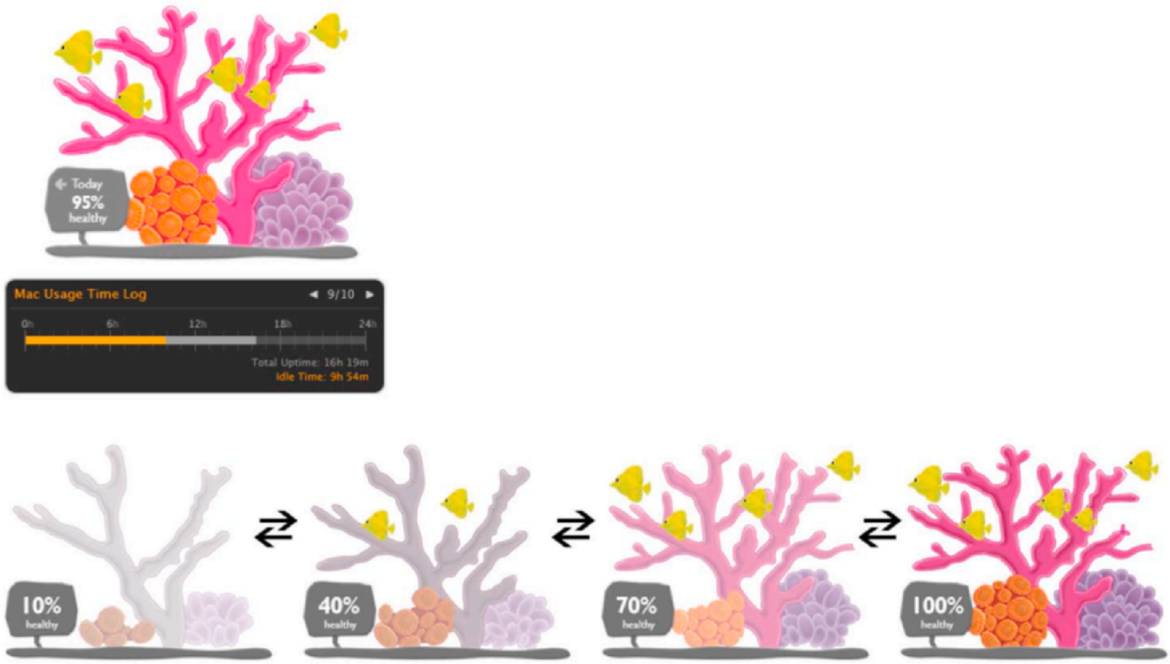

Fig. 40. The artistic visualisation pattern developed by Ref. [139] in their eco-feedback system. It includes a bar graph and animation of coral reefs whose colour and size change based on the participants idle time.

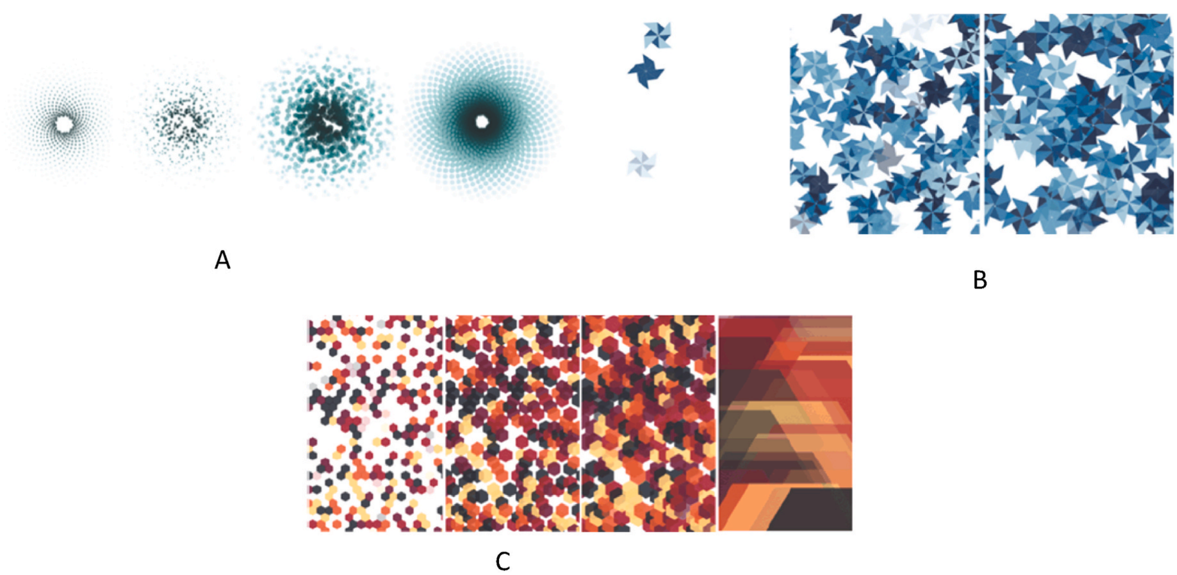

Fig. 41. The abstract visualisation techniques developed by Ref. [141]. A) represents The Phyllotaxis design pattern; B) illustrates The Pinwheel design; C) shows the Hive design.

effects for various energy sources, including solar (yellow), wind (light blue), hydro (dark blue), and thermal energy (dark purple). To provide end-users with feedback about their energy usage/production and to draw their attention, the scholars used the following methods: a) coloured power socket (red colour for high consumption and green for low usage); b) Colour intensity of liquid (brighter when consumption is low and vice-versa); c) Size of the vortex (0–27.3 cm depending on the energy usage). While participants liked different prototype elements, including kinetic and colour-based visualisation, they found the coloured power socket the most useful, easiest to understand, allowing them to act immediately upon colour feedback. This supports the findings of [79], suggesting that feedback is most effective when offered close to the point of interactions and time of decisions. However, six of them advised that such visualisations are not enough and needed more

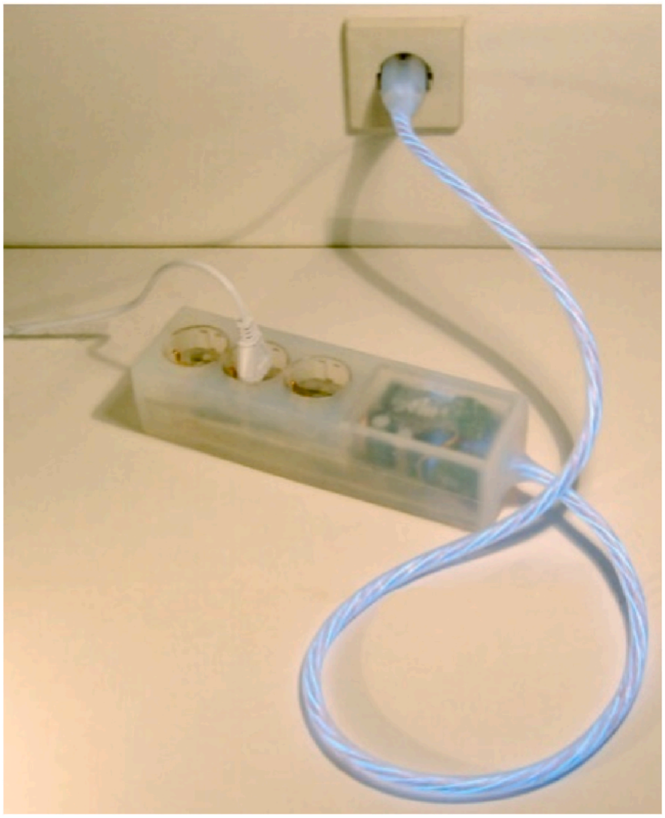

Fig. 42. The Watt-Lite system developed by Ref. [144] and which using physical-based artistic visualisation.

Fig. 43. PowerCord, a physical-based artistic visualisation developed by [143].

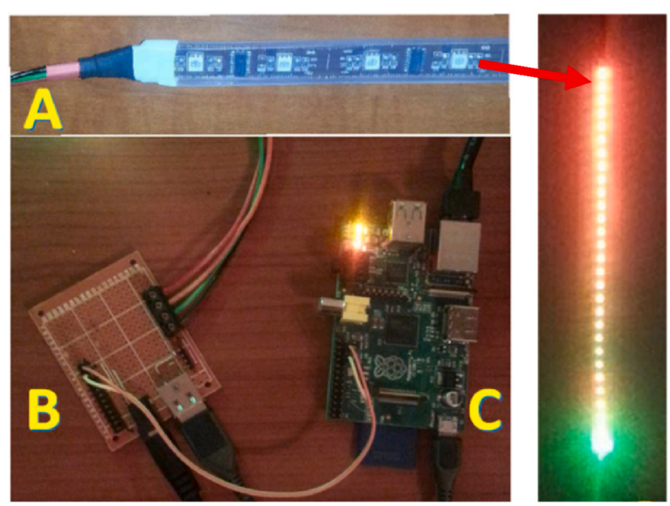

Fig. 44. The low-cost a VU meter visualisation pattern created by Ref. [145].

information in the form of line graphs and bar charts, which agrees with the findings of [139,141,144].

[130] created a handmade physical tree which has seven branches and is illuminated by solar-powered LED light to make the group energy savings tangible to a group of 24 pupils (aged 8–11 years). The seven branches lighten progressively one by one depending on the day of the week, whereas the LED lights illuminate based on the daily energy-saving score of the group. Additionally, pupils have the chance to consult the tree status online. While participants had varying preferences regarding physical or digital tree visualisations, the authors found this visualisation technique effective as it made the groups with installed meters engage in energy-saving activities. Furthermore, publishing the tree status on the participants' Facebook attracted other pupils who contacted the researchers to participate in this study. In an interesting study by Ref. [147], the authors developed a smart plug ambient eco-feedback (Wattom) which permits end-users to obtain feedback about the use of particular appliances (e.g. kettle), turn them on/off using hand gestures (mid-air input), or schedule their operation time using a smartwatch. After testing the system with 20 participants, the study advised that it was perceived as effective and interactive, even though it lacked graphical and numerical information (mainly feedback through LED lights). Finally, the angle at which end-users interact with Watton did not seem to affect their experience, although they preferred to point straight at the system.

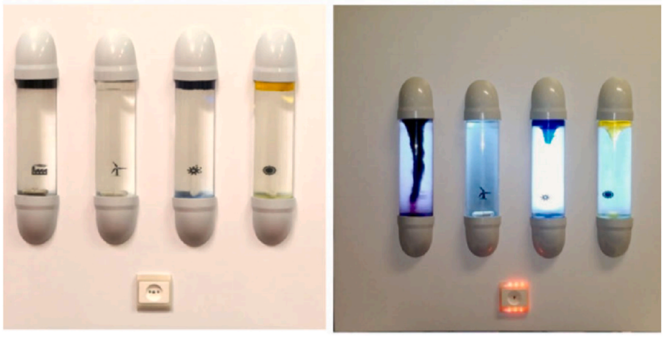

Fig. 45. The ambient visualisation developed by [146].

5.5. Emerging visualisation

Whilst technological advancement in recent years has led to the evolution of well-known statistical graphical representations as discussed in 5.1, it has also resulted in the emergence of new visualisation techniques that were not utilised before the year 2014 in the area of Eco-feedback, such as thermal imaging and Mixed reality [148].

5.5.1. AR visualisations

Augmented reality is a technology that overlays virtual objects and/or information on the physical environment [149]. Although AR (augmented reality) initiatives go back to the early 1960s (Morton Heilig Sensorama), their implementation in the area of eco-feedback has been limited and only received attention in the last 5–10 years [150].

Despite the lack of AR-based eco-feedback applications, two out of the two studies we found seem to rely on geolocation features. According to Ref. [151], this enables a greater context awareness and offers opportunities for social learning by combining the real world with visual information (Table 11). Particularly [152], developed a community-based eco-feedback application to enable community members to check the energy performance of different public buildings in their areas (Fig. 47). Their interface contained two parts, where the first one shows points of interest of buildings with available data on a small 2D map. Conversely, the second part includes a camera view of a given building with a coloured textbox indicating its name, year of construction, and energy use intensity (KWh/sq-ft). This part of the interface also includes a colour coded legend label that explicitly indicates how the building is performing compared to other buildings in the community (normative comparisons). The study findings advised that the participants accurately and promptly understood the purpose of colour coded legend labels and textbox. Moreover, they found information such as the year of construction very useful and wanted to get more details, including recent renovations. However, they preferred to see energy graphs integrated with the AR view, which was in line with the findings of [96].

In contrast to the above study, the work of [153] concentrated on using AR to visualise metered appliances' data in the workplace in a meaningful way. Specifically, their developed smartphone application detects appliances through the phone camera and with the help of image recognition algorithms in Vuforia (AR development library). The energy data related to the detected (appliances) was then mapped (using text) onto the real scene using the Unity 3D gaming engine (Fig. 46). Feedback from participants suggested that AR would positively influence their energy related-behaviour. However, 50% of them were concerned about their privacy, especially when others can look at appliances' usage. Our previous findings [9] advised that this issue could be initially prevented by allowing end-users to fully control their data sharing preferences.

5.5.2. Thermal imaging visualisations

The release of low-cost thermal camera smartphones or thermal camera attachments for smartphones has led to the development of a wide range of applications supporting thermography [148].

Thermal visualisation is primarily composed of a heat map which is generated using dedicated cameras detecting infrared radiation that is not visible to the human eye. In a heat map, objects' surfaces with similar temperatures are represented with similar colours, which help users identify areas of unexpected heat escape from the building envelope, Fig. 48, (e g., areas with poor insulation and faulty door/window seal) [154]. If end-users can make changes to their environment, thermal imaging visualisation was proven to help develop more effective and sustainable actions (e.g. upgrading insulation) than curtailment behaviours such as turning off lights when not in use [155] shown in Table 10. In this respect [156], conducted a study on 43 participants where 17 were given thermal images of their homes, 17 provided with a carbon footprint audit, and 9 were given no materials (control group). After one year, only the group who received the thermal images managed to reduce their home energy usage and up to five times more than the control group. Moreover, their reported actions were directly related to the issues identified in the thermal images. However, despite the above benefits, a study by Ref. [148] on 10 participants showed that

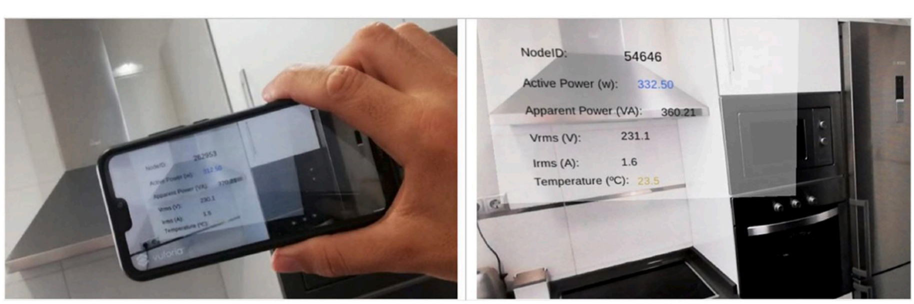

Fig. 46. The AR visualisation pattern developed by [153].

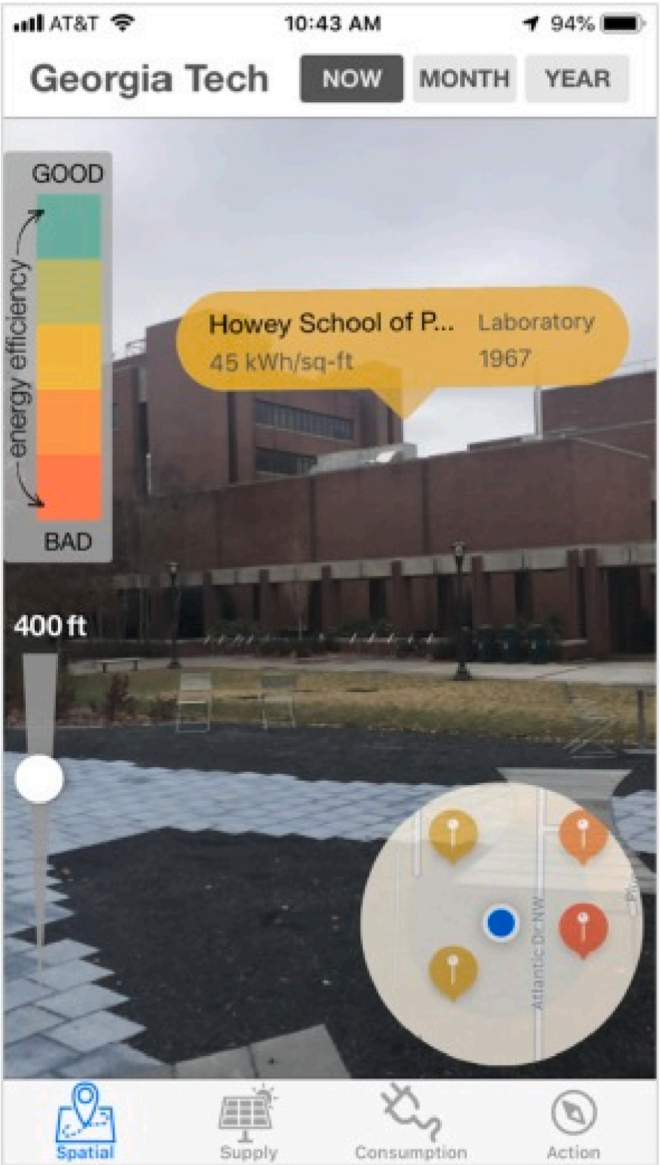

Fig. 47. The Eco-feedback system developed by Ref. [152] and which utilises AR visualisation patterns.

users with little or no knowledge about thermography struggled to determine the severity of issues they detected. Moreover, they had difficulties identifying the right repair measure and its impact on building energy performance. Based on that, most participants proposed integrating dedicated algorithms to enable automatic anomalies detection from the thermal images while allowing an estimation of the problem severity and potential savings made from the relevant retrofitting measures. Participants also advised embedding useful information such as the age of building and type of insulation to help them choose

Table 10
The applicability of AR and thermal imaging visualisations in eco-feedback systems.

		AR visualisations	Thermal imaging visualisations
When to use	Analyse change in one dataset or multiple datasets over time	×	Possible but more evidence is needed
	Comparing quantities in different groups/ categories/spaces	✓[a]	✓
	Representing aggregate data	✓[b]	×
	Explore and compare the effect of different retrofitting measures	✓	Not discussed in the studies, more evidence is needed
	Assist end-users in making decisions to reduce their carbon footprint	Not discussed in the studies, more evidence is needed	✓[d]
	Help end-users understand the spatial dimension of their energy data	✓[c]	×
	Setting goals and normative comparisons	✓	✓
	Encourage a sense of community	✓	✓[e]
	Promote peer-to-peer learning	✓	Not discussed in the studies, more evidence is needed

[a] It is possible to compare the energy performance of different buildings if combined with maps and colour coded legend labels as addressed in the study of [152].
[b] It is also adequate for the visualisation of disaggregated energy data.
[c] If combined with 2D or 3D geographic representations.
[d] End-users with little or no knowledge about thermography require algorithms to help them identify the severity of detected problems.
[e] Possible but it needs to be combined with other measures such as discussion forums and workshops.

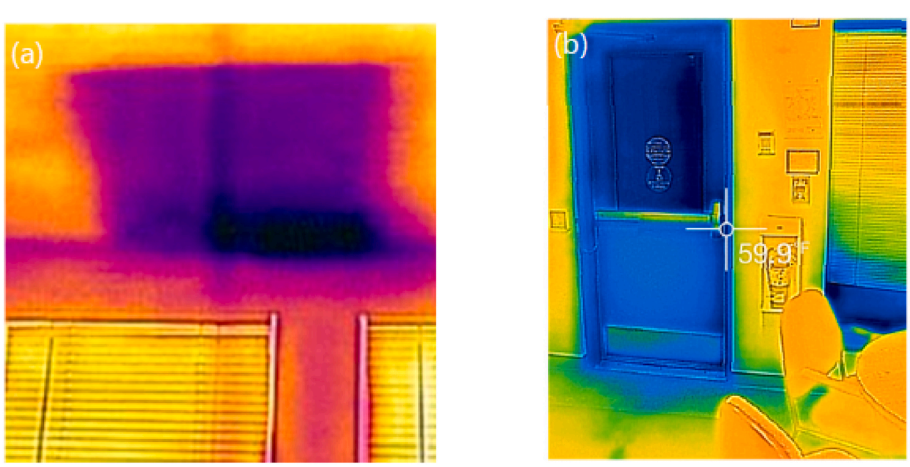

Fig. 48. An example of thermal imaging visualisation taken by participants in the study of [156].

Table 11
Summary of the appropriateness of the reviewed visualisation categories in different scenarios based on the discussions in section 5 and related good practice recommendations.

	Statistical	Architectural	Geospatial	Game-based	Artistic	AR	Thermal imaging
Applicability scenarios							
Identifying high-energy consuming practices	Highly Appropriate	Appropriate	Appropriate	Not known, more evidence is needed	Somewhat appropriate	Not known (more evidence required)	Appropriate
Analysing energy trends and relationships	Highly Appropriate	Not appropriate	Somewhat Appropriate	Not appropriate	Not appropriate	Not appropriate	Not known (more evidence needed)
Comparing activities/ spaces usage and identifying their overall contribution	Highly Appropriate	Somewhat appropriate	Somewhat appropriate	Somewhat appropriate	Somewhat appropriate	Not very appropriate	Somewhat appropriate
Allowing quick access to energy feedback	Highly Appropriate	Appropriate	Appropriate	Appropriate	Highly appropriate	Appropriate	Not appropriate
Enabling awareness to the spatial context of energy usage and conservation measures	Not appropriate	Appropriate	Highly Appropriate	Somewhat appropriate	Not appropriate	Somewhat appropriate	Not appropriate
Fostering community interaction and engagement in pro-environmental behaviour	Not appropriate	Not appropriate	Highly Appropriate	Highly Appropriate	Somewhat appropriate	Appropriate	Somewhat appropriate
Provoking curiosity and developing an emotional attachment	Not appropriate	Not appropriate	Not appropriate	Somewhat appropriate	Highly appropriate	Not known (more evidence needed)	Somewhat appropriate
Drawing reference to efficient energy practices	Somewhat appropriate	Appropriate	Highly appropriate	Highly appropriate	Appropriate	Somewhat appropriate	Appropriate
Recommendations	Recommendations **1**–**31**. See Table 12, Table 13, Table 14	Recommendations **38**–**42**. See Table 15	Recommendations **32**–**37**. See Table 15	Recommendations **43**–**51**. See Table 16	Recommendations 52–60. See Table 17	Recommendations 61–63. See Table 18	Recommendations **64**–**66**. See Table 18
Sampled studies	[7,15,20,24,30, 35–39,41–48,56–58, 60,61,67,70,73, 75–79,105,159–162]	[96–99,102–104, 106]	[9,36,88,90,91,93, 163]	[107,112–114,116, 118,119,123,125, 126,164–167]	[21,44,130,131, 135–137,139,141, 143–147]	[152,153,168]	[41,88,148,156]

adequate retrofitting measures. The study of [88] supported these findings. Specifically, providing participants with examples of thermal images of efficient and inefficient dwellings while explaining relevant physical measures helped them become more aware of similar issues in their dwellings. This study also concluded that thermal imaging was the most effective visualisation in engaging participants in pro-environmental behaviour compared to 2D GIS carbon maps. In addition to the superiority of thermal imaging to other visualisation techniques [41], also found that thermal imaging visualisation invoked end-users emotions. Moreover, it triggered their vivid images in their memory later on, which enhanced their motivation as well as helped them set energy efficiency goals and triggered actions.

6. Conclusion and recommendations for future work

This comprehensive review of a wide range of eco-feedback visualisation techniques has provided good practice guidelines and recommendations to assist practitioners (e.g., designers and researchers) in the design of effective eco-feedback systems. A total of 1050 studies were identified from the literature search, of which 82 were included in this review. The visualisation techniques have been reviewed under five categories which we have identified: (a) Statistical visualisation, (b) Architectural and Geospatial visualisation, (c) Game-based visualisation, (d) Artistic visualisation, (e) Emerging visualisation. The latter category included two visualisation techniques not covered by previous reviews: Augmented-Reality (AR) and thermal imaging visualisation.

Table 11 (below) summarises and compares the applicability of different visualisation categories based on the discussions in section 5. Tables 12–18; however, provide **recommendations** to enhance their effectiveness while highlighting their limitations. In general, architectural and geospatial visualisations proved to be adequate for helping end-users understand the spatial dimension of their energy-related data, which makes them necessary for community-based eco-feedback systems. Equally, the game-based visualisation group shares similar patterns with the previous category. However, their storytelling nature and reliance on social techniques such as competition render them superior

Table 12
Eco-visualisation recommendation table (Part 1).

Visualisation Category	Technique (s)	Recommendations/considerations	Example of studies
Statistical visualisation	Line and area graphs	1. Multiple lines graphs should be avoided because they are complex to read and interpret unless transformed into area line graphs. 2. Using a traffic light system to encode values in line graphs helps end-users differentiate data quickly and grab their attention to high usage patterns. However, there should be enough contrast between text and colour to allow good readability. 3. Disaggregated area line graphs are more effective than the aggregate ones when it comes to monitoring appliances usage. 4. When using disaggregated area line graphs to help end-users monitor the electricity usage of their appliances, it is better to use a normalised time scale (0–1) instead of reporting the usage time in minutes in the x-axis.	[35–39]
	Bar column graphs	5. Bar/column graphs should not be used to track change over time. This is because they are hard to interpret unless changes are significantly large. 6. Column/bar charts should be combined with colours as this enhances users perception, especially when there are many categories to visualise. 7. Soft colours should be used to visualise most information. However, dark colours should be employed to highlight information that requires great attention. 8. When multiple graphs are used, there should be consistent use of colours across categories/groups (e.g. blue for appliances) 9. Allocating a green bar/column to act as a target aids end-users to gauge their actual usage and how much energy should be reduced to meet the target. 10. Axis representing the values of the dependent variable (e.g. co2 emission) should start from zero. Otherwise, the data will be skewed. 11. Gaps between uneven or large bars/columns should be smaller than the size of the bar/column. This also should be consistent. 12. To avoid readability issues, bars/columns should be organised logically (e.g., chronologically, by size, etc..). 13. 3D bar/columns graphs are harder to read than the 2D ones. 14. If categories/groups have long labels, it is better to use bar graphs as this enhances views interpretation.	[15,30,37, 41–48]

Table 13
Eco-visualisation recommendation table (Part 2).

Category	Technique (s)	Considerations/recommendations	Example of studies
Statistical visualisation	Other statistical charts	**Pie charts**	[20,36,56–58, 159,160]
		15. Including more than 5–6 categories in a pie chart decreases its effectiveness. 16. Using contrasting colours in pie charts was proven to enhance its legibility. 17. Pie charts' slices should be organised by their size. 18. Long labels affect the readability of pie charts.	
		Gauge/Dial charts	[24,37,44,60,67]
		19. Dial/gauge charts are user-friendly and easy to interpret even with those unfamiliar with technology. 20. A disadvantage of gauge charts is that they occupy a large space in the interface 21. They are not suitable for representing multiple variables, especially those with various scales	
		Radar charts	[61,70,161,162]
		22. Radar charts are more difficult to read and interpret than bar/column graphs. Thus, they should be only used when the purpose is to compare variables with different scales/units. 23. Their interpretability decreases when including more than 3 variables/categories. 24. Radar charts are not suitable for measuring variables visually because values are based on radial distance.	

Table 14
Eco-visualisation recommendation table (Part 3).

Category	Technique (s)	Considerations/recommendations	Example of studies
Statistical visualisation	Emerging Charts	**Time-Pie charts**	[73]
		25. If each slice of the time-pie chart is broken down by category/group, it is possible to roughly determine the contribution of each group/category at a given period. However, for the exact measurement of each contribution, length-based visualisations such as time-stack graphs should be used instead.	
		Time-Stack graphs	[75]
		26. Time-stack visualisation is easier and quicker to interpret than time-pie visualisation	
		Time-tone visualisation	[76]
		27. It is advisable to use a larger range of tonal variations of a single hue to better represent a larger range of variation in the data (e.g. energy consumption) 28. Ordinary users have difficulties understanding certain units such as KWh in this visualisation technique. Thus, is better to show the percentage of energy used by each category. 29. When the variation in energy is small over time, it is better to use area graph visualisation.	
	Numerical text	30. Numerical text representations are the quickest to interpret by different users 31. Numerical text representations work best when a combination of different units is used (e.g., cost, usage in KWh, CO2 reduction, etc.)	[7,24,77–79, 105]

Table 15
Eco-visualisation recommendation table (Part 4).

Category	Technique (s)	Considerations/recommendations	Example of studies
Architectural and Geospatial visualisation	2D/3D geographic representations	32. Geographic representations help end-users make informed decisions about the type of retrofitting measures to implement for their dwellings based on their circumstances (budget, availability, etc.). 33. Geographic visualisation can be more effective when combined with measures including public information campaigns and online discussion forums, as it has been proven to support peer-learning activities and lead to better engagement. 34. Geographic representations are more effective when they reflect a change over time as a result of implementing specific measures (e.g., change in CO2 emission as a result of retrofitting measures). This encourages end-users to explore and compare the effect of different measures. 35. 3D geographic representations can be costly, complex, and time-consuming to integrate and process in eco-feedback systems compared to the 2D ones. 36. End-users should be given a choice between 2D and 3D geographic representations. 37. To avoid privacy issues/concerns, it is recommended to map data at the block level instead of the building level.	[9,36,88,90,91,93,163]
	2D/3D Architectural visualisation	38. Architectural visualisations provide ameliorated interpretation of eco-feedback. However, before using this type of visualisation, the availability of 2D/3D data must be checked beforehand. 39. Close-range photogrammetry should be considered when developing 3D Architectural visualisation as it is cost-effective. 40. Thematic mapping with a colour spectrum legend enhances the understandability and clarity of architectural visualisation. 41. Mapping detailed and diverse information in Architectural visualisation worsens their effectiveness. 42. 2D and 3D plan-based visualisation can be more engaging and motivating than some statistical visualisation techniques such as bar charts.	[96–99,102–104,106]

Table 16
Eco-visualisation recommendation table (part 5).

Category	Technique (s)	Considerations/recommendations	Example of studies
Game-based visualisation	2D stylised visualisation	43. It promotes sharing ecological values across end-users, which in turn helps maintain a level of engagement as well as their sustainable actions. 44. Unlike the 3D ones, it is cost-effective and suitable for different age groups due to its flexibility and versatility. 45. The electricity consumption of end-users tends to increase post-game. Thus, more attention needs to be placed on fostering a sense of community between them.	[112–114,116,164,165]
	2.5D stylised visualisation	46. Implementing this technique helps foster a sense of community, especially when combined with social techniques such as social sharing, competition, and collaboration. 47. It is accepted by a wide range of groups. 48. It is an efficient technique for representing large urban areas and is accessible for end-users with limited internet bandwidth.	[107,118,119,166,167]
	3D stylised visualisation	49. Since this visualisation is not cost-effective and complex to process, player interaction should be made minimal through the use of idle game storyboards. 50. This technique effectively enables end-users, particularly children, to acquire knowledge during the gameplay. Furthermore, it helps understand the implications of different sustainable actions and allows them to apply it. 51. If the audience is composed of children and teenagers, including scenes/themes they are passionate about them (e.g. racing) in the storyboard can offer an engaging and fun experience.	[123,125,126]

for educating end-users from different age groups about various environmental issues and their consequences. Moreover, help them act on the received feedback in real situations. A common obstacle facing both visualisation categories (architectural and geospatial and game-based), especially the 3D ones, is the unavailability of relevant data (e.g., 3D buildings, floor plans, energy information) and the complexity and cost associated with its processing. Thus, more attention should be paid to developing platforms that allow affordable and open integration of such visualisation patterns in the future. Like game-based visualisations, artistic visualisation techniques can be utilised to make end-users more aware of the implication of their actions, but their strength lies in their ability to emotionally connect end-users with their environment. Although the analysis of studies on augmented reality and thermal imaging visualisations showed some promises in terms of end-users engagement over other techniques, more work needs to be carried out in the future to gain a deeper insight into their applicability, effectivity, and strengths and limitations in the context of eco-feedback.

Despite differences amongst the reviewed visualisation categories,

Table 17
Eco-visualisation recommendation table (part 6).

Category	Technique (s)	Considerations/recommendations	Example of studies
Artistic visualisation	Digital-based artistic visualisation	52. End-users who develop an emotional attachment to nature-inspired representations show more concern for the environment. 53. It is advisable to incorporate digital-based artistic visualisation techniques with statistical ones such as bar graphs as this seems to increase end-user engagement with pro-environmental behaviour. 54. There should be careful considerations when developing visualisation patterns for high consumption. Some studies have shown that some end-users with high consumption might reject this type of eco-feedback visualisation due to feeling guilty about their energy usage. 55. Abstract visualisation can make end-users curious about their energy usage and help engage them in energy savings activities. However, they need to be combined with other visualisation techniques because they do not suit everyone. 56. Artistic visualisation patterns need to be carefully developed and tested by the end-users themselves before being implemented in an eco-feedback system. This is to make sure end-users perceive them correctly.	[21,44,131, 135–137,139,141]
	Physical-based artistic visualisation	57. When using lighting patterns on a power cord system, it is advisable to constant light glow with varying intensities instead of pulsing and flowing lighting patterns. Some participants in the study of [143] found constant light glow calming and visually pleasing. 58. Some end-users might find the feedback of physical-based artistic visualisation insufficient. Thus, it is advisable to provide detailed information using other visualisation techniques such as statistical ones. 59. Sharing data from eco-feedback systems using physical-based artistic visualisation on social media platforms can encourage community members to engage in pro-environmental behaviour. 60. Eco-feedback systems using physical-based artistic visualisation are more effective when installed close to points of interaction (e.g., living room, communal areas, etc..). However, the angle at which end-users interact with them does not have any effect on their effectiveness.	[130,143–147]

Table 18
Eco-visualisation recommendation table (part 7).

Category	Technique (s)	Considerations/recommendations	Example of studies
Emerging visualisation	AR visualisation	61. Combining AR visualisation with geographic visualisation helps end-users develop context awareness and offer opportunities for social learning. 62. There should be careful considerations for privacy issues when developing Eco-feedback systems for communities. 63. Incorporating textual information, colour coding, and statistical visualisation techniques with AR visualisation enhances its effectiveness.	[152,153, 168]
	Thermal imaging visualisations	64. End-users who employed thermal imaging visualisation can save up to 5 times more energy than those who don't. 65. End-users with little or no knowledge about thermography struggle to determine the severity of issues they identify and how to address them. Thus, it is advisable to utilise one of the following measures: • Algorithms that enable automatic anomalies detection while providing useful information and tips. • A detailed guide with examples of thermal images of efficient and inefficient dwellings while explaining the nature of implemented measures based on various scenarios. 66. Thermal imaging can be more engaging in pro-environmental behaviour than 2D geographic visualisation because the former triggers vivid images in the memory of users which enhances their motivation and trigger sustainable actions.	[41,88,148, 156]

there was a general consensus in the literature that visualisation techniques should be combined to accommodate a wide range of end-users profiles. However, such combinations must be carefully planned based on usage scenarios. Furthermore, they need to include statistical visualisation techniques, which are essential in any eco-feedback system.

The design of eco-feedback tools must not be developed in isolation, though. Many of the recommendations for the different tools allude to user-engagement. The primary purpose of this paper has been to review the specific features of the range of tools, but it would be remiss of us not to draw attention to the growing body of research highlighting the complexity around behaviour change. In both the domestic and commercial built environment, people's energy use is affected by a range of structural, organisational and societal constraints, habits and cultures that an app alone will fail to address. This so-called 'engagement gap' [157] needs exploring more as organisations and communities consider how they successfully deploy their chosen tool. Findings from a recent European research project, eTeacher, for example, offers interesting insights and techniques around concerted user-centred workshops to help design and implement eco-feedback tools [158] to good effect.

Reducing energy use in the built environment is vital if we are to reach net-zero by 2050. These eco-feedback tools have a key role to play in organisations to help them improve their energy efficiency, and this review has provided important information for decision-makers in helping select the most appropriate option.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

A- Review data set file

To access the review database file, please click on this link.

B- Game-based visualisation studies' tables

Table 19
A summary of some game-based eco-feedback applications using 2D stylised visualisation

	Example of games	Game genre	Elements visualised	Target audience	Reported findings
2D stylised visualisation	Power Explorer [113]	Platform games	2D Avatars and 2D landscape scenes	Different age groups including teenagers (12–14 years)	14% reduction in energy usage during the game. Improvement in participants' attitude to energy saving. End-users gained knowledge
	EcoIsland [112]	Idle games	2D avatars, 2D landscape scenes, pie charts, and numerical information.	Different age groups	No significant change in the participants' energy-related behaviour Positive relationship between game time and frequency of reporting eco-friendly activities
	Power Agent [116]	Platform games	2D scenes, statistical visualisation techniques (e.g,. column/bar graphs), texts	Different age groups including teenagers (12–14 years)	End-users gained knowledge about energy-saving strategies during the game. Up to 28% reduction in electricity use during the game period but 46% increase post-game.
	PowerHouse [114]	Role-playing	2D section of a three-storey house with an emphasis on appliances, gauges, 2D avatars, texts	Adults aged between 18 and 55 years	A rise in energy-friendly behaviour but a minor reduction in electricity usage during the post-game period.
	ECOPET [164]	Idle games	2D pet avatar, 2D internal scenes with emphasis on appliances (e.g., kitchen, bedroom, and living room), and texts	Graduate students	The game motivated end-users to learn about energy conservation
	Kukui Cup [165]	Idle games	A simple 2D traffic light with texts, coloured clickable tables, and simple tables.	University students	The research focused on user experience more than the change in their environmental attitude

Table 20
A summary of some game-based eco-feedback systems using 2.5D stylised visualisation.

	Example of games	Game genre	Elements visualised	Target audience	Reported findings
2.5D stylised visualisation	Enercities [107]	strategy games (mostly)/ simulation games	2.5D map of urban areas with numerical text display and symbols such as currency and smileys. Some applications such as EnergyVille use statistical visualisation techniques such as pie charts.	People aged 8–40 years	Increased awareness of energy/ environmental issues. Positive change in the attitude of participants towards energy-saving activities
	Energy City [166]			Children	Not reported
	ElectroEnergy [167]			University students	Not reported
	EnergyVille [119]			Students and educators	Not reported

Table 21
A summary of some game-based eco-feedback applications using 3D stylised visualisation

	Example of games	Game genre	Elements visualised	Target audience	Reported findings
3D stylised visualisation	Residence Energy Saving (RES) Battle [123] Energy Cat by EnerGAware [125]	Strategy/ Idle games	3D internal scenes of a house space (e.g., kitchen) with more emphasis on appliances. Numerical information and texts.	Secondary school audience	Improvement in the attitude and knowledge of energy sustainability
	Super Delivery [126]	Role-playing	3D player avatars, 3D street views, 2D schematic maps, and texts	Sixth-grade students	Prior knowledge, playing motivation, and gaming experience indirectly influenced knowledge acquisition.

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