The impact of digital energy conservation interventions for households

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Master Thesis

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Contents

Thesis outline

This thesis explores the aspect of digital energy interventions that are designed to reduce energy consumption. It will focus on energy consumption within households. A systematic literature review will document and analyze the current state of the literature, understanding the gaps and the areas where more research will be beneficial. The research will focus on the effectiveness of the interventions used in experiments, and also discuss some resources needed for the implementation and operation of the interventions technologies.

The scientific paper that is written will first start by outlining the importance of energy consumption reduction. This section will also include the research gaps, questions, and objectives. The related works section will follow with some reviewing of existing literature, focusing on intervention research that has already be done and explaining the need for further research. After that, the research method will be introduced, including the process of the systematic literature review. The results section will then categorize and assess the effectiveness of different interventions and some of the resources needed for the implementation and operation of these interventions. It will also identify some common limitations that resulted from the literature review. The discussion will interpret the results and highlight some significant findings and directions for future research. Finally, the conclusion will summarize the key insights and contributions of this research. After the scientific paper, an annotated appendix is added to gain some insights into the process of this thesis and outline some changes that were made along the way. This will include a section regarding the research context, research questions, methodology, and some further explanation of pivot points in the overall process.

Scientific paper

The impact of digital energy conservation interventions for households

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Abstract: This paper investigates the effectiveness of digital energy interventions and their impact on energy consumption in households. The study examines different types of energy reductions, including overall energy, electricity, and gas, and provides a detailed analysis based on the gathered data. It aims to classify and evaluate various digital energy interventions and contribute to a comprehensive analysis of the literature. This research is executed in the form of a systematic literature, with the final inclusion of 66 articles. There are some promising results already in terms of the environmental benefits of intervention technologies in households. However, to ensure technological feasibility, and the reliability and validity of digital energy intervention research, more robust empirical experiments are needed, which will also focus on studying the impact of the intervention in the long term.

Keywords: Digital energy interventions, energy consumption, electricity reduction, gas reduction, behavior change

1 Introduction

Climate change remains one of the most important issues of the 21st century [119]. The conversation around sustainable energy has, therefore, also expanded dramatically in recent decades [84]. Especially the academic field is creating more awareness around this sustainability topic [33, 127]. This academic expansion also enhances awareness in society, regarding the effects that sustainable energy practices have in addressing global environmental challenges [60]. A central aspect of this extended awareness is also understanding how energy is being used in the context of households [55, 100, 113]. Ever since smart technology was developed, an effort has been made to utilize it to its full potential as an encouragement for energy reduction in the context of households [38]. The aim of reducing energy consumption is to use less energy and reduce wasteful energy use [114]. This also means showing how digital tools can assist households in creating awareness of their energy usage, specifically by using interventions [23, 95, 123]. Through interventions and metrics tools, it will be possible to assist in bridging the gap between individual household behavior and sustainability goals, by giving feedback to the households concerning their energy consumption.

Despite the increased awareness and the progress that has already been made, an overview of sustainability potentials and the technological resources used to implement and operate digital energy interventions is still missing and has not been fully investigated according to [74, 109, 120]. Such an overview can be beneficial to decide whether an intervention is worth the sustainability benefit it claims to provide. The increasing debate on climate change solutions has been emphasizing technologies and their options based on cost and effectiveness to reach the climate goals [37]. Different meta-analyses of interventions have been conducted. However, these tended to focus on different subsets of the interventions. For example, analysis that solely focuses on pricing [45], or that only looks at social comparison [11]. Some research into energy consumption technologies has also indicated that there is often a lack of theoretical understanding and the underlying technology often remains unclear [81]. While there is research done on analyzing the behavior of a household that could lead to reducing energy consumption, these studies often do not specifically examine the possibilities of different strategies to change this behavior in practice, such as interventions, that could encourage households to change their behavior pattern [94]. Besides that, research is also mostly focused on providing a general overview of the digital energy intervention research area and expressing the need for energy reduction, rather than looking at specific ways to reduce a household's energy consumption [126]. Research that is specifically focused on the effectiveness of digital interventions in households aimed at reducing energy consumption yields mixed results [19, 20, 86, 109]. For example, research done by [50] concludes that the majority of implemented interventions so far in households have faced challenges as well as successes. Additional studies also show that research into the effectiveness of household interventions to reduce energy consumption can be employed with an overall success [46, 71, 121], however, most of the time there is little attention given to the actual environmental impact of those interventions, making it often unclear whether the intervention will maintain successful over a longer period of time.

Overall, there remains a significant gap in providing a comprehensive analysis of digital household interventions, resources, and their potential to reduce energy. This gap makes it more difficult to fully grasp the effectiveness and underlying resources of various digital energy interventions. Consequently, it is challenging to understand the current state of the interventions in the area of energy consumption reduction research and summarize where more research could be needed [56].

This research aims to bridge the gap by categorizing and analyzing various applications and technologies that offer interventions aimed at energy reduction, contributing to a comprehensive analysis of the literature. This will be done through the execution of a systematic literature review, which will focus on finding literature that contributes to identifying the environmental benefits and resources that are required for the development and operation of the interventions in households. An overview (e.g., in the form of a table) will be presented to create a clearer idea about the real effectiveness of such digital energy interventions and the state of the literature regarding experiments and research in this area. This overview will not only assess their effectiveness but also examine the technological resources regarding the architecture of digital energy interventions. Highlighting the currently missing overview between the perceived environmental impact and the resources needed for the operation of these interventions.

To address the research gap and to achieve the research objective, the following main research question (MRQ) is formulated:

What are the environmental benefits of sustainable energy interventions, the resources required to build and operate them within households, and the current state of reliability and validity of the corresponding research?

The main research question can be divided into different research questions (RQ) to support in answering the MRQ:

RQ1: How do different types of digital energy interventions vary in terms of their energy efficiency?

RQ2: What are the main resources required for the development and operation of digital energy interventions?

RQ3: What is the current status and what are the necessary next steps in intervention research?

2 Related work

To create an idea of the current state of the research surrounding digital energy interventions in households, it is important to first understand why such research is needed and what the underlying drivers for this research are. This section will dive deeper into the reason behind digital energy interventions and will explain why this technology is important.

2.1 Household energy consumption

In the 1970s, society began to first worry about fossil fuel depletion and the threatening energy crisis [56]. Since the 1980s, there have been studies done on energy use or energy transition, for example, studies by [139] in 1983 and [17] in 1986. In 2021, nearly one-third (27%) of the global primary energy demand, which includes electricity and gas consumption, was met by household energy usage in the EU [41], significantly affecting the environment [56]. This was an increase of 5.5% compared to 2020 [41]. Data gathered from [42] shows that household energy consumption has not been reduced since 2013, which is also evidence that reduction is necessary to reach global climate goals. However, in 2022, a small reduction was seen and the total energy consumption in the residential sector in the EU decreased to 25.8% [43]. This decrease was a consequence of the fact that 2022 had a mild winter in Europe, which caused less energy needed for space heating in households [41, 43]. Space heating is the largest contributor to household energy consumption [41, 43], so a reduction in this showed a significant reduction in overall consumption. It is not expected that this decrease will be sustained in the upcoming years. It is even expected that the demand for the consumption of electricity, which also contributes to the total energy consumption, will rise by 65% by the end of 2050 if it sustains the current trend [116]. All of these numbers show that a further decrease is necessary if the EU wants to meet the 2030 targets on energy consumption, which is why further research into technologies that can aid in reducing this consumption is critical[125].

2.2 Energy source depletion

Traditional energy sources such as fossil fuels are getting more and more attention as they propose a future challenge, due to their economic and physical limitations [59]. In 2016, it was estimated that the world's dominant fuel sources would last only another 50.6 years (oil), 52.5 years (natural gas), and 153 years (coal) for global energy production. This does mean that these sources will most likely not last for the next generation [63]. This emphasizes the crucial need to take drastic steps toward optimizing their application across all sectors. This also shows that there is a need for energy-reducing strategies, such as energy interventions, with a focus on households, since they consume a significant portion of the world's energy. Households are also a major contributor to the emission of greenhouse gasses and, consequently, to global warming [31].

2.3 Intervention research

Research into the effectiveness of digital interventions in households aimed at reducing energy consumption yields mixed results, as stated in the introduction. The biggest limitation that results in these mixed results is caused because of the often relatively short duration of the experiments (e.g. a couple of weeks), there are rarely any studies that show strong and confident results regarding the success of household interventions aimed at reducing energy consumption [3, 35, 63, 86]. A meta-analysis done by [74] concluded that the duration of the intervention experiment does influence the results. The mean duration of their sample (122 studies) was only 21.5 weeks, which underlines the importance of more long-term experiments. The experiments that are considered long-term are those that have a duration of more than a year [15, 25, 65]. The results of these long-term studies are a bit more promising and provide stronger conclusions, however, they often have other limitations. What also contributes to the mixed conclusions is the limited availability of empirical studies [3, 11]. There are often inconsistencies in the methodologies [73] and data is incomplete or biased [3, 80]. This does not allow for any advanced analysis or strong conclusions [3]. The lack of data can also be caused by the relatively small sample size in intervention experiments, often only a few households participate or make it to the final stage of the experiment period [63].

These mixed conclusions lead to other research questioning the effectiveness of these interventions, such as [22]. Besides the mixed results of the digital energy interventions, there has been an ongoing debate about the environmental implications of manufacturing and deploying these digital technologies themselves, because the production might often require energy-intensive processes. These processes can contradict the intended purpose of environmental sustainability, as the resources and energy consumed in creating and maintaining these technologies could potentially outweigh the environmental benefit derived from their use in reducing household energy consumption [128]. If looked at in the broader sense, it is already mentioned that there is a negative environmental burden that is a result of digitalization [32] and generating and processing large amounts of data [106].

All of the mixed conclusions and limitations might raise the question if intervention research is still necessary and worth exploring further. First of all, there is still a crucial need for long-term studies to understand the sustained impact of the interventions. Without those long-term studies, it will be difficult to generalize results and actually provide some information and knowledge about the effectiveness of digital energy interventions. Long-term studies are especially important since short-term studies do show some significantly promising results [77]. Besides that, there is also a need for further refinement of intervention strategies, as [133] mentions. This includes addressing the methodological inconsistencies [73] and needing more studies that make use of unbiased and complete datasets. Energy consumption keeps increasing, still with no direct indication of slowing down [36], emphasizing the crucial need for strategies and technologies that aim to change energy use behavior [63].

2.4 Intervention technologies

The need for digital energy interventions is clear, what remains is how these interventions can be implemented and operate in households. Digital energy intervention technologies can be of different types, such as in-home displays or through websites. The most common types, and proven to have potential for energy reduction in households are web portals [111], web-based applications [29], smartphone applications [29], in-home display (IHD) [112], and game-based applications [66]. A commonly used resource technology in digital energy interventions in households is a smart meter, it is even seen as a key factor in the success of energy reduction in households [24]. It is often used as the underlying technological resource needed for the operation of the above-mentioned intervention types. Each of these types can be explained as follows:

- *Web portal*
  Through web portals, users can log in to view information about their energy consumption, cost, and potential savings. Web portals usually have limited interaction possibilities and primarily function as a display of information and recommendations [61].

- *Web-based application*
  This refers to an application that is accessed over a network such as the internet or an intranet. A web-based application is highly interactive, as users can interact with the application to fill in questionnaires, view their energy usage, and receive advice on how to reduce energy consumption [102].

- *Smartphone application*
  Has the same functions and features as a web-based application, but offers this in

the form of an application that can be accessed through a handheld device, such as a smartphone or tablet [26].

- *In-home display (IHD)*
  They can be seen as physical displays that can be placed anywhere in the house and provide real-time information regarding energy consumption. IHDs can empower users to adjust their consumption patterns, by making it easier to understand the impact of their behavior [46].

- *Game-based application*
  Games-based applications can be incorporated into intervention technologies in two ways, gamification and serious games. Gamification is defined as *"...the use of game elements in non-game contexts to improve user experience and user engagement"*[40], and serious games are defined as *"any form of interactive computer-based game software for one or multiple players to be used on any platform and that has been developed with the intention to be more than entertainment"*[103]. Although games themselves are not technologies, they make use of technological platforms, such as computers and smartphones, to enhance interventions.

- *Smart meter*
  A smart meter gathers data directly from household appliances, tracks their real-time energy usage, and allows one to readily access this data [47].

3 Research method

The methodology consists of two main parts, the first part consists of collecting the literature (corpus collection) and the second part consists of analyzing this found literature (corpus analysis). The goal of this methodology is to provide an accurate overview of the already existing literature on digital energy interventions in households and, thereby, also identify knowledge that can bridge the gaps that this research addresses.

3.1 Corpus collection

The systematic literature review, which will be done on digital interventions for household energy consumption, is conducted based on the following four steps: identification, screening, eligibility, and inclusion. These steps are based on PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) method, which is designed to help literature reviews to be transparently reported. This transparency will ensure that it is completely clear how the literature review is conducted and how the, ultimately used, literature was found [89]. A description of each step is given in the sections below and an overview of the whole methodology can be seen in Figure 1.

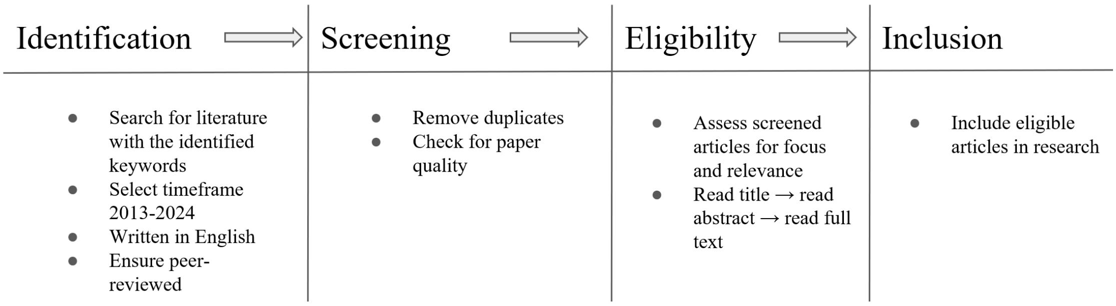

Figure 1: *Overview of literature review methodology steps.*

3.1.1 Step 1: Identification

The first step of *Identification* includes searching for literature by using specific pre-defined keywords or a combination of those. For this step, three inclusion criteria were identified. These were that the article needed to be published between 2013-2024, the article must be written in the English language, and the article must come from a peer-reviewed source. For this step, a number of search engines have also been chosen, these are ACM Digital Library, IEEEXplore, Web of Science, and Scopus. Due to the extensive database of ACM Digital Library, only the journal Proceedings of the ACM on Human-Computer Interaction (PACM) are opted in the search query. The keywords used in this step were:

- Digital intervention
- Household
- Residential
- Smart grid intervention
- Energy
- Monitoring intervention
- Sustainable
- Residential efficiency
- Energy consumption
- Trade-off
- In-home display
- Smart meter
- Technology resources
- Operation
- Cost(s)
- Wireless sensor network
- Technology architecture
- Smartphone applications
- Web-based applications
- Feedback
- Intervention methods

By combining these keywords, a list of search queries is created in this first step to identify the literature. The complete list of queries can be seen in Appendix section 4.2. These queries were all entered into the search engines in April/May of 2024, and it is important to note that these might yield different results when repeating them in the future. Furthermore, all of the search queries were used in the advanced search option of the search engine. Additionally, for IEEEXplore the filter *Year range* was set to 2013-2024, this is not displayed directly in the search queries in 4.2, as there was no option found to export this data. Therefore, this is added as an additional filter. For some IEEEXplore queries, an additional filter of *Open access* was added to ensure the ability to have access to read the literature.

3.1.2 Step 2: Screening

The second step *Screening* is about removing duplicates and screening the remaining records based on the expected quality, making sure that they adhere to the inclusion criteria. This quality check should be based on checking if an article is published in a peer-reviewed source.

3.1.3 Step 3: Eligibility

In the *Eligibility* step, the screened articles will be assessed for their focus and their relevance. This is done through a review process, starting with reading the title, then the abstract, methods, and outcomes. If the research is still deemed relevant, the full text will be read to ensure complete alignment.

When reading the titles and abstracts, the following criteria should be taken into account to decide to keep an article on the list.

Remove when an article:

- Mentions economically developing countries
- Has a none-relevant topic
- Is not household-specific
- Is not energy-related

If an article does not meet any of these criteria, it should remain in the literature list of the eligibility phase. If in doubt when reading the title, the article should remain on the list to gain further clarification when reading the abstract.

3.1.4 Step 4: Inclusion

The final step *Inclusion* will result in including the articles that fully meet the selection criteria. After this list has been established, the corpus analysis can commence.

3.2 Corpus analysis

The articles that have made it through the final inclusion step will be further analyzed by categorizing them based on the type of literature they provide and the technology they describe if that applies to the article. This ensures an enhanced overview and creates a better understanding of the current situation regarding the state of the literature in intervention research focused on households. Besides that, this section will also introduce the measurements used to aid in answering the three different research questions. This ensures that the corpus analysis is precise and is focused on answering each of the research questions of this research with the right approach and measures. For each research question, the following measures are used and analyzed:

- *RQ1: How do different types of digital energy interventions vary in terms of their energy efficiency?*

This is measured and answered by looking at the overall energy reductions found in the literature. Thereby, the technology found in the literature combined with their frequently used resources can also help in understanding the energy efficiency of a digital energy intervention technology. For the technology, a categorization will be used, to ensure clarity.

  - **RQ measurements:** Overall energy reduction numbers in intervention experiments, categorization of technologies, and resource effectiveness measured in literature.

- *RQ2: What are the main resources required for the development and operation of digital energy interventions?*
  This will be answered by also using the categorization of the technologies and, thereby, also looking for commonly used resources in literature within these technologies. By doing so, it will become clear which technology is mainly used in digital energy intervention research, combined with their effectiveness.

  - **RQ measurements:** Categorization of techniques and their corresponding used resources, and measured effectiveness.

- *RQ3: What is the current status and what are the necessary next steps in intervention research?*
  The measurement used for this research question will be the categorization of the literature. This will give more insights into the existing literature based on the availability of empirical data, preliminary results, and literature reviews.

  - **RQ measurements:** Categorization of literature.

The categorization of the technologies and the literature will be explained further in the following sections, describing how the different categories are defined.

3.2.1 Categorization of technologies

Categorization has also been applied to gain insights into the different technologies and resources that are used in research regarding energy intervention methods and systems. This information can be combined with the resources that are often used in these interventions to identify promising technologies based on their resource effectiveness, which correlates to their energy efficiency. This categorization was based on the same categories that were described in section 2.4. The following categories are used:

- *Web portal*
- *Web-based application*
- *Smartphone-based application*
- *In-home display*

- *Game-based application*
- *Smart meter*

3.2.2 Categorization of literature

The literature will be categorized based on the type of research and if they include empirical data, to create an enhanced understanding of the state of the current literature in regards to the availability of large-scale, and long-term experiments. The categorizations are based on the types of research that were presented in the different papers. It has to be noted that this categorization is a first attempt, as such categorization has not been found in current literature in the context of digital energy interventions in households. The numbers mentioned in the different categories are arbitrarily chosen and could not be found in any current literature. This means that any future attempts might differ in categorization.

- ***Empirical research with strong conclusions:***
  1. $Samplesize \geq 100 households$
  2. $Duration \geq 12 months$
  3. The author(s) mentions that their conclusions can be perceived as strong

  If at least two out of the three criteria are met, place the article in this category.

- ***Empirical research with tentative conclusions:***
  1. *Sample*size 40-100 *households*
  2. *Duration* 4-12 *months*
  3. The author(s) mentions that their conclusions can be perceived as tentative

  If at least two out of the three criteria are met, place the article in this category.

- ***Empirical research with mixed conclusions:***
  1. *Sample*size$\leq 40 households$
  2. $Duration \leq 4 months$
  3. The author(s) mentions that their conclusions can be perceived as mixed

  If at least two out of the three criteria are met, place the article in this category.

- ***Preliminary empirical findings:***
  1. No empirical data, or less than 10 households. Can include pilot results.
  2. The author(s) mentions that their conclusions can be seen as preliminary results

If at least one out of the two criteria are met, place the article in this category. Duration does not need to be taken into account for this category.

- ***Literature review with calls for further research:***
  1. Reviews existing literature and provides high-level results.
  2. And/or the author(s) mention writing a literature review.

  If at least one out of the two criteria are met, place the article in this category.

If an article is missing a criterion, such as the duration of the experiment not being mentioned, the sample size being unclear, or if the article meets criteria in multiple categorizations, the researcher should use their own judgment and expertise to determine the most appropriate category for the article. As said before, this categorization is a first attempt, and further refinement is still needed.

4 Results

4.1 Selection of papers

During the execution of the methodology, articles were identified, screened, and finally included in the research. The identification phase was ended with a total of 774 identified articles. These were all identified based on keyword combinations across the different search engines. Finally, the inclusion step included 66 relevant articles for this research. The total number of articles that concluded each phase can be seen in Table 1.

Table 1: *Methodology phases with the corresponding articles that concluded each phase.*

Phase	**Number of articles**
Identification	774
Screening - duplicates removed	598
Screening - quality assessment	567
Eligibility - title	376
Eligibility - abstracts	71
Eligibility - full text	66

4.2 Energy efficiency of interventions

Among the different articles that studied the effectiveness of digital energy interventions, some results can be derived. This is that of the effectiveness of interventions. Some articles did mention some actually measured reductions, while others concluded with changes in behavior that led to reductions in energy consumption. From the actual measured reduction in consumption, there are three different types measured in the literature. These are numbers regarding the total energy consumption reduction, electricity reduction, and gas reduction. The exact ranges found in the articles can be seen in Table

2. It has to be noted that these reductions are overall positive, however, studies often made a small footnote regarding their results as there were also some limitations that influenced the results. Taking this into account, Table 2 does create an initial idea of the ranges found in current intervention research.

Table 2: *Energy efficiency of interventions based on the actual reduction numbers found in the literature.*

Consumption type	**Range found in literature**	**Article sources**
Total energy	4%-21%	[5, 14, 27, 44, 48, 53, 76, 98, 124, 132, 134, 135, 138]
Electricity	2.5%-9.5%	[25, 58, 78, 86, 87, 99]
Gas	3.5%-21%	[25, 82, 110]

4.3 Resources

Among the 66 included articles, some also reported the elements that are present in the architecture of different intervention technologies. A summary of these findings can be seen in Table 3. They are presented in combinations of resources that were present in the literature. Some studies even showed some preliminary results about the effectiveness of these interventions, including the resources needed for the technology.

Table 3: *Summary of commonly used resources in digital energy interventions and their effectiveness, if measured. This table is in no specific order.*

Resources mentioned	**Category**	**Effectiveness**
Wireless sensor network, power meter, database [51]	Smartphone-based application	Not measured
RFID tags, RFID reader, PLC [122]	Smartphone-based application	Not measured
WiFi network architecture, LoRaWAN network, Arduino IDE (microcontroller) [90]	Web-portal	Not measured
IoT network, sensors, microcontroller units [135]	Web-portal	21%-30% energy reduction
Arduino, sensor network, communication (WiFi) and power system [2]	Web-based application + smart meter	Reduction in electricity, not quantitatively measured
Smart meter, HEM (Home energy manager), network [79]	Smartphone-based application	27%-40% energy reduction
Measurement node, NFC, LoRaWAN protocol, central unit, web services [12]	Smartphone-based application	Reduction in electricity, not quantitatively measured
Sensors, power unit, GSM module [92]	Web- and smartphone-based application	Not measured
Sensors, control unit, network and server, signal conditioning circuit [68]	Smart meter	Not measured
Microcontroller, transformer sensors, motion sensors, light sensors [9]	Smartphone-based application	Not measured
NFC, NET [101]	Smartphone-based application	Not measured
Power source, sensors, ATmega328P (microcontroller), bluetooth module [67]	Smartphone-based application	Not measured
Sensors, wireless sensor network, Raspberry Pi (microcontroller), database [10]	Smartphone-based application	Not measured
Server, Arduino (microcontroller), network, bluetooth module [27]	Smartphone-based application	10%-30% energy reduction
Sensor, actuators, database, triggering module, controller [107]	Smartphone-based application	Reduction in energy, not quantitatively measured

When it comes to the actual effectiveness of these resource combinations, this is often not measured quantitatively, making it difficult to gather any results from this. Most studies mention that they are in need for real-world studies to test the actual effectiveness of their designed intervention system. The resource combinations that are, however, quantitatively measured show significant promising results.

4.4 Categorization of technologies

Table 4 shows how the literature was divided into these categories. It is important to mention that some research included multiple techniques and resources, which caused some articles to be included in multiple categories. It is also noted that not every article mentioned the use of a technology or resource, so that is why there is also a *none* category included.

Table 4: *Categorization of literature, showing how many papers were included in each category and their percentage as part of the 66 articles.*

Category	**Number of articles**	**Percentage**
Web portal	4	6%
Web-based application	9	13%
Smartphone-based application	25	38%
In-home display	5	7%
Game-based application	7	11%
Smart meter	9	14%
None	7	11%

What can be seen from this table is that the majority of the techniques that are mentioned in the literature are using smartphone-based applications (38%), smart meters (14%), and web-based applications (13%).

4.5 Categorization of literature

The 66 articles, that made it to the final inclusion phase, were all categorized into one of these categories, which resulted in some interesting insights. Table 5 shows each of these categorizations and the corresponding number of papers that were assigned to each of these categories. It also mentioned what percentage of the total number of papers belonged to a specific category.

4.6 Limitations found in literature

There are some limitations mentioned in digital energy intervention research, that were identified during the analysis of the literature. The most common ones will be discussed. First of all, the main limitation of the articles was the missing of long-term data regarding behavior change and energy reduction. This was seen as a limitation in 23% of the included articles. A study that observed the effectiveness of an intervention shorter

Table 5: *Categorization of literature, showing how many papers were included in each category and their percentage as part of the 66 articles.*

Category	**Number of articles**	**Percentage**	**Article sources**
Empirical research with strong conclusions	3	5%	[70, 97, 98]
Empirical research with tentative conclusions	17	26%	[4, 6, 14, 25, 27, 28, 49, 52, 53, 58, 75, 78, 83, 105, 130, 137, 138]
Empirical research with mixed conclusions	13	19%	[7, 15, 21, 44, 48, 54, 65, 82, 87, 99, 117, 124, 132]
Preliminary empirical findings	26	39%	[2, 9, 10, 12, 30, 51, 67, 69, 72, 76, 79, 88, 90, 91, 92, 93, 96, 101, 107, 108, 110, 115, 122, 134, 135, 136]
Literature review with calls for further research	7	11%	[5, 8, 18, 35, 86, 109, 131]

than a 1-year period was often deemed a short-term study. Some authors mention it themselves regarding their own results, but this was also derived from the analysis of the data and the conclusions during this research. Experiments that lasted a shorter period of time often had some unreliable results and data. The studies that could give some confident results regarding the long-term effects of the intervention had a duration between 12 to 18 months, an example of such a study is that of [65]. This implies that the reliability of the results in the long term will be enhanced if the intervention observation has a duration of more than a year.

Another limitation that was seen frequently in research is that of a small sample size of participants. This was seen as a limitation in 17% of the articles. It can be noted that articles that had a participating group of less than 100 households are seen as a small sample size, which influenced the reliability of the conclusions. If the experiment group included more than 100 households, the small sample size limitation was not mentioned or seemed to influence the measured effectiveness. Due to the small sample size limitation, experiments were often also not able to fully generalize the results to overall society. This limitation was derived from the authors mentioning it in their own conclusions, but also from analyzing the data from the different articles.

The third most common limitation was that of engagement. Keeping the participant engaged throughout the whole experimental process often seemed more difficult than anticipated beforehand, as stated by a few of the author(s) of the papers. This limitation was evident as some experiments reported some participants dropping out before the experiment phase ended. This was a limitation in 6% of the articles, where it was influencing the results. This was most often the case in experiments where a game was being implemented into the household's energy consumption. This can be explained by the fact that not everyone is interested in gaming, games can also take quite some time out of your day to interact with it, which is not always something that participants will prioritize. Some games can also be quite difficult to understand at first, which can also decrease participant engagement.

The fourth limitation that was identified from the included articles is that of self-selecting participants. In 5% of the articles, it was observed that the participants could self-select into the experiment. This limitation was noted by the author(s) themselves. Finding other articles that dealt with this limitation during the analysis was difficult because authors did not always disclose all of the details regarding their participant's selection process. This can affect the results, as participating households are often already interested in energy-saving behavior before the trial period begins. This means that the results of the experiments are more difficult to generalize, resulting in unreliable conclusions.

5 Discussion

When looking at the results, some interesting insights can be derived, which can be linked to the different research questions mentioned in the introduction. Overall, the field of digital energy interventions holds a significant promise for addressing a critical challenge in the world of climate change in the 21st century. There is already some evidence demonstrating the potential for energy savings through the application of various digital energy intervention technologies. For example, interventions utilizing smart meters, energy management systems, and integrated IoT networks have shown reductions in energy consumption ranging from 10% to 40%. Experiments, that have been analyzed in this research, also show highly effective strategies with evidence of energy consumption reductions up to 21%. However, the field of digital energy interventions is not without its limitations. There is an overall need for collaboration in this field of research, as there is still a significant amount of inconsistent methodologies or incomplete data sets, which results in unreliable conclusions. There is often a focus on behavioral changes, without really quantifying the potential energy reductions that are a result of the intervention. Behavioral changes can be the first indication that a digital energy intervention can provide a reduction in energy consumption, but researching the actual numbers can support these claims. On the other side, the research that does provide actual reduction numbers, often overlooks how people will interact with the digital energy interventions, thus, overlooking the possible long-term effects. This lack of interdisciplinary collaboration between the behavioral sciences and the technical/engineering sciences means that important insights might still be missing. To balance the perspective, it is essential to acknowledge the already existing achievements, as well as the existing gaps. The current evidence, available in the literature, does support the potential of digital energy interventions in reducing energy consumption in households. However, integrating behavioral and technical aspects could be crucial in learning more about sustainability in the long run. Collaboration between the different involved sciences, such as technical effectiveness and behavior analysis, can move toward more impactful strategies in these interventions. To dive deeper into the field of research regarding digital energy interventions and discuss the results from this research, each of the research questions will be addressed in the following sections.

5.1 Energy efficiency (RQ1)

First of all, digital energy interventions can lead to significant overall energy reductions, some interventions are highly effective (up to 21%), while others achieve more modest savings (as low as 4%). Secondly, interventions that specifically target electricity reduction have a more narrow range (2.5%-9.5%), this suggests a more consistent effect across different studies, although it is generally lower than the overall energy reduction. Thirdly, interventions aimed at gas reductions have a wide range (3.5%-21%), which indicates variability in effectiveness, although similar to overall energy reduction, but generally higher than electricity reductions. Even though there are actual reduction numbers in research, this was only present in 21 out of the 66 included articles, as seen in Table 2. So, these numbers should be interpreted with caution, which is a result of the fact that there are still a significant amount of studies that solely focus on behavioral changes. Energy conservation research is often focused on changing behavior and the result of such research is the change in a behavior pattern. Behavioral changes can be difficult to measure, which makes it a challenge to decide whether an intervention was successful or not. This is because some research can conclude that there was a change in behavior, but often does not provide any strong evidence that there was also a reduction in energy consumption. This could also affect the results of this research, as some interventions were deemed successful based purely on behavioral change and not on actual quantitative data, making it difficult to generalize if an intervention will actually be successful in terms of energy consumption.

Besides the overall energy reduction that was found in the literature for digital energy interventions, it is also possible to create an initial idea of the corresponding resource effectiveness. Although this is even less significantly researched, there are already some percentage measures, as shown in Table 3. These reductions vary from 10% to 40% of the total energy consumption. However, there is still a limited availability of literature about the architecture behind digital energy interventions. The resources mentioned are still in an early preliminary state, and currently still missing any large-scale implementation experiments. This makes it so that it was only possible to describe some of the resources, without being able to confidently analyze their effectiveness. The field of intervention research often focuses on the user side of the intervention, ignoring the underlying architecture. Some articles even explicitly mention that the architecture of the researched intervention is unknown to the author(s), making it even more difficult to draw any conclusions regarding the effectiveness of the technology itself. Many studies prioritize understanding how individuals interact with these technologies, without any in-depth research into the resource requirements needed for the operation and implementation of these digital energy interventions.

To answer RQ1, overall energy interventions vary in their energy efficiency in different aspects. From a more global point of view, interventions aimed at energy reduction do show some reduction in energy consumption, the interventions aimed at electricity reduction show a more narrow reduction range, meaning that research into that area might already be a bit more consistent. Interventions specifically aimed at gas reduction show more promising numbers than interventions for electricity reduction, but the reliability of these experiments seems a bit more inconsistent. Although not explicitly mentioned in the literature, there can be a few explanations for these ranges and differences in gas and electricity reductions. First of all, gas consumption is often influenced by a wide range of variables, such as weather conditions, the quality of the household's insulation, or heating systems. This was also the case for the reduction in energy consumption in 2022 as stated in section 2.1, where the weather significantly affected the total energy consumption in the residential sector in the EU, due to a decrease in space heating [43]. This makes measuring gas consumption more complex to measure and monitor. Besides that, smart meters for electricity are widely available in the literature, while similar technologies for measuring gas consumption are less commonly found. Another explanation for the inconsistencies in interventions specifically aimed at gas reductions can be that electricity consumption is easier to monitor because most electric appliances can be simply switched on and off with ease. Gas appliances, on the other hand, are primarily related to cooking and heating, which are both influenced by external factors, such as the weather and might require more complex adjustments in measuring technologies. As seen in Table 2, interventions aimed at gas reduction are least present in the literature (only three articles mention gas interventions). This is most likely because feedback mechanisms for gas consumption are not that well present in experiments and are not as developed as real-time energy or electricity feedback technologies. This can be, again, explained due to the fact that gas-measuring technologies have to take more complex variables into account. A report by [62] states that at the end of 2021, there were nearly 163 million smart electricity meters, while there were only 46 million smart gas meters in the EU. This shows that the market share for electricity meters is way more present than the market for smart gas meters, thus, further explaining literature on intervention research with gas meters is not that commonly found.

It is also possible to answer this research question more narrowly, as a categorization of the technologies (Table 4) and their corresponding effectiveness (Table 3) was made.

From Table 3, it can be derived that although the effectiveness is not always measured quantitatively, it appears that smartphone-based applications are a promising technology to be used in digital energy interventions. This can be derived from the fact that they are the most commonly found technologies during this research (in 38% of the included literature) and the measured reductions are mostly from experiments that used smartphone-based applications. This could be explained due to the fact that most people have a smartphone always within reach and know how to use it, making it more feasible to implement interventions in a household. Smartphone-based applications also allow for flexibility in the design of intervention technologies, for example, through the possibility of incorporating game-based elements.

Future research regarding this research question is most needed in the form of more research that combines behavioral studies with the technical architecture of digital energy intervention research. Therefore focusing on the effectiveness of interventions when combined in both aspects (behavioral and technical). Besides that, more research is also needed that solely focuses on reducing gas consumption in households through the use of intervention technologies. To make this possible, there should also be some further research in gas monitoring technologies, as that can aid in reducing the variability in gas reduction results. Another possibility for future research in measuring the effectiveness of different types of digital energy interventions is in the field of smartphone-based applications. More research can lead to the development of more effective interventions, ensuring that both user behavior and technical feasibility are implemented into the design.

5.2 Resources (RQ2)

To answer the second research question, some resources were found in the literature. These are summarized in Table 3 together with their corresponding category and effectiveness if this was measured. When it comes to the resources used in digital energy interventions, it can be summarized that most intervention technologies make use of sensors in some way. One type of sensor measures the energy consumption of appliances. They can monitor electricity, gas, or overall energy consumption and provide real-time data. These types of sensors can also aid in identifying patterns and areas that have the potential to save energy. The second type of sensor is used to establish communication between different parts of the system. Examples are RFID tags or NFC (Near Field Communication). For these sensors, there is most often also some connection needed to ensure seamless collecting and sharing of data. As seen in Table 3, this connection is often established through WiFi or Bluetooth. WiFi has widespread availability and familiarity, which makes it a practical choice for the connection between household devices. Bluetooth is particularly useful in scenarios where devices need to communicate directly, with no need for a centralized WiFi network.

The intervention technologies most often also have a microcontroller installed to regulate all of the different parts. Some examples of technology, used as microcontrollers, in intervention technologies are an Arduino, ATmega328P, or a Raspberry Pi. These microcontrollers can function as kind of the brains of the digital energy intervention system. Their use is collecting the data from the sensors, and thereby controlling various components.

What is also mentioned in these architectures is the implementation of some sort of database or somewhere to store the retrieved data. These combined are the main resources that are often required in some form for the development and operation of a digital energy intervention in households. By storing the data in a database, it will allow for more efficient data management. It will provide a way to gain insights into the data and recognize any energy consumption patterns.

So, to answer this second research question, the main resources required for the development and operation of digital energy interventions can be broadly defined as sensors, microcontrollers, and databases. It is advised that each intervention system in a household has at least one technology of each of these groups to ensure the possibility of developing and operating digital energy interventions. It has to be mentioned that these groups are not based on any literature, but mainly through analyzing Table 3, focusing on finding commonly mentioned resources in architectures of digital energy interventions.

The main focus for future research regarding the resources is to dive deeper into the architectures of these digital energy interventions. Thereby also experimenting with different types of technologies and different combinations of resources. Currently, the different resources are often only described, without measuring their effectiveness in some way. There should also be a focus on the resources specifically required for the operation of smartphone-based applications for digital energy interventions, as those seem to have some preliminary promising measurements. It also remains unclear if some specific types of resources have a greater impact on the measured energy reduction than other resources. This could also be something to research further because that will create more insights into specific resources and how they affect the overall effectiveness of the intervention. Another aspect that could be interesting in future research regarding the resources are comparison studies. Where types of resources are compared to each other in terms of their effect on the overall system. An example of such research could be to compare the Arduino and Raspberry Pi and see which microcontroller could be more suited for specific interventions.

5.3 Status of the literature (RQ3)

To answer the third research question, a look at the categorization of the literature is needed. As seen in Table 5, the majority of the literature consisted of tentative (26%) and mixed conclusions (19%), and the findings were mostly preliminary empirical (39%). Meaning that the findings offered initial empirical insights but lacked comprehensive data, with the acknowledgment of the exploratory nature of the study with possibilities for further research. This distribution can be explained in a few different ways. First, there is a significant amount of inconsistencies in the methodologies and in the data sets, as also mentioned in section 2.3. This was also analyzed when reading the literature. For example, some experiments only focused on one type of appliance, such as a washing machine [21]. Other times, the participants could self-select into the experiments, resulting in participants who already had some motivation and interest to reduce their energy consumption, for example as in [87]. In both experiments, the conclusions were not very valid and reliable. Some experiments also had the participants self-report their behavioral changes, such as [28], which resulted in the conclusion that participants often only reported positive behavioral changes. This was also noted by the authors as a limitation of their research.

Overall, with the percentages seen in Table 5 it can be mentioned that this field of research is still in an exploratory stage. The majority of the literature found included preliminary empirical findings (39%). Many current studies provide initial insights and are laying the foundation for further research. There is also a need for stronger evidence, as currently only 5% of the literature offered strong conclusions. This should include experiments with larger sample sizes, long-term observation, and more consistent methodologies and data sets. This is supported by the observation that there is still a lot of variability in research regarding digital energy interventions, as 19% of the literature presents mixed conclusions. This variability can be due to, for example, differences in methodologies, as mentioned before, or participants that were not very reliable due to self-selecting or self-reporting. Future research should be aimed at understanding these variabilities and try to develop more consistent approaches in intervention research. The 26% of the studies with tentative conclusions do highlight some optimism, as these experiments suggest potential benefits, but still lack the strong evidence for those. Future research needs to be focused on expanding the validation of these results.

To answer this third research question, the current state of the literature in intervention research has significant potential. There is a crucial need for more comprehensive studies, and to create an understanding of the current inconsistencies and how to deal with those. The necessary next steps include studies with larger sample sizes, long-term observations, addressing inconsistencies, and making sure that the participants are not biased. It is also important to further validate the experiments that already show some promising conclusions.

5.4 Related field

Since the three research questions have been discussed, it is also possible to place the discussed results into a different, perhaps broader, context besides households. Such a field can be that of digital energy interventions in the context of businesses or large organizational buildings. [64] mentions a reduction of up to 30% of the annual energy costs, thus, reducing energy consumption in a large building. This higher reduction can be explained because large businesses or organizations often have a more structured and resource-intensive energy management system when comparing them to household buildings. Most large organizations have more financial capabilities to implement such digital energy interventions, and technical feasibility is often not a limitation for the operation and deployment of energy-reducing technologies [85].

5.5 Limitations

There were also some limitations to the execution of this research. One limitation is the exclusion of economically developing countries, although they are often not technologically ready for the implementation and operation of certain technologies, it is possible that some interesting literature is not included in this research as a consequence of the exclusion of these countries. Another limitation of this research that has to be mentioned has to do with the search engines used. ACM Digital Library has a significantly large database, so it was needed to limit this to specific journals and conferences. Although this did make the results more clear and easier to process, it could also have resulted in some articles that were not included. Articles that were present in other journals and conferences, besides the selected ones for this research were not included, which could lead to missing out on some literature. Another limitation in regards to the search engine was the added filter of *Open Access* on IEEEXplore. This filter was needed to ensure that it was possible to access and read the identified literature. However, this could have resulted in some literature not being included in this research, because it was not accessible. A fourth limitation of this research is that the focus is on energy-saving behavior in households. There may be other ways in which energy consumption can be reduced without the need for intervening in behavioral changes. However, these have not been incorporated into this research. Examples could be to look into improving the insulation or the building materials of a building, which could also lead to a reduction in energy consumption.

6 Conclusion

During this research, the focus was on identifying literature in the field of digital energy interventions through a systematic literature review, which included 66 articles. Specifically, looking at the effectiveness measured in the literature, as well as the resources and technologies that are commonly used in these interventions. Thereby also looking at the current state of the literature and identifying where future research could be beneficial. After the literature has been identified, a few aspects can be mentioned. First, it can be said that there is already some progress made by implementing interventions in households, as energy reductions are indeed happening as a result of this implementation. During the literature review, ranges from 3.5% to 21% of reduction in the total energy consumption, electricity consumption, and gas consumption were found, highlighting the potential of different interventions in terms of their energy efficiency. When it comes to the effectiveness of digital energy interventions in terms of their energy efficiency, smartphone-based applications are the most promising. To create stronger conclusions regarding the effectiveness of digital energy interventions, there is also a need for interdisciplinary collaboration between the behavioral sciences and the technical/engineering sciences, to identify important insights, that currently might still be missing.

On the other side, it is also possible to draw some conclusions about the underlying architecture of these intervention technologies. Most digital energy interventions rely on sensors to measure energy consumption in a household. These could be sensors for light, motion, heat, etc. The communication within the intervention system is often via WiFi or Bluetooth, incorporating microcontrollers to manage these systems. By storing the data in a database, it will allow for more efficient data management. To effectively design an architecture for digital energy intervention technologies, it can be advised to use at least these three types of resources, which are sensors (including sensors for communication), microcontrollers, and databases.

Then for the current state of the literature regarding the empirical data concerning digital energy intervention experiments. It can be confirmed that there is a lack of empirical research that can provide strong conclusions, as only 5% of the articles in this research belonged to that category. Most research includes only the beginning phase of empirical research, by providing preliminary findings, indicating that much research is still in its early stages and further validation is needed. Some evidence is available, but often not supported enough to form definite conclusions. The most important next step in digital energy intervention research needs to be in the form of long-term (more than 1 year) experiments that include sample sizes of at least 100 households.

In conclusion, the environmental benefits of digital energy interventions are promising but vary widely, mostly depending on the type of intervention that is being implemented. The current state of the research in this field is mixed and the reliability and validity are still not quite sufficient. There is a need for more empirical research to establish and provide more confident conclusions. Although digital energy interventions do offer significant opportunities for environmental benefits by reducing energy consumption within households, they do require advanced technological resources and further research is crucial.

References

[1] About the peer process. Accessed on: 13/2/2024.

[2] Iot-based power management system with home environment control. In *2018 IEEE International Conference on Information and Automation for Sustainability (ICIAfS)*, pages 1–6, 2018. https://doi.org/10.1109/ICIAFS.2018.8913359.

[3] Wokje Abrahamse, Linda Steg, Charles Vlek, and Talib Rothengatter. A review of intervention studies aimed at household energy conservation. *Journal of environmental psychology*, 25(3):273–291, 2005. https://doi.org/10.1016/j.jenvp.2005.08.002.

[4] NL Adnane Kendel. The diffusion of smart meters in france: A discussion of the empirical evidence and the implications for smart cities. sh technol res 53: 194–200, 2015. https://doi.org/10.1108/jsma-04-2015-0034.

[5] Rishika Agarwal, Madhur Garg, Dharani Tejaswini, Vishal Garg, Priyanka Srivastava, Jyotirmay Mathur, and Rajat Gupta. A review of residential energy feedback studies. *Energy and buildings*, 290:113071, 2023. https://doi.org/10.1016/j.enbuild.2023.113071.

[6] Datu Buyung Agusdinata, Muhammad Hanif, Rachael Shwom, David Watkins, Kristin Floress, Cara Cuite, and Kathleen E Halvorsen. Effectiveness of conservation messages to reduce households' ghg emissions: A serious-gaming experiment. *Journal of Environmental Management*, 351:119948, 2024. https://doi.org/10.1016/j.jenvman.2023.119948.

[7] Datu Buyung Agusdinata, Heide Lukosch, Muhammad Hanif, and David Watkins. A playful approach to household sustainability: Results from a pilot study on resource consumption. *Simulation & Gaming*, 54(1):104–130, 2023. https://doi.org/10.1177/10468781221138583.

[8] Rajesh K Ahir and Basab Chakraborty. A meta-analytic approach for determining the success factors for energy conservation. *Energy*, 230:120821, 2021. https://doi.org/10.1016/j.energy.2021.120821.

[9] Salma Alomar, Maryam Alashwan, Nabaa Busbaih, and Conrado Vizcarra. Smart home: Household appliance usage recommender and monitoring system (harms). In *2022 2nd International Conference on Computing and Information Technology (ICCIT)*, pages 278–284. IEEE, 2022. https://doi.org/10.1109/iccit52419.2022.9711598.

[10] Abdullah Alsalemi, Yassine Himeur, Fayal Bensaali, Abbes Amira, Christos Sardianos, Iraklis Varlamis, and George Dimitrakopoulos. Achieving domestic energy efficiency using micro-moments and intelligent recommendations. *IEEE Access*, 8:15047–15055, 2020. https://doi.org/10.1109/access.2020.2966640.

[11] Mark A Andor and Katja M Fels. Behavioral economics and energy conservation–a systematic review of non-price interventions and their causal effects. *Ecological economics*, 148:178–210, 2018. https://doi.org/10.1016/j.ecolecon.2018.01.018.

[12] Sérgio HMS Andrade, Gustavo O Contente, Lucas B Rodrigues, Luiguy X Lima, Nandamudi L Vijaykumar, and Carlos Renato L Francês. A smart home architecture for smart energy consumption in a residence with multiple users. *IEEE Access*, 9:16807–16824, 2021. https://doi.org/10.1109/ACCESS.2021.3051937.

[13] Association for Computing Machinery. Peer review in acm publications, 2024. Accessed: 23-06-2024.

[14] Simon Bager and Luis Mundaca. Making 'smart meters' smarter? insights from a behavioural economics pilot field experiment in copenhagen, denmark. *Energy Research & Social Science*, 28:68–76, 2017. https://doi.org/10.1016/j.erss.2017.04.008.

[15] Nicholas Bardsley, Milena Büchs, Patrick James, Anastasios Papafragkou, Thomas Rushby, Clare Saunders, Graham Smith, Rebecca Wallbridge, and Nicholas Woodman. Domestic thermal upgrades, community action and energy saving: A three-year experimental study of prosperous households. *Energy policy*, 127:475–485, 2019. https://doi.org/10.1016/j.enpol.2018.11.036.

[16] Lori Beaman and Andrew Dillon. Do household definitions matter in survey design? results from a randomized survey experiment in mali. *Journal of Development Economics*, 98(1):124–135, 2012. https://doi.org/10.1016/j.jdeveco.2011.06.005.

[17] Alfredo Behrens. Total energy consumption by brazilian households. *Energy*, 11(6):607–611, 1986. https://doi.org/10.1016/0360-5442(86)90108-8.

[18] Holly Berman, Rachael Shwom, and Cara Cuite. Becoming few conscious: A conceptual typology of household behavior change interventions targeting the food-energy-water (few) nexus. *Sustainability*, 11(18):5034, 2019. https://doi.org/10.3390/su11185034.

[19] Miriam Berretta, Joshua Furgeson, Yue Wu, Collins Zamawe, Ian Hamilton, and John Eyers. Residential energy efficiency interventions: A meta-analysis of effectiveness studies. *Campbell Systematic Reviews*, 17(4):e1206, 2021. https://doi.org/10.1002/cl2.1206.

[20] Stephen Bird and Lisa Legault. Feedback and behavioral intervention in residential energy and resource use: a review. *Current Sustainable/Renewable Energy Reports*, 5:116–126, 2018. https://doi.org/10.1007/s40518-018-0106-8.

[21] Jacky Bourgeois, Janet Van Der Linden, Gerd Kortuem, Blaine A Price, and Christopher Rimmer. Conversations with my washing machine: an in-the-wild

study of demand shifting with self-generated energy. In *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, pages 459–470, 2014. https://doi.org/10.1145/2632048.2632106.

[22] Kathryn Buchanan, Riccardo Russo, and Ben Anderson. The question of energy reduction: The problem (s) with feedback. *Energy Policy*, 77:89–96, 2015. https://doi.org/10.1016/j.enpol.2014.12.008.

[23] T Carapeto, D Coelho, and C Oliveira. Assessment of energy efficient retrofitting measures in the residential building sector. In *2016 51st International Universities Power Engineering Conference (UPEC)*, pages 1–6. IEEE, 2016. https://doi.org/10.1109/upec.2016.8113982.

[24] Paula Carroll, Tadhg Murphy, Michael Hanley, Daniel Dempsey, and John Dunne. Household classification using smart meter data. *Journal of official statistics*, 34(1):1–25, 2018. https://doi.org/10.1515/jos-2018-0001.

[25] Miquel Casals, Marta Gangolells, Marcel Macarulla, Núria Forcada, Alba Fuertes, and Rory V Jones. Assessing the effectiveness of gamification in reducing domestic energy consumption: Lessons learned from the energaware project. *Energy and Buildings*, 210:109753, 2020. https://doi.org/10.1016/j.enbuild.2019.109753.

[26] Francesca Cellina, Piero Fraternali, Sergio Luis Herrera Gonzalez, Jasminko Novak, Marco Gui, and Andrea Emilio Rizzoli. Significant but transient: The impact of an energy saving app targeting swiss households. *Applied Energy*, 355:122280, 2024. https://doi.org/10.1016/j.apenergy.2023.122280.

[27] Desiree I Cendana, Neriza V Bustillo, Thelma D Palaoag, Mark Anthony Marcial, and Arjay E Perreras. Harnessing energy consumption in a smarthome iot framework. In *2018 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData)*, pages 88–96. IEEE, 2018. https://doi.org/10.1109/cybermatics$_2$018.2018.00048.

[28] Rumeysa Ceylan and Aysegül Özbakır. Increasing energy conservation behavior of individuals towards sustainable and energy-efficient communities. *Smart Cities*, 5(4):1611–1634, 2022. https://doi.org/10.3390/smartcities5040082.

[29] IM Chatzigeorgiou and GT Andreou. A systematic review on feedback research for residential energy behavior change through mobile and web interfaces. *Renewable and Sustainable Energy Reviews*, 135:110187, 2021. https://doi.org/10.1016/j.rser.2020.110187.

[30] Ching-Han Chen, Ching-Yi Chen, Chih-Hsien Hsia, and Guan-Xin Wu. Big data collection gateway for vision-based smart meter reading network. In *2014 IEEE International Congress on Big Data*, pages 266–269. IEEE, 2014. https://doi.org/10.1109/bigdata.congress.2014.47.

[31] Jun Chen, Xiaohong Wang, and Koen Steemers. A statistical analysis of a residential energy consumption survey study in hangzhou, china. *Energy and Buildings*, 66:193–202, 2013. https://doi.org/10.1016/j.enbuild.2013.07.045.

[32] Xiaoxia Chen, Mélanie Despeisse, and Björn Johansson. Environmental sustainability of digitalization in manufacturing: A review. *Sustainability*, 12(24):10298, 2020. https://doi.org/10.3390/su122410298.

[33] Valentina Cillo, Antonio Messeni Petruzzelli, Lorenzo Ardito, and Manlio Del Giudice. Understanding sustainable innovation: A systematic literature review. *Corporate Social Responsibility and Environmental Management*, 26(5):1012–1025, 2019. https://doi.org/10.1002/csr.1783.

[34] Clarivate. Web of science core collection: Explanation of peer-reviewed journals, 2024. Accessed: 23-06-2024.

[35] Jordana W Composto and Elke U Weber. Effectiveness of behavioural interventions to reduce household energy demand: a scoping review. *Environmental Research Letters*, 17(6):063005, 2022. https://doi.org/10.1088/1748-9326/ac71b8.

[36] John Conti, Paul Holtberg, Jim Diefenderfer, Angelina LaRose, James T Turnure, and Lynn Westfall. International energy outlook 2016 with projections to 2040. Technical report, USDOE Energy Information Administration (EIA), Washington, DC (United States ..., 2016. https://doi.org/10.2172/1329373.

[37] Felix Creutzig, Blanca Fernandez, Helmut Haberl, Radhika Khosla, Yacob Mulugetta, and Karen C Seto. Beyond technology: demand-side solutions for climate change mitigation. *Annual Review of Environment and Resources*, 41, 2016. https://doi.org/10.1146/annurev-environ-110615-085428.

[38] Sarah Darby. Smart metering: what potential for householder engagement? *Building research & information*, 38(5):442–457, 2010. https://doi.org/10.1080/09613218.2010.492660.

[39] De Montfort University. Scopus content focus, 2024. Accessed: 23-06-2024.

[40] Sebastian Deterding, Miguel Sicart, Lennart Nacke, Kenton O'Hara, and Dan Dixon. Gamification. using game-design elements in non-gaming contexts. In *CHI'11 extended abstracts on human factors in computing systems*, pages 2425–2428. 2011. https://doi.org/10.1145/1979742.1979575.

[41] Eurostat. Energy consumption in households, 2023. Accessed on: 11/6/2024.

[42] Eurostat. Energy balance sheets, 2024. Accessed on: 5/2/2024. https://doi.org/10.2908/NRG_BAL_C.

[43] Eurostat. Energy consumption in households, 2024. Accessed on: 11/6/2024.

[44] H Fan, IF MacGill, and AB Sproul. Impact of feedback interventions on residential electricity demand in australia's first large scale smart grid project. 2015 ieee innovative smart grid technologies-asia (isgt asia), 1–6, 2015. https://doi.org/10.1109/isgt-asia.2015.7387090.

[45] Ahmad Faruqui and Sanem Sergici. Arcturus: international evidence on dynamic pricing. *The Electricity Journal*, 26(7):55–65, 2013. https://doi.org/10.2139/ssrn.2288116.

[46] Ahmad Faruqui, Sanem Sergici, and Ahmed Sharif. The impact of informational feedback on energy consumption—a survey of the experimental evidence. *Energy*, 35(4):1598–1608, 2010. https://doi.org/10.1016/j.energy.2009.07.042.

[47] Diego Castro Fettermann, Antonio Borriello, Andrea Pellegrini, Caroline G Cavalcante, John M Rose, and Paul F Burke. Getting smarter about household energy: the who and what of demand for smart meters. *Building Research & Information*, 49(1):100–112, 2021. https://doi.org/10.1080/09613218.2020.1807896.

[48] Jan Dirk Lou Fijnheer, Herre van Oostendorp, and Remco Veltkamp. Household energy conservation intervention: A game versus dashboard comparison. *International Journal of Serious Games*, 6(3):23–36, 2019. https://doi.org/10.17083/ijsg.v6i3.300.

[49] Daphne Geelen, Ruth Mugge, Sacha Silvester, and Annemieke Bulters. The use of apps to promote energy saving: A study of smart meter–related feedback in the netherlands. *Energy Efficiency*, 12(6):1635–1660, 2019. https://doi.org/10.1007/s12053-019-09777-z.

[50] Howard Geller and Sophie Attali. The experience with energy efficiency policies and programmes in iea countries. *Learning from the Critics. Paris: IEA. IEA Information Paper*, 2005.

[51] Shu-Cheng Gu, Ching-Hung Cheng, and Gwo-Jia Jong. The power monitor system combined green energy. In *2013 1st International Future Energy Electronics Conference (IFEEC)*, pages 757–760. IEEE, 2013. https://doi.org/10.1109/ifeec.2013.6687603.

[52] Rajat Gupta, Laura Barnfield, and Matthew Gregg. Exploring innovative community and household energy feedback approaches. *Building Research & Information*, 46(3):284–299, 2018. https://doi.org/10.1080/09613218.2017.1356130.

[53] Rajat Gupta and Johanna Morey. Evaluation of residential demand response trials with smart heat pumps and batteries and their effect at the substation feeder. *Journal of Cleaner Production*, 403:136760, 2023. https://doi.org/10.1016/j.jclepro.2023.136760.

[54] Rebecca Hafner, Alba Fuertes, Sabine Pahl, Rory Jones, Christine Boomsma, Marta Gangolells, and Miquel Casals. Results and insight gained from applying the energycat energy-saving serious game in uk social housing. *International journal of serious games*, 7(2):27, 2020. https://doi.org/10.17083/ijsg.v7i2.333.

[55] Robert Hahn and Robert Metcalfe. The impact of behavioral science experiments on energy policy. *Economics of Energy & Environmental Policy*, 5(2):27–44, 2016. https://doi.org/10.5547/2160-5890.5.2.rhah.

[56] Xiao Han and Chu Wei. Household energy consumption: State of the art, research gaps, and future prospects. *Environment, Development and Sustainability*, 23(8):12479–12504, 2021. https://doi.org/10.1007/s10668-020-01179-x.

[57] Tom Hargreaves and Lucie Middlemiss. The importance of social relations in shaping energy demand. *Nature Energy*, 5(3):195–201, 2020. https://doi.org/10.1038/s41560-020-0553-5.

[58] Marisa L Henry, Paul J Ferraro, and Andreas Kontoleon. The behavioural effect of electronic home energy reports: Evidence from a randomised field trial in the united states. *Energy Policy*, 132:1256–1261, 2019. https://doi.org/10.1016/j.enpol.2019.06.039.

[59] Mikael Höök and Xu Tang. Depletion of fossil fuels and anthropogenic climate change—a review. *Energy policy*, 52:797–809, 2013. https://doi.org/10.1016/j.enpol.2012.10.046.

[60] Nicole MA Huijts, Eric JE Molin, and Linda Steg. Psychological factors influencing sustainable energy technology acceptance: A review-based comprehensive framework. *Renewable and sustainable energy reviews*, 16(1):525–531, 2012. https://doi-org.proxy.library.uu.nl/10.1016/j.rser.2011.08.018.

[61] Naseer Ali Hussien, Alaa Abdulhussein Daleh Al-Magsoosi, Haider Th Salim Alrikabi, and Faisal Theyab Abed. Monitoring the consumption of electrical energy based on the internet of things applications. *International Journal of Interactive Mobile Technologies*, 15(7), 2021. https://doi.org/10.3991/ijim.v15i07.20183.

[62] Berg Insight. Smart electricity meter penetration rate in europe reached 56 percent at the end of 2022, 2023. Accessed: 08-07-2024.

[63] Obiajulu Iweka, Shuli Liu, Ashish Shukla, and Da Yan. Energy and behaviour at home: A review of intervention methods and practices. *Energy Research & Social Science*, 57:101238, 2019. https://doi.org/10.1016/j.erss.2019.101238.

[64] Dr Lal Jayamaha. *Energy-efficient building systems*. Mcgraw-hill publishing Company, 2007.

[65] Rikke Hagensby Jensen, Jesper Kjeldskov, and Mikael B Skov. Assisted shifting of electricity use: a long-term study of managing residential heating. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 25(5):1–33, 2018. https://doi.org/10.1145/3210310.

[66] Daniel Johnson, Ella Horton, Rory Mulcahy, and Marcus Foth. Gamification and serious games within the domain of domestic energy consumption: A systematic review. *Renewable and Sustainable Energy Reviews*, 73:249–264, 2017. https://doi.org/10.1016/j.rser.2017.01.134.

[67] Samia Khondoker Joya, Smita Das, Bidyut Baran Saha, and Sampad Ghosh. Bluetooth based smart plug design for energy monitoring in household applications. In *2021 5th International Conference on Electrical Information and Communication Technology (EICT)*, pages 1–5. IEEE, 2021. https://doi.org/10.1109/eict54103.2021.9733488.

[68] Tutun Juhana and Arif Indra Irawan. Smart non intrusive power consumption monitoring system. In *2016 10th International Conference on Telecommunication Systems Services and Applications (TSSA)*, pages 1–4. IEEE, 2016. https://doi.org/10.1109/TSSA.2016.7871102.

[69] Tutun Juhana and Arif Indra Irawan. Smart non intrusive power consumption monitoring system. In *2016 10th International Conference on Telecommunication Systems Services and Applications (TSSA)*, pages 1–4. IEEE, 2016. https://doi.org/10.1109/tssa.2016.7871102.

[70] Serhiy Kandul, Ghislaine Lang, and Bruno Lanz. Social comparison and energy conservation in a collective action context: A field experiment. *Economics Letters*, 188:108947, 2020. https://doi.org/10.1016/j.econlet.2020.108947.

[71] Beth Karlin, Joanne F Zinger, and Rebecca Ford. The effects of feedback on energy conservation: A meta-analysis. *Psychological bulletin*, 141(6):1205, 2015. https://doi.org/10.1037/a0039650.

[72] Atieh Kashani and Yusuf Ozturk. Residential energy consumer behavior modification via gamification. In *2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA)*, pages 1221–1225. IEEE, 2017. https://doi.org/10.1109/icrera.2017.8191247.

[73] Ingo Kastner and Paul C Stern. Examining the decision-making processes behind household energy investments: A review. *Energy Research & Social Science*, 10:72–89, 2015. https://doi.org/10.1016/j.erss.2015.07.008.

[74] Tarun M Khanna, Giovanni Baiocchi, Max Callaghan, Felix Creutzig, Horia Guias, Neal R Haddaway, Lion Hirth, Aneeque Javaid, Nicolas Koch, Sonja Laukemper, et al. A multi-country meta-analysis on the role of behavioural change in reducing energy consumption and co2 emissions in residential buildings. *Nature Energy*, 6(9):925–932, 2021. https://doi.org/10.1038/s41560-021-00866-x.

[75] Y Kiguchi, M Weeks, and R Arakawa. Predicting winners and losers under time-of-use tariffs using smart meter data. *Energy*, 236:121438, 2021. https://doi.org/10.1016/j.energy.2021.121438.

[76] Konstantinos Koasidis, Vangelis Marinakis, Alexandros Nikas, Katerina Chira, Alexandros Flamos, and Haris Doukas. Monetising behavioural change as a policy measure to support energy management in the residential sector: A case study in greece. *Energy Policy*, 161:112759, 2022. https://doi.org/10.1016/j.enpol.2021.112759.

[77] Ksenia Koroleva, Mark Melenhorst, Jasminko Novak, Sergio Luis Herrera Gonzalez, Piero Fraternali, and Andrea E Rizzoli. Designing an integrated socio-technical behaviour change system for energy saving. *Energy Informatics*, 2(1):1–20, 2019. https://doi.org/10.1186/s42162-019-0088-9.

[78] Nathalie Lazaric and Mira Toumi. Reducing consumption of electricity: A field experiment in monaco with boosts and goal setting. *Ecological Economics*, 191:107231, 2022. https://doi.org/10.1016/j.ecolecon.2021.107231.

[79] Seungwoo Lee, Gilyoung Ryu, Yohan Chon, Rhan Ha, and Hojung Cha. Automatic standby power management using usage profiling and prediction. *IEEE Transactions on Human-Machine Systems*, 43(6):535–546, 2013. https://doi.org/10.1109/thms.2013.2285921.

[80] Xiaoyan Li, Jia Liu, and Peijie Ni. The impact of the digital economy on co2 emissions: A theoretical and empirical analysis. *Sustainability*, 13(13):7267, 2021. https://doi.org/10.3390/su13137267.

[81] Hui Liu, Mengyu Han, and Yang Shen. Technology-driven energy revolution: The impact of digital technology on energy efficiency and its mechanism. *Frontiers in Energy Research*, 11:1242580, 2023. https://doi.org/10.3389/fenrg.2023.1242580.

[82] KJ Lomas, David Allinson, Stephen Watson, Arash Beizaee, VJ Haines, and M Li. Energy savings from domestic zonal heating controls: Robust evidence from a controlled field trial. *Energy and Buildings*, 254:111572, 2022. https://doi.org/10.1016/j.enbuild.2021.111572.

[83] Jean-Nicolas Louis, Antonio Caló, Kauko Leiviskä, and Eva Pongrácz. Modelling home electricity management for sustainability: The impact of response levels, technological deployment & occupancy. *Energy and Buildings*, 119:218–232, 2016. https://doi.org/10.1016/j.enbuild.2016.03.012.

[84] Yuehong Lu, Zafar A Khan, Manuel S Alvarez-Alvarado, Yang Zhang, Zhijia Huang, and Muhammad Imran. A critical review of sustainable energy policies for the promotion of renewable energy sources. *Sustainability*, 12(12):5078, 2020. https://doi.org/10.3390/su12125078.

[85] Rafael Martínez-Peláez, Alberto Ochoa-Brust, Solange Rivera, Vanessa G Félix, Rodolfo Ostos, Héctor Brito, Ramón A Félix, and Luis J Mena. Role of digital transformation for achieving sustainability: mediated role of stakeholders, key capabilities, and technology. *Sustainability*, 15(14):11221, 2023. https://doi.org/10.3390/su151411221.

[86] Ryan McAndrew, Rory Mulcahy, Ross Gordon, and Rebekah Russell-Bennett. Household energy efficiency interventions: A systematic literature review. *Energy Policy*, 150:112136, 2021. https://doi.org/10.1016/j.enpol.2021.112136.

[87] Daire McCoy and Sean Lyons. Unintended outcomes of electricity smart-metering: trading-off consumption and investment behaviour. *Energy Efficiency*, 10(2):299–318, 2017. https://doi.org/10.1007/s12053-016-9452-9.

[88] Tsvetelina Mladenova and Vladimir Cankov. Smart home based on iot-architecture and practices. In *2023 5th International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA)*, pages 1–5. IEEE, 2023. https://doi.org/10.1109/hora58378.2023.10156739.

[89] David Moher, Alessandro Liberati, Jennifer Tetzlaff, Douglas G Altman, Prisma Group, et al. Preferred reporting items for systematic reviews and meta-analyses: the prisma statement. *International journal of surgery*, 8(5):336–341, 2010. https://doi.org/10.1016/j.ijsu.2010.02.007.

[90] Anshu Prakash Murdan and Krishna Kullootee. Wi-fi and lorawan based interactive control system for household energy management. In *2020 IEEE International Conference on Power Systems Technology (POWERCON)*, pages 1–6. IEEE, 2020. https://doi.org/10.1109/powercon48463.2020.9230579.

[91] Latha Murugesan, Rashina Hoda, Zoran Salcic, and Piyush Verma. Policy recommendations to induce behavioural changes through interactive energy visualisation. In *2018 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia)*, pages 1091–1096. IEEE, 2018. https://doi.org/10.1109/isgt-asia.2018.8467776.

[92] Genevieve C Ngo, Judd Kristian I Floriza, Christine May C Creayla, Felan Carlo C Garcia, and Erees Queen B Macabebe. Real-time energy monitoring system for grid-tied photovoltaic installations. In *TENCON 2015-2015 IEEE Region 10 Conference*, pages 1–4. IEEE, 2015. https://doi.org/10.1109/tencon.2015.7372784.

[93] Simon Pettersen Nguyen. Mobile application for household energy consumption feedback using smart meters: Increasing energy awareness, encouraging energy savings and avoiding energy peaks. In *2014 International Conference on Collaboration Technologies and Systems (CTS)*, pages 291–296. IEEE, 2014. https://doi.org/10.1109/cts.2014.6867579.

[94] Claudia F Nisa, Jocelyn J Bélanger, Birga M Schumpe, and Daiane G Faller. Meta-analysis of randomised controlled trials testing behavioural interventions to promote household action on climate change. *Nature communications*, 10(1):4545, 2019. https://doi.org/10.1038/s41467-019-12457-2.

[95] Vasileios Ntouros, Nikolaos Kampelis, Martina Senzacqua, Theoni Karlessi, Margarita-Niki Assimakopoulos, Dionysia Kolokotsa, and Cristina Cristalli. Smart meter awareness in italy, ancona. In *Smart and Sustainable Planning for Cities and Regions: Results of SSPCR 2019—Open Access Contributions 3*, pages 47–66. Springer International Publishing, 2021. https://doi.org/10.1007/978-3-030-57764-3_4.

[96] Caroline Sofie Olsen. Visualization of energy consumption: Motivating for a sustainable behaviour through social media. In *2014 International Conference*

on Collaboration Technologies and Systems (CTS), pages 641–646. IEEE, 2014. https://doi.org/10.1109/cts.2014.6867642.

[97] Christian Oltra, Alex Boso, Josep Espluga, and Ana Prades. A qualitative study of users' engagement with real-time feedback from in-house energy consumption displays. *Energy Policy*, 61:788–792, 2013. https://doi.org/10.1016/j.enpol.2013.06.127.

[98] Simona-Vasilica Oprea and Adela Bara. Setting the time-of-use tariff rates with nosql and machine learning to a sustainable environment. *IEEE Access*, 8:25521–25530, 2020. https://doi.org/10.1109/access.2020.2969728.

[99] Jessie Parrish and Hannah V Uren. Communicating energy efficiency to senior citizens: the influence of solar-pv and role of technology. *Energy Procedia*, 121:254–261, 2017. https://doi.org/10.1016/j.egypro.2017.08.025.

[100] Sebastian Prost, Elke Mattheiss, and Manfred Tscheligi. From awareness to empowerment: Using design fiction to explore paths towards a sustainable energy future. In *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing*, pages 1649–1658, 2015. https://doi.org/10.1145/2675133.2675281.

[101] Vishamlall Ramrecha, Girish Bekaroo, Aditya Santokhee, and Suraj Juddoo. Exploring the application and usability of nfc for promoting self-learning on energy consumption of household electronic appliances. In *2017 IEEE 4th International Conference on Soft Computing & Machine Intelligence (ISCMI)*, pages 154–158. IEEE, 2017. https://doi.org/10.1109/iscmi.2017.8279617.

[102] Thomas Rist and Masood Masoodian. Promoting sustainable energy consumption behavior through interactive data visualizations. *Multimodal Technologies and Interaction*, 3(3):56, 2019. https://doi.org/10.3390/mti3030056.

[103] Ute Ritterfeld, Michael Cody, and Peter Vorderer. *Serious games: Mechanisms and effects*. Routledge, 2009.

[104] Jose I Rojas-Mendez, A Parasuraman, and Nicolas Papadopoulos. Demographics, attitudes, and technology readiness: A cross-cultural analysis and model validation. *Marketing Intelligence & Planning*, 35(1):18–39, 2017. https://doi.org/10.1108/mip-08-2015-0163.

[105] Andrew Royal and Galib Rustamov. Do small pecuniary incentives motivate residential peak energy reductions? experimental evidence. *Applied Economics*, 50(57):6193–6202, 2018. https://doi.org/10.2139/ssrn.3061299.

[106] Gabrielle Samuel, Federica Lucivero, and Lucas Somavilla. The environmental sustainability of digital technologies: Stakeholder practices and perspectives. *Sustainability*, 14(7):3791, 2022. https://doi.org/10.3390/su14073791.

[107] Christos Sardianos, Iraklis Varlamis, Christos Chronis, George Dimitrakopoulos, Yassine Himeur, Abdullah Alsalemi, Faycal Bensaali, and Abbes Amira. Data analytics, automations, and micro-moment based recommendations for energy efficiency. In *2020 IEEE Sixth International conference on big data computing service and applications (BigDataService)*, pages 96–103. IEEE, 2020. https://doi.org/10.1109/bigdataservice49289.2020.00022.

[108] Aya Sayed, Yassine Himeur, Abdullah Alsalemi, Faycal Bensaali, and Abbes Amira. Intelligent edge-based recommender system for internet of energy applications. *IEEE Systems Journal*, 16(3):5001–5010, 2021. https://doi.org/10.29117/quarfe.2021.0161.

[109] Sanja Šćepanović, Martijn Warnier, and Jukka K Nurminen. The role of context in residential energy interventions: A meta review. *Renewable and Sustainable Energy Reviews*, 77:1146–1168, 2017. https://doi.org/10.1016/j.rser.2016.11.044.

[110] Jim Scheer, Matthew Clancy, and Sadhbh Ní Hógáin. Quantification of energy savings from ireland's home energy saving scheme: an ex post billing analysis. *Energy Efficiency*, 6:35–48, 2013. https://doi.org/10.1007/s12053-012-9164-8.

[111] Joachim Schleich, Marian Klobasa, Sebastian Gölz, and Marc Brunner. Effects of feedback on residential electricity demand—findings from a field trial in austria. *Energy Policy*, 61:1097–1106, 2013. https://doi.org/10.1016/j.enpol.2013.05.012.

[112] P Wesley Schultz, Mica Estrada, Joseph Schmitt, Rebecca Sokoloski, and Nilmini Silva-Send. Using in-home displays to provide smart meter feedback about household electricity consumption: A randomized control trial comparing kilowatts, cost, and social norms. *Energy*, 90:351–358, 2015. https://doi.org/10.1016/j.energy.2015.06.130.

[113] Ghasson Shabha, Francesca Barber, and Paul Laycock. A qualitative assessment of the impact of smart homes and environmentally beneficial technologies on the uk 2050 net-zero carbon emission target. *Smart and Sustainable Built Environment*, 12(2):341–360, 2023. https://doi.org/10.1108/sasbe-07-2021-0112.

[114] E Shanthini, M Jagadeeswari, S Kavya, I Pavinitha, and V Preethi. Implementation of automatic power saving system. In *2023 2nd International Conference on Vision Towards Emerging Trends in Communication and Networking Technologies (ViTECoN)*, pages 1–5. IEEE, 2023. https://doi.org/10.1109/vitecon58111.2023.10157363.

[115] Meng Shen, Yujie Lu, Harn Wei Kua, and Qingbin Cui. Eco-feedback delivering methods and psychological attributes shaping household energy consumption: Evidence from intervention program in hangzhou, china. *Journal of Cleaner Production*, 265:121755, 2020. https://doi.org/10.1016/j.jclepro.2020.121755.

[116] Jitender Pal Singh, Omar Alam, and Abdulsalam Yassine. Influence of geodemographic factors on electricity consumption and forecasting models. *IEEE Access*, 10:70456–70466, 2022. https://doi.org/10.1109/access.2022.3188004.

[117] Alan F Smeaton and Aiden R Doherty. Persuading consumers to reduce their consumption of electricity in the home. In *International Conference on Persuasive Technology*, pages 204–215. Springer, 2013. https://doi.org/10.1007/978-3-642-37157-8$_2$5.

[118] Beata Smela, Mondher Toumi, Karolina Świerk, Clement Francois, Małgorzata Biernikiewicz, Emilie Clay, and Laurent Boyer. Rapid literature review: definition and methodology. *Journal of Market Access & Health Policy*, 11(1):2241234, 2023. https://doi.org/10.1080/20016689.2023.2241234.

[119] Mette Talseth Solnørdal and Lene Foss. Closing the energy efficiency gap—a systematic review of empirical articles on drivers to energy efficiency in manufacturing firms. *Energies*, 11(3):518, 2018. https://doi.org/10.3390/en11030518.

[120] Lidia Stermieri, Tom Kober, TJ Schmidt, Russell McKenna, and Evangelos Panos. Quantifying the implications of behavioral changes induced by digitalization on energy transition: A systematic review of methodological approaches. *Energy Research & Social Science*, 97:102961, 2023. https://doi.org/10.1016/j.erss.2023.102961.

[121] Jon Stinson, Alexandra Willis, Julio Bros Williamson, John Currie, and R Sean Smith. Visualising energy use for smart homes and informed users. *Energy Procedia*, 78:579–584, 2015. https://doi.org/10.1016/j.egypro.2015.11.015.

[122] Senthilkumar Subramanian, M Bindhu, Shradha Umathe, Sarveswara Rao, Shanmugavel Deivasigamani, and M Ramarao. Wireless sensor & rfid based smart energy management for automated home. In *2022 International Conference on Augmented Intelligence and Sustainable Systems (ICAISS)*, pages 1125–1129. IEEE, 2022. https://doi.org/10.1109/icaiss55157.2022.10010710.

[123] Verena Tiefenbeck, Anselma Wörner, Samuel Schöb, Elgar Fleisch, and Thorsten Staake. Real-time feedback reduces energy consumption among the broader public without financial incentives. *Nature Energy*, 4(10):831–832, 2019. https://doi.org/10.1038/s41560-019-0480-5.

[124] Uros Tomic, Bernadette Sütterlin, Evelyn Lobsiger-Kägi, Reto Marek, Curdin Derungs, and Ernst Sandmeier. Reducing hot water consumption through real-time feedback and social comparison using persuasive technologies: evidence from a swiss energy-efficient district. *Energy Efficiency*, 17(3):15, 2024. https://doi.org/10.1007/s12053-024-10199-9.

[125] Sofia Tsemekidi Tzeiranaki, Paolo Bertoldi, Francesca Diluiso, Luca Castellazzi, Marina Economidou, Nicola Labanca, Tiago Ribeiro Serrenho, and Paolo Zangheri. Analysis of the eu residential energy consumption: Trends and determinants. *Energies*, 12(6):1065, 2019. https://doi.org/10.3390/en12061065.

[126] Tian Wang, Qinfeng Zhao, Weijun Gao, and Xiujuan He. Research on energy consumption in household sector: a comprehensive review based on bibliometric analysis. *Frontiers in Energy Research*, 11, 2024. https://doi.org/10.3389/fenrg.2023.1209290.

[127] Richard T Watson, Marie-Claude Boudreau, and Adela J Chen. Information systems and environmentally sustainable development: energy informatics and new directions for the is community. *MIS quarterly*, pages 23–38, 2010. https://doi.org/10.2307/20721413.

[128] Eric Williams. Environmental effects of information and communications technologies. *nature*, 479(7373):354–358, 2011. https://doi.org/10.1038/nature10682.

[129] Kimberly Wolske, Kenneth Gillingham, P. Wesley Schultz, et al. Social dynamics of energy behaviour. *Nature Energy*, 5:179, 2020. https://doi.org/10.1038/s41560-020-0595-8.

[130] Georgina Wood, Rosie Day, Emily Creamer, Dan Van Der Horst, Atif Hussain, Shuli Liu, Ashish Shukla, Obiajulu Iweka, Mark Gaterell, Panagiotis Petridis, et al. Sensors, sense-making and sensitivities: Uk household experiences with a feedback display on energy consumption and indoor environmental conditions. *Energy Research & Social Science*, 55:93–105, 2019. https://doi.org/10.1016/j.erss.2019.04.013.

[131] Seth Wynes, Kimberly A Nicholas, Jiaying Zhao, and Simon D Donner. Measuring what works: quantifying greenhouse gas emission reductions of behavioural interventions to reduce driving, meat consumption, and household energy use. *Environmental Research Letters*, 13(11):113002, 2018. https://doi.org/10.1088/1748-9326/aae5d7.

[132] Qian Xu, Shengping Li, Liyin Shen, Ruidong Chang, Qian-Cheng Wang, Xuan Liu, and Yang Chen. Pricing strategy for household energy-saving option (heso): A novel option-based intervention for promoting household energy efficiency. *Environmental Impact Assessment Review*, 98:106969, 2023. https://doi.org/10.2139/ssrn.4170050.

[133] Qian Xu, Yujie Lu, and Bon-Gang Hwang. Effectiveness of innovative intervention—household energy saving option (heso) on promoting energy conservation in residential buildings. In *International Symposium on Advancement of Construction Management and Real Estate*, pages 1801–1817. Springer, 2019. https://doi.org/10.1007/978-981-15-8892-$1_1$26.

[134] Qian Xu, Yujie Lu, Bon-Gang Hwang, and Harn Wei Kua. Reducing residential energy consumption through a marketized behavioral intervention: The approach of household energy saving option (heso). *Energy and buildings*, 232:110621, 2021. https://doi.org/10.1016/j.enbuild.2020.110621.

[135] Wahiba Yaïci, Evgueniy Entchev, Michela Longo, and Andres Annuk. Internet of things (iot) monitoring and control for smart heating and cooling in a residential building. In *2023 12th International Conference on Renewable Energy Research and Applications (ICRERA)*, pages 387–392. IEEE, 2023. https://doi.org/10.1109/icrera59003.2023.10269351.

[136] Xing Yan, Dustin Wright, Sunil Kumar, Gordon Lee, and Yusuf Ozturk. Enabling consumer behavior modification through real time energy pricing.

In *2015 IEEE International Conference on Pervasive Computing and Communication Workshops (PerCom Workshops)*, pages 311–316. IEEE, 2015. https://doi.org/10.1109/percomw.2015.7134054.

[137] Datong P Zhou, Maximilian Balandat, and Claire J Tomlin. Estimation and targeting of residential households for hour-ahead demand response interventions–a case study in california. In *2018 IEEE Conference on Control Technology and Applications (CCTA)*, pages 18–23. IEEE, 2018. https://doi.org/10.1109/ccta.2018.8511520.

[138] Datong Paul Zhou, Maximilian Balandat, and Claire Jennifer Tomlin. Estimating treatment effects of a residential demand response program using non-experimental data. In *2017 IEEE International Conference on Data Mining Workshops (ICDMW)*, pages 95–102. IEEE, 2017. https://doi.org/10.1109/icdmw.2017.18.

[139] Hang Zhu, Michael R Brambley, and Robert P Morgan. Household energy consumption in the people's republic of china. *Energy*, 8(10):763–774, 1983. https://doi.org/10.1016/0360-5442(83)90050-6.

Annotated Appendix

1 Introduction

During the process of writing the research paper and this thesis, multiple decisions have been made. Each of these decisions scoped the research further into the final result. Some aspects of the research process will be highlighted in this annotated appendix because they were crucial for the development of the findings and the overall project. It will, hopefully, give some ideas of why certain aspects were incorporated or left out of the research.

2 Research context

Besides the decisions made about the design of the research, such as the questions and the methodology, there were also some decisions made in regard to the contents of the research. These decisions were made beforehand to define the context of the research and making sure that there would be an clear understanding of the research goal. These decisions will be discussed in the following sections.

2.1 Households

This research is solely focused on households, because when looking at interventions in larger organizations, energy consumption will have to be monitored on a much larger scale, which can make the research unnecessarily difficult and extensive. The definition of a household can be a bit ambiguous and can be adapted to the local context, but for this research, a household has been broadly defined as a group of people who live together and eat their meals together [16]. With interventions, the focus will mostly be on intervening in an individual's behavior and, thereby, affecting a larger group in the households. Because energy consumption within a household is most likely based on the social dynamic. For example, decisions made about heating the home are most likely based on the different comfort needs of the people who live there. However, the foundation of an intervention lies in making an individual aware of their behavior, striving to modify and adjust the behavioral pattern, while keeping in mind that the behavior can be based on multiple people's needs [57][129]. It is, thereby, advised that when implementing interventions in households, tailor it to the specific needs and goals of the people that are part of that household [49].

2.2 Economically developing countries

This research also has incorporated data that is gathered in countries with a strong developed economy. As these countries usually have more financial resources and infrastructures, that can support the adaptation of sustainable energy technologies. This makes the implementation and integration of digital energy interventions more feasible. Economically developed countries often have a higher level of technological readiness, which makes households more likely to access sustainable technologies. Households in developed countries are also more likely to afford and use digital energy interventions [104].

3 Research questions

3.1 Main Research question

Formulating research questions is always an important process during research. For this thesis, the initial main research question was formulated as follows:

What are the trade-offs between the environmental benefits provided by sustainable energy technologies and the resources that are required to build them, and how can this balance be improved?

This question was initially promising but seemed a bit too challenging along the way. It reflects on multiple aspects in the context of digital energy interventions. And especially the second part regarding the balance was a bit too much for this thesis. There was limited research that could provide any insights into this balance and it would, thus, require far more work than required for the process of this research. The question was then refined to:

What are the trade-offs between the environmental benefits provided by sustainable energy interventions and the resources that are required to build and operate them within households?

Due to the nature of this question, the initial idea was to focus on two different aspects of digital energy interventions aimed at energy reduction. However, after extensive literature research, it turns out that the resources are rarely discussed in the literature and their effectiveness is most often not measured quantitatively. This would make a trade-off significantly difficult to describe. That is why the main research question was, again, updated to the following:

How can the trade-offs between the environmental benefits of sustainable energy interventions and the resources required to build and operate them within households be identified and evaluated to develop effective research guidelines?

However, this research question made it seem like the research would go into how to do research. It shifts the focus towards the methodology of developing guidelines for doing research, rather than focusing on the environmental benefits and resources of the interventions. Developing guidelines was not the main purpose of the results and overall process. A fourth attempt at the main research question was made:

What are the environmental benefits of sustainable energy interventions, the resources required to build and operate them within households, and the current state of research on their reliability and validity?

This question was still a bit unclear in regards to what it would refer to. After five attempts, the final main research question is formulated as:

What are the environmental benefits of sustainable energy interventions, the resources required to build and operate them within households, and the current state of reliability and validity of the corresponding research?

3.2 Other research questions

Besides the main research question, there was also a process of defining the other research questions. These together will add up to aid in answering the main research question. This refinement did not take quite as long as the main research question, but there were still some adjustments made along the way. The first attempt at these research questions was:

RQ1: How do different types of technological features vary in terms of their energy efficiency?

RQ2: What are the main resources required for the development and operation of digital energy interventions?

The first question was refined a bit to shift from technological features to a broader term of digital energy interventions, this still includes technological features but makes the question a bit more understandable if read. Thereby also including the overall energy efficiency of the interventions, not solely focused on the energy efficiency of the technological features. A third research question was added after the fourth attempt of the main research question, to support the main research question regarding the current state of the literature in intervention research. The final three research questions were as follows:

RQ1: How do different types of digital energy interventions vary in terms of their energy efficiency?

RQ2: What are the main resources required for the development and operation of digital energy interventions?

RQ3: What is the current status and what are the necessary next steps in intervention research?

4 Methodology

4.1 Keyword refinement

Before the initialization of the methodology, before the identification phase, it was needed to identify some keywords that would be used as input in the search queries. Defining keywords beforehand will help with the search strategy and can make the project more manageable because the pre-defined keywords can ensure that the key conclusions will be extracted faster [118]. The following keywords have been defined through initial literature research. Using these keywords, individually or in combination, for search queries has resulted in finding literature that provides valuable information for this research. These keywords will, thereby, provide a foundation for the literature review, and also a first step in the process of defining more precise keywords. The following keyword list was the first attempt at this. These were purely derived from initially read literature in phase 1 of the thesis:

- Digital intervention
- Household
- Energy
- Sustainable
- Efficiency

However, after a first attempt at finding literature from different search engines, it turned out that the keywords were relatively broad and that queries with these keywords resulted in very general results, often not even aimed at interventions for energy reduction but rather at household sustainability in general. Further investigation into the keywords was necessary. Some keywords were added to the list, which resulted in the following:

- Digital intervention
- Household
- Residential
- Smart grid intervention
- Energy
- Monitoring intervention
- Sustainable
- Residential efficiency
- Energy consumption
- Trade-off

After the second attempt, the results looked more promising, as some interesting articles were found. The aspect that was still missing, was that of the resources. In some preliminary literature study, some keywords were identified that could aid in finding more literature about the resources side of digital energy intervention research. These keywords were added to the list:

- Digital intervention
- Household
- Residential
- Smart grid intervention
- Energy
- Monitoring intervention
- Sustainable
- Residential efficiency
- Energy consumption
- Trade-off
- In-home display
- Smart meter
- Technology resources
- Operation
- Cost(s)
- Wireless sensor network

After working with this keyword list, some categories were identified. It became clear that feedback through smartphones and web-based applications was commonly used in household interventions to reduce energy consumption. So, these should be incorporated into the keywords list attempt to find the majority of the literature in this research area. The word *architecture* was also found during this process, which was deemed as an keyword that could even find more literature regarding the resources, as that was already difficult to find. The following, and also final, list of keywords was established:

- Digital intervention
- Household
- Residential
- Smart grid intervention
- Energy
- Monitoring intervention
- Sustainable
- Residential efficiency
- Energy consumption
- Trade-off
- In-home display
- Smart meter
- Technology resources
- Operation
- Cost(s)
- Wireless sensor network
- Technology architecture
- Smartphone applications
- Web-based applications
- Feedback
- Intervention methods

This final list of identified keywords was used to identify literature that included such keywords in titles and abstracts.

4.2 Search queries

During the process of finding the appropriate keywords to encapsulate this research, there was also already an insight into what could be expected in regard to the search queries. During this, it also became clear that some search queries were not sufficient enough to find the right literature. It turned out that some keyword combinations resulted in significantly large results (between 80-240 articles). In that case, further refinement of the keywords was necessary to decrease the articles that resulted from the query. These queries can be seen on the left of Figure 2. It was also decided to refine by using the filter option through the search engine. For example, looking for keywords to appear not only in the abstract of an article but also in the keywords, to attempt to limit the search results. The updated search queries can be seen in Figure 2 on the right.

The final used set of queries to gather all of the literature in the identification phase is as follows:

ACM Digital Library

- """query"": Title:(Household energy interventions) AND Abstract:(Household energy interventions) AND Keyword:(Household energy interventions) ""filter"": Published in: Proceedings of the ACM on Human-Computer Interaction, E-Publication Date: (01/01/2013 TO 12/31/2024), ACM Content: DL "
- """query"": Title:(Residential smart grid intervention) AND Abstract:(Residential smart grid intervention) AND Keyword:(Residential smart grid intervention) ""filter"": Published in: Proceedings of the ACM on Human-Computer Interaction, E-Publication Date: (01/01/2013 TO 12/31/2024), ACM Content: DL "

IEEEXplore

- ("All Metadata":Residential smart grid intervention)
  - *Additional filter:* Year range=2013-2024
- ("All Metadata":Household intervention technology costs)
  - *Additional filter:* Year range=2013-2024
- ("All Metadata":Household smart meter costs)
  - *Additional filter:* Year range=2013-2024, Open Access Only
- ("All Metadata":Smart meter technology household energy reduction)

- *Additional filter:* Year range=2013-2024, Open Access Only

- ("All Metadata":Wireless sensor network household energy reduction)
  - *Additional filter:* Year range=2013-2024
- ("All Metadata":Wireless sensor network household implementation intervention)
  - *Additional filter:* Year range=2013-2024
- ("All Metadata":Smart meter energy usage costs)
  - *Additional filter:* Year range=2013-2024, Open Access Only
- ("All Metadata":Smart meter architecture implementation costs)
  - *Additional filter:* Year range=2013-2024, Open Access Only
- ("All Metadata":Household intervention experiment)
  - *Additional filter:* Year range=2013-2024
- ("All Metadata":Energy cost of in-home display)
  - *Additional filter:* Year range=2013-2024
- ("All Metadata":Operation costs smart meter household)
  - *Additional filter:* Year range=2013-2024, Open Access Only
- ("All Metadata":Web-based application household energy)
  - *Additional filter:* Year range=2013-2024
- ("All Metadata":Residential smart meter implementation)
  - *Additional filter:* Year range=2013-2024, Open Access Only
- ("All Metadata":Smartphone application household energy consumption)
  - *Additional filter:* Year range=2013-2024

Web of Science

- (AB=(household energy intervention) AND TI=(household energy intervention)) AND (PY==("2013" OR "2014" OR "2015" OR "2017" OR "2016" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023" OR "2024"))
- (AB=(household sustainability energy intervention) AND TI=(household sustainability energy intervention)) AND (PY==("2013" OR "2014" OR "2015" OR "2017" OR "2016" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023" OR "2024"))
- (AB=(residential energy consumption reduction) AND TI=(residential energy consumption reduction)) AND (PY==("2013" OR "2014" OR "2015" OR "2017" OR "2016" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023" OR "2024"))
- (ALL=(Residential efficiency energy intervention trade-off)) AND (PY==("2024" OR "2023" OR "2021" OR "2019" OR "2019" OR "2017"))
- (AB=(Household intervention feedback) AND TI=(Household intervention feedback)) AND (PY==("2024" OR "2023" OR "2022" OR "2021" OR "2020" OR "2019" OR "2018" OR "2017" OR "2016" OR "2015" OR "2014" OR "2013") AND DT==("ARTICLE")) (ALL=(residential smart grid intervention)) AND (PY==("2024" OR "2023" OR "2022" OR "2021" OR "2020" OR "2019" OR "2018" OR "2017" OR "2016" OR "2015" OR "2014" OR "2013"))
- (AB=(household sustainability technology energy consumption)) AND (PY==("2023" OR "2024" OR "2022" OR "2021" OR "2020" OR "2019" OR "2018" OR "2017" OR "2016" OR "2015" OR "2014" OR "2013"))

- (AB=(household sustainability technology energy consumption)) AND (PY==(”2023” OR ”2024” OR ”2022” OR ”2021” OR ”2020” OR ”2019” OR ”2018” OR ”2017” OR ”2016” OR ”2015” OR ”2014” OR ”2013”))
- (ALL=(Web-based application household energy)) AND (PY==(”2023” OR ”2022” OR ”2021” OR ”2020” OR ”2019” OR ”2018” OR ”2014”))
- (ALL=(Intervention technology methods for energy reduction household)) AND (PY==(”2023” OR ”2022” OR ”2021” OR ”2020” OR ”2019” OR ”2018” OR ”2016” OR ”2014”))
- (ALL=(household intervention technology architecture)) AND (PY==(”2024” OR ”2023” OR ”2022” OR ”2021” OR ”2020” OR ”2019” OR ”2018” OR ”2016” OR ”2015” OR ”2014” OR ”2013”))

Scopus

- TITLE-ABS-KEY (digital AND energy AND interventions AND household) AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2025 AND (LIMIT-TO (DOCTYPE , ””cp””) OR LIMIT-TO (DOCTYPE , ””ar””)) AND (LIMIT-TO (LANGUAGE , ””English””))
- TITLE-ABS-KEY (residential AND smart AND grid AND intervention) AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2025 AND (LIMIT-TO (DOCTYPE , ”cp”) OR LIMIT-TO (DOCTYPE , ”ar”)) AND (LIMIT-TO (LANGUAGE , ”English”))
- TITLE-ABS-KEY (household AND intervention AND energy AND reduction AND sustainability) AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2025 AND (LIMIT-TO (DOCTYPE , ”cp”) OR LIMIT-TO (DOCTYPE , ”ar”)) AND (LIMIT-TO (LANGUAGE , ”English”))
- TITLE-ABS-KEY (residential AND intervention AND technology AND implementation AND costs) AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2025 AND (LIMIT-TO (DOCTYPE , ”cp”) OR LIMIT-TO (DOCTYPE , ”ar”)) AND (LIMIT-TO (LANGUAGE , ”English”))
- TITLE-ABS-KEY (residential AND efficiency AND energy AND intervention AND trade-off) AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2025 AND (LIMIT-TO (DOCTYPE , ”cp”) OR LIMIT-TO (DOCTYPE , ”ar”)) AND (LIMIT-TO (LANGUAGE , ”English”))
- TITLE-ABS-KEY (household AND sustainability AND technology AND energy AND consumption AND intervention) AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2025 AND (LIMIT-TO (LANGUAGE , ”English”))
- TITLE-ABS-KEY (household AND energy AND reduction AND smartphone) AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2024
- TITLE-ABS-KEY (household AND intervention AND experiment AND energy AND reduction) AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2025 AND (LIMIT-TO (LANGUAGE , ”English”))
- TITLE-ABS-KEY (household AND intervention AND energy AND feedback AND technology) AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2025 AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2025 AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2025 AND (LIMIT-TO (LANGUAGE , ”English”))
- TITLE-ABS-KEY (intervention AND technology AND methods AND for AND energy AND reduction AND household) AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2025 AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2024
- TITLE-ABS-KEY (in-home AND display AND intervention AND method AND energy AND feedback) AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2024
- TITLE-ABS-KEY (web-based AND application AND household AND energy AND reduction) AND PUBYEAR ¿ 2012 AND PUBYEAR ¡ 2019

- TITLE-ABS-KEY (household AND energy AND intervention AND wireless AND sensor AND network) AND PUBYEAR ¿ 2013 AND PUBYEAR ¡ 2022

4.3 Search engines

When the search engines that are going to be used were determined, an initial attempt at the identification step was made. This was executed in order to gain some insight into the available literature from each search engine. An example of such a search has been provided in Figure 3. What was immediately noticed is that the number of hits from the ACM Digital Library is significantly different compared to the other search engines when using the exact same keywords.

Due to the extensive number of hits for the ACM Digital Library, further refinement of the search strategy was necessary. The refinement process involved the evaluation of various journals and conferences accessible through the ACM Digital Library. This was executed to identify the articles most aligned with the topic of sustainable energy technologies. By focusing on specific journals and conferences, the search within the ACM Digital Library was tailored to yield more relevant results. The following list has been established:

- Journals:
  - Proceedings of the ACM on Human-Computer Interaction (PACM HCI)
  - Personal and Ubiquitous Computing
  - ACM Transactions on Information Systems (TOIS)
- Conferences:
  - CHI Conference on Human Factors in Computing Systems
  - DIS (Designing Interactive Systems) Conference Proceedings

Each of the journals and conferences was selected for their specific relevance to the topic of digital energy interventions. They are all likely to publish literature that can be valuable for the focus of this research. Because the areas of each of these journals and conferences are often in the fields of sustainability, energy efficiency, and innovative technologies. Their focus will allow for a more targeted and relevant selection of academic literature. In the literature review, for any further identification search within the ACM Digital Library, these journals and conferences will be selected.

Eventually, after the identification phase, it turned out that only PACM was able to find relevant results. The other journals and conferences were searched, however, they mostly did not find significant literature that was relevant enough to be included. It might be possible that other conferences and other journals had some relevant results that may have been missed with the current selection of journals and conferences. However a choice had to be made in the process after the large search queries on ACM Digital Library, and these conferences and journals were seen as having the highest chances to find relevant literature. This choice was made based on the description of the journals and conferences and having a look at the topics that they usually publish.

Search query	Search engine	# of hits
Digital energy intervention	IEEEXplore	238
Household intervention technology	Web of Science	142
Abstract:(household intervention sustainability)	ACM Digital Library	102
household AND intervention AND technology AND energy AND consumption	Scopus	89
household AND intervention AND energy AND consumption AND reduction	Scopus	92
Abstract:(energy "cost" of "household" intervention technology energy consumption reduction) AND Title:(energy "cost" of "household" intervention technology energy consumption reduction) AND Keyword:(energy cost household intervention technology energy consumption reduction)	ACM Digital Library	82
Title:(residential smart meter implementation and operation) AND Abstract:(residential smart meter implementation and operation) AND Keyword:(residential costs)	ACM Digital Library	85

Search query	Search engine	# of hits
Residential smart grid intervention	IEEEXplore	17
(AB=(household energy intervention) AND TI=(household energy intervention)) AND (PY==("2013" OR "2014" OR "2015" OR "2017" OR "2016" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023" OR "2024"))	Web of Science	18
Title:(Household energy interventions) AND Abstract:(Household energy interventions) AND Keyword:(Household energy interventions)	ACM Digital Library	30
digital AND energy AND interventions AND household	Scopus	33
household AND intervention AND energy AND reduction AND sustainability	Scopus	19
[Search query was removed as further refinement led to no significant results]		
[Search query was removed as further refinement led to no significant results]		

Figure 2: *Refined search queries based on the initial search queries that yield too much results.*

Year	**1st seach term**	**2nd search term**	**3rd search term**	**Search engine**	**Number of hits**
2013-2024	Digital energy intervention	Household		ACM Digital Library	46.310
				IEEE Xplore (Doesn't show before 2019)	8
				Web of Science	24
				Scopus	29
2013-2024	Digital energy intervention	Residential		ACM Digital Library	41.857
				IEEE Xplore (Doesn't show before 2018)	7
				Web of Science	20
				Scopus	34

Figure 3: *A first attempt of the identification step.*

5 Identification phase

For the identification phase, some aspects are encountered during the process that are worth further explanation. It was quite a search to find queries that resulted in somewhat useful literature. Some queries were large, while others had very limited results. It turned out that ACM Digital Library did not provide that much literature, which was not expected in advance due to the size of the database. The majority of useful queries were from the search engines IEEEXplore, Web of Science, and Scopus. In addition to the search queries themselves, the overall identification phase had to be appropriately scoped. It was possible to find a large volume of literature, however, that would make the whole research and process too large to handle. The identification phase had to conclude with a sufficient corpus of literature to be able to confidently say that the most important literature had been found when it comes to digital energy interventions. There is always the possibility that some relevant literature is not included in this research, due to not being captured in the identification phase, but that was a necessary trade-off to ensure the feasibility of the process.

6 Screening phase

When it comes to the screening phase, the first step was to remove duplicates from the list of literature that concluded the identification phase. This was initially done automatically through an Excel file but also checked manually. Because a DOI is unique for each article, this was used as the main resource to identify duplicates, as the same articles might have been found twice with slightly different titles.

After the duplicates were removed, the next step was to check the quality of the articles and ensure that they were peer-reviewed and of scientific quality. The search engines were already chosen based on providing mostly peer-reviewed articles, so this step only resulted in the exclusions of a relatively small amount of literature. For each of the search engines, their peer-reviewing process was analyzed:

- **ACM Digital Library**: Peer-reviewed [13].
- **IEEEXplore**: Peer-reviewed [1].
- **Scopus**: Mostly peer-reviewed, however, no function to remove the small number of non-peer-reviewed articles [39].
- **Web of Science**: Mostly peer-reviewed, however, some journals are not, but these are generally long-established journals that have been indexed for many years [34].

Scopus and Web of Science had the highest possibility of including an article that was not peer-reviewed. In order to still be able to ensure the peer-reviewed quality of the included articles, the retrieved literature from these search engines was double-checked. This was done by searching if they were published anywhere else, in journals or conferences, and seeing if those required a peer-reviewed process. If this was the case, the articles were included in the list that concluded the quality check. In the end, the majority of the articles from Scopus and Web of Science were indeed also published in journals and conferences that required a peer-review process.

7 Eligibility phase

The third step in the process is that of the eligibility phase. This was the largest and most time-consuming phase of the research. It started by excluding articles based on their title. The following criteria were used to determine if a title was eligible. Where if at least one of the criteria was met, the article would be removed from the list.

Removed when an article:

- Mentions economically developing countries
- Has a none-relevant topic
- Is not household-specific
- Is not energy-related

These four criteria were not derived from any existing literature, but were determined based on the goal and scope of the research. If it was not clear if an article met one of these criteria based on the title, or if the title remained a bit vague, the article was **not** removed from the list. This was so that the abstract of the article could be read in order to, hopefully, gain some more insights to see if the article was deemed eligible or not. After all the titles were read and checked, the remaining articles were checked for eligibility based on the abstract. Exclusion was based on the same set of criteria as used for the title eligibility.

8 Categorization

The process of categorizing based on the literature and the techniques described was also a process involved in this research. Establishing each of the categories took some time, as a predefined categorization, in the context of this research, was not found in the existing literature. This meant that the categorization had to be established from knowledge gained from reviewing the literature. Given the inconsistencies in digital energy intervention research, as stated in the research paper, making a categorization to generalize the overall literature took some effort. The categorization for the literature, as well as for the techniques is still not completely comprehensive. There are still some outliers that do not fit neatly into a certain category based on their quantitative data but were categorized based on the conclusions drawn from the research. These could be conclusions derived by the author(s) of the article themselves or based on the knowledge that was already established through researching other articles.