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Review

A Systematicity Review on Residential Electricity Load-Shifting at the Appliance Level

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Abstract: Load-shifting is a demand-side management (DSM) strategy to support the efficiency of the electricity grid during hours of peak demand. Load-shifting at the appliance level is an interesting topic to review, since appliance usage is one of the main inputs of the load-profile analysis. More literature reviews on load-shifting at the appliance level are required, as this is a specific issue in the body of literature on load-profile research, though only a limited number of studies are available at this time. It is also essential to focus on appliance usage patterns to improve our understanding of the impacts and characteristics of different appliances. Existing studies on load-shifting have used commonly structured literature reviews; our work addresses the transparency of each stage and substage in the selection of the final list of studies. The findings show that efficiency has been achieved in installed-capacity reductions; costs, including those of emission reductions; and peak consumption reductions. The most frequently used method in load-shifting at the appliance level is to develop load-shifting optimization algorithms. This work contributes by providing a transparent process of drawing up a systematicity literature review as a source of knowledge and grounded theory. It also contributes to specific research on load-shifting at the appliance level by highlighting and discussing the key findings for the reader. In particular, it contributes to improving energy efficiency by describing load-shifting methods at the appliance level and identifying both controllable and uncontrollable appliances. This detailed literature review at the appliance level can make valuable contributions in support of decision- and policymaking by illuminating new dynamic systems specifically in load-shifting and in demand-side management in general for energy efficiency purposes.

Keywords: load-shifting; controllable appliance; uncontrollable appliance; Home Energy Management System; systematicity and transparency review; demand-side management; demand response

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1. Introduction

Demand-side management (DSM) strategies are key to energy efficiency, resulting in a substantial reduction in the installed capacity [1–4]. DSM is designed to manage utility activities, include planning, implementing, and monitoring energy consumption efficiently and maintaining the stability of the grid [5]. It may influence the time pattern and utility load, which can be controlled through load management [2], a specific branch of DSM [2], and it can allow the customer to control the peak-load demand [6]. One load-management strategy in DSM is load-shifting (Figure 1), a technique to shift peak-hour demand to off-peak hours by reallocating the load demand [6] without changing the total energy consumption [7]. This can also reduce the cost [1,6,8–15] as well as the capacity of the electricity grid. In practice, Yilmaz et al. (2019), quoted in [16], defined load-shifting as a "process where consumers time-shift demand, either through behaviour

change or automation, in response to particular conditions within the electricity system, and [it] is therefore a potential solution to equilibrate the network". The fundamental step in achieving load-shifting is to involve and motivate consumers [1,10], underlining the importance of focusing on the residential sector. In load-shifting at the appliance level, some studies have grouped appliances based on their operating times into controllable and uncontrollable load appliances [1,17,18]. According to Yildiz et al. (2017), quoted in [19], controllable load appliances are ones where "the operation may be controlled and also interrupted as the loads can resume at a later time without much negative consequence or inconvenience for the users". Examples of controllable load appliances are air conditioners (ACs), electric water-heaters (EWHs), electric-vehicle (EV) chargers, pool pumps, washing machines, dishwashers, and freezers [1,19]. Conversely, uncontrollable load appliances are those where "the operation of these loads should not be altered at any time as they are highly important for the users" [19]. Examples are lighting systems, computers, televisions, hairdryers, and entertainment devices [17–19].

Based on the results of the review, ACs and EWHs are the most frequently simulated appliances, in line with the study in [20], where ACs and EWHs are included in the selection of electrical appliances to be analysed because they are used in all seasons. This makes it interesting to review load-shifting at the appliance level, as reviews serve as the fundamental and benchmark tool for analysing, summarizing, or synthesizing the existing literature [21]. It is also essential to conduct a review study of load-shifting at the appliance level, since studies on load-shifting are not conducted as extensively as those that focus on load-profile analyses [17,22–31]. Therefore, it is important to contribute a literature review in this area, as load-shifting at the appliance level is an even more specific issue, though only limited studies are currently available. Existing studies of load-shifting, such as [7,15], or those that use the term 'load-scheduling' as in [32], are beneficial as grounded knowledge, though most of them have not applied the usual guidelines for a structured literature review.

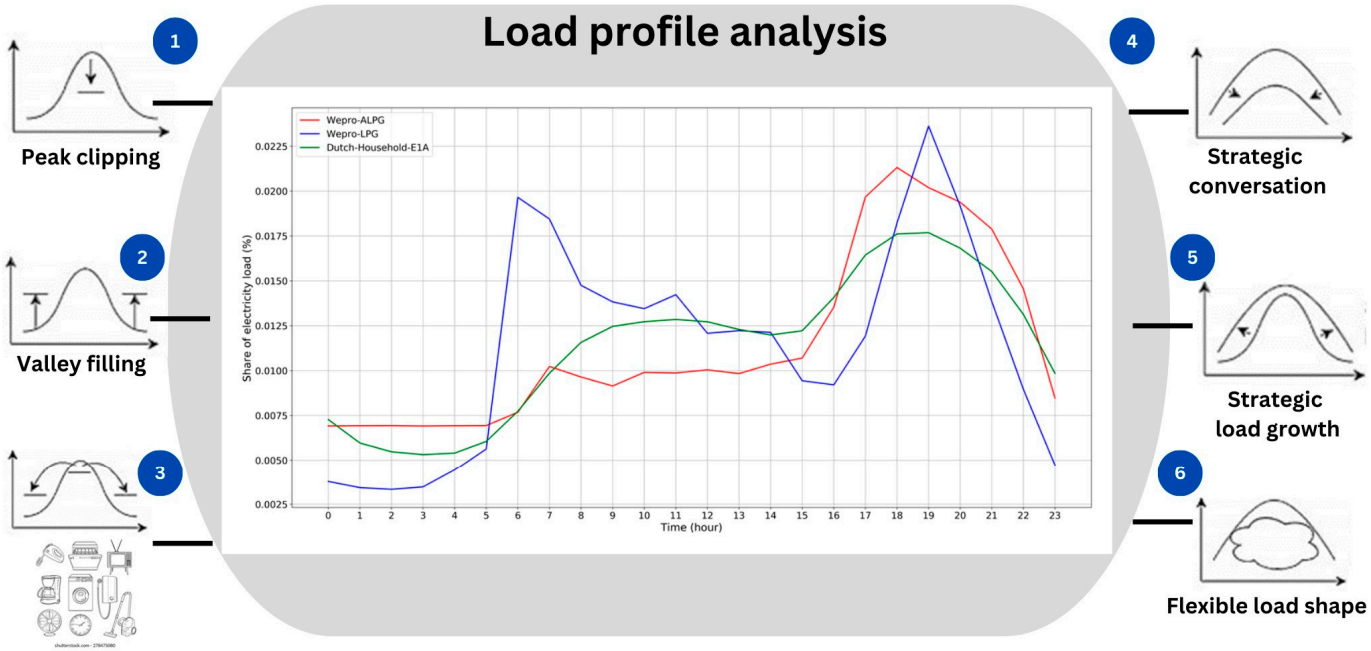


Figure 1. Load-shifting as a research topic is part of the load-profile analysis in the DSM research area. The six basic load-shaping icons have been adopted from Gellings (1985). The load-profile figure in the centre is the authors' own figure based on the load-profile analysis result shown in [28].

This work forms part of the CITIES and EUDP, Det Energiteknologiske Udviklings- og Demonstrations program, Danish participation in the IEA Annex 83—Positive Energy

Districts (PEDs) research bodies. In the CITIES project, it is being conducted as part of the CITIES work package 1: Energy Services and Demand. CITIES is a research project on smart energy systems and smart cities, which was funded by Innovation Fund Denmark [33]. The EUDP, Det Energiteknologiske Udviklings- og Demonstrations program, Danish participation in the IEA Annex 83—Positive Energy Districts (PEDs) project shares the overarching goal of Annex 83, namely, to develop the necessary information and guidance for the planning and implementation of PEDs. This includes both technical and urban planning perspectives, i.e., it covers economic, social, and environmental impact assessments for various alternative development pathways [34]. Therefore, research on the modelling and analysis of residential electricity load profiles will contribute to the energy demand in specific areas: neighbourhoods, districts, cities, or regions and, specifically, the CITIES and PEDs research projects. One of the fundamental aims of these projects is to understand residential electricity consumption behaviour by synthesising local load profiles within cities [28,35]. The residential sector is of great importance, as it contributes to approximately 30% of the global demand for electricity [2]. A detailed understanding of the load profile plays a vital role in modelling decentralized energy systems such as Positive Energy Districts. Moreover, load-shifting is a strategy used in controlling load profiles. As a consequence, load-shifting forms part of our research on DSM in the residential sector (Figure 1). In our previous works on synthesising residential electricity load profiles [28,35–37], we found that appliances are mainly used to synthesize domestic load profiles. In accordance with what was revealed in [15], there is a need to incorporate the consumption patterns of electrical appliances into DSM models. It is also essential to focus on appliance usage patterns to improve our understanding of the impacts and characteristics of individual appliances, as mentioned in [38]. In addition, reviewing work at the appliance level is beneficial in supporting decision makers in allocating investments in renewable energy capacities for the residential sector locally [39].

Furthermore, our work proposes a structured literature review and addresses the transparency of each stage and substage in selecting the final list of studies. Transparency is one of the main attributes besides those of systematicity and comprehensiveness in a high-quality review [40]. As this is regarded as an important aspect of all scientific activity [41], reviews should be as transparent as possible [42,43] by providing a clear procedure for each step in the review process, thus improving its replicability by other researchers [21,40]. Moreover, this enhances the clear connections between the research question and purpose, or analysis and synthesis, in the review [21], as well as explaining any contradictory results [42,43]. Therefore, in this study, the twin concept of systematicity and transparency proposed by [44] has been selected and applied in order to review residential electricity load-shifting at the appliance level. Our review provides an analysis based on the criteria of research objective, method, validation, results, time resolution data, and year of publication.

The objective of this review is, therefore, to present knowledge on residential electricity load-shifting at the appliance level, which focuses on the research goal, applicable methods, simulated appliance(s), validation, results, time resolution data, and year of publication by conducting a structured systematic and transparent literature review. Therefore, the contributions of this work are twofold. First, it describes a transparent process of applying a literature review on systematicity. Second, it is a source of knowledge and grounded theory, as it contributes to the limited and specific research on load-shifting at the appliance level by highlighting and discussing the key findings for the reader, namely, the proposed methods and/or models, research aims, implications, data characteristics, validation method, etc. In this sense, it constitutes important progress on load-shifting methods, its essential role relating to a broader area of load-profile analysis. Additionally, in practice, it contributes to improving energy efficiency by describing the load-shifting method at the appliance level and identifying the controllable and uncontrollable appliances that apply these methods.

The remainder of this paper is organized as follows. Section 2 presents the methodology of the twin-concepts review based on [44], with particular reference to systematicity

and transparency. Section 3 describes the application of the adopted twin concepts. Section 4 discusses the analysis. Section 5 summarises and concludes the review and highlights the research implications.

2. Review Method

In this work, the twin concepts of systematicity and transparency proposed in [44] are selected for application in order to produce a high-quality review process and result. The concept has six generic review steps in which each step combines the systematicity and transparency aspects as listed in Table 1: developing a review plan, searching the literature, selecting studies, assessing quality, extracting data, and analysing data. These generic steps are commonly used in conducting stand-alone literature reviews [44]. Moreover, we are putting forward our contribution in order to provide transparent results in numbers and judgements at each stage and substage, as is also required.

Table 1. Instantiations of systematicity and transparency based on the concepts proposed in [44].

Systematicity ↓	**Transparency** ↓
Developing a review plan	
Research question Review method Review plan	Research objective Description of review type and method Review protocol
Searching the literature	
Defining criteria for inclusion Selecting database and search method Defining analytical process Defining tools and procedures to manage referencing	Describe search strategy Inclusion and exclusion criteria Present full electronic search strategy Identify the reference manager tool
Selecting studies	
Defining analytic screening Procedure for maintaining records	Describe the process of screening The screening criterion with the inclusion and exclusion results
Assessing quality	
Selecting validated quality appraisal Specifying quality appraisal procedures Defining methods for incorporating assessment into the analysis	Present quality assessment validation Describe the procedures to check the studies' quality Describe the procedure for incorporating assessment into analysis
Extracting data	
Data extraction plan/framework Identifying items to consider and developing data extraction forms Method for managing collected data	Present the mapping of data extraction Present the extracted items Provide the data extraction table, code the studies, and define the standard naming
Analysing	
Selecting analysing method Developing appropriate plans to present the findings Formulating a conclusion and research implication	Describe the method of data analysis Identify the principal outcomes Present the conclusions and research implications

3. Application of the Twin Concepts Review: Systematicity and Transparency

In this stage, a twin concept is adopted and applied in order to review the literature on residential electricity load-shifting at the appliance level. The six steps based on [44] are conducted and elaborated in the following substages.

3.1. Developing a Review Plan

Formulating a research question is essential as the basis for developing a review plan. In this study, the research question is: What are the applicable methods of load-shifting at the appliance level in the residential sector? This serves as the fundamental source of knowledge in the load-shifting area of interest. The objective of this work is to provide a systematic and transparent stand-alone literature review of works on residential electricity load-shifting at the appliance level. Furthermore, the research plan regarding the systematicity and transparency review is constructed in Table 2 based on the instantiation guidelines proposed in [44].

Table 2. The twin concepts of systematicity and transparency in reviewing residential electricity load-shifting at the appliance level.

Systematicity ↓	**Transparency** ↓
Developing a review plan	
Research question: what are the applicable methods of load-shifting at the appliance level in the residential sector?	Research objective: to provide a systematic and transparent stand-alone literature review on residential electricity load-shifting at the appliance level
Review method	The twin concepts of systematicity and transparency review as proposed in [44]
Review plan	Review protocol: the six steps in Table 1
Searching the literature	
Defining criteria for inclusion Selecting database and search method Defining analytical process	Search strategy Database: WoS Present full electronic search strategy
Defining tools and procedure to manage references	Mendeley reference manager Authors' journal and diary
Selecting studies	
Defining analytic screening Procedure for maintaining records	Screening process is described "Saved search/list": list of included studies List of excluded studies with reasons for exclusion
Assessing quality	
Selecting validated quality appraisal	Peer-reviewed journals
Specifying quality appraisal procedure	Procedure: Visit the journal, check the review process, and check the journal's rank
Defining methods for incorporating assessment in the analysis	Abstract and paper reading: research objective, methods, result, time resolution, validation, country, and publication year
Extracting data	
Data extraction plan/framework	Research objective, method, result, time resolution, validation, country, and publication year
Identifying items to consider and developing data extraction forms	Present the extracted items in Table A2 (Appendix B)
Method for managing collected data	Code the studies, extract the data, and define naming convention for each extracted category
Analysing	
Selecting analysing method	Principal information of the required criterion: research objective, method, result, time resolution, validation, country, and publication year
Developing appropriate plan to present the findings	The statistics of each criterion: e.g., the most applied method
Formulating conclusion and research implications	Conclusions based on the findings in context of the review method and the data extraction Research implication: Review of the load-shifting satisfaction model

3.2. Searching the Literature

The literature search used was the Web of Science (WoS) database, a global citation database that provides access to multiple databases with over 171 million record references [45]. Furthermore, as already mentioned, the aim of this review is to identify methods of residential electricity load-shifting at the appliance level. Therefore, the main phrase is defined in the searching as: residential electricity load-shifting.

TS = Residential Electricity Load-Shifting

In the WoS search, TS refers to the topic, where it is searched in the following fields within a record: the title, abstract, author keywords, and Keywords Plus®. The Keywords Plus® field is also searched within a record, where the data include words or phrases occurring in reference lists, but not necessarily in articles' titles [46,47]. We do not search this phrase with the additional term "at the appliance level", despite it being what we specifically focus on, because in the preliminary brief study, most studies will not specifically mention which appliance(s) they are concerned with on in their TS. This more generic level of searches will also minimize the exclusion of potentially related works. As a result of this initial search, this query has identified 408 related documents consisting of 235 articles includes 13 reviews, 2 early access works, 1 book chapter, and 170 proceeding papers. The publication years of the English documents are given in Figure 2, where 2018 is the year with the most publications, with 70 documents, closely followed by 2017 with 68 articles. The oldest article was published in 1991, followed by others in 1998 and 1999, with each year having at least one document. Figure 2 shows that load-shifting has gained momentum in the last decade, the most significant period being from 2017 to 2018.

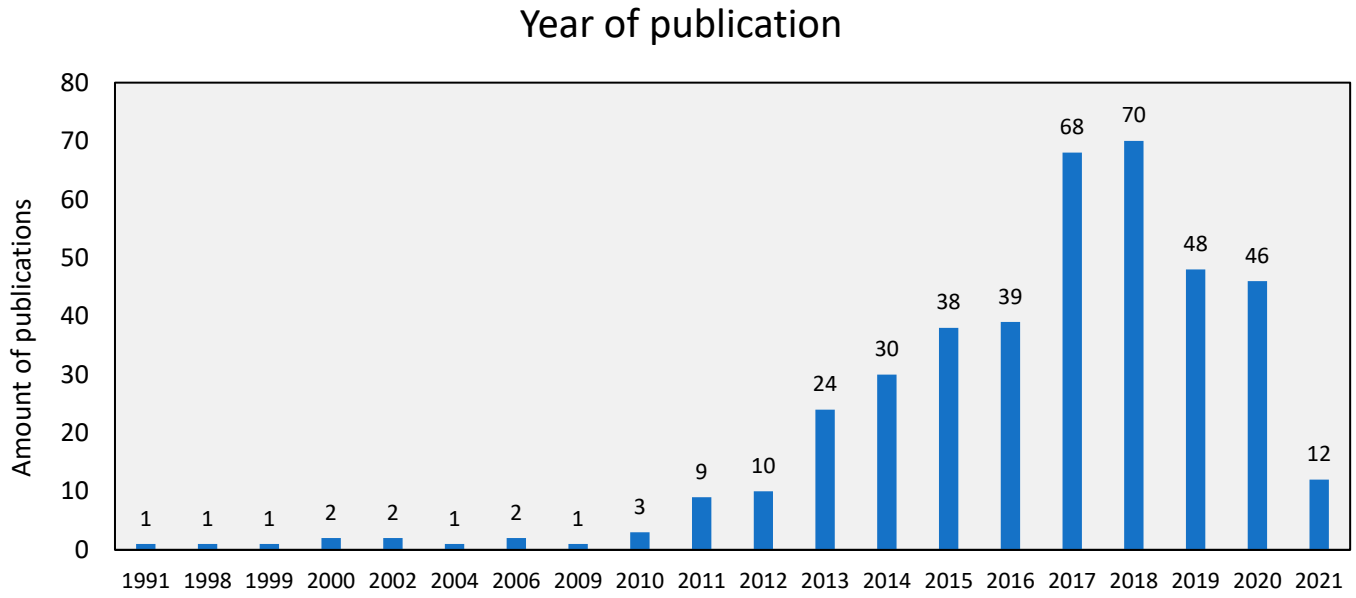


Figure 2. Years of publication of the initial searched results from 1991 to 2021.

3.3. Selecting Studies

Studies were selected based on clear inclusion and exclusion criteria. The detailed results are provided below to guarantee the transparency of each substage.

3.3.1. Screening 1: Language

The first screening concerns the document's language, where English, the main universal language of science, was selected for inclusion. Of the initial results, all 408 documents were written in English. Thus, no document was excluded on these grounds.

Included: 408 English documents;

Excluded: 0 non-English documents.

3.3.2. Screening 2: Publication stage

The second screening is the publication stage. Of the 408 English documents, 406 were at the final stage of having been published, while the remaining two were in the early access stage. Early access is defined as publication electronically by a journal. This type of article is also known as an "article in press" [45]. In this case, we selected the final stage of publication, since the early access documents had not yet been assigned to a definite volume and issue.

Included: 406 final stage documents;

Excluded: 2 early access documents.

3.3.3. Screening 3: Document Type

The third screening is for document type. Of the 419 final-stage documents, there were 235 articles, 1 book chapter, and 170 proceeding papers. In this case, we focused on the articles only, as the reviews will usually not present any new information on a subject [45], though they are useful as grounded theories for our research background.

Included: 235 articles;

Excluded: 1 book chapter and 170 proceeding papers.

3.3.4. Selecting Subject Areas

Furthermore, some subject areas were not relevant to this study and thus were excluded from the 235 initially included articles. In WoS, there are five broad research categories: arts and humanities, life sciences and biomedicine, physical sciences, social sciences, and technology, each of which has a specific research area, with terms being listed under the broad areas [45]. In our work, we selected the following specific areas: energy fuels (145 articles), engineering (120 articles), automation control systems (5 articles), environmental sciences ecology (33 articles), operations research management science (5 articles), construction and building technology (31 articles), science and technology (31 articles), thermodynamics (29 articles), and computer science (14 articles). In fact, one article could be linked to several specific areas; therefore, the sum of the articles in all specific areas is different from the total in our last collection study, which, in this case, was 235 articles. Therefore, after selecting the relevant subject areas above, we found 228 articles that should be included and seven articles to be excluded.

Included: 228 relevant articles;

Excluded: 7 not-relevant articles.

3.4. Assessing Quality

We assessed the quality of the 228 articles for reasons of quality assurance. Therefore, we limited the scope to peer-reviewed journals alone. The 228 article sources were published in 74 journals. Therefore, we visited each journal to identify the peer-review process. In this stage, all articles are based on peer-reviewed journals. In accordance with WoS, all articles are subject to peer review, as most journals in the WoS core collection are peer-reviewed. However, WoS does not specifically mention the journals' peer-review status [48].

Included: 228 peer-reviewed articles;

Excluded: 0 articles.

Furthermore, the title and abstract of each peer-reviewed article has been read to elicit a clearer understanding and evaluation of the aims and results of the article [49]. In this substage, we first sorted the articles based on their relevance in WoS. The records are sorted in descending order in a ranking system based on the following fields: title, abstract, keywords, and Keywords Plus®. Most of the 228 collected articles were focused on load-shifting. However, as our focus is on load-shifting at the appliance level, we excluded non-relevant load-shifting topics. This resulted in 27 peer-reviewed articles.

Included: relevant content of load-shifting at the appliance level = 27 articles

Excluded: Load-shifting but not specific at the appliance level = 201 articles

The following are the topics and the number of excluded articles from each, where some topics are categorized in the related group. 'Related group' here means that the study is closely related to load-shifting, but that load-shifting is not their main discussion or the aim of the study or other than load-shifting at the appliance level. The list of topics is sorted by the largest number of articles:

1. Economics covering price, electricity rate structure, electricity tariff, incentives, economic optimization, peak-off-peak-load-shifting, and customer satisfaction: 71 articles.
2. Demand-side management (DSM) includes segmentation based on Demand Response (DR) programs, smart-grids, micro-grid systems: 49 articles.
3. Technical aspects including control, electricity infrastructure, intelligent building, building thermal models, grid inverter size, and grid architecture: 28 articles.
4. Storage or the use of a battery storage system: 16 articles.
5. Environmental issues, including emissions, sustainability, renewable energy (RE) sources, and RE penetration: 9 articles.
6. Social practice, including flexibility to shifts in demand: 8 articles.
7. The load-shifting at manufacture, industrial, road lighting, commercial, and transport sectors: 6 articles.
8. Load-profile model or synthesised load profile: 4 articles.
9. Policy: 4 articles.
10. Real-time electricity consumption: 3 articles.
11. Scenario of future electricity demand: 2 articles.
12. Load-shifting scope of building materials: 1 article.

These 27 peer-reviewed articles were read to emphasise that the article had discussed and provided a description of load-shifting data at the appliance level, besides mentioning it in the abstract, research objective, and conclusion. These twenty-seven articles were derived from 25 journals, the remaining two being conference proceeding papers that journals had invited for publication. Technically, the 27 articles received a temporary ID with the format A for the article, followed by the number. Therefore, the temporary IDs run from A1 to A27. Furthermore, ten articles were excluded from the final collection for the following reasons.

Included: 17 articles
Excluded: 10 articles
The excluded articles:

1. A1 [50] provided a series of analyses based on consumption data for appliance electrification efforts, but it did not specifically discuss load-shifting or mention the specific appliance.
2. A2 [51] discussed non-intrusive load-monitoring (NILM) at the appliance level, with the focus on disaggregating the power-consumption profiles of the appliances: ovens, microwaves, kitchen outlets, dishwashers, and refrigerators.
3. A3 [52] proposed the methodologies that capture the variation in sequences of activities that occur in peak electricity demand and introduced a set of analytical tools to examine the time-use survey (TUS) data on the energy demand side. This paper is relevant in that it presents the grounded theories of our review.
4. A4 [53] focused on thermal energy storage, which offers load-shifting from the off-peak hours through sensitive and/or latent methods.
5. A10 [54] investigated the impact of load-shedding on a block of multiple buildings.
6. A13 [55], which has been retracted, proposed a simple algorithm for the operational efficiency of water pumps at peak hours.
7. A14 [56] discussed load-shifting at the grid level.
8. A15 [57] showed a building's thermal flexibility and thermal energy storage (TES) used in supplying domestic hot water (DHW). The aim was to move the operation of the heat pump to periods of photo-voltaic generation.
9. A17 [3] discussed load-shifting at the grid level.

10. A21 [58] proposed a multi-objective model predictive of the control strategy at the grid level.

As a result, after reading these papers, seventeen articles in Appendix A were selected for the final collection to be extracted and synthesised. These seventeen articles mentioned and discussed specific appliance(s) for application of the load-shifting term. They had been published in twelve journals of six publishers. Of these seventeen articles, two were conference papers that the journals invited to be published.

An overview of the selected studies and associated quality processes, and statistical figures for the included and excluded articles, is represented in Table 3, which is inspired by the waterfall statistics provided in [49].

Table 3. Waterfall statistics showing how many articles were included in and excluded from the process.

Waterfall Statistics	Bulk	Reduced
Initial searched	408	-
Screening 1: Language	408	0
Screening 2: Publication stage	406	2
Screening 3: Document type	235	171
Selecting subject areas	228	7
Assessing quality 1: Peer-review article	228	0
Assessing quality 2: Title and abstract reading	27	201
Assessing quality 3: Paper reading	17	10
Final number of selected studies	17	-

3.5. Extracting Data

Data extraction was carried out to provide information on how the primary studies were conducted. In this work, data from the final list of studies are extracted: the research objective, methodology, dedicated appliance(s), result, time resolution, limitation, validation of the proposed method, and year of publication. Appendix B provides more detailed information on the data extraction in the final list of studies. Additionally, the overview of the load-profile methods and their appliances is presented in the methods map (Figure 3). The map shows that the methods in the final list of studies can be categorized into eight groups, load-shifting optimization algorithms being the most frequently proposed methods in the final list of studies. Furthermore, most final studies (a2, a4, a5, a6, a9, a12, a13, a14, and a17) proposed Home Energy Management System (HEMS)-based models or methods that applied smart controls with comfort aspects, smart control scheduling, and physical settings with a mathematical model. The HEMS is described as a system that consists of hardware, software, network, data, and processes to monitor energy data and control energy usage in a building containing a household. The objectives of the HEMS are to increase awareness in energy consumption and achieve greater energy efficiency. According to Wang et al. (2018), quoted in [59], the HEMS allows for "optimal scheduling of each electrical appliance and distributes generators according to an objective function (e.g., the energy cost) predefined by the customer or an aggregator and according to some external information (e.g., weather, electricity price, incentive signal, etc.) in order to help residential customers to efficiently manage their energy consumption" [8]. Each method, such as the fuzzy logic model (a16), clustering technique (a3), DSM-based model (a15), and stochastic thermal model (a10), was proposed by a single study, which applies to a single appliance.

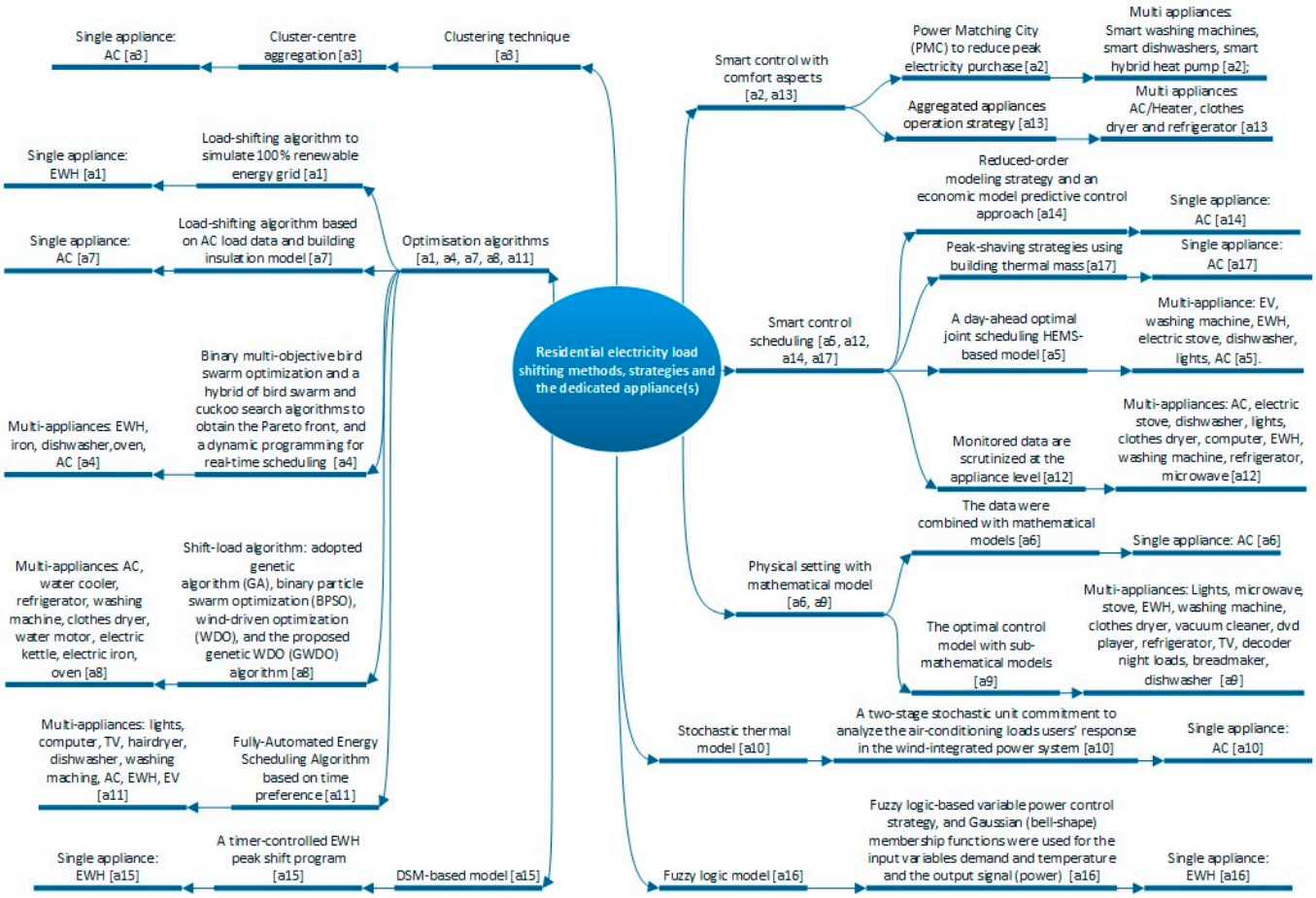


Figure 3. The map of the methods, strategies, and dedicated appliance(s) proposed in the final list of studies. See the article's ID in Appendix A.

4. Analysis and Discussion

In this section, the proposed methods and/or models, research aims, and implications of the final list of studies are discussed to answer the fundamental research question: What are the applicable methods of load-shifting at the appliance level in the residential sector? In particular, to support fundamental knowledge about the research question, this study also gives the data characteristics, validation methods, and data-quality scores for each article. The data-quality scores can be used to quantify the quality of the information regarding the review's research questions.

Data syntheses are divided into three main forms: quantitative, qualitative, and integrative (mixed) [44], and the data extraction ended with seventeen articles, as shown in Table 3. According to the data extraction, improving efficiency is the most common research aim of the final list of studies. This means either efficiency in reducing the peak load [60–63], shifting the coincidental and substantial peak-load demand [64–66], or achieving more energy conservation [38]. Furthermore, the methods of using load-shifting algorithms mentioned in the studies can mostly be applied to many different appliances, where more than five appliances are being simulated simultaneously. For instance, the appliances being analysed simultaneously in [67] are the AC, water cooler, refrigerator, washing machine, clothes dryer, water motor, EWH, electric iron, and oven. According to [1], although load-shifting has gained attention, each study prefers to provide its own algorithm, rather than use the available modelling tools.

As shown in the data extraction in Figure 3, load-shifting optimization algorithms were the most frequently proposed methods where a1 proposed a load-shifting algorithm to simulate a 100% renewable energy grid; a7 applied the load-shifting algorithm based

on AC load data and a building insulation model; a4 developed a binary multi-objective bird swarm optimization and a hybrid of bird swarm and cuckoo search algorithms to obtain the Pareto front, and a dynamic programming for real-time scheduling; and a11 proposed a fully automated energy scheduling algorithm based on time preference. The clustering technique in a3 applied a cluster-centre aggregation to aggregate a large and diverse building stock of residential buildings to a smaller, representative ensemble of buildings. Furthermore, the DSM strategy in a15 proposed a timer-controlled EWH peak-shift program to avoid the peak hours.

In the category of smart control with comfort aspects, a Power Matching City (PMC) system is applied to reduce peak-electricity consumption in a2, and an aggregated appliance operation strategy is proposed in a13. For the category of smart control scheduling methods, a14 proposed a reduced-order modelling strategy and an economic model predictive control approach; a17 suggested peak-shaving strategies in which the building's thermal mass is applied; a5 applied a HEMS-based model of day-ahead optimal joint scheduling; and a12 proposed a monitored data system that is scrutinized at the appliance level.

Furthermore, for the category of physical settings with mathematical models, a6 combined the data with mathematical models, and a9 developed an optimal control model with sub-mathematical models. A two-stage stochastic unit commitment model to analyse the air-conditioning loads users' response in the wind-integrated power system is proposed in a10. A fuzzy logic-based variable power control strategy and Gaussian (bell-shape) membership functions were used for the input variables demand, and the temperature and the output signal (power) are applied in a16.

The HEMS-based models are also suitable for the simulation of certain appliances and multiple appliances simultaneously [8,38,60]. In addition, smart control with the comfort aspects has been applied to some representative appliances in [63] and to a dedicated appliance like AC in [64,68]. The physical settings with mathematical models have been used to simulate multiple appliances [69] and a single appliance, in this case, AC [61]. Other methods, such as the DSM-based model [65], the stochastic thermal model [62], the fuzzy logic model, and the clustering technique [70], have been applied to simulate a single appliance, either an AC or an EWH.

It is apparent that AC is discussed in the majority of the final list of studies, twelve studies in total, six of which only analysed the AC as a single object in the discussion. The reason might be in line with the results of [71], cited in [1], namely, that AC is mainly selected as a shiftable load because at the peak period of electricity demand, it contributes a significant share of about 10–35% in the residential sector. EWH was also simulated in nine studies, where three of them dedicated EWH as a single appliance in their studies. In addition, the simulation of multiple appliances is analysed in eight studies. Table 4 categorizes and lists the controllable and uncontrollable appliances based on the data extraction of the load-shifting methods of the final list of studies.

Furthermore, most studies simulated the load-shifting in hourly resolutions, while two studies provided the simulation at thirty-minute and twelve-minute resolutions. In the context of energy efficiency and the green transition, the share of renewable energy (RE) feed-in is increased by having a high-resolution load profile [72]. Moreover, the results obtained in the final list of studies show that efficiency is being achieved in most studies that accord with the aims of most of these research studies. Most results have shown that the efficiency share is being achieved in the installed capacity reduction [1,2,62] and the cost [8,18,61,63,67,70], including emissions reductions [69] and peak consumption reductions [64–66,68]. However, the centralized AC in [64] increased the total energy consumption by 13.3%. The result in [60] shows the significant contribution from the smart appliances. Demand flexibility is achieved in [20], and conservation behaviour is achieved in [38].

Table 4. Applicable load-shifting methods based on the appliance's operating time.

Load-Shifting Method	Appliance's Operating Time		Limitation of the Methods or Performance
	Controllable	Un-Controllable	
Optimization algorithms	EWH, AC, washing machine, dishwasher, refrigerator	Lighting, oven, computers, TV, blender, hairdryer, electric stove	a1, a7: Less flexible algorithms in adding new technologies or appliance(s). a4: Waiting time caused some fees. a8: To improve reliability in the load forecasting and power trading. a11: Control-wise modelling and multi-scale control approaches should be considered.
Clustering technique	AC	-	a3, a2: Limited sample size.
Smart control with comfort aspects	AC, heater, washing machine, dishwasher, clothes dryer, refrigerator	-	a13: The assumption that the smart control system manages the power consumption during the day in response to price signals, while at the same time maintaining the inside temperature within pre-set comfort limits may yield different results. a14: It should include more variety in the sample size of home types that are representative across the simulated grid-service area.
Stochastic thermal model	AC		a10: It should improve the generalizability and degree of precision by including humidity as a comfort factor.
Fuzzy logic	EWH		a16: The assumption that the temperature cannot exceed a certain limit on the amount of power during periods when the demand for electricity is low may yield different results.
Smart control-scheduling	Washing machine, dishwasher, hybrid heat pump	Lighting, TV, electric stove, computer	a5: This should consider the distributed renewable generations in the optimal scheduling model. a12: This should accurately understand the impact of feedback on single-appliance consumption. a17: This should involve the heat capacity of the building in terms of the immediate and long-range development of thermostatic controls.
Physical setting with mathematical model	EWH, AC, washing machine, dishwasher, refrigerator	Lighting, TV, electric stove	a6: Adjustments to the power factor were not identified in the monitored Data. a9: The assumption that the combined heat and power (CHP) fuel does not create emissions, though the energy hub is charged, may yield different results.
DSM-based model	AC	-	a15: This should improve the physical design that considers the comfort model that meets the daily domestic consumption.

Most of the results from the final list of studies have been validated in comparison with other studies, techniques, or scenarios [1,2,8,20,61,67]. Some studies have been tested on more than one case or model [18,62,64,70], while others have been compared with the real data [68,69]. Performance metrics were evaluated in [63]. The remaining studies were validated based on their proposed methods by the case study's demonstration.

This work also identifies the limitation(s) of each final study. The results in a7 and a1 [1,2] indicated that the applied optimization algorithm is less flexible, as adding other demand-response technologies like storage in the simulation of a1 and a7, and other controllable appliances in a7, may yield different results. Furthermore, the limited sample sizes in a2 and a3 [60,70] might have an effect on the average value. Thus, the performance of the applied smart control method in [60] and the clustering technique in [70] need to be simulated with a larger sample size. A bias was also uncovered in the sampling in [70], where the absence of a smart meter in a building was not correlated with certain

building characteristics. In a4 [20], the waiting time is the limitation of the proposed hybrid technique, where the user must pay some cost in the context of waiting time while reducing the electricity bill.

Further work on a5 [8] should consider the distribution of renewable energy generation in the optimal scheduling model. In a6 [61], adjustments to the power factor were not identified in the data captured by the monitoring tool, which has an accuracy of ±10%. The effect of this limitation on the results is unknown. The required improvement in a8 [67] is in the load-forecasting and power-trading concept between the prosumers and the utility grid, as it is considered that this may cope with the gap between supply and demand to improve the reliability of the power system. Furthermore, in a9 [69], the assumption is that the combined heat and power (CHP) fuel does not create emissions, even though the energy hub is charged. The assumption in a13 [63] is that the system is equipped with smart controls that manage power consumption during the day in response to price signals, while at the same time maintaining the inside temperature within pre-set comfort limits. The assumption in a16 [66], finally, is that the temperature cannot exceed a certain limit on the amount of power which can be applied to the EWH during the periods where the demand for electricity is low. These assumptions in a9, a13, and a16 may yield different results.

An effort to improve the generalizability and degree of precision by including humidity as a comfort factor could be a research implication of a10 [62]. Also, future work based on a11 [18] should consider control-wise modelling and multi-scale control approaches. Future work on a12 [38] should concentrate on single appliances and their time-usage patterns in order to precisely understand the impact of feedback on single-appliance consumption. Future work on a14 [64] should include a greater range of sample sizes of home types that are representative of those across the simulated grid-service area. As a consequence, it will identify the effects of thermostat-control strategies on the overall grid peak. Improvement upon a15 [65] relies on the physical design as a part of the designed DSM, which should consider the comfort model that meets daily domestic consumption. In addition, the practical aspects of a17 [68] in including the heat capacity of the building in terms of immediate and long-range developments of thermostatic controls have room for future improvement.

In general, the implications for future studies include the use of distributed renewable systems in the load-shifting and application of approaches to control usage on multiple scales. In relation to the thermodynamic aspects, it would be interesting to include more comfort factors in improving the degree of precision. Five such studies have been simulated in the United States; three in Australia; one each in the Netherlands, China, South Africa, and Turkey; and the remaining five studies are unspecified. The years of publication range from 1991 to 2019, with load-shifting gaining momentum since 2017. The studies in the 1990s were specifically focused on AC in 1991 and EWH in 1999.

In addition, from the studies excluded after the substage of reading the title and abstract to assess their quality, it can be seen that most studies addressed load-shifting in relation to its economic aspects, including price, electricity rate structure, electricity tariff, incentives, economic optimization, or customer satisfaction. This is followed by the more technical aspect, namely, applications of DSM, including segmentation based on the DR program, and smart-grid and micro-grid systems.

It can be concluded that there are two main categories of processes, which apply to our review based on the twin concepts of normative and subjective judgements. Normative processes occur at the study selection stage and in assessing quality through peer-review checks, where the inclusions and exclusions are based on defined criteria or rules. These normative processes can mostly be carried out automatically using WoS's internal features, except for checking the peer-reviewed journals. At the moment, this must be performed manually, as WoS does not provide the peer-review status of journals. The remaining steps are subjective judgements, where the researchers have to judge the inclusion and exclusion of the final list of studies based on reading the title and abstract as well as the paper, which may be revisited several times.

As already mentioned, a basic data-quality score was created to measure the quality of the information. This included ten measurable attributes, as shown in Table 5: research objective, approach, method, result, limitation, model's input, data resolution, validation, simulated appliance, and country where the method or model was simulated. It is important to recognize the simulation's location in order to have a deeper understanding of the data characteristics and the developed model, whether it is applicable only to a specific region or can be applied to other regions in general. In the final list of selected articles, the availability of each attribute is uniformly weighted and given a single score. Table 5 gives the distribution scores for the final seventeen articles. According to the data-quality score, ten articles were recommended as being in the priority review list, as they fully addressed all eleven attributes. Three of the seventeen articles did not clearly identify the validation method applied in their research, and five did not specify the simulation's location. The lowest score was article a16, with a score of nine, because it did not clearly mention where the simulation was performed, nor how the method was validated.

Table 5. Basic data-quality score of the final articles.

Article ID	Objective	Approach	Method	Result	Limitation	Model's Input	Time Resolution	Validation	Simulated Appliance	Country/ Region	Score
a1	1	1	1	1	1	1	1	1	1	1	11
a2	1	1	1	1	1	1	1	1	1	1	11
a3	1	1	1	1	1	1	1	1	1	1	11
a4	1	1	1	1	1	1	1	1	1	0	10
a5	1	1	1	1	1	1	1	1	1	1	11
a6	1	1	1	1	1	1	1	1	1	1	11
a7	1	1	1	1	1	1	1	1	1	1	11
a8	1	1	1	1	1	1	1	1	1	0	10
a9	1	1	1	1	1	1	1	1	1	1	11
a10	1	1	1	1	1	1	1	1	1	0	10
a11	1	1	1	1	1	1	1	1	1	0	10
a12	1	1	1	1	1	1	1	0	1	1	10
a13	1	1	1	1	1	1	1	1	1	1	11
a14	1	1	1	1	1	1	1	1	1	1	11
a15	1	1	1	1	1	1	1	0	1	1	10
a16	1	1	1	1	1	1	1	0	1	0	9
a17	1	1	1	1	1	1	1	1	1	1	11

5. Conclusions

This work has applied a structured literature review based on the twin concepts of systematicity and transparency. It reveals that providing transparent results at each stage and substage is essential. Therefore, we have provided detailed information on the reviewed studies to ensure transparency, such as the number of excluded and included studies and the reasons for the exclusion. The findings show consistency between the research aim of the most final list of studies in the literature review and their statistical results, where efficiency was achieved with respect to the installed capacity reduction, the cost of including emission reductions, and peak-consumption reductions.

The most frequently applied method in relation to load-shifting at the appliance level is developing load-shifting algorithms. The algorithms are mostly applied to the load-shifting simulations that involve multi-appliances. Furthermore, AC is selected as the most frequently discussed shiftable load in the final list of studies, followed by EWH. Most results were validated in comparison to other studies or scenarios and real data. All works in the final list of studies provide the simulation in high-resolution data, which is essential in the load-shifting work that requires near-real-time data in high resolution—hourly, every thirty minutes, and every twelve minutes—to be obtained. Moreover, to quantify the quality of the information, a basic data-quality score was created. It comprises ten measurable attributes: research objective, approach, method, result, limitation, model input, data resolution, validation, simulated appliance, and country where the method or model was simulated. The availability of each attribute in the final selection of articles was given a uniform weighting. Based on the quantification of the data-quality score, ten articles were recommended for inclusion in the priority review list. This means that 58 percent of the final list of studies fully addressed all the relevant attributes. The remaining six studies

lacked an attribute's information, and only one study did not provide information on the two attributes.

Some major limitations in the final selected studies were identified in this work, where the defined assumptions may yield different results. This also accords with the less flexible algorithm applied in the case studies, where adding other demand-response technologies may yield different results. Furthermore, the limited sample size in the studies might have an impact on the average value. Thus, the performance of the applied methods must be simulated with a larger sample size.

In addition, the future directions of the final list of selected studies aim to analyse the use of distributed renewable systems in load-shifting and the application of approaches to multi-scale controls. In relation to the thermodynamic aspects, more comfort factors should be included in improving the degree of precision.

Our work is replicable and beneficial to researchers as a source of knowledge on residential electricity load-shifting at the appliance level. This detailed review can make valuable contributions in support of decision- and policymaking by illuminating new dynamic systems in the load-shifting area specifically and demand-side management in general for purposes of energy efficiency. It will also contribute to the energy incentive programs and other economic policies. As an implication, a review of the load-shifting satisfaction model would make for interesting future work. Furthermore, in future work, it would provide a more comprehensive picture to apply this review method to two databases, e.g., WoS vs. Scopus, and compare the results.

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Appendix A

Table A1. The final list of articles.

ID	Ref.	Article Title
a1	[2]	Ali, S.M.H.; Lenzen, M.; Tyedmers, E. Optimizing 100%-renewable grids through shifting residential water-heater load. Int. J. Energy Res. 2019, 1479–1493.
a2	[60]	Gercek, C.; Reinders, A. Smart appliances for efficient integration of solar energy: A Dutch case study of a residential smart grid pilot. Appl. Sci. 2019, 9
a3	[70]	Patteeuw, D.; Henze, G.P.; Arteconi, A.; Corbin, C.D.; Helsen, L. Clustering a building stock towards representative buildings in the context of air-conditioning electricity demand flexibility. J. Build. Perform. Simul. 2019, 12, 56–67.

Table A1. *Cont.*

ID	Ref.	Article Title
a4	[20]	Khan, Z.A.; Khalid, A.; Javaid, N.; Haseeb, A.; Saba, T.; Shafiq, M. Exploiting Nature-Inspired-Based Artificial Intelligence Techniques for Coordinated Day-Ahead Scheduling to Efficiently Manage Energy in Smart Grid. IEEE Access 2019, 7, 140102–140125.
a5	[8]	Li, K.; Zhang, P.; Li, G.; Wang, F.; Mi, Z.; Chen, H. Day-Ahead Optimal Joint Scheduling Model of Electric and Natural Gas Appliances for Home Integrated Energy Management. IEEE Access 2019, 7, 133628–133640.
a6	[61]	Goldsworthy, M.J.; Sethuvenkatraman, S. The off-grid PV-battery powered home revisited; the effects of high efficiency air-conditioning and load shifting. Sol. Energy 2018, 172, 69–77.
a7	[1]	Muhammad, S.; Ali, H.; Lenzen, M.; Huang, J. Shifting air-conditioner load in residential buildings: benefits for low-carbon integrated power grids. IET Renew. Power Gener. 2018.
a8	[67]	Hafeez, G.; Javaid, N.; Iqbal, S.; Khan, F.A. Optimal residential load scheduling under utility and rooftop photovoltaic units. Energies 2018, 11, 1–27.
a9	[69]	Setlhaolo, D.; Sichilalu, S.; Zhang, J. Residential load management in an energy hub with heat pump water heater. Appl. Energy 2017, 208, 551–560.
a10	[62]	Han, X.; Zhou, M.; Li, G.; Lee, K.Y. Stochastic unit commitment ofwind-integrated power system considering air-conditioning loads for demand response. Appl. Sci. 2017, 7.
a11	[18]	Park, L.; Jang, Y.; Bae, H.; Lee, J.; Park, C.Y.; Cho, S. Automated energy scheduling algorithms for residential demand response systems. Energies 2017, 10, 1–17
a12	[38]	Kantor, I.; Rowlands, I.H.; Parker, P. Aggregated and disaggregated correlations of household electricity consumption with time-of-use shifting and conservation. Energy Build. 2017, 139, 326–339
a13	[63]	Liu, M.; Quilumba, F.; Lee, W.J. A Collaborative Design of Aggregated Residential Appliances and Renewable Energy for Demand Response Participation. IEEE Trans. Ind. Appl. 2015, 51, 3561–3569
a14	[64]	Cole, W.J.; Rhodes, J.D.; Gorman, W.; Perez, K.X.; Webber, M.E.; Edgar, T.F. Community-scale residential air conditioning control for effective grid management. Appl. Energy 2014, 130, 428–436
a15	[65]	Atikol, U. A simple peak shifting DSM (demand-side management) strategy for residential water heaters. Energy 2013, 62, 435–440.
a16	[66]	Lameres, B.J.; Nehrir, M.H.; Gerez, V. Controlling the average residential electric water heater power demand using fuzzy logic. Electr. Power Syst. Res. 1999, 52, 267–271.
a17	[68]	Reddy, T.A.; Norford, L.K.; Kempton, W. Shaving residential air-conditioner electricity peaks by intelligent use of the building thermal mass. Energy 1991, 16, 1001–1010.

Appendix B

Table A2. Data extraction of the final list of studies where it includes research objective, method, simulated appliance, time resolution, result, and in which country the simulation was conducted.

ID	Research Objective	Method	Dedicated or Simulated Appliance	Time Resolution	Result	Country
a1	To analyse potential capacity reductions in a renewable-only grid that can be achieved through load-shifting.	Load-shifting algorithm to simulate the capacity reduction/optimization of the 100%-renewable electricity grid	EWH	Hourly	The installed capacity of a 100% renewable electricity grid in Australia can be reduced between 4 and 20% by applying 1 to 18 h of load-shifting on residential water heaters (the total electricity demand in Australia).	Australia
a2	To evaluate the smart homes' efficiency, their ability to reduce peak-electricity purchases, and their effects on self-sufficiency and on the local use of solar electricity.	Detailed monitoring data: Power Matching City (PMC). An energy management software has been used to operate power flows.	Smart appliances: washing machines, dishwashers, and smart hybrid heat pumps (SHHP) with a condensing boiler.	Hourly	Smart appliances significantly contributed to load-shifting in peak times. Cleaning practices are potentially highly flexible for residential sector.	The Netherlands

Table A2. *Cont.*

ID	Research Objective	Method	Dedicated or Simulated Appliance	Time Resolution	Result	Country
a3	To apply an aggregation method to effectively characterize the electrical energy demand of air-conditioning (AC) systems in residential buildings under flexible operation.	Cluster-centre aggregation (CCA): clustering techniques to aggregate a large and diverse building stock of residential buildings to a smaller, representative ensemble of buildings	AC	5 min or 60 min resolution	Reached demand flexibility of good agreement between the energy demand predicted by the aggregated model and by the full model during normal operations (normalized mean absolute error, NMAE, below 10%), even with a small number of clusters (sample size of 1%)	USA
a4	To shift the electricity load from on-peak to off-peak hours according to the load curve for electricity.	MBBSO (an extension of existing algorithm BSO) and MBHBCO (hybrid version of MBBSO and MOCSO) algorithms to optimize the search space for load-shifting under DR.	Multi-appliance	Hourly	Results reveal that coordination-based day-ahead scheduling is more effective in reducing the electricity cost and PAR as compared to without coordination.	Not mentioned
a5	To consider the interaction between electric and natural gas appliances in households, a day-ahead optimal joint scheduling model of electric and natural gas appliances for HEMS is proposed.	HEMS model based on different types of appliances	Multi-appliance	Hourly	Save total energy costs up to 30% for customers whilst ensuring their satisfaction levels	China
a6	To analyse the effect of high efficiency AC and load-shifting.	The sub-circuit load, ambient temperature, and irradiance data were combined with mathematical models of a crystalline silicon PV array and lithium-ion battery storage system	AC	30 min	Improve the economics considerably, even accounting for the fact that the appliance efficiency improvements also reduce the grid-connected electricity costs.	Australia
a7	To present a simulation of low-carbon electricity supply by demonstrating the benefit of load-shifting in residential buildings for downsizing renewable electricity grids.	Novel load-shifting algorithm for AC	AC	Hourly	Reduce 14% installed capacity requirements in renewable electricity grid due to 1 h of load-shifting.	Australia

Table A2. *Cont.*

ID	Research Objective	Method	Dedicated or Simulated Appliance	Time Resolution	Result	Country
a8	To focus on the problem of load-balancing via load-scheduling under utility and rooftop photovoltaic (PV) units to reduce electricity cost and peak-to-average ratio (PAR) in demand-side management.	Shift-load algorithm: genetic algorithm (GA), binary particle swarm optimization (BPSO), wind-driven optimization (WDO), and our proposed genetic WDO (GWDO) algorithm.	Multi-appliance	12 min	Reduced electricity cost and PAR by 22.5% and 29.1% in scenario 1, 47.7% and 30% in scenario 2, and 49.2% and 35.4% in scenario 3, respectively, as compared to unscheduled electricity consumption.	Not mentioned
a9	To formulate a practical optimal control model for ED within a hub with modelling of appliances with a heat pump and coordination of all considered resources.	The optimal control model with sub-mathematical models	Multi-appliance	Hourly	Achieved cost-saving due to appliance-shifting is affected by the disparity between the peak and off-peak price, which in this case is 30%. A CO^2 signal could give customers a motivation to shift or reduce loads during peak-hour reductions.	South Africa
a10	To introduce air-conditioning loads (ACLs) as a load-shedding measure in the DR project.	A two-stage stochastic unit commitment (UC) model to analyse the ACL users' response in the wind-integrated power system	AC	Hourly	System peak load can be effectively reduced through the participation of ACL users in DR projects.	Not mentioned
a11	To estimate a user's convenience without configuring the convenience of fully automated energy scheduling.	Energy-scheduling optimization model and an algorithm to automatically search the preferred time for each type of appliance	Multi-appliance	Hourly	Significantly reduce the electricity bill by 10% and satisfy user convenience	Not mentioned
a12	To show which groups of appliances are responsible for observed shifts in usage times or conservation.	Monitored data are checked for quality, and periods of missing data are filled in according to the household consumption near the gap in data and whether normalisation is considered	Multi-appliance	Hourly	Conservation behaviour is found in two of eighteen households and is correlated to the consumption pattern of air-conditioning units, major loads, and discretionary loads	Canada
a13	To shift the coincidental peak-load to off-peak hours to reap financial benefits	Aggregated appliances operation strategy: smart control with comfort aspect	Representative appliances: AC/heater, clothes dryer, and refrigerator	Hourly	The results show that by performing load control and utilizing renewable resources, the total cost can be reduced significantly.	USA

Table A2. *Cont.*

ID	Research Objective	Method	Dedicated or Simulated Appliance	Time Resolution	Result	Country
a14	To achieve substantial reductions in peak electricity demand	Reduced-order modelling strategy and an economic model predictive control approach	AC	Hourly	The centralized, coordinated control of residential air-conditioning systems reduces overall peak by 8.8% but increases total energy consumption by 13.3%. Decentralized control reduces overall peak by 5.7%, demonstrating that the value of information-sharing for peak reduction is 3.1%.	USA
a15	To avoid peak hours	EWH peak shift DSM model	Water heater	Hourly	An effective way of shifting the load from peak hours to off-peak hours.	Turkey
a16	To shift the average power demand of residential electric water heaters from periods of high demand for electricity to off-peak periods.	Fuzzy logic-based variable power-control strategy and Gaussian (bell-shape) membership functions for for the input variables of demand, temperature, and output signal (power).	Water heater	Hourly	Reduced the peaks of average residential water heater power demand profile and shifted them from periods of high demand for electricity to low demand using the proposed customer-interactive DSM strategy.	Not mentioned
a17	To predict the thermal performance of the residence when the air-conditioner is switched off and to illustrate the validity of such simplified estimates with monitored data from an actual residence.	Peak-shaving strategies using building thermal mass	AC	Hourly	Reduced the peak load using the intelligent building thermal mass	USA

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