Energy demand and its temporal flexibility: approaches, criticalities and ways forward

Article

Lo Piano, S. ORCID logoORCID: https://orcid.org/0000-0002-2625-483X and Smith, S. T. ORCID logoORCID: https://orcid.org/0000-0002-5053-4639 (2022) Energy demand and its temporal flexibility: approaches, criticalities and ways forward. Renewable and Sustainable Energy Reviews, 160. 112249. ISSN 1364-0321 doi: https://doi.org/10.1016/j.rser.2022.112249 Available at https://centaur.reading.ac.uk/103874/

To link to this article DOI: http://dx.doi.org/10.1016/j.rser.2022.112249

Publisher: Elsevier

Renewable and Sustainable Energy Reviews 160 (2022) 112249

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Energy demand and its temporal flexibility: Approaches, criticalities and ways forward

S. Lo Piano [*], S.T. Smith

School of the Built Environment, University of Reading, Reading, United Kingdom

ARTICLE INFO

Keywords:
Flexibility
Energy demand
Social practice theory
Demand response
Demand management
Temporality

ABSTRACT

This contribution reviews the options proposed to reduce and/or act on the temporal profile of energy demand (flexibility), mainly at the residential level. Automated technology-driven options and/or monetary incentives towards behaviour shifting from end users are firstly examined. A relevant finding is the existing potential points of frictions between options aimed to reduce energy demand and those acting on its temporality.

The identified socio-economic drivers of residential energy demand patterns and temporality are discussed through the application of analytical frameworks for the coupling of energy and social systems, with the overall aim to gather a thorough understanding of energy demand and its temporality for more aware options for the control of energy demand and its temporal flexibility. A particular focus is dedicated to the perspective of social-practice theory for its capability of capturing relations between users and material artefacts, with a discussion of its theoretical principles and of its application in practical examples. Through examination of the dialogue between technological and social dimensions of energy demand and its temporality in the literature, assumption and epistemic uncertainty exploration lead to more aware energy demand options. Despite its significance, this research avenue remains largely unexplored. We suggest critical areas for development of this dialogue are: (i) the translation of meaning of demand in relation to concepts of non-negotiable energy end use effects associated with technology efficacy/efficiency, (ii) issues of new fixities resulting from intended technological demand flexibility, (iii) addressing issues of determinism in accounts of new technology impacts, (iv) implementation of demand side management and response technology with respect to social accounts of demand temporality.

1. Introduction

The increasing proportion of highly distributed, renewable energy sources with intermittent and limited control of energy (electricity) generation, have led the call for a more sophisticated account of the energy demand profiles of end users. In seemingly mature energy grids, end users are accustomed to have their energy needs fulfilled as per the performance typically offered by a portfolio of primary energy sources and generators having different supply and generation/conversion characteristics; Fossil-fuel fired and nuclear power plants can continuously function and respond to demand in as much as their primary energy sources are stockpiled and supplied in the furnace/reactor. The intermittency of renewable energy sources, however, not only follows the temporal (daily and seasonal) and spatial variability of associated meteorology (e.g. solar radiation, wind speed, air temperature and precipitation level [1]), but these technologies typically lack the inherent long-term storage and predictability of supply associated with current predominant energy sources. Controlling, or influencing, the temporal and spatial characteristics of demand are, therefore, seen as a necessity that is raising technical, economic and social challenges.

At the time of writing, the influence of the COVID-19 pandemic – through the slowdown of the world economy, shifting in use of demand-side technology (e.g. home office increase and reduced transportation), and enforced changes in social behaviours – has contributed to an increased share of the residential energy and electricity demand [2]. Decrease in magnitude of daily peaks in electricity demand as well as of the required ramp up/ramp down power capacity from the grid to sustain them have also been documented as a side-effect of lockdown enforcements, leading to grid-stability issues [3]. This trend unveils the massive impact on energy demand of flexibility in social structure through technology and other means, hence it reinforces the case for implementation of energy demand-side measures.

---

[*] Corresponding author.
E-mail address: s.lopiano@reading.ac.uk (S. Lo Piano).

[1] See Section 4 for our adopted definition.

https://doi.org/10.1016/j.rser.2022.112249
Received 21 July 2021; Received in revised form 18 January 2022; Accepted 6 February 2022

Acronyms

DSM	Demand Side Management
DSR	Demand Side Response
DVR	Demand as Voltage control Reserve
EV	Electric Vehicle
HPs	Heat Pumps
HVAC	Heating Ventilation and Air Conditioning
ICT	Information and Communication Technology
PV	Photo-Voltaic
SPT	Social-Practice Theory
V2G	Vehicle-to-Grid

In this contribution, we review the approaches proposed to understand the social and technical aspects of energy demand and the availability of demand shifting, with a particular focus in terms of temporal *flexibility*.[1] Previous literature reviews on energy demand were mainly focused on a unique or a limited set of aspects, such as: (i) supporting policy schemes [4] and business models [5]; and (ii) theoretical frameworks [6]. However, Shimoda et al. [7] developed a more encompassing appraisal of energy demand by cutting across scales and representative domains of this phenomenon.

Our enquiry is novel in that this review covers the interplay between technological and social dimensions of energy demand; demonstrating some of the complexity and conflict that arises in understanding demand flexibility issues through these different perspectives. This is with particular focus on the application of time-use surveys and of one theoretical lens adopted in the energy-demand literature for coupling between energy demand and social systems, the Social-Practice Theory (SPT). Our intention is not to promote any one particular approach, but rather to explore how a dialogue between very different disciplines in energy demand research can inform understanding of energy demand and its temporality in relation to *flexibility*.

The main questions addressed in this review are: (i) What approaches have been proposed in the literature to curtail energy demand and/or enact energy-demand temporal shifts? (ii) What are the differences between the social and technical framings of approaches? (iii) What are the levels of separation between the technological modelling and the theoretical frameworks from the domain of social science/humanities? This literature review will guide us across these dimensions and point to open challenges.

After presentation of the searching criteria of our literature review in Section 2, we discuss energy-demand technologies (Section 3), and *flexibility* in relation to the technological and monetary-driven perspective of demand-side management (Section 4) before exploration of the socio-economic drivers of energy demanding actions, their associated temporalities, highlighting the perspective of SPT (Section 5). In the concluding section (Section 6), we reflect on the points of frictions in the policy goals, the criticalities of the approaches proposed, as well as the potential of the integration of the dimensions discussed.

The main focus of this contribution is on the residential sector, yet we discuss technological and monetary approaches that specifically go beyond this dimension and encompass the secondary and tertiary sector. Even the sections on SPT go well beyond the mere residential level by dealing with phenomena occurring at higher hierarchical (societal) levels.

2. Literature review criteria

A literature search was performed on *Scopus* on January 21, 2020 (see Fig. 1) with ad hoc updates thereafter. Several combinations of key-words have been tested, especially in the case of frameworks from the domain of social sciences, with the aim to include a non-engineering perspective on energy demand (Fig. 1). “Energy demand” has been excluded from the combinations “flexibility”+“social activities”, and “flexibility” + “time allocation” since the addition of this keyword phrase returned no items. The same leave-one-out approach has been pursued by excluding “flexibility” from the combination of “energy demand” with other keywords. The screening of contributions led to removal of duplicates, publications deemed out of scope, or because of language barriers that impeded our scrutiny of the documents. The final pool of documents consisted of manuscript written in English, Spanish or Portuguese. The full list of contributions is available from the *Supporting Material*.

A limitation of our approach is that it does not include the so-called grey literature of policy briefs and technical reports. The rationale for this choice was that this type of material presented pre-existing ideas, rather than challenging approaches that inform our understanding of energy demand. Another limitation of our work is its focus on energy demand in the understanding of how the technological and social perspectives interact: further points of learning could come from outside of this thematic domain. Additionally, this contribution covers only the particular interaction of the perspective of SPT and the temporality of activities through time use surveys with technology perspectives.

With the above search criteria, the number of published contributions has been stably increasing from the mid 2000s onwards with the annual rate of publication close to 30 for 2018–2020 (Fig. 2). The five most common journals were: Energy Research and Social Science (24), Applied Energy (12), Energy Policy (10), Building Research and Information (9), Energy and Buildings (9). We categorised the contributions depending on the dimension tackled: technology (145), theoretical frameworks for the coupling between energy and social systems (87), modelling activity (61), monetary incentives (36), user behaviour (19), time dimension (15). Of these articles, 153 presented exclusively on a single dimension, 78 covered two dimensions, 18 covered three dimensions, and the remainder covered four. The contributions focusing on modelling, technological and monetary options for energy demand and its temporality are examined in Sections 3 and 4, whereas those on the coupling of energy and social systems in Section 5. When embracing more than one dimension, contributions are discussed in the most adequate section of the manuscript as per their analytical aspects and findings.

3. Demand-side technologies

We consider demand-side technologies to be a particular subset of artefacts of the energy system that are *able to directly affect energy demand and/or shift the spatial and/or temporal patterns of demand*. The direct affect of the technology is considered in terms of acting upon (or within) energy distribution networks close to (or at) the point where energy is used. With this definition we exclude the potential for considering many artefacts as influencing energy demand (e.g. the humble washing line [8,9]) as our intention is to capture the scope of technology considerations within the engineering literature on *demand-side* technologies. With this recognition of a limited representation of demand-influencing technology in the literature, we identify a small number of technological categories with a particular energy demand rationale (purpose), see Table 1.

Historically, larger adoption of demand-side technologies were already advocated for in the 1980’s and early 1990’s [10]. For instance, Outhred and Kaye [11] proposed energy storage as an effective means to reduce the needs of terminal reticulation of an electric grid. Kraines et al. [12], however, demonstrated a need for careful reflection on the links between technology and demand. These authors referred to rooftop solar Photo-Voltaics (PV) panels in residential and commercial buildings as a demand-side technology, or more precisely, a demand-side *counter-measurement* as it allows the fulfilment of the building energy demand by using an energy supply harvested in situ. This idea of in situ demand-side technology can also extend to integrated systems

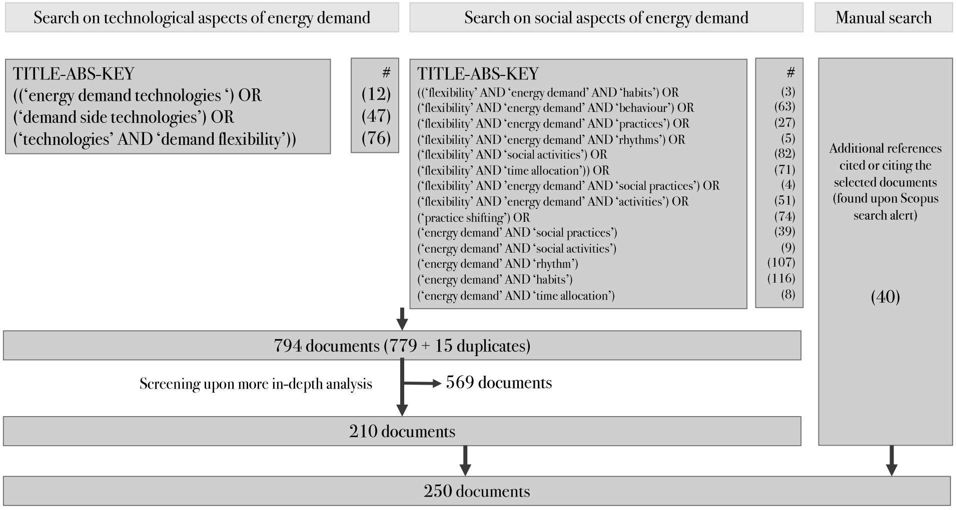

Fig. 1. Search keys per domain and returned number of items in brackets.

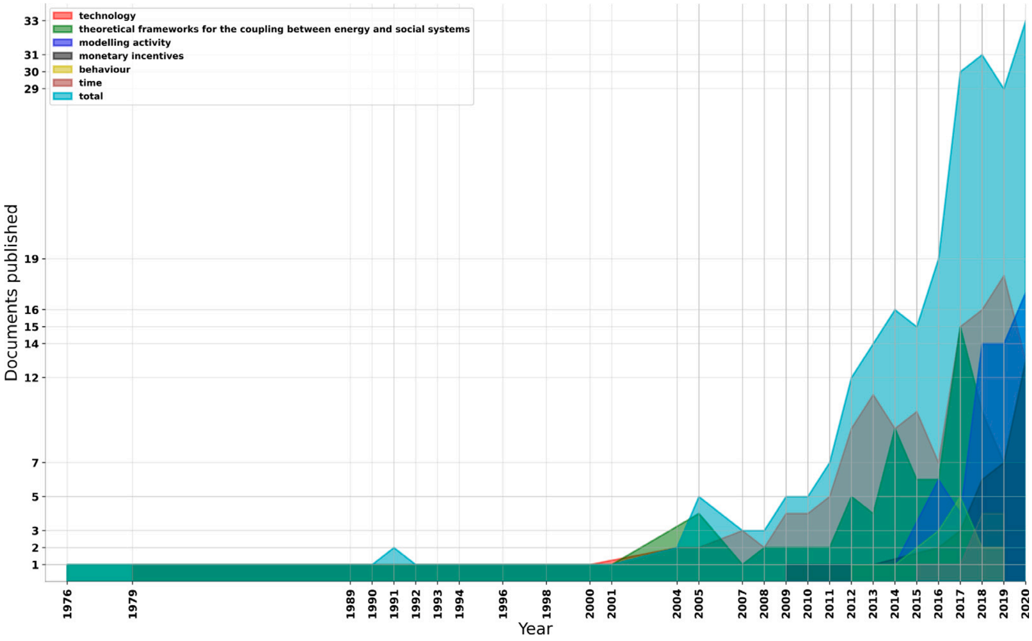

Fig. 2. Articles production over years.

of technology that move beyond in situ supply to one of supply–demand temporal disconnection. These combined measures are not simply confined to electricity generation and electrical storage; they can be more integral to the design and fabric of buildings (i.e. use of thermal mass as energy store) and incorporate control strategies to make use of designed building features. Higher use of local energy harvested from PV has, for instance, been demonstrated by enabling pre-heating strategies [13] that shift demand from the evening to the afternoon, more in line with electricity generation from PV.

Reduction in energy demand from buildings may be attained through thermal insulation [14], whose effectiveness depends on the local climate, the pattern of heating demand of the building (continuous for households, or at specific hours of the day in the case of schools/shops), the presence of windows and their relative orientation with respect to the cardinal points [15] as well as the presence of unoccupied properties in multi-resident buildings [16]. Papadopoulos et al. [17] reported reduction in gas consumption up to 24% for a sample of eight buildings retrofitted in Milton Keynes, UK. However, this reduction was partially compensated by an increase in electricity consumption of 12%. The opposite trend was observed for retrofits performed for socially vulnerable elderly households in Australia [18]: winter decrease in electricity consumption, but increase in gas consumption. The authors interpreted this finding in terms of the heating needs of this category of consumers as a means towards health preservation (more details in Section 5.1). Shading panels [19], green façades and adiabatic cooling technologies [20] have been proposed to reduce building energy demand for cooling.

Demand-side technological options have also been conceptualised for appliances, similarly motivated more by energy demand and GHG emission reductions over temporal shifting. The potential benefits of deploying more efficient appliances were already discussed in the literature in the 1990’s [21] by factoring in potential CO_{2eq} savings as per the time of day the appliances were typically used (and the related carbon-intensity of electricity at those hours). For example, the

Table 1
Demand-side technologies overview: approaches, targets and purpose.

Approach	Target	Purpose
Energy storage	Overall electricity and thermal demand	Permitted increase in use of intermittent renewable\locally generated energy when higher than demand
Building thermal mass, thermal insulation	Heating and cooling system	Reducing thermal energy demand
Shading panels, green façades, adiabatic cooling	Cooling system	Reducing cooling energy demand
Domestic-hot-water connection for appliances	Wet appliances	Reduce electricity demand from wet appliances upon more efficient building design
More efficient appliances	All appliances types	Reduce electricity demand from appliances under the same usage pattern
Context aware energy management systems	Lighting appliance, HVAC system	Reduce electricity demand from lower\less-intensive temporal use

contribution to the environmental savings of a more energy-efficient fridge was considered against the carbon-intensity coefficient of base-load electricity (as a reflection of the continuous cycling nature of a fridge's operation), whilst lamps were accounted for as primarily contributing to mid- and peak-load demands. Tanatvanit et al. [22] estimated that 80% of peak-load demand in Thailand could be avoided through the deployment of more efficient air conditioners. Yun et al. [23] assessed potential energy savings of almost 40% for *light emitting diodes* in comparison with standard technologies. This figure is achieved even when the emitted light wavelength range is tuned as per the users preference, which may deviate from the range for optimal energy performance. We will go back to the interaction between technologies and users in Section 5. Koller et al. [20] proposed connecting wet appliances (washing machines, dishwashers) to domestic-hot-water circuits as a means to reduce their contribution to domestic electricity demand.

The coordinated use of sensors for switching off (or diminishing power demand from) Heating Ventilation and Air Conditioning (HVAC) [24] and lighting systems when users are not present is another option largely explored to reduce energy demand. These systems are also known as *context-aware energy management systems*. Ayan and Turkay [25] described dimmer controls, photo sensors, and occupancy sensors as typologies of lighting control systems. Gupta et al. [26] discussed the working mechanism and features of these systems, whose performance is also affected by the machine-learning-based prediction algorithms of users position that gets adopted [27].

4. Flexibility in energy demand

The recent historical development of the identified categories of demand-side technologies clearly indicate that efficiency improvements within technology types and through technology operation have primarily been motivated by overall energy demand reduction. However, the increasing levels of electrical appliances and intended transitions towards greater electrification (e.g. transport and heating) is diverting attention on the 'shifting' (both temporal and spatial) capability of demand-side technologies. The meso-temporal (daily to seasonal) patterns/rhythms of demand that emerge at scale on energy networks present potential system constraint issues as more loads coalesce to one energy carrier (i.e. electrification) with greater variability in supply, so 'flexibility' (here to mean *the measure of how rhythms of demand change in time* [28]) is considered of importance to overall system energy and CO_{2eq} reductions [29].

Two complementary approaches can be identified in the context of *demand-side integration* to vary the temporal pattern of demand: Demand Side Management (DSM) and Demand Side Response (DSR) [30]. DSM is enacted by technologies assisting the temporal variation in the demand pattern, such as switchable (less time critical) loads and batteries (storage). DSM is typically top-down and utility-driven, for instance to optimise power generation through load shifting [14]. DSR is enacted by households shifting demands through a monetary leverage dependent on the overall electricity demand and availability. Higginson et al. [31] consider DSR an optimistic approach: upon adequate compensation, all demand can be flexible. Conversely, DSM rests upon the pessimistic assumption that this is to be achieved in an automated form. Patteeuw et al. [32] use the terms *passive* and *active demand response* to refer to DSM and DSR, respectively, to highlight the level of involvement of the end users.

The next Section 4.1 presents flexibility strategies at the utility level, whereas the following examines the level of flexibility of individual appliances Section 4.2. Sections 4.3–4.5 cover DSM, DSR, and joint DSM - DSR approaches, respectively.

4.1. Flexibility strategies

Technologies for energy demand reduction typically seek this single goal. Conversely, strategies for flexibility are more nuanced and can be set as per different goals. For Ósorio and Estanqueiro [33], the ultimate goal of flexibility in energy demand would be reverting the current paradigm of electricity generation triggered by demand by actually making the load follow the generation. Hong et al. [14] share this standpoint, and suggest the onus of control should entirely be on the energy-demand side, ideally in a purely technological form such that satisfaction is not compromised: no awareness or action would be on the users side. For Bruninx et al. [34] customer satisfaction should even increase upon adopting demand-side approaches.

From Hong et al. [14],Gellings [35],Sallam and Malik [36] aggregated demand flexibility can be considered for: peak clipping, valley filling and load shifting, strategic conservation, strategic load growth, and flexible load shape (Fig. 3).

Some of these strategies are utterly incompatible and are to be adopted when seeking diametrically opposite goals. For instance, strategic conservation and peak clipping are implemented when one is seeking a reduction in electricity demand. Conversely, strategic growth of energy demand may be resorted to along with valley filling when an increase in electricity demand is foreseen [37] (due to development of new activities; energy-carrier shifting; or the availability of unused power capacity). As for load shifting, constraints may emerge on the shifting boundaries (the shifting time lapse, short vs. long time shifts) as well as the shifting direction (forward or backward, i.e. anticipated or delayed peak, respectively).

In general, loads from appliances can be shifted from a coordinated management architecture as we shall see in the section below. Highly flexible household appliances (such as those laundry related appliances) may assist in sub-hourly load shifts, while hourly or longer shifts can be produced through DSR from thermal heaters, Electric Vehicle (EV)s or industrial processes [38]. These provide some indication that the constraints on shifting boundaries (the theoretical level of flexibility) will depend on types of appliance, although a primary role is also played by the interaction with the user (see Section 5 for more details).

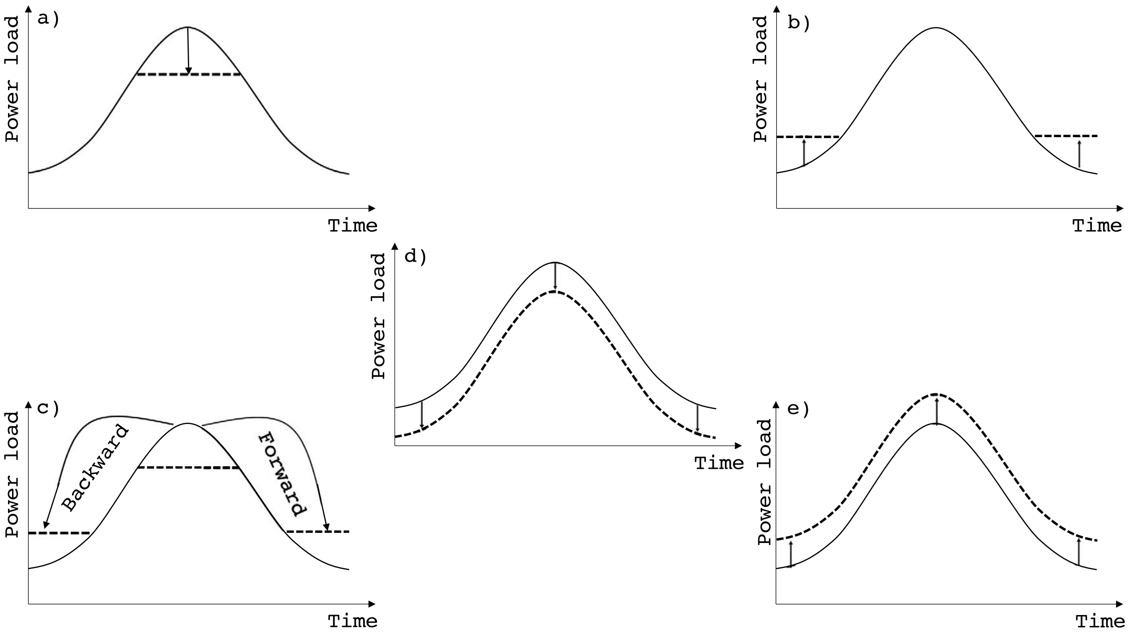

Fig. 3. Strategies for the temporal shift of peak demand. (a) Peak clipping; (b) Valley filling; (c) Load shifting; (d) Strategic conservation; (e) Strategic load growth.
Source: Adapted from Sallam and Malik [36].

4.2. Flexibility level attainable with appliances

Energy consumption from appliances can sustain different levels of flexibility [14] in terms of how a temporary power disconnection impacts on the service/function they are expected to deliver (Table 2). Electrical-based heating, cooling appliances and integrated-battery devices (laptops, mobiles, etc.) offer a high potential level of flexibility: a temporary (sub-hourly) power disconnection does not critically impact on their functioning. Even EVs potentially rest on very flexible charging patterns [39]. Washing machines and dishwashers also allow a medium degree of flexibility in so far as their working activity can be rescheduled to another period of time [40]. Irons, a type of appliance frequently overlooked in the discourse on its flexibility potential [41], whilst associated with a medium degree of flexibility, the nature of its use means the flexibility entirely rests with the user. Other appliances with direct connection to the end-user are identified in the literature as: vacuum cleaners, lighting, cooking appliances, hairdryers and microwave ovens (low flexibility). For these appliances, despite some developments around automated technology [14], the flexibility associated with user demands (temporal) is considered from a technology perspective to be low (medium at best) - user satisfaction/requirement is considered fixed. Further to this, entertainment devices cannot be considered to contain *passive* flexibility, unless they have an integrated battery, since their power demand is completely driven by user(s): any disconnection would massively impact on their level of functionality. However, screen brightness may be tuned to some extent and more attention towards switching off (rather than putting in standby) could reduce their energy consumption by about 10% [42], although indirect energy demand from networks and data centres would remain unaffected [43].

4.3. Flexibility through technological demand-side management: passive and algorithmic control

This section deals with DSM approaches, the concerns and benefits that users have in relation with their adoption, with a final brief closure on DSM approaches beyond the residential level.

DSM strategies can rely on a specific architecture [44], which encompasses Information and Communication Technology (ICT) elements such as ambient intelligence, wireless sensor networks, non-intrusive load monitoring, virtual power plants, interconnected through a network of relationships and rules [45]. Demand-side control algorithms are designed to switch off or reduce the appliance's demand of power (supply inferior to the demand), or turn appliances on for increased demand (supply higher than demand). When supply is inferior to demand, action on highly-flexible appliances are prioritised, vice versa when supply overcomes demand, to fully take advantage of appliance responsiveness and mitigate appliance inertia, respectively. *Demand-side management control algorithms* can be designed to act upon two properties [14]: (i) the duration of the load; and, (ii) the power level of the load. The higher the appliance flexibility, the more its demand pattern can be remotely tuned to the supply-side availability. When comparing the performances of different flexible appliances, Neupane et al. [46] found that devices with significant time flexibility but lower power-demand flexibility, such as wet appliances, can potentially enact more savings for the end users than devices with higher power-demand than time flexibility (e.g., Heat Pumps (HPs)).

The temporal and storage capacity features of technology (and their intended end goal) provides further distinction in the technology's flexibility offering. In the case of thermal storage in buildings, the capacity of domestic water storage is typically larger than the thermal storage for spatial heating and the timing of power demand to hot water demand is less tightly coupled than that of a space heating system. The higher storage capacity implies a higher (shorter response) flexibility potential [47] but the decoupling also implies an ability to be more reactive than proactive in its flexibility offering. Summer pre-cooling and winter pre-heating is another strategy involving HVAC appliances [48]: the environment is cooled (heated) at a slightly lower (higher) temperature in the hours before peak demand so as to shift the actual energy consumption entailed and reduce the peak load. In summer months, night ventilation can also be resorted to as an additional measure for cooling [49]. Flexibility resulting from a technology's thermo-physical properties can go further than a demand shift; Demand as Voltage control Reserve (DVR) has been proposed to counteract potential grid short-term voltage imbalances [50] through short disconnections (of seconds or minutes) of electric appliances having high thermal loads (e.g., freezers, refrigerators, or heat pumps) and whose thermal storage capacity attains minutes or hours. Hence, a short disconnection of these

Table 2
Demand-side management overview: targets, level of flexibility, temporal features and strategies.

Target	Level of flexibility	Temporal flexibility	Enacting options
Electrical-based heating, cooling appliance, integrated-battery devices	High	Sub-hour flexibility	Internet of things, smart home
Electric vehicles, thermal loadings	High	Hour flexibility and beyond	Internet of things, virtual power plant voltage control reserve
Wet appliances, iron, (and vacuum cleaner)	Medium	Hour flexibility and beyond	Internet of things, smart home
Lighting, cooking appliances and microwave oven, hairdryer, (and vacuum cleaner)	Low	Sub-hour/ Hour flexibility and beyond	Internet of things, smart home
Entertainment devices	None	None	Not defined

appliances from the grid can help to speed up recovery from a voltage imbalance, and minimise the risk of black-outs.

A large contribution to the future electric grid flexibility is expected from HPs [40,51,52] and EVs [53,54], estimated to be largely adopted in a significant number of countries. These technologies can contribute to flexibility through thermal storage in space heating and temporally variable charging (and discharging with Vehicle-to-Grid (V2G)) patterns, provided a flexibility in timing of heat/charging demand exists. Dedicated algorithms can be designed as a solution to enabling the flexibility by, for instance, promoting a coordinated spatio-temporal charging profile for EVs [55–57]. Carmo et al. [58] ranked HPs against a *wind-friendliness* indicator on the basis of their capacity to tune their energy demand in response to the available electricity generated from wind turbines. Gill et al. [59] proposed an *active management network* for the Shetland Islands, which included DSM approaches based on flexible electric heating equipped with frequency response systems to reduce wind curtailment as well as the reliance on diesel-powered generators.

DSM strategies based on switchable loads and storage batteries have been proposed as *virtual power plants*, a cloud-based system of distributed power plants [30,60,61]. Roossien et al. [62] showcased an application of such a system, in which local energy trading across twenty-two households (with HPs and EVs) connected on a micro-grid to a local wind turbine, was demonstrated to reduce the grid-imbalance caused by the intermittent wind-generated electricity. Several kinds of algorithms have been proposed to govern the electricity flows within micro-grids, including fuzzy-logic based genetic algorithms [63], artificial neural networks [64] and deep reinforcement learning [65]. The approach to control is also informed by system coordination architectures that at the neighbourhood level identified as [66]: (i) centralised architecture, in which all appliances of individual households are controlled by service providers; (ii) decentralised architecture, in which each household can take action individually, independently from the other households, on which it has no information; (iii) hierarchically distributed, where each household has information from the service provider on the power demand of the other users; (iv) non-hierarchically distributed, which has the same feature of the hierarchically distributed but the information on power demand is directly shared among users.

The deployment of DSM approaches is confronted with some difficulties [67]. Scepticism from end users towards DSM options has been reported in the literature, primarily in relation to privacy (risk of data leakage) when using connected devices. For this reason, Rottondi and Verticale [68] proposed a privacy-friendly framework for the load scheduling of appliances that reduced the risk of personal information leakage resulting from attacks on the network. Safeguarding the privacy dimension comes at a cost of slightly reducing the system performance, especially by increasing temporal delays (typically around thirty minutes) between the service request and the actual appliances starting time provided. Immonen et al. [69] underlined that lack of potential financial advantages, if not additional cost, was one of the main concerns of end users to adopt DSM options in a survey performed in Finland. Additional concerns included the previously-discussed loss of privacy, lack of confidence in the technology and the operators, the reluctance to hand over household equipment control to an external manager, technological anxiety [67], and lack of information. This last aspect was echoed in a survey performed in the Netherlands, where Li et al. [41] showed that 60% of the users were unaware of what a smart grid was. Further to that, only 5% were willing to use an EV with a smart charging and discharging system and only 11% of survey respondents were willing to change their temporal demand or comfort condition.

Other concerns are related to the increased energy consumption entailed by DSM options. For instance, the software-update approach at the basis of smart-home technologies may amount to 10% of the overall data traffic for smartphones and tablet [70]. Additionally, connecting smart-lights to gateway networks may drive significant energy consumption, comparable to the energy consumption of the lighting devices themselves [70]. Strategies involving thermal appliances and the coordinated use of thermal pumps and storage [71] may (based on timespan of demand shifting requirements and associated thermal losses) also result in increasing the final electricity consumption [32, 72]. Finally, intermittent disconnections from the grid may affect the life of the appliances and devices involved [50].

The difficulties identified in these studies to flexibility implementation are not, however, ubiquitous as financial doubts are also countered by financial incentives [41], and the acknowledgement of their results in terms of energy-virtuous behaviours [73] were mentioned as a potential driver towards the engagement with smart technologies. How ‘culturally informed socio-technical system transitions’, technology type, and exposure to DSM programmes influence attitudes will also play a part in the characterisation of the challenges or limitations to DSM flexibility offerings. For example, in contrast to the surveyed scepticism in Li et al. [41],Immonen et al. [69], Yamaguchi [74] reported an overall positive attitude of the engaged households towards DSM for laundry appliances in the Kanto region (Japan) with more than 70% of the users willing to participate.

DSM do not necessarily need to focus on the residential sector alone. For instance, the secondary sector can also resort to specifically tailored demand-side strategies for temporal flexibility [75]. The scheduling flexibility and process energy demand profiles depend on the specific industrial sector, which map onto the involved production rates and the energy demand profiles of the production machines, respectively. Overall, flexibility in the industrial sector needs to be benchmarked against the optimisation of industrial processes in terms of costs and performance [76] (e.g. volume and quality of production, [77]). Onsite

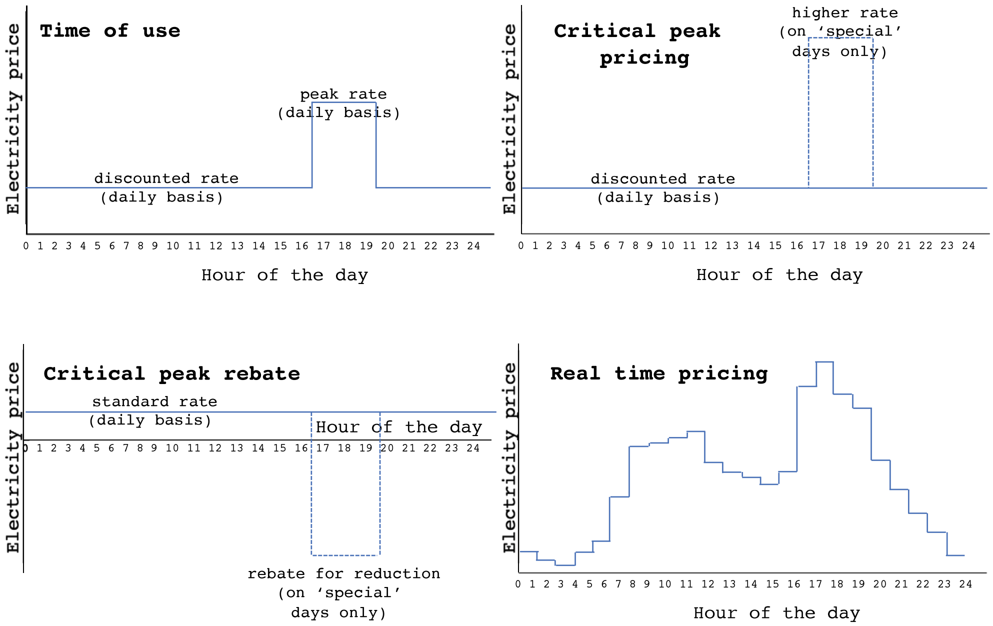

Fig. 4. Price-based tariff schemes and temporal profiles.
Source: Adapted from Faruqui and Sergici [82].

generation can also be boosted as a means to reduce the temporal load on the grid [78] by activating auxiliary industrial systems for electricity conversion and storage, which include *compressed air storage* [75], batteries and supercapacitors [79].

4.4. Flexibility through active technological demand-side response, monetary leverage

Monetary triggers for enacting flexibility can be traced back to the beginning of large-scale electric grid deployment, with debates around time-of-day pricing schemes to foster changes in lighting practices [80]. On more recent schemes, Chen et al. [48] distinguished between incentive-based and price-based DSR: The former is a *direct, system-led* or *emergency* approach, while the latter is *indirect, market-led* or *economic based*. Incentive-based DSR encompass [81] direct load control, curtailable load, demand side bidding, capacity market, ancillary services and emergency services. All these strategies rest on a load reduction performed either (i) directly from the system operator, who can control certain equipments of the participants; (ii) upon a load-reduction signal in case of emergency services (reserve shortfalls periods); ; or (iii) upon various forms of bids from the customers.

Four price-based (DSR) tariff schemes exist [48]: time-of-use tariffs, critical peak pricing tariffs, critical peak rebate tariffs, real time pricing tariffs (Fig. 4). The first approach schematically defines peak hours on which higher fares apply. The second is similar, but utilities can call critical events/emergencies and raise price accordingly. Pallonetto et al. [81] use the expression *extreme day pricing* when the critical peak pricing tariff is defined at a daily resolution, thus encompassing one or more days. Critical peak rebate tariffs are also similar to critical peak pricing tariffs, but the prices are constant and users receive refunds upon their capability of reducing demand. Finally, the real-time prices follow the wholesale market prices, which are typically volatile as they vary with the actual generation available from the electric grid at an (half-)hourly resolution.

The monetary schemes for active flexibility strategies are detailed in Table 3 along with the targeted users and appliances. Faruqui and Sergici [82] reported higher reductions in peak demand for tariff schemes other than time-of-use. The authors attributed this to the limited number of days over a year that reactions from users are elicited, leading thus to more responsiveness.

DSR is seen to not only enable better alignment between renewable generation and demand, but it can be enacted to prevent violation of grid network operational constraints [83,84]; helping reduce investment costs associated with grid augmentation (i.e. improved mesh topologies — ring networks). To understand the role DSR can play in offsetting network upgrade, the potential capacity (and temporal characteristics) of different end users in delivering flexibility services is an aspect to take into account. Curtis et al. [28] examined the responsiveness of hotels in implementing a reduction in load when the network aggregator elicited a DSR. The response time varied between four and twenty minutes dependent on the inertia in reducing/switching off the load of the facility and its involved appliances. For domestic demand, Sanchez et al. [85] proposed a clustering algorithm based on the temporal profiles of household energy use to identify the categories of users to primarily target in an active-demand management scheme. This information was complemented by qualitative surveys on household energy habits. Households were clustered as per their temporal profile and those with higher potential in terms of peak-demand reduction were targeted.

The effectiveness of the DSR schemes proposed can be evaluated regarding the medium-to-long-term trends documented in the end users energy demand profiles, in which the understanding of users and the rationale for their actions plays once again a prominent role. For instance, Nguyen et al. [86] reported positive data for a DSR pilot project in Japan: virtuous energy behaviours in households endured even after the end of the pilot scheme. Martin and Rivers [87] observed the same trend for the electricity use of 7000 households in Canada upon time-of-use tariffs and energy monitors rollout over twenty weeks. While slightly decreasing over time, enduring savings up to 3% of the energy consumption were documented over the investigated period, which the authors attributed to a conjoint effect of time-of-use tariffs and energy monitors that triggered the formation of new habits along with adjustments in the use of thermostat. Counter-peaks have also been documented just after the end of: (i) DSR events [28] and (ii) high-price peak hours; in case of significant monetary charges [44]. Additionally, rises in futile energy demand, that is to say energy demand emerging out of less considerate uses driven from inferior prices, have also been reported [14].

Table 3
Monetary-driven demand-side response: strategy, temporal flexibility requested, targets.

Strategy	Temporal flexibility requested	Target
Incentive-based demand-side response	Variable, typical hour flexibility and beyond	Large costumers (industry, commercial, hotels, etc.)
Time-of-use tariffs	Hour flexibility and beyond	Residential (all types of appliances) and medium (industry and commercial) costumers
Critical peak pricing tariffs	Sub-hour, hour flexibility and beyond	Residential, medium and large costumers
Extreme day pricing tariffs	Daily flexibility	Medium and large consumers
Critical peak rebate tariffs	Sub-hour, hour flexibility and beyond	Mostly residential
Real time prices	Sub-hour flexibility	Residential (highly flexible appliance, see details in Table 2), medium and large costumers

4.5. Joint passive and active demand-side management implementation

Hybrid approaches that resort to both DSM and DSR events have also been considered in the literature. For instance, Kiliccote et al. [88] presented six variable-temporal-scale strategies for energy-demand management: (i) Continuous energy consumption minimisation (through so-called energy efficiency measures); (ii) monthly peak demand management; (iii) daily time-of-use management; (iv) day-ahead response; (v) day-off response; and, (vi) fast-demand response. Most of these approaches resort to automated control, although manual intervention is also possible, e.g. in demand-response programmes. Semi-automated demand responses occur when the shift in some types appliance use (typically HVAC) is coordinated through a centralised control system, whereas the others remain under manual control.

In general, Faruqui and Sergici [82] reported larger peak-consumption reductions for joint DSM and DSR approaches in comparison with DSR options only. Also Ruokamo et al. [89] considered shifting thermal load as the likely low-hanging fruit under an integrated DSM-DSR strategy in pursuing flexibility at the household level due to its significant share in the overall residential energy consumption. Automated controls can be enacted upon financial compensations for participation in the scheme. On the users preference, a survey carried out in the Netherlands [41] showed that the majority of building users favoured automated control options for their appliances. However, Xu et al. [90],Chen et al. [91] found a spread reluctance to pay for *home energy management systems* in a survey carried out in New York city and Tokyo. The readiness of DSM and DSR has, however, been brought into question by Kohlhepp et al. [92] on the basis of the too-few demonstration projects built. The question of readiness not only raises concern in relation to technological maturity but also in relation to the response and engagement of energy end-users with active, passive, or combined approaches to flexibility.

5. Drivers of users energy demand

According to the reading of the socio-humanistic disciplines in energy studies, understanding energy demand drivers goes beyond the mere technological or economic description of provision of energy services [93,94]. Looking into these dimensions helps to expose uncertainties and decisive elements of a broader socio(-)technical system [95] that can inform the policy making associated with energy demand and technology adoption, hence its importance.

Depending on the scale of interest, demand profiles can be seen as regular and organised (the issue of network-wide peak loading for electricity grids) as well as highly variable when comparing households. The larger scale organisation of demand has a longstanding connection in the literature (over 40 years [96]) to social habits and societal organisation (i.e. domestic economic sectors) that motivates addressing the relation of habits and seeming fixity [97,98] with the required flexibility in demand. In some sense, many of the demand side technology approaches presented in the literature have this social fixity embedded in design.

At the residential and household scale, variability in energy demand is more visible but the underlying reasons take on technological, social, psychological and physiological interpretations. Variability in built form, technology options associated with heating and lighting, amongst others, will inform demand efficacy but alone do not explain all variability as demonstrated by Karlsson et al. [99]. Seligman et al. [100] reported that occupant behaviour, driven by internalised comfort and health concerns, was primarily responsible for variability in household heating demand. However, Gram-Hanssen [101] showed how cultural norms and technological design can lead to similar approaches to thermal energy demanding practices for notably different households. Yet broader social externalities that influence factors such as knowledge/know-how, financial, and technical ability lead to marked differences in energy demand. Whilst education can inform environmental-awareness and therefore motivation (or ‘meanings’ [101]) to change/reduce demand [102], the demand response must consider other contextual influencing factors. For instance, demographic factors such as gender- [103] and age-informed comfort standards [104,105]. Positing that multiple interacting and competing factors will inform energy demand supports a systems-based approach to understanding drivers of demand; something that Chappells [106] reviewed with four different systems-based models: human-ecological systems, systems of provision, large technical systems and systems of practices. This contribution focuses on the use of systems of practices theory (also known as social-practice theory as presented by Chappells [106]). In so doing, we do not seek to promote SPT over others per se. Given SPT’s capacity to consider the relations between users, technological artefacts (aligned with socio-technical understandings [101]) and social system structures, our aim is to highlight the value of this framing to understanding temporality in energy demand and the implications on technological options/artefacts for DSR and DSM. How SPT understands the making of energy demand is presented in Section 5.1, whereas Section 5.2 covers its temporal aspects.

5.1. The reading of energy demand from the social-practice theory perspective

Reckwitz [107] puts practice as an ‘interconnection of (three) elements’ (‘knowledge’, ‘things’, and ‘their use’) that are understood only through their collective interaction. Schatzki [108] refers to these elements in terms of material artefacts, conventions and competencies. Higginson et al. [109] highlights how these elements are shared across practices with a graphical network as a visual representation of the connections and interplays among practices (Fig. 5). For instance, a convention, like hygiene, pertains both to laundry and bathing; or a competence, like self-care, is shared across laundry and relaxation.

As to understand the energy dimension of practices, it is important to evaluate both the connections with the other activities on

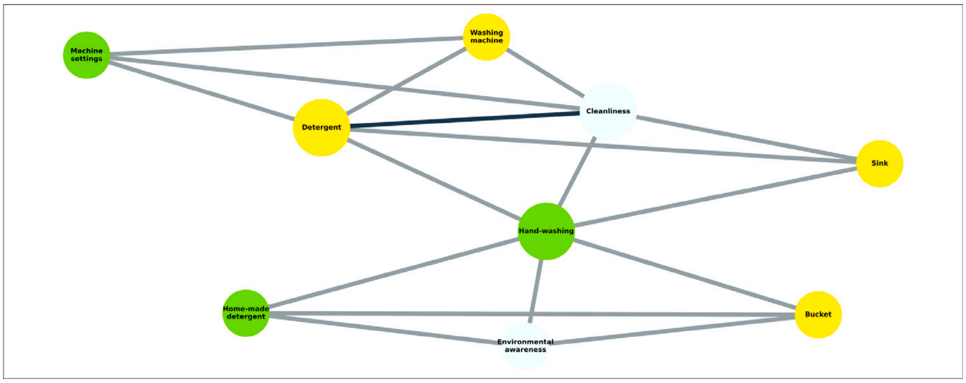

Fig. 5. Network of three laundry practices combined. Conventions (*environmental awareness*, *cleanliness*) are shown in azure, competences (*home-made detergent*, *hand-washing* and *machine settings*) in chartreuse, while material artefacts (*bucket*, *sink*, *detergent* and *washing machine*) in yellow. Darker edges refer to multiple connections (between *detergent* and *cleanliness*) that cut across more practices.
Source: Adapted from [109].

a larger scale, as well as their constitutive elements, and the relations entailed across the material artefact/convention/competency triads within a given practice. For instance, a household pattern of energy consumption for heating is determined by the interaction of the heating technology available, the heating practices the household occupants carry as well as their expectations in terms of indoor temperature [110]. Yet it is the overall understanding of thermal comfort (as a meaning) that helps to characterise the energy-intensiveness of practices and their outcome. An example is found in Hansen et al. [111], who reported the tendency to wear warmer clothes in winter in less thermally energy efficient houses as well as the tendency to set higher thermostat temperatures in more efficient houses in Denmark. Even the effects of a retrofit intervention [18,112–117] in terms of *health-preserving practices* may be downplayed due to the prioritisation of personal comfort standards over energy savings [18]. Overall, these examples show that controlling thermal comfort, not set point temperatures, goes beyond the control and efficiency of a central heating (or cooling) system.

Even for lighting, an increase in energy use at the household level has been observed over several decades in the UK and Denmark despite the larger deployment of more efficient light bulbs [118]. This trend stemmed from the large reconfiguration in the lighting practice from single-ceiling bulbs to multi-ceiling bulbs and table lamps (Fig. 6). So, even if more energy-efficient appliances are deployed, new uses and additional demand emerge with the evolution of the lighting practice.

Additionally, technology artefact–user relations may produce outcomes differing from design expectations. For instance, in the case of heating for a set of Finnish households, Rinkinen and Jalas [119] documented how the actual practices developed upon moving house can lead to unforeseen patterns due to the encounter of the occupant with technology and arrangements one may not be used to.

Other practices can also be brought in to understand the user–technology interaction, for instance in terms of *reflection practice* [120]. A device that conveys energy-consumption information in a user-friendly fashion can effectively enable practice shifting by triggering individual reflection on the alignment between one's behaviour on the one hand, and one's own personal motivations, values and life goals [121] on the other. Along these lines, Abhijith et al. [122] conceptualised a web-based application, a form of e-practice, in which users can benchmark their energy demand against users having similar energy needs. Also for Verkade and Höffken [123] and Jalas et al. [124], e-practices, i.e. active involvement in energy practices (including activism and participation in energy storage/generation), are required to deliver tangible effects in energy-demand reduction rather than entrusting energy-monitoring devices to achieve this goal.

Embracing the reading that energy demand is a feature determined by practices and its components [125] implies that these would also need to be acknowledged at the level of policy making. For instance, SPT questions the thesis of immutable levels of energy demand [126] by also criticising the concept of energy efficiency. According to Shove [127], this concept is framed as per the assumption that the current unsustainable lifestyles are to be preserved along with the same types of energy services and it is precisely for this very reason that seeking energy efficiency fails to deliver on its own goals. In general, for SPT scholars, social change can only be understood and triggered by focusing on the very nature of social practices and their constitutive elements [128], also in terms of their cultural and institutional aspects [74]. These dimensions can help to gather an understanding of the evolution of energy demand and should be at the basis of the making of energy policies in terms of the relation between practices and their material arrangements (including technologies of energy provision, distribution and consumption) as well as how these elements may jointly evolve [125,129,130].

For instance, infrastructure can sustain multiple coexisting practices [131]. In this sense, planners and policy-makers can target less energy-intensive practices and shape the infrastructure use accordingly, for instance by allocating more space on roads to non-motorised forms of transport. Even the opposite phenomenon can take place, with Yamaguchi [74] that identified indirect institutional phenomena (e.g. in terms of evolving housing construction systems over decades, or meanings, needs and values of household members) as the basis of the observed increasing residential energy demand in Japan. Analogously, Kuijer and Watson [132] found two elements which played a prominent role in shifting household heating practices in a Northern English town between 1920 and 1970: (i) the materialisations of ideals for separating domestic activities; and (ii) the emergence of new uses for heat following from a shift towards more sedentary, indoor activities. Indoor practices were both contributing to the design of and being shaped by: (i) the room configurations in the dwelling, (ii) the uptake of given types of appliances, and (iii) the technology used for heating these environments.

The introduction of new policies can in turn trigger changes in practices. One prominent example is the *Coolbiz* initiative in Japan, which prohibited the use of heating or cooling systems within the 20–28 °C range of indoor temperature. The policy was accompanied by a relaxation in the dress code in working places with the encouragement of loose fitting garments and short sleeved shirts [133]. Even non-energy policies do play a role in affecting the energy-intensity of practices, for instance in defining standards for health (introductions of best-before labels with a higher tendency towards food wastage), work (the introduction of company cars with the related tendency towards more driving), and hygiene (more laundry of clothes worn for less time) [134]. All these aspects drove the energy intensification of practices due to the complexification of social-practice meanings.

Fig. 6. An instance of the changing practice of lighting from single- to multiple-ceiling bulbs.

5.2. The reading of the temporality of energy demand from the social-practice theory perspective

As regards energy demand temporality, the SPT reading comes useful as the energy demand level and temporal profile is defined and created by shifting practices. This section deals firstly with useful theoretical frameworks from the SPT and then showcases applications.

Cass and Shove [135] identified different hierarchical levels of flexibility. From the micro to the macro, one can identify: flexibility of practices, flexibility of people and flexibility at the societal level. Shove [136],Blue et al. [137] remarked the link between flexibility and socio-temporal organisation of practices, also in terms of their rhythm/sequences [137,138]. Southerton [98] showed that temporalities and practices are profoundly woven with a two-way relation: practices can occur in accordance with temporalities, which are in turn defined by the rhythms of these practices. On a similar line of reasoning, Walker [139] underlined the interlinkage between social practices and energy demand along variable temporal scales in terms of change, rhythm and synchronicity. When it comes to rhythms, Southerton [140,141] argued that collective and temporal rhythms play a pivotal role in our societies, characterised by a series of *hot spots* (activities rushed) and *cold spots* (chill times) where the temporal pace of the former is embraced in order to allow quality time for the latter [141]. This dimension profoundly shapes the temporal profile of practices along with defining their energy demand profile.

The triad competence–convenience–material artefact of practices come also useful to understand their temporality. For instance, Gram-Hanssen et al. [142] reported that manual workers typically shower after work, unlike office workers. While the timing is different, the practice of showering is carried out with the common aim of being clean before socialising. The same also takes place for the arrangement in sequence and rhythms of practices, which occurs on an individual basis, dependent for instance on one's own compromise between care and convenience, which is in turn potentially affected by one's search for additional times for cold spots in daily routines [140].

In addition to affecting the overall level of energy demand, the introduction of new elements (material artefacts) can also influence the sequences and synchronicity of the socio-temporal organisation of practices. An example comes from hospitals [143], where the inclusion of faster testing in pathology reverted the diagnostics/radiography sequence by bringing radiography immediately after the patient admission, before the diagnosis stage, so changing its connection with the other hospital practices. However, fixities and bottle-necks made impossible to rearrange the timing of particular energy intensive activities (e.g. radiography). New interconnections among practices also emerged upon the introduction of the new breast cancer services, which brought different hospital jurisdictions to work together to provide a faster test outcome to the patients, on the same day.

Institutional phenomena do also play a role in affecting the temporality of practices (flexibility at the societal level). For instance, the adoption of *day-light saving schemes* produces fixities in terms of the actual timing of social activities [144]. Even increasing the number of activities dependent upon electricity supply through the electrification plan of an increasing number of energy end uses introduces fixities, that could negatively affect social flexibility and resilience [145].

SPT can also contribute to the understanding of the potential evolution of present energy demand trends in terms of change. For instance, the increasing share of households owning a pet and the related practice to improve the household thermal comfort for the pet through heating and cooling could contribute to a more regular demand pattern at the household levels throughout the day [146]. The same applies to the increasing teleworking and homeschooling due to the current COVID-19 pandemic [147]. This trend could reduce the daily peak phenomenon, although it would likely entail an overall increase in the residential energy demand.

Coming to DSM options, SPT can help understand the actual flexibility potential of appliances upon their use. For instance, Higginson et al. [31] discuss the case of washing machines, a medium-level flexibility appliance. This actual potential is severely affected by the household needs (flexibility of people), with many occupants reluctant to having their washing machine running while asleep or away, or whose use may be driven by the urgency of having clean clothes. The agency ultimately resides with the user, thus significantly diminishing the potential of an automated shift.

5.2.1. Time-use surveys and activities

Although social practices cannot be equated to activities [148], activity (bodily and mental as Reckwitz [107] put it) along with technological artefacts do form part of practices when shared and routinised. Associating demand, therefore, with the combination of activity and artefact offers an alternative (linked, yet incomplete and limited) approach to assessing the temporality of demand [125]. The value in this 'reframing' lies in the ability to access more granular and continuous information needed for study of demand temporality. This requirement of better data on the households temporal energy demand profile was already discussed in the early nineties [149], when pioneering experiments towards more demand-side data also took place [150]. The time resolution of the data available plays a crucial role as

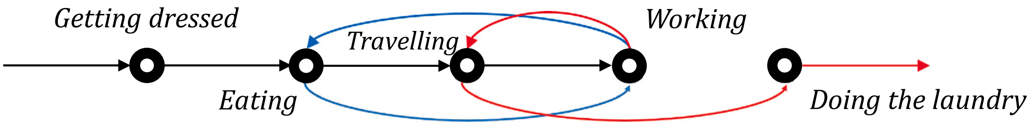

Fig. 7. Example of a graphical representation of a temporal sequence of activities.
Source: Adapted from Mckenna et al. [156].

Fransson et al. [151] showed by estimating power demand for electric heating at the residential level and finding significant differences for an assessment at an hourly vs monthly temporal resolution.

Time-use surveys filled by volunteers on their daily time allocation are one of the most widely used tools to investigate energy demand temporality. These surveys are being extensively used to model the energy demand emerging from the reported activities [152–154]. For instance, this information can be used to infer what activities are mainly carried out at peak times as well as to identify sequences and patterns of activities so as to target specific households [155]. The sequential time arrangement of the activities reported in the time use surveys can also be represented in graphical networks (see Fig. 7).

Time-use surveys have also been used to infer what drives the temporal patterns in energy demand at the household level. For instance, Palm et al. [157] clustered time-use-survey diarists in Sweden on the basis of weekday/weekend patterns of activities such as cooking, doing the laundry and watching television. The authors found that the time of the day at which energy-intensive activities took place was affected by demographic components: older female respondents tended to perform them during the daytime, while younger respondents favoured the evenings. Even the economic component affects the temporality of the activities with tangible consequences on the daily peaks [158]: lower-income households showed a more constant demand throughout the day.

The information conveyed by time-use surveys on the temporal patterns of activities can be used to garner insights on their potential flexibility[2] or fixities. For instance, Torriti [159] unveiled the time dependence of activities at the household level, that is their tendency to regularly occur at the same time of the day: washing was highly time dependent, while the opposite applies to computer use, which could happen at almost any hour of the day. On activities requiring the use of entertainment devices, data demand peaks have been reported at later times than electricity demand evening peaks [43] Conversely, the cold-season pattern of watching television on weekday evenings had a full match with the yearly electricity peak demand occurring in winter [43].

On fixities, Burkinshaw [160] documented fixed commuting times even when workers may have access to flexible working hours. The reason was that commuting was not simply linked to the daily working schedules, it was actually affected by other dependent activities (including school time, sport and leisure hours, etc.) which contributed to its fixity. Food preparation and consumption [161], and child-caring [162] have also been shown to be informed by or to inform schedules and related activity, respectively.

On more flexible activities, teleworking [163] may be an effective means to stimulate flexible allocations of time, primarily amidst house chores (e.g. laundry) and the working activity [164]. One may also wonder to what extent teleworking could be arranged towards energy needs by factoring in energy demand (and its hourly price) in the sequence of activities one is performing.

Flexibility in teleworking is typically embraced as a means of daily self organisation, which may accidentally produce consequences on the household energy demand pattern. Whether the total rearrangement of the sequence, and the concomitancy of daily practices, could be reoriented from an energy-demand driver is entirely to be explored along its desirability against other contrasting needs [31]. Related to this aspect, Southerton [141] reported that multitasking was determined by fixities, activities forcefully occurring at the same time as imposed by social rhythms (e.g. by child care), rather than a deliberate choice. Hence, it may not be obvious how one could achieve flexibility by fostering different allocation of time activities, given the potential energy demand in the background entailed by parallel ongoing activities. In some cases, multitasking may even drive extra energy demand, like in the case of intensive use of smartphones and other devices during commuting [165].

The relative timing, scheduling and sequencing of activities highlights the importance that social structures have to understanding constraints on the timing and location of activities. However, these structural constraints do not preclude the notion of flexibility in activity, as structure also provides choice (opportunity for agency [166]) that in the collective literature above has been demonstrated to lead to both fixed and flexible energy-demanding activity.

When attempting to govern the temporality of energy demand, *time use surveys* could be an important ingredient to integrate the SPT framework with DSR and/or DSM options. Introducing a new material artefact can profoundly affect the temporal sequence and the network of activities (Fig. 8). Therefore, knowing what people are doing at a given point in time can foster technological options towards adjusting their residential energy demand [152] as these interventions along with DSR may introduce elements of arrhythmia in daily routines and rhythms [167].

Additionally, understanding the rhythm and synchronisation of the social practices of different categories of users, especially vulnerable and fuel poor, is pivotal in determining the effects of active and passive demand-side interventions [139,157]. For instance, it has been shown that end users may be willing to sustain a cost four orders of magnitude higher than the standard price to charge their mobile phone under urgent conditions [29]. On the other hand, lower-income households are those showing the least pronounced peaks [158] and this limits their potential benefits when participating in a DSR scheme. This leads to the paradox that those that could potentially benefit the most from these interventions are the most likely to be unaffected.

Time-of-use pricing schemes for electricity consumption also contribute to create another institutional time in as much as they constrain energy-intensive activities that define household temporalities to specific time frames [168]. In this sense, this measure achieves the opposite of flexibility as it sets a constraint on the temporal organisation of household practices. Being bound to electricity generation from intermittent forms of renewable energy contributes to bringing back the coupling of energy-intensive activities to the rhythms of nature, which was removed upon the large-scale adoption of fossil fuels as primary energy sources [168,169]. In a pilot case study involving more than one-hundred households in Denmark, no significant difficulties were reported for charging electric vehicles at night, when electricity was cheaper [168]. Conversely, rearranging other activities coupled with the use of flexible appliances, such as unloading the dishwasher and the laundry machine in the morning, after these appliances had run at night, was less appreciated by the users. The reason was the sacrifice of

---

[2] Activity-led responses for flexibility can be conceptualised [29] as: (i) (temporal) activity shift; (ii) substitute practice (e.g. a cold meal in lieu of a hot one); (iii) substitute metabolic energy (using a hand mower in place of a motorised one); (iv) changing practitioner (laundry by a service provider instead of at home).

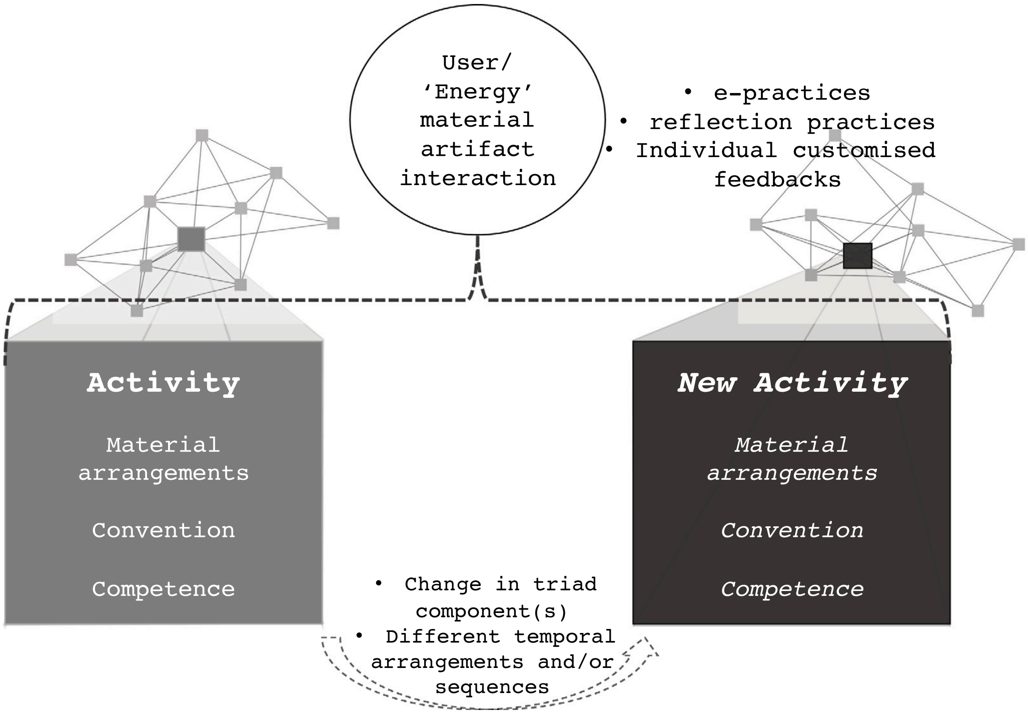

Fig. 8. Activity-practice shifting upon user/'energy' material artefact interaction. The adoption of a new (technological) component can lead to a total rearrangement in an activity as well as in its temporal sequence and interaction with other activities.

a *cold spot*, breakfast – a moment of togetherness – with a *hot spot*, house chores squeezed in the morning, before the daily work/school routine. When asked, most of the involved households would prioritise the temporalities of their daily routines over the savings led by the time-of-use tariffs. Finally, time-of-use tariffs proved more effective than real-time-pricing tariffs for these users, given the difficulty to closely follow them and adjust one's practices accordingly. Powells et al. [167] reported contrasted findings in the UK, with households willing to shift dishwasher and washing machine use to low-tariff hours unlike cooking or watching television, which were considered more fixed activities.

6. Discussion and conclusion

The contributions in the reviewed literature develop along two main overarching goals: on the one hand, the reduction in energy demand and on the other, the flexibilisation of energy demand. The latter refers to seeking a temporal variation of the typical daily demand pattern as a means to: (a) move away from the one-to-three daily (and costly) peaks in energy demand; and/or, (ii) seek an energy demand pattern more in line with the production from intermittent renewable energy (primarily, solar PV and wind turbines). This second condition may imply raising demand at some points in time. Capacity building and valley filling are utilities' strategies also aimed to increase energy demand, although at different times from peak-demand hours.

As to achieve these goals, technological options have been proposed (**Research Question 1**). Technologies for the *reduction of energy demand* include more efficient appliances, or better thermal insulation, just to name some of the most widely adopted options to reduce energy demand. Technologies for *flexibility in energy demand* encompass the use of communication devices to switch on appliances, and tune their demand temporal pattern on the basis of a signal. However, this border may be blurry, switches are also used in *context-aware energy management* to reduce energy demand. The position of storage is also borderline as it contributes to reduce the demand from the grid and also affects the temporal profile of energy demand at the same time. Examples in the literature discussing storage without making reference to its potential role in temporal flexibility exist. In agreement with the existing literature [7], a level of separation between technologies for *energy demand reduction* and technologies for *flexibility in energy demand* occurs in as much as they may be deployed to seek contrasting goals (i.e. altering the temporality of energy demand resulting in its overall increase).

Another level of separation is the one between the actual and the expected performance of a technology (**Research Question 2**). Through review of social-practice theory applied to energy demand, we highlight one particular lens (admittedly with the extension of time-use activity readings) from social sciences and humanities that is able to challenge some of the deterministic expectations of the reviewed DSR/DSM technology. The social dimension does not provide per se an alternative route to ex ante evaluation of flexibility offerings, necessary for understanding the operational grid constraints of increased renewable generation and increased electrification scenario from a technical systems perspective. Yet it does help to examine why technical system performance expectations are not always met. Further to the exposure of these limitations in the technical determinism of many DSR/DSM offerings, opportunities to re-evaluate the role of "material artefacts" in relation to the continuation, or changing of, conventions in energy demanding behaviour exist. The artefacts at play for a given energy flexibility (as exemplified with thermal comfort) can indeed be challenged and expanded. Perhaps then the options for DSR are not just in terms of the shift of when, but also in relation to how underlying demands can be met.

A level of separation also exists between household activities temporal accountings (time use surveys) and the temporality of energy demand given the different representations and granularity captured. Additionally, parallel tasks and activities occurring in the background; the potential effects of temporal disconnections, rhythm, and convenience; are all crucial aspects when enacting flexibility options that are not captured in time use surveys.

As regards future research avenues, new attention has been focused on the contribution of social sciences and humanities to the energy field with dedicated research fundings and growing expectations. We endorse this trend to promote an integrated view of the technological and social dimensions of energy demand, and its temporal pattern, as also advocated in the literature [7,94] with a new research agenda.

Integrating the views offered from these disciplines can effectively contribute to understand (**Research Question 3**):

- what energy is for and in doing so questioning the non-negotiability of comfort standards (e.g. upon variable practices)
- how measures aimed at shifting the temporal pattern of energy demand may result in producing new fixities caused by specific dimensions and acting at multiple scales
- how energy consumption may backfire upon the adoption of more efficient appliance due to changing practices/comfort standards and/or the addition of new functionalities (complexification of social meanings)
- how the introduction of new technologies may affect activities and the entailed energy demand and result in an energy consumption level and temporal profile different from that expected
- the overall effect of societal complexification on societal energy consumption
- how DSM and DSR should be implemented by taking into account how demand temporality emerges from rhythm, synchronisation and sequences of users' practices

Each perspective, individually, has limitations and failings that the other can expose and inform. In this contribution, we do not just advocate a sociotechnical or socio-technical perspective but rather the development of a structured dialogue between technical and socio(-)technical perspectives to help each discipline become more informed on the impact of its epistemic positioning. New forms of collaboration between energy system modellers on the one hand and social-theory practitioners on the other can be fostered towards this end. The quantitative assessments of DSR and DSM models can be further scrutinised through different framings such that a more encompassing understanding of the phenomena at play can result from iterative rounds of (socio-)technical modelling and social practice theory practitioners joint assessments.

Declaration of competing interest

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

Acknowledgements

This research has received funding from UK Research and Innovation grant agreement EP/R035288/1 as part of the Centre for Research into Energy Demand Solutions. We further acknowledge the points of reflection and comment on earlier drafts from colleagues in the wider CREDS flexibility theme and the useful comments of two anonymous reviewers. We note the viewpoint expressed in this review remain solely with the authors.

Appendix A. Supplementary data

The full list of documents reviewed is available from the Supporting Material.

References

[1] Engeland K, Borga M, Creutin J-D, François B, Ramos M-H, Vidal J-P. Space-time variability of climate variables and intermittent renewable electricity production – A review. Renew Sustain Energy Rev 2017;79:600–17.

[2] Carmon D, Navon A, Machlev R, Belikov J, Levron Y. Readiness of small energy markets and electric power grids to global health crises: Lessons from the COVID-19 pandemic. IEEE Access 2020;8:127234–43, Conference Name: IEEE Access.

[3] Zhong H, Tan Z, He Y, Xie L, Kang C. Implications of COVID-19 for the electricity industry: A comprehensive review. CSEE J Power Energy Syst 2020;6(3):489–95, Conference Name: CSEE Journal of Power and Energy Systems.

[4] Warren P. A review of demand-side management policy in the UK. Renew Sustain Energy Rev 2014;29:941–51.

[5] Behrangrad M. A review of demand side management business models in the electricity market. Renew Sustain Energy Rev 2015;47:270–83.

[6] Meyabadi AF, Deihimi MH. A review of demand-side management: Reconsidering theoretical framework. Renew Sustain Energy Rev 2017;80:367–79.

[7] Shimoda Y, Yamaguchi Y, Iwafune Y, Hidaka K, Meier A, Yagita Y, et al. Energy demand science for a decarbonized society in the context of the residential sector. Renew Sustain Energy Rev 2020;132:110051.

[8] Golden JS, Subramanian V, Irizarri GMAU, White P, Meier F. Energy and carbon impact from residential laundry in the united states. J Integr Environ Sci 2010;7(1):53–73, Publisher: Taylor & Francis _eprint: http://dx.doi.org/10.1080/19438150903541873.

[9] Fuchs Heidner A, Heidner DL. Thinking outside the box: The clothes drying process is more than the dryer. In: Proceedings of the 9th international conference on energy efficiency in domestic appliances and lighting (EEDAL '17): part II. Vol. II. Luxemburg, EUR: Publications Office of the European Union; 2017, p. 816–32.

[10] Hirst E. Electric-utility demand side programs; resources for the 1990s. In: Proceedings of the American power conference; USA. Vol. 51. 1989.

[11] Outhred H, Kaye R. Choices for the future of Australia's electricity industries. 1991, p. 29–33.

[12] Kraines SB, Ishida T, Wallace DR. Integrated environmental assessment of supply-side and demand-side measures for carbon dioxide mitigation in Tokyo, Japan. J Ind Ecol 2010;14(5):808–25.

[13] Wang Y, Mauree D, Wennersten R, Scartezzini J-L, Sun Q. Improving self-consumption of on-site PV generation through deploying flexibility in building thermal mass. J Phys Conf Ser 2019;1343:012087, Publisher: IOP Publishing.

[14] Hong J, Johnstone CM, Kim JM, Tuohy P. Demand-side management and control in buildings. In: The future of electricity demand: customers, citizens and loads. Cambridge: Cambridge University Press; 2012, p. 129–60.

[15] Bianco V, Rosa MD, Scarpa F, Tagliafico LA. Analysis of energy demand in residential buildings for different climates by means of dynamic simulation. Int J Ambient Energy 2016;37(2):108–20, Publisher: Taylor & Francis _eprint: http://dx.doi.org/10.1080/01430750.2014.907207.

[16] Oliveira R, Figueiredo A, Vicente R, Almeida RMSF. Impact of unoccupied flats on the thermal discomfort and energy demand: Case of a multi-residential building. Energy Build 2020;209:109704.

[17] Papadopoulos F, Whiffen TR, Tilford A, Willson C. Actual energy and environmental savings on energy retrofit works at the lakes estate, milton keynes. Sustain Cities Soc 2018;41:611–24.

[18] Willand N, Maller C, Ridley I. Addressing health and equity in residential low carbon transitions – insights from a pragmatic retrofit evaluation in Australia. Energy Res Soc Sci 2019;53:68–84.

[19] Liu S, Kwok YT, Lau KK-L, Chan PW, Ng E. Investigating the energy saving potential of applying shading panels on opaque façades: A case study for residential buildings in hong kong. Energy Build 2019;193:78–91.

[20] Koller C, Talmon-Gros MJ, Junge R, Schuetze T. Energy toolbox—Framework for the development of a tool for the primary design of zero emission buildings in European and Asian cities. Sustainability 2017;9(12):2244, Number: 12 Publisher: Multidisciplinary Digital Publishing Institute.

[21] Shrestha RM, Khummongkol P, Biswas WK, Timilsina GR, Sinbanchongjit S. CO_2 mitigation potential of efficient demand-side technologies: The case of Thailand. Energy Sources 1998;20(4–5):301–16.

[22] Tanatvanit S, Limmeechokchai B, Shrestha RM. CO_2 mitigation and power generation implications of clean supply-side and demand-side technologies in Thailand. Energy Policy 2004;32(1):83–90.

[23] Yun GY, Jung H, Kim JT. Energy-saving potential of LED lighting systems. Indoor Built Environ 2013;22(1):235–41, Publisher: SAGE Publications Ltd STM.

[24] Jazizadeh F, Joshi V, Battaglia F. Adaptive and distributed operation of HVAC systems: Energy and comfort implications of active diffusers as new adaptation capacities. Build Environ 2020;186:107089.

[25] Ayan O, Turkay BE. Comparison of lighting technologies in residential area for energy conservation. In: 2017 2nd International conference sustainable and renewable energy engineering. ICSREE, 2017, p. 116–20.

[26] Gupta R, Majid S, Yadav M. Design of smart lighting control for the built environment. In: Ahmed S, Abbas SM, Zia H, editors. Smart cities—opportunities and challenges. Lecture notes in civil engineering, Singapore: Springer; 2020, p. 29–36.

[27] Shaptala R, Kyselova A. Location prediction approach for context-aware energy management system. In: 2016 IEEE 36th international conference on electronics and nanotechnology. ELNANO, 2016, p. 333–6.

[28] Curtis M, Torriti J, Smith ST. Demand side flexibility and responsiveness: Moving demand in time through technology. In: Hui A, Day R, Walker G, editors. Demanding energy: space, time and change. Cham: Springer International Publishing; 2018, p. 283–312.

[29] Grunewald P, Diakonova M. Flexibility, dynamism and diversity in energy supply and demand: A critical review. Energy Res Soc Sci 2018;38:58–66.

[30] Fenn B, Hopp O, Ahner M, Buchholz B, Buehner V, Doss A, et al. Advanced technologies of demand side integration by VPPs and through smart metering in households Experiences from a lighthouse project - PDF Free Download. Tech. rep. C6-108, Paris; 2012, URL: https://docplayer.net/145191508-Advanced-technologies-of-demand-side-integration-by-vpps-and-through-smart-metering-in-households-experiences-from-a-lighthouse-project.html.

[31] Higginson S, Thomson M, Bhamra T. ‘‘For the times they are a-changin’’: the impact of shifting energy-use practices in time and space. Local Environ 2014;19(5):520–38, Publisher: Routledge _eprint: http://dx.doi.org/10.1080/13549839.2013.802459.

[32] Patteeuw D, Bruninx K, Arteconi A, Delarue E, D’haeseleer W, Helsen L. Integrated modeling of active demand response with electric heating systems coupled to thermal energy storage systems. Appl Energy 2015;151:306–19.

[33] Ósorio J, Estanqueiro A. Exploring demand side management to cope with variable generation from renewable energy sources. In: Symposium lisbon - 2013. Vol. 2. Lisbon: Cigré; 2013, p. 1–8.

[34] Bruninx K, Patteeuw D, Delarue E, Helsen L, D’haeseleer W. Short-term demand response of flexible electric heating systems: The need for integrated simulations. In: 2013 10th International conference on the European energy market. EEM, 2013, p. 1–10, ISSN: 2165-4077.

[35] Gellings C. The concept of demand-side management for electric utilities. Proc IEEE 1985;73(10):1468–70, Conference Name: Proceedings of the IEEE.

[36] Sallam AA, Malik OP. Electric distribution systems. 2019, URL: https://onlinelibrary.wiley.com/doi/book/10.1002/9781119509332. OCLC: 1139916801.

[37] Riva F, Gardumi F, Tognollo A, Colombo E. Soft-linking energy demand and optimisation models for local long-term electricity planning: An application to rural India. Energy 2019;166:32–46.

[38] Krakowski V, Assoumou E, Mazauric V, Maïzi N. Feasible path toward 40–100% renewable energy shares for power supply in France by 2050: A prospective analysis. Appl Energy 2016;171:501–22.

[39] Rajabi F, Salami A, Azimi M. Hierarchical and multi-level demand response programme considering the flexibility of loads. IET Gener Trans Distrib 2020;14(6):1051–61, Publisher: IET Digital Library.

[40] Papadaskalopoulos D, Strbac G. Investigation of the impact of flexible loads’ participation in electricity markets. IET Digital Library; 2013, p. 1126, URL: https://digital-library.theiet.org/content/conferences/10.1049/cp.2013.1084.

[41] Li R, Dane G, Finck C, Zeiler W. Are building users prepared for energy flexible buildings?—A large-scale survey in the Netherlands. Appl Energy 2017;203:623–34.

[42] Pothitou M, Hanna RF, Chalvatzis KJ. ICT entertainment appliances’ impact on domestic electricity consumption. Renew Sustain Energy Rev 2017;69:843–53.

[43] Morley J, Widdicks K, Hazas M. Digitalisation, energy and data demand: The impact of internet traffic on overall and peak electricity consumption. Energy Res Soc Sci 2018;38:128–37.

[44] Law YW, Alpcan T, Lee VC, Lo A, Marusic S, Palaniswami M. Demand response architectures and load management algorithms for energy-efficient power grids: A survey. In: 2012 Seventh international conference on knowledge, information and creativity support systems. 2012, p. 134–41, ISSN: null.

[45] Capitanelli A, Germani M, Landi D, Papetti A. A methodology to design a knowledge-based tool for residential buildings simulation. American Society of Mechanical Engineers Digital Collection; 2016, URL: https://asmedigitalcollection.asme.org/IMECE/proceedings/IMECE2015/57540/V011T14A013/256324.

[46] Neupane B, Šikšnys L, Pedersen TB. Generation and evaluation of flex-offers from flexible electrical devices. In: Proceedings of the Eighth international conference on future energy systems. e-Energy ’17, Shatin, Hong Kong: Association for Computing Machinery; 2017, p. 143–56.

[47] Hirmiz R, Teamah HM, Lightstone MF, Cotton JS. Performance of heat pump integrated phase change material thermal storage for electric load shifting in building demand side management. Energy Build 2019;190:103–18.

[48] Chen Y, Xu P, Gu J, Schmidt F, Li W. Measures to improve energy demand flexibility in buildings for demand response (DR): A review. Energy Build 2018;177:125–39.

[49] Sánchez Ramos J, Pavón Moreno M, Guerrero Delgado M, Álvarez Domínguez S, F. Cabeza L. Potential of energy flexible buildings: Evaluation of DSM strategies using building thermal mass. Energy Build 2019;203:109442.

[50] Garcia-Valle R, Silva LCPd, Xu Z, Østergaard J. Smart demand for improving short-term voltage control on distribution networks. IET Gener Trans Distrib 2009;3(8):724–32.

[51] Ramírez P, Papadaskalopoulos D, Strbac G. Impact of electric vehicles flexibility on generation expansion planning. In: IEEE PES ISGT Europe 2013. 2013, p. 1–5, ISSN: 2165-4824.

[52] Bessler S, Drenjanac D, Hasenleithner E, Silva N. Using flexibility information for planning the energy demand of households. In: Helfert M, Krempels K-H, Klein C, Donellan B, Guiskhin O, editors. Smart cities, green technologies, and intelligent transport systems. Communications in computer and information science, Cham: Springer International Publishing; 2015, p. 216–33.

[53] Marrero GA, Perez Y, Petit M, Ramos-Real FJ. Electric vehicle fleet contributions for isolated systems. the case of the canary islands. Int J Autom Technol Manag 2015;15:171, Publisher: Inderscience.

[54] Yang B, Wang L-f, Liao C-l, Ji L. Coordinated charging method of electric vehicles to deal with uncertainty factors. In: 2014 IEEE conference and expo transportation electrification Asia-Pacific. ITEC Asia-Pacific, 2014, p. 1–6.

[55] Markel T, Mai T, Kintner-Meyer M. Transportation electrification load development for a renewable future analysis: preprint. Tech. rep. NREL/CP-5400-49181, National Renewable Energy Lab. (NREL), Golden, CO (United States); 2010, URL: https://www.osti.gov/biblio/1001439.

[56] Heredia WB, Chaudhari K, Meintz A, Jun M, Pless S. Evaluation of smart charging for electric vehicle-to-building integration: A case study. Appl Energy 2020;266:114803.

[57] Staudt P, Schmidt M, Gärttner J, Weinhardt C. A decentralized approach towards resolving transmission grid congestion in Germany using vehicle-to-grid technology. Appl Energy 2018;230:1435–46.

[58] Carmo C, Detlefsen N, Nielsen M. Smart grid enabled heat pumps: An empirical platform for investigating how residential heat pumps can support large-scale integration of intermittent renewables. In: International conference on applied energy, ICAE2014, Energy Procedia In: International conference on applied energy, ICAE2014, 2014;61.1695–8,

[59] Gill S, Dolan M, Emhemed A, Kockar I, Barnacle M, Ault G, et al. Increasing renewable penetration on islanded networks through active network management: a case study from Shetland. IET Renew Power Gener 2015;9(5):453–65, Publisher: IET Digital Library.

[60] International Energy Agency. Empowering variable renewables - options for flexible electricity systems. Tech. rep. 21248886, Paris, France: International Energy Agency; 2009, p. 36.

[61] Jenkins JD, Luke M, Thernstrom S. Getting to zero carbon emissions in the electric power sector. Joule 2018;2(12):2498–510.

[62] Roossien B, van den Noort A, Kamphuis R, Bliek F, Eijgelaar M, de Wit J. Balancing wind power fluctuations with a domestic virtual power plant in Europe’s first smart grid. In: 2011 IEEE trondheim powertech. 2011, p. 1–5.

[63] Manjili YS, Vega R, Jamshidi M. Cost-efficient environmentally-friendly control of micro-grids using intelligent decision-making for storage energy management. Intell Autom Soft Comput 2013;19(4):649–70.

[64] Ponoćko J, Milanović JV. Forecasting demand flexibility of aggregated residential load using smart meter data. IEEE Trans Power Syst 2018;33(5):5446–55, Conference Name: IEEE Transactions on Power Systems.

[65] Touzani S, Prakash AK, Wang Z, Agarwal S, Pritoni M, Kiran M, et al. Controlling distributed energy resources via deep reinforcement learning for load flexibility and energy efficiency. Appl Energy 2021;304:117733.

[66] Hu M, Xiao F, Wang S. Neighborhood-level coordination and negotiation techniques for managing demand-side flexibility in residential microgrids. Renew Sustain Energy Rev 2021;135:110248.

[67] Li W, Yigitcanlar T, Erol I, Liu A. Motivations, barriers and risks of smart home adoption: From systematic literature review to conceptual framework. Energy Res Soc Sci 2021;80:102211.

[68] Rottondi C, Verticale G. Privacy-friendly appliance load scheduling in smart grids. In: 2013 IEEE international conference on smart grid communications. SmartGridComm, 2013, p. 420–5.

[69] Immonen A, Kiljander J, Aro M. Consumer viewpoint on a new kind of energy market. Electr Power Syst Res 2020;180:106153.

[70] Hazas M, Strengers Y. Promoting smart homes. In: Energy fables. Abingdon-on-Thames: Earthscan from Routledge; 2019, p. 142.

[71] Moretti D, Galloway S. Electric heating as flexible demand for enhanced network operation. CIRED - Open Access Proc J 2017;2017(1):1733–6, Conference Name: CIRED - Open Access Proceedings Journal.

[72] Schellenberg C, Lohan J, Dimache L. Operational optimisation of a heat pump system with sensible thermal energy storage using genetic algorithm. Therm Sci 2018;22(5):2189–202.

[73] Chadoulos S, Koutsopoulos I, Polyzos GC. Mobile apps meet the smart energy grid: A survey on consumer engagement and machine learning applications. IEEE Access 2020;8:219632–55, Conference Name: IEEE Access.

[74] Yamaguchi Y. A practice-theory-based analysis of historical changes in household practices and energy demand: A case study from Japan. Technol Forecast Soc Change 2019;145:207–18.

[75] Beier J, Thiede S, Herrmann C. Increasing energy flexibility of manufacturing systems through flexible compressed air generation. In: CIRPe 2015 - Understanding the life cycle implications of manufacturing, Procedia CIRP In: CIRPe 2015 - Understanding the life cycle implications of manufacturing, 2015;vol. 37.18–23,

[76] Unterberger E, Buhl HU, Häfner L, Keller F, Keller R, Ober S, et al. The regional and social impact of energy flexible factories. In: 15th Global conference on sustainable manufacturing. Vol. 21. Procedia Manuf 2018;468–75.

[77] Heffron R, Körner M-F, Wagner J, Weibelzahl M, Fridgen G. Industrial demand-side flexibility: A key element of a just energy transition and industrial development. Appl Energy 2020;269:115026.

[78] Weitzel T, Glock CH. Scheduling a storage-augmented discrete production facility under incentive-based demand response. Int J Prod Res 2019;57(1):250–70, Publisher: Taylor & Francis _eprint: http://dx.doi.org/10.1080/00207543.2018.1475764.

[79] Schulze C, Blume S, Herrmann C, Thiede S. Energy storage technologies to foster energy flexibility in learning factories. In: Research. experience. education. 9th conference on learning factories 2019 (CLF 2019), Braunschweig, Germany. Vol. 31. Procedia Manuf 2019;330–6.

[80] Hausman WJ, Neufeld JL. Time-of-day pricing in the U.S. electric power industry at the turn of the century. RAND J Econ 1984;15(1):116–26, Publisher: [RAND Corporation, Wiley].

[81] Pallonetto F, De Rosa M, D'Ettorre F, Finn DP. On the assessment and control optimisation of demand response programs in residential buildings. Renew Sustain Energy Rev 2020;127:109861.

[82] Faruqui A, Sergici S. Arcturus: International evidence on dynamic pricing. Electr J 2013;26(7):55–65.

[83] Domínguez J, Chaves-Ávila JP, Román TGS, Mateo C. The economic impact of demand response on distribution network planning. In: 2016 Power systems computation conference. PSCC, 2016, p. 1–7.

[84] Vo TH, Haque ANMM, Nguyen PH, Kamphuis IG, Eijgelaar M, Bouwman I. A study of congestion management in smart distribution networks based on demand flexibility. In: 2017 IEEE manchester PowerTech. 2017, p. 1–6.

[85] Sanchez IB, Espinos ID, Sarrion LM, Lopez AQ, Burgos IN. Clients segmentation according to their domestic energy consumption by the use of self-organizing maps. In: 2009 6th International conference on the European energy market. 2009, p. 1–6, ISSN: 2165-4093.

[86] Nguyen TTK, Shimada K, Ochi Y, Matsumoto T, Matsugi H, Awata T. An experimental study of the impact of dynamic electricity pricing on consumer behavior: An analysis for a remote island in Japan. Energies 2016;9(12):1093, Number: 12 Publisher: Multidisciplinary Digital Publishing Institute.

[87] Martin S, Rivers N. Information provision, market incentives, and household electricity consumption: Evidence from a large-scale field deployment. J Assoc Environ Resour Econ 2018;5(1):207–31, Publisher: The University of Chicago Press.

[88] Kiliccote S, Piette MA, Ghatikar G. 15 - Improved energy demand management in buildings for smart grids: The US experience. In: Bessède J-L, editor. Eco-friendly innovation in electricity transmission and distribution networks. Oxford: Woodhead Publishing; 2015, p. 315–38, URL: http://www.sciencedirect.com/science/article/pii/B978178242010100015X.

[89] Ruokamo E, Kopsakangas-Savolainen M, Meriläinen T, Svento R. Towards flexible energy demand – preferences for dynamic contracts, services and emissions reductions. Energy Econ 2019;84:104522.

[90] Xu X, Chen C-f, Washizu A, Ishii H, Yashiro H. Willingness to pay for home energy management system: A cross-country comparison. In: 2018 IEEE power energy society general meeting. 2018, p. 1–5, ISSN: 1944-9933.

[91] Chen C-f, Xu X, Adams J, Brannon J, Li F, Walzem A. When East meets West: Understanding residents' home energy management system adoption intention and willingness to pay in Japan and the United States. Energy Res Soc Sci 2020;69:101616.

[92] Kohlhepp P, Harb H, Wolisz H, Waczowicz S, Müller D, Hagenmeyer V. Large-scale grid integration of residential thermal energy storages as demand-side flexibility resource: A review of international field studies. Renew Sustain Energy Rev 2019;101:527–47.

[93] Ingeborgrud L, Heidenreich S, Ryghaug M, Skjølsvold TM, Foulds C, Robison R, et al. Expanding the scope and implications of energy research: A guide to key themes and concepts from the social sciences and humanities. Energy Res Soc Sci 2020;63:101398.

[94] Labanca N, Pereira ÂG, Watson M, Krieger K, Padovan D, Watts L, et al. Transforming innovation for decarbonisation? Insights from combining complex systems and social practice perspectives. Energy Res Soc Sci 2020;65:101452.

[95] Orlikowski WJ, Scott SV. 10 Sociomateriality: Challenging the separation of technology, work and organization. Acad Manag Ann 2008;2(1):433–74, Publisher: Academy of Management.

[96] Penner SS. Challenges in the implementation of energy conservation. In: Proceedings of a conference on non-fossil fuel and non-nuclear fuel energy strategies. Energy 1979;4(5):911–8.

[97] Zerubavel E. Hidden rhythms: schedules and calendars in social life. University of California Press; 1985.

[98] Southerton D. Habits, routines and temporalities of consumption: From individual behaviours to the reproduction of everyday practices. Time Soc 2013;22(3):335–55, Publisher: SAGE Publications Ltd.

[99] Karlsson F, Rohdin P, Persson M-L. Measured and predicted energy demand of a low energy building: important aspects when using building energy simulation. Build Serv Eng Res Technol 2007;28(3):223–35, Publisher: SAGE Publications Ltd STM.

[100] Seligman C, Darley JM, Becker LJ. Behavioral approaches to residential energy conservation. Energy Build 1978;1(3):325–37.

[101] Gram-Hanssen K. Residential heat comfort practices: understanding users. Build Res Inf 2010;38(2):175–86, Publisher: Routledge _eprint: http://dx.doi.org/10.1080/09613210903541527.

[102] Niamir L, Ivanova O, Filatova T, Voinov A, Bressers H. Demand-side solutions for climate mitigation: Bottom-up drivers of household energy behavior change in the netherlands and Spain. Energy Res Soc Sci 2020;62:101356.

[103] Fabi V. Main physical environmental drivers of occupant behaviour with regard to space heating energy demand. In: 10th International conference on healthy buildings 2012. 2012, p. 2219–24, ISBN: 9781627480758 Publisher: International Society of Indoor Air Quality and Climate.

[104] Bardazzi R, Pazienza MG. Switch off the light, please! energy use, aging population and consumption habits. Energy Econ 2017;65:161–71.

[105] Bardazzi R, Pazienza MG. When I was your age: Generational effects on long-run residential energy consumption in Italy. Energy Res Soc Sci 2020;70:101611.

[106] Chappells H. Systematically sustainable provision? The premises and promises of 'joined-up' energy demand management. Int J Environ Technol Manag 2008;9(2/3):259.

[107] Reckwitz A. Toward a theory of social practices: A development in culturalist theorizing. Eur J Soc Theory 2002;5(2):243–63, Publisher: SAGE Publications Ltd.

[108] Schatzki TR. Social practices: a wittgensteinian approach to human activity and the social. Cambridge University Press; 1996.

[109] Higginson S, McKenna E, Hargreaves T, Chilvers J, Thomson M. Diagramming social practice theory: An interdisciplinary experiment exploring practices as networks. Indoor Built Environ 2015;24(7):950–69, Publisher: SAGE Publications Ltd STM.

[110] Stephenson J, Barton B, Carrington G, Gnoth D, Lawson R, Thorsnes P. Energy cultures: A framework for understanding energy behaviours. In: The socio-economic transition towards a hydrogen economy - findings from European research, with regular papers, Energy Policy In: The socio-economic transition towards a hydrogen economy - findings from European research, with regular papers, 2010;38(10).6120–9,

[111] Hansen AR, Gram-Hanssen K, Knudsen HN. How building design and technologies influence heat-related habits. Build Res Inf 2018;46(1):83–98.

[112] Ascione F, Bianco N, De Masi RF, Mastellone M, Mauro GM, Vanoli GP. The role of the occupant behavior in affecting the feasibility of energy refurbishment of residential buildings: Typical effective retrofits compromised by typical wrong habits. Energy Build 2020;223:110217.

[113] Horne R. Policies to promote the environmental efficiency of housing. Elsevier; 2012, p. 286–92.

[114] Tweed C. Socio-technical issues in dwelling retrofit. Build Res Inf 2013;41(5):551–62, Publisher: Routledge _eprint: http://dx.doi.org/10.1080/09613218.2013.815047.

[115] Chiu LF, Lowe R, Raslan R, Altamirano-Medina H, Wingfield J. A socio-technical approach to post-occupancy evaluation: interactive adaptability in domestic retrofit. Build Res Inf 2014;42(5):574–90, Publisher: Routledge _eprint: http://dx.doi.org/10.1080/09613218.2014.912539.

[116] Larsen SP, Johra H. User engagement with smart home technology for enabling building energy flexibility in a district heating system. IOP Conf Ser Earth Environ Sci 2019;352:012002, Publisher: IOP Publishing.

[117] Salvia G, Morello E, Rotondo F, Sangalli A, Causone F, Erba S, et al. Performance gap and occupant behavior in building retrofit: Focus on dynamics of change and continuity in the practice of indoor heating. Sustainability 2020;12(14):5820, Number: 14 Publisher: Multidisciplinary Digital Publishing Institute.

[118] Jensen CL. Understanding energy efficient lighting as an outcome of dynamics of social practices. J Clean Prod 2017;165:1097–106.

[119] Rinkinen J, Jalas M. Moving home: houses, new occupants and the formation of heating practices. Build Res Inf 2017;45(3):293–302.

[120] Pullinger M, Lovell H, Webb J. Influencing household energy practices: a critical review of UK smart metering standards and commercial feedback devices. Technol Anal Strateg Manag 2014;26(10):1144–62, Publisher: Routledge _eprint: http://dx.doi.org/10.1080/09537325.2014.977245.

[121] Groves C, Henwood K, Shirani F, Butler C, Parkhill K, Pidgeon N. Energy biographies: Narrative genres, lifecourse transitions, and practice change. Sci Technol Hum Values 2016;41(3):483–508, Publisher: SAGE Publications Inc.

[122] Abhijith V, Anju Parvathy LB, Binoy J, Vimal N, Anjali C. Synergy — An energy optimization technique. In: 2017 International conference on networks advances in computational technologies. NetACT, 2017, p. 426–31.

[123] Verkade N, Höffken J. Is the resource man coming home? Engaging with an energy monitoring platform to foster flexible energy consumption in the netherlands. Energy Res Soc Sci 2017;27:36–44.

[124] Jalas M, Hyysalo S, Heiskanen E, Lovio R, Nissinen A, Mattinen M, et al. Everyday experimentation in energy transition: A practice-theoretical view. In: Experimentation for climate change solutions, J Clean Prod In: Experimentation for climate change solutions, 2017;169.77–84,

[125] Shove E, Walker G. What is energy for? Social practice and energy demand. Theory Cult Soc 2014;31(5):41–58, Publisher: SAGE Publications Ltd.

[126] Shove E. Comfort, cleanliness and convenience: the social organization of normality. Oxford: Berg Publishers; 2003.

[127] Shove E. What is wrong with energy efficiency? Build Res Inf 2018;46(7):779–89, Publisher: Routledge _eprint: http://dx.doi.org/10.1080/09613218.2017.1361746.

[128] Strengers Y. Peak electricity demand and social practice theories: reframing the role of change agents in the energy sector. In: Fudge S, Peters M, Hoffman SM, Wehrmeyer W, editors. The global challenge of encouraging sustainable living. Edward Elgar Publishing; 2013, p. 18–42.

[129] Jensen CL, Goggins G, Fahy F, Grealis E, Vadovics E, Genus A, et al. Towards a practice-theoretical classification of sustainable energy consumption initiatives: Insights from social scientific energy research in 30 European countries. In: Special issue on the problems of methods in climate and energy research, Energy Res Soc Sci In: Special issue on the problems of methods in climate and energy research, 2018;45.297–306,

[130] Holmes T. Roles, responsibilities and capacities: Theorizing space, social practice, and the relational constitution of energy demand in and beyond manchester. Energy Res Soc Sci 2021;82:102293.

[131] Shove E, Watson M, Spurling N. Conceptualizing connections: Energy demand, infrastructures and social practices. Eur J Soc Theory 2015;18(3):274–87, Publisher: SAGE Publications Ltd.

[132] Kuijer L, Watson M. ‘That's when we started using the living room’: Lessons from a local history of domestic heating in the united kingdom. Energy Res Soc Sci 2017;28:77–85.

[133] Hampton S, Adams R. Behavioural economics vs social practice theory: Perspectives from inside the United Kingdom government. Energy Res Soc Sci 2018;46:214–24.

[134] Greene M, Fahy F. Steering demand? Exploring the intersection of policy, practice and lives in energy systems change in Ireland. Energy Res Soc Sci 2020;61:101331.

[135] Cass NF, Shove EA. Time, practices and energy demand:implications for flexibility. Working papper, 2018, URL: https://eprints.lancs.ac.uk/id/eprint/130369/, Num Pages: 14.

[136] Shove E. The fixities of flexibility: ironies and implications. 2019, p. 136–9, Lancaster, United Kingdom.

[137] Blue S, Shove E, Forman P. Conceptualising flexibility: Challenging representations of time and society in the energy sector*. Time Soc 2020. 0961463X20905479. Publisher: SAGE Publications Ltd.

[138] Shove E, Trentmann F, Wilk R. Time, consumption and everyday life: practice, materiality and culture. Berg; 2009, Google-Books-ID. xvkfzdNlf7QC.

[139] Walker G. The dynamics of energy demand: Change, rhythm and synchronicity. Energy Res Soc Sci 2014;1:49–55.

[140] Southerton D. ‘Squeezing time’: Allocating practices, coordinating networks and scheduling society. Time Soc 2003;12(1):5–25, Publisher: SAGE Publications Ltd.

[141] Southerton D. Temporal rhythms: comparing daily lives of 1937 with those of 2000 in the UK (manchester escholar - the university of Manchester). In: Shove E, Trentmann F, Wilk R, editors. Time, consumption and everyday life: practice, materiality and culture. Oxford: Berg; 2009, p. 49–63.

[142] Gram-Hanssen K, Christensen TH, Madsen LV, do Carmo C. Sequence of practices in personal and societal rhythms – showering as a case. Time Soc 2020;29(1):256–81, Publisher: SAGE Publications Ltd.

[143] Blue S. Reducing demand for energy in hospitals: Opportunities for and limits to temporal coordination. In: Hui A, Day R, Walker G, editors. Demanding energy: space, time and change. Cham: Springer International Publishing; 2018, p. 313–37.

[144] Durand Daublin M. Time Use policies, energy demand and seasonal rythms: daylight saving time. Lancaster, United Kingdom; 2019, p. 130–5.

[145] Moezzi M. Grid dependencies and change capacities: People and demand response under renewables. In: Labanca N, editor. Complex systems and social practices in energy transitions: framing energy sustainability in the time of renewables. Green energy and technology, Cham: Springer International Publishing; 2017, p. 283–303.

[146] Strengers Y, Pink S, Nicholls L. Smart energy futures and social practice imaginaries: Forecasting scenarios for pet care in Australian homes. Energy Res Soc Sci 2019;48:108–15.

[147] Morse ML, Bell SM. Homeschooling: A growing school choice option for meeting special educational needs. Int J Educ Reform 2018;27(2):156–72, Publisher: SAGE Publications Inc.

[148] Schatzki T. Timespace and the organization of social life. In: Time, consumption and everyday life. Routledge; 2009, Num Pages: 14.

[149] Hirst E, Goldman C. Review of demand-side data needs for least-cost utility planning. Energy 1990;15(5):403–11.

[150] Peterson F, Patton J, Miller M, Gillman R, Warwick W, Sandusky W. End-use load and consumer assessment program: motivation and overview. Energy Build 1993;19(3):159–66.

[151] Fransson V, Bagge H, Johansson D. Impact of variations in residential use of household electricity on the energy and power demand for space heating – variations from measurements in 1000 apartments. Appl Energy 2019;254:113599.

[152] López M, Santiago I, Bellido-Outeiriño F, Moreno-Munoz A, Trillo-Montero D. Active occupation profiles in the residential sector in Spain as an indicator of energy consumption. In: 2012 IEEE second international conference on consumer electronics - Berlin. ICCE-Berlin, 2012, p. 1–5, ISSN: 2166-6822.

[153] Dhar S, Srinivasan B, Srinivasan R. Simulation and analysis of Indian residential electricity consumption using agent-based models. In: Friedl A, Klemeš JJ, Radl S, Varbanov PS, Wallek T, editors. Computer aided chemical engineering. 28 European symposium on computer aided process engineering, vol. 43, Elsevier; 2018, p. 205–10, URL: http://www.sciencedirect.com/science/article/pii/B9780444642356500371.

[154] Gonzalez-Longatt F, Sanchez F, Singh SN. Chapter 19 - on the topology for a smart direct current microgrid for a cluster of zero-net energy buildings. In: Chauhan RK, Chauhan K, editors. Distributed energy resources in microgrids. Academic Press; 2019, p. 455–81, URL: http://www.sciencedirect.com/science/article/pii/B9780128177747000193.

[155] Torriti J. Temporal aggregation: Time use methodologies applied to residential electricity demand. Util Policy 2020;64:101039.

[156] Mckenna E, Higginson S, Hargreaves T, Chilvers J, Thomson M. Exploratory analysis of time-use activity data using network theory. Lancaster, United Kingdom; 2016, p. 1–20.

[157] Palm J, Ellegård K, Hellgren M. A cluster analysis of energy-consuming activities in everyday life. Build Res Inf 2018;46(1):99–113.

[158] Xu X, Chen C-f. Energy efficiency and energy justice for U.S. low-income households: An analysis of multifaceted challenges and potential. Energy Policy 2019;128:763–74.

[159] Torriti J. Understanding the timing of energy demand through time use data: Time of the day dependence of social practices. Energy Res Soc Sci 2017;25:37–47.

[160] Burkinshaw J. The tenuous and complex relationship between flexible working practices and travel demand reduction. In: Hui A, Day R, Walker G, editors. Demanding energy: space, time and change. Cham: Springer International Publishing; 2018, p. 165–81.

[161] Hoolohan C, McLachlan C, Mander S. Food related routines and energy policy: A focus group study examining potential for change in the united kingdom. Energy Res Soc Sci 2018;39:93–102.

[162] Torriti J, Hanna R, Anderson B, Yeboah G, Druckman A. Peak residential electricity demand and social practices: Deriving flexibility and greenhouse gas intensities from time use and locational data:. Indoor Built Environ 2015. Publisher: SAGE PublicationsSage UK: London, England.

[163] Sullivan C, Lewis S. Home-based telework, gender, and the synchronization of work and family: perspectives of teleworkers and their co-residents. Vol. 8. No. 2. Gender Work Organization; 2001, p. 123–45.

[164] Hampton S. An ethnography of energy demand and working from home: Exploring the affective dimensions of social practice in the united kingdom. Energy Res Soc Sci 2017;28:1–10.

[165] Wiig A. Demanding connectivity, demanding charging: The co-production of mobile communication between electrical and digital infrastructures. In: Hui A, Day R, Walker G, editors. Demanding energy: space, time and change. Cham: Springer International Publishing; 2018, p. 31–50.

[166] Hays S. Structure and agency and the sticky problem of culture. Sociol Theory 1994;12(1):57–72, Publisher: [American Sociological Association, Wiley, Sage Publications, Inc.].

[167] Powells G, Bulkeley H, Bell S, Judson E. Peak electricity demand and the flexibility of everyday life. Geoforum 2014;55:43–52.

[168] Friis F, Haunstrup Christensen T. The challenge of time shifting energy demand practices: Insights from Denmark. Energy Res Soc Sci 2016;19:124–33.

[169] Shove E. Energy and social practice: From abstractions to dynamic processes. In: Labanca N, editor. Complex systems and social practices in energy transitions: framing energy sustainability in the time of renewables. Green energy and technology, Cham: Springer International Publishing; 2017, p. 207–20.