A review of flexibility of residential electricity demand as climate solution in four EU countries

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Abstract

Increased flexibility at the grid edge is required to achieve ambitious climate goals and can be provided by smart energy solutions. By systematically reviewing the literature, we provide an overview of the potential flexibility of different residential electrical loads for France, Germany, Sweden, and the United Kingdom. While 85% of the studies aimed to identify potentials for shifting electrical energy use in time, the other 15% aimed to identify energy-saving potentials. Most of the data were found for the German and British electrical systems. A wide range of flexibility measures (e.g. price mechanisms, user-centered control strategies for space heating and water heating, automated shifting of appliances’ use, EV charging algorithms, and consumer feedback) and methods (e.g. simulations, trials, and interviews) have been used. Potentials obtained from the literature have been upscaled to the national level, including corresponding effects in terms of carbon dioxide (CO₂) emissions. The results show that between 2% and 18% of residential sector electricity in the four countries could be shifted, resulting in total emission reductions of 10 MtCO₂ from peak shaving, or 24 MtCO₂ per year if optimizing the deployment of renewables. The literature identifies substantial economic, technical, and behavioral benefits from implementing flexibility measures. In all the cases, it seems that the current regulatory framework would need to change to facilitate participation. Recognized risks include higher peaks and congestions in low price-hours and difficulties in designing electricity tariffs because of conflicts with CO₂ intensity as well as potential instability in the entire electricity system caused by tariffs coupling to wholesale electricity pricing.

Nomenclature

| Abbreviation | Description |
|--------------|-------------|
| CO₂          | carbon dioxide |
| COP          | coefficient of performance |
| DNO          | distribution network operator |
| DSO          | distribution system operator |
| DSR          | demand side response |
| DSM          | demand side management |
| EV           | electric vehicle |
| GHG          | greenhouse gas |
| HFA          | heated floor area |
| HP           | heat pump |
| MFD          | multifamily dwelling |
| RES          | renewable energy source |
| RTP          | real-time pricing |
| SES          | smart energy solutions |
| SFD          | single-family dwelling |
| ToU          | time of use (tariff) |
| TCL          | thermostatically controlled loads |
| TSO          | transmission system operator |

1. Background

The residential sector is responsible for 34% of global energy use, and most greenhouse gas (GHG) emissions...
come from electricity use in buildings. In the 28 member nations of the European Union (EU-28), the residential sector accounts for 28% (3311 TWh, year 2016) of final energy consumption, with 24% (808.3 TWh, year 2016) stemming from electricity use in residential buildings.

To maintain global warming at a 1.5 °C target, a carbon dioxide (CO₂) emissions reduction of 9 Gt is required from the global building sector alone. High-income regions must take the lead in this mitigation effort (Wang et al 2018). One possible pathway for achieving large-scale CO₂ emission reductions for residential sector electricity use can be found in the concept of demand side response (DSR) and load shifting, both of which can be facilitated using smart energy solutions (SES). Such solutions are also expected to offer consumers opportunities to reduce costs through shifting demand, providing better information and automation to optimize energy use, bringing them a step toward becoming prosumers. Shivakumar et al (2018) provided an overview of the status of smart metering in France, Switzerland, Ireland, the United Kingdom (UK), and Sweden, followed by a discussion of the demand response potential and how estimating this potential can be improved. This study concluded that SES can help balance energy supply and demand and consequently help Europe achieve its emission reduction targets and promote an increased use of RES.

Interest in the environmental effects of DSR has increased lately (Gyamfi and Krumdieck 2011) and some recent pilot projects have included analyzes of the environmental impact of load shift as a secondary aim (e.g. Nilsson et al 2017); however, previous studies have primarily focused on savings in both peak electricity demand and costs. For all sectors in Europe, DSR shows an estimated 26% of reduction in annual peak load and a power decrease of 172 GW (with an average of 93 GW: 25 GW in industry, 31 GW in tertiary sector, and 37 GW in the residential sector) (Gils 2014). Similar estimates of 73 GW (in a moderate scenario) were provided by Capgemini (2008). Some national multisectoral estimates are available. For instance, for a typical German city in an outlook for 2030 (including the commercial sector), a simulation of DSR finds peak power load reductions of 10%–20% (Stötzter et al 2015). In the UK (all sectors), a study examining pathways for a green electricity system by 2050 found that demand side measures, such as shifting demand a few hours, can reduce peak net demand by 10 GW (13%–25%) in three different scenarios (The Economist (2014)). More recently, a study focusing on the UK pointed out that the potential for load shifting depends on time of day and time of year, but 15–27 GW of all electricity loads (in all sectors) is available for short-term load shifting during evening hours (Aryandoust and Lilliestam 2017).

Numerous studies have evaluated the potential for DSR in residential electricity consumption, with a focus on the impacts of dynamic price tariffs and varying results (Nilsson et al 2017) in Europe and the United States. Additionally, a compilation of results from different real-time feedback studies identified an average energy savings of 5%–15% (Darby 2006). Within Scandinavia, different demand response programs also show a wide variation in their results. For instance, a pilot project in Norway that included a distribution tariff for varying energy rates and demand charges showed a 5% reduction in demand during peak hours (Stokke et al 2010). However, in Sweden, Zimmermann (2009) suggested that flexible load represents about 10% of total electricity consumption. In contrast, Bartusch and Alvehag (2014) included time-of-use-based electricity distribution tariffs and suggested a more modest result of up to 1% demand reduction during peak hours.

In summary, although prospects are good, accurate assessments of DSR potentials, including environmental effects for all EU member states, are needed (Aryandoust and Lilliestam 2017). ‘A consumer and country-specific analysis of the flexible loads on the European continent is missing so far,’ and it is important to correspondingly assess the techno-economic potential of SES in the EU, given the diversity of energy systems within its member states (Gils 2014).

To address this gap, we have defined the following research question: ‘How can digitalization of the grid edge contribute to climate mitigation from residential buildings of France, Germany, Sweden, and the United Kingdom?’

The following secondary questions are of interest.

- What insights are offered by applicable literature in terms of definitions of digitalization of the grid edge and taxonomies of flexibility measures?
- What are the types of technical and techno-economical potentials that are reported in terms of both energy and CO₂ emissions?
- What is the feasibility of these potentials in terms of additional benefits and challenges for implementing them?
- What are the research trends and gaps?

2. Methods

We performed a literature review of previous assessments of the potential demand response in Sweden, France, Germany, and the UK. The main stages of this review were literature search, appraisal, analysis and data extraction, and upsampling. The methodological steps follow a semi-systematic review methodology, which we have documented using the so-called ROSES support tools (Haddaway et al 2018) specific for this purpose. The methodology was originally developed by the Evidence for Policy and Practice Information and Coordinating Centre (EPPI-Centre) (Peersman 1996, Oakley et al 2005) and has been adapted to
environmental sciences (James et al 2016). Our approach mainly differs from Collaboration for Environmental Evidence (CEE) guidelines (CEE Collaboration for Environmental Evidence 2018) in that we conducted the search using only one database (Scopus). As required by the selected methodological approach, from the early stage of the work, we involved a reference group containing a well-balanced combination of stakeholders with different interests and perspectives. The review progress was discussed on three occasions with the reference group over the duration of the work performed before the paper was submitted for the first time (January–April 2019).

We included scientific publications and grey literature, as well as direct input from the stakeholder group1. The articles resulting from the search were appraised through a screening process to select appropriate articles for inclusion. Selected articles were analyzed in depth, and data on the amount of energy shifted or saved using different DSR measures were extracted and summarized. Finally, the extracted data were upscaled to represent the total potential within each studied country. Each of the methodological steps is described in detail in later sections.

2.1. Search
We identified key elements of our research question using a PICO approach, which is presented right below. In environmental science, the most common question to answer is what type of impact an intervention or exposure has on the environment, and generally four key elements must be specified: what is the affected population (P), what is the intervention/exposure (I/E), what is the comparator (C), and what is the outcome (O)? (James et al 2016). In this project, these elements are

- Population: Residential buildings.
- Intervention: Digitalization of the grid edge.
- Comparator: Savings or changes compared with reference or base case scenarios.
- Outcome: Effects in energy demand, load profiles, or carbon emissions.

Two search queries were initially developed and updated with input from the project reference group.

The first query reflected aspects of grid edge digitalization solid-state breakers, and includes, but is not limited to, the terms grid edge, demand side management, load switching, load curtailment, smart home management, consumer behavior, digital communication interface, and current limit. The second query aimed to capture all issues around deploying solid-state circuit breakers, which is a technology typically used in the digitalization of the grid edge, in the residential sector and included all specific mentions of solid-state circuit breakers in relation to energy savings and mitigation potentials in the building sector. The searches were conducted in English and encompassed the four stated nations.

The search was performed in the scientific database Scopus. The reference group provided specific literature tips and suggestions on how to improve search queries by using synonyms and additional terms to capture the targeted aspects of each query. The resulting search result amounts from Scopus are summarized in table 1. The complete list of studies has been provided as supplementary material is available online at stacks.iop.org/ERL/15/073001/mmmedia.

2.2. Appraisal
Scopus search results (2166 studies) and literature tips from the reference group (26 studies) were imported into the APSIS tool for screening (MCC 2018). Criteria for inclusion and exclusion were developed on the basis of the PICO framework described previously. The inclusion criteria were relevant population (residential buildings), intervention (digitalization of the grid edge), comparator (reference or baseline clearly stated), and outcome (effects in energy demand or carbon emissions). The number of excluded articles and reasons for exclusion at each stage were documented.

For example, some of the search terms gave results irrelevant to our search, such as the term ‘consumption’ leading to studies focusing on food, the term ‘building’ leading to studies focusing on building materials, and the term ‘optimization’ leading to studies focusing on all types of algorithms, frequently related to indoor air quality or thermal comfort. At the same time, the defined geographical scope included author affiliations, which returned studies performed, e.g. by French authors that did not study French buildings.

A total of 261 documents were selected for inclusion. Of these, 218 full texts could be retrieved (12 documents were not accessible, and 30 were not found) (see supplementary material).
2.3. Analysis

We developed additional inclusion and exclusion criteria for screening at the fulltext level, along with a data extraction questionnaire. At this point, inclusion criteria were: (i) clear quantification of an impact in terms of energy or emissions, and (ii) a clear population studied. We excluded works that did not describe methods as well as review articles citing other pieces of work without providing an appropriate context.

A total of 27 documents fulfilled the inclusion criteria, and the number of excluded articles and reasons for exclusion at each stage were documented (see supplementary material). This rate of inclusion after the initial results ($n = 2166$) is marginally higher than the estimate by the tool PredicTER (Haddaway and Westgate 2019). PredicTER has been specifically designed for high quality systematic reviews and systematic maps conducted according to the recommended standards of the Collaboration for Environmental Evidence. This tool estimates that for a systematic review using one Academic Database with a total number of 2166 articles that did not contain duplicates, data would be extracted for 19 articles.

For the selected documents, the data extracted included the following:

- quantified changes in energy demand or mitigation potential;
- geographical scope;
- stock unit/population for upscaling: subsector or household type (single-family dwelling [SFD] and multifamily dwelling [MFD]); end use (electricity,

Table 2. Description of different estimates of average and marginal carbon intensities for electricity, including sources.

| Abbreviation | Description | References |
|--------------|-------------|------------|
| Average carbon intensity of electricity | | |
| El 1 | Average carbon intensity homogeneously compiled from national statistics on carbon emissions and fuel mix | Mata et al 2018 |
| El 2 | Average carbon intensity from different sources and years | Germany: SVK, 2014; for Sweden 2013: Nilsson et al 2017; for UK unknown year: DEFRA. |
| GWP | Global warming potential (100 years), excluding biogenic carbon, for the annual fuel mix for electricity production in each country, derived for this report | IEA 2019, Thinkstep 2018 |
| CO₂ fossil | Carbon intensity for the annual fuel mix for electricity production in each country, derived for this report | IEA 2019, Thinkstep 2018 |
| AVERAGE avg | Average of all estimates above | |
| Marginal carbon intensity of electricity | | |
| Marginal El avg | Hourly marginal carbon intensity of electricity, average over 2 years | IPCC 2014, ElectricityMap 2019 |
| Marginal El avg (incl. imports) | Hourly marginal carbon intensity of electricity (including imports), average over 2 years | IPCC 2014, ElectricityMap 2019 |
| Marginal El 1 avg | Based on the fuel mix for the hourly marginal generation of electricity, average over 2 years, derived for this report | ElectricityMap 2019, Thinkstep 2018 |
| Marginal El 2 | Marginal carbon intensity of electricity from different sources and years | Reference group |
| AVERAGE Marginal | Average of all estimates above | |
space heating, and hot water); load (lighting, appliances, photovoltaic panel [PV], and electrical vehicle [EV]; see full list of loads in figure 2);

• studying a concrete type of flexibility measure in terms of interpreting the digitalization of the grid edge;
• approach used (model, pilot, etc);
• other findings: benefits, challenges, trade-offs, costs (qualitative), effects on grid development, and investments.

The data extraction matrix was documented and stored. Review articles not fulfilling the inclusion criteria (Gyamfi and Krumdieck 2011, Shivakumar et al 2018, Aryandoust and Darby 2006, Cappgemini 2008, Zimmermann 2009, Stokke et al 2010, Gils 2014, Aryandoust and Lilliestam 2017), are presented in the Introduction (section 1) of this paper because they give overviews of the demand side management potential for an entire country but not specifically for the residential sector for example.

2.4. Upscaling

The selected studies and articles presented data with varying levels of detail and for different electrical load types within the residential sector. For example, one study could examine the load shifting potential of space heating in a population of a few households (Boait et al 2017) whereas another study estimates the load shifting potential for all residential electricity in an entire country (Klobasa 2008). Therefore, data on energy savings, flexibility, and mitigation potentials were upscaled to represent the entire country where needed. If the studies did not present mitigation potentials, but only potentials for DSR in terms of saved of flexible energy demand, the corresponding effects in terms of carbon emission reductions were calculated.

2.4.1. Energy demand

The quantified changes in energy demand, i.e., saved or shifted electrical load, from the studies were upscaled on the basis of stock description data (with stock units being subsector, typology, end use, and load) of the residential sector of the four countries investigated.

Because data on fuel type, end use, and floor areas were typically not available in national and international statistics (e.g. Eurostat, Odyssey, and Building Stock Observatory) by building typology (SFD or MFD) and end use (space heating, hot water, and electrical uses), we derived such data using a building stock model (Mata et al 2013a) in combination with a methodology for building stock aggregation (Mata et al 2014). Therefore, energy use per fuel type, end use, and building typology, as well as the heated floor areas (HFAs) and amount of buildings per typology, were obtained from Mata et al (2013b, 2014). The CO₂ emissions of households, total CO₂ emissions of households (including electricity), and residential electricity consumption were obtained from the Odyssee database.

2.4.2. Associated emissions

To estimate the effects on carbon emissions from saved or shifted electrical load in each country, data on each country’s electricity production mix were needed. Average carbon intensity of electricity production reflects non-peak hours, while marginal carbon intensity is associated with peak demand hours. The estimates depend on the methodological choices for GHG accounting, such as time resolution of (additional) unit production, e.g. hourly or yearly. Descriptions and critique of possible methods for GHG accounting, including protocols, standards, and guidance for emissions associated with purchased electricity, are provided in Brander et al (2018) and Tranberg et al (2019).

Carbon intensities of electricity production were compiled from the literature for a variety of possible representative approaches (figure 1 and table 2):

• National averages were compiled from national statistics of a specific source (Mata et al 2018) as well as from different sources and years (SVK 2014, Nilsson et al 2017, DEFRA). Moreover, in this study, we derived the global warming potential and carbon intensity for the annual fuel mix for electricity production in each country by using data from IEA (2019) and Thinkstep (2018).
• Marginal emissions were compiled based on hourly estimates of electricity production that use a real-time consumption-based accounting approach based on flow tracing. Power flows are traced from producer to consumer, thereby representing the underlying physics of the electricity system, in contrast with the traditional input–output models of carbon accounting, allowing the exploration of the hourly structure of electricity trade across Europe (ElectricityMap, 2019, Tranberg et al 2019). Additionally, the reference group provided estimates of marginal carbon intensities of electricity production according to their knowledge, for which sources could not be traced (labelled as Marginal El 2 in figure 1 and table 2).

The compiled values, illustrated in figure 1, vary substantially depending on the fuel mix considered for electricity production and the year for which the estimate is made. However, some general trends confirm the expectations. First clear differences can be observed among all estimates for the different countries. Second, the marginal values are generally higher than the average. As an exception, several sources give marginal carbon intensities for France and Germany that are lower than average, owing to the fact that marginal hourly units are on average produced by hydropower to a large extent in both countries.

The methodology used in this review is limited in that it only considers one value for the carbon intensity of marginal and average electricity production. In
reality, the carbon intensity of both types of electricity production varies depending on several factors such as time of day and year, trade between electricity markets, fuel prices, and many others. To more accurately capture the savings from the measures studied in this review, more complex modelling methods and scenarios can be used.

Given the varying estimates of carbon intensity of electricity, we used three different combinations of carbon intensity of electricity production as a form of sensitivity analysis in this paper. The different scenarios are presented in table 3 and are made up of combinations of emission data in table 2 with the aim to homogeneously illustrate for all the countries studied a range of results that could be obtained depending on the assumptions for calculating the carbon intensities of electricity production.

### 3. Results

#### 3.1. Potentials

##### 3.1.1. Load flexibility

Load shifting is the practice of moving loads in time for reasons such as grid congestion, consumer cost optimization, or production optimization and takes place during peak hours. Of the studies in the analysis, 85% had the objective of identifying potentials for shifting electrical energy use in time, thereby decreasing peak electricity demand (23 in total: 2 for France (Crossley, 2008, Nguyen et al 2010), 5 for Germany (Klobasa 2008, Stötzer et al 2012, Belitz et al 2013, Bradley et al 2016, Aryandoust and Lilliestam 2017), 5 for Sweden (Bartusch and Alvehag 2014, Chrysopoulos et al 2016, Liljeblad 2016, Nyholm et al 2016, Nilsson et al 2017) and 11 for the UK (Lampaditou and Leach 2005, Navarro et al 2012, Papadaskalopoulos and Srbrac 2012, POST 2014, Drysdale et al 2015, 2015, Bradley et al 2016, Qiao and Yang 2016, Boait et al 2017, Qiu et al 2018, Sweetnam et al 2019). Most of the data found were for the German and British electrical systems; however, this does not mean that there is a larger potential for load flexibility in Germany and the UK than in Sweden or France, but rather that our search method fewer studies for Sweden and France. The geographical scope of the work being clearly stated in the title or abstract was an inclusion condition; therefore, we may have missed other studies that addressed one of the four investigated countries in the full text without mentioning that in the title or abstract.

The studies addressed a wide range of flexibility measures (e.g. price mechanisms, user-centered control strategies for space heating and water heating, automated shifting of appliances’ use, EV charging algorithms, and consumer feedback) and methods (e.g. simulations, trials, and interviews). See table A1 in the appendix for details on each estimate, including the units and scale in which the potential flexibility is presented in each reference. Figure 2 presents a summary of obtained flexibility potentials expressed as a percentage of the total corresponding load for each country.
upscaled at the country level. ‘Wet appliances’ include dishwashers, washing machines, and tumble dryers, whereas ‘All appliances’ include refrigerators, freezers, and cooking appliances. When several sources provide an estimate for a category, the average of the estimates is shown in figure 2. For instance, figure 2 shows that 11.7% of wet appliances load in the UK could be shifted. This estimate is an average based on values of 13.9% provided by Drysdale et al (2015) and 9.5% provided by Papadaskalopoulos and Strbac (2012).

The potential flexibility for the total electricity load varied greatly among the countries investigated, with the largest potential found in Germany [17.7% average of estimates by Klobasa (2008) and Stötzer et al (2012)] and the lowest potentials were found in Sweden [1.9% average of estimates] by Bartusch and Alvehag (2014), Nilsson et al (2017), Chrysopoulos et al (2016), and Liljeblad (2016).

For Germany and Klobasa (2008) simulated power plant operation and balancing capacity activation and concluded that 29.4% of the electricity load in the residential sector in 2008 could be shifted. This corresponds to 37.9 TWh/yr, of which 26.6 TWh/yr is for cooling and electrical heating and 11.3 TWh/yr is for households without electrical heating. More recently, Stötzer et al (2012) modeled load profile optimization and RES integration for a representative German region with 500 000 inhabitants and found a more modest potential of 6% of the electrical load from Germany’s residential sector by 2020, corresponding to a shiftable capacity of 21 GW.

For Sweden, different types of price mechanisms including real-time price (RTP) visualization (Nilsson et al 2017), time of use (ToU) tariff (Bartusch and Alvehag 2014) and monetary demand response scheme (Chrysopoulos et al 2016) have been tested and managed to shift a maximum of 1.0% of the electricity load. Nilsson et al (2017) found that residential electricity consumers are willing to respond to spot price visualization and shift approximately 5% of their daily total electricity consumption from peak hours to off-peak hours. However, no evidence can be found to support real-time spot price visualization contributing to a reduction in overall household electricity consumption. The result of the household load shift was an annual electricity cost decrease of 1%, whereas the CO₂eq emissions increased approximately 3%. Other estimates (Liljeblad 2016) are somewhat higher, amounting to 6% of the domestic load. Household flexibility comes mainly from heating and depends on outdoor temperature and allowed variations in indoor temperature. During the summer, there may be no heating demand; thus, energy use for heating cannot be decreased.

Although most of the individual load potentials between 3.2% and 16.8% have been identified depending on load and country, the potential flexibility of heat pumps seems limited. For Germany, Romero Rodriguez et al (2019) modeled a cluster of heat pumps and found it was unable to reduce overall electricity costs, meaning that DSR participation from heat pumps was not financially viable. For the UK, Sweetnam et al (2019) a field trial of a new control system to optimize heat pump performance was conducted, including under time-varying tariff conditions. This trial involved monitoring 76 properties with heat pumps without dedicated heat storage, 31 of which received the control system. The system successfully delivered short-term demand reductions; however, longer-term demand shifting risked causing unacceptable disturbances to occupants. Future control systems could overcome some of the issues identified in this trial through more effective zoning, using temperature caps or installing dedicated heat storage, but these could limit the available flexibility or be challenging to achieve.

See table A1 in the appendix for more details on the sources on which figure 2 is based.

3.1.2. Energy savings

Energy savings are the overall reductions in energy use taking place during any hour of the day, not only during peak hours. These estimated potential energy savings, presented in different units, are summarized in table 4.

Only 15% of the studies (four in total) aimed to identify energy-saving potentials. Most of the studies focused on Germany and implemented different measures and methods. Simulation studies estimated higher potential savings; for instance, Alzate et al (2015) modeled the implementation of a state-of-the-art connected heating control system in MFDs in Germany found that if heating control systems could overcome some of the issues identified in this trial through more effective zoning, using temperature caps or installing dedicated heat storage, but these could limit the available flexibility or be challenging to achieve.

See table A1 in the appendix for more details on the sources on which figure 2 is based.

3.1.3. Effects in CO₂ emissions

3.1.3.1. Peak shaving

Table 5 presents potential reductions in CO₂ emissions from load shifting, calculated for the three carbon intensity scenarios presented in table 3. These reductions are given for the different loads and countries. The annual potential carbon emission reductions range from close to 0 MtCO₂/yr in Sweden, where the
electricity is already low emissive, to almost 6 MtCO$_2$/yr in Germany. A reduction of a total of roughly 10 MtCO$_2$/yr can be attained through load shifting in France, Germany, Sweden, and the UK.

The effect of assumptions regarding carbon intensity in electricity production becomes evident here, as some of the resulting reductions in CO$_2$ emissions under C1 and C3 are negative, indicating increased emissions due to load shifting. This is because the marginal carbon intensity is lower than the marginal in those scenarios because of the use of hydropower to produce marginal units (figure 1).

Our negative reduction results agree with the literature summarized in Nilsson et al (2017). Although energy savings (described in section 3.2) imply an absolute reduction of electricity consumption and ultimately always lead to reduced carbon emissions, the impact of load shifts during off-peak hours (presented in section 3.1) may decrease or increase CO$_2$ emissions as the carbon intensity of electricity production varies over time. The possible increase in CO$_2$ emissions due to load shift has been addressed in a study that analyzed the correlation between hourly dynamic price and hourly dynamic emissions for three different energy markets and found that the impact of load shift is strongly connected to intraday variations in the electricity grid mix (Stoll et al 2014). Additionally, Song et al (2014) simulated household consumption behavior under price and CO$_2$ emission signals in Sweden found that carbon emissions may increase by roughly 3%, depending on the load shift amount.

Table 4. Summary of energy-saving potentials found in the literature, including sources.

| References | Load | Country | TWh/yr | kWh/m$^2$ HEA | % of total residential energy consumption | % of total residential electricity consumption |
|------------|------|---------|--------|--------------|-----------------------------------------------|------------------------------------------------|
| (Rehm et al 2018) | Space heating–All fuels | GE | 8.7 | 6.2 | 1.3 | 6.8 |
| (Nägele et al 2017) | Space heating–All fuels | GE | 29.1 | 28.9 | 4.3 | Not given |
| (Alzate et al 2015) | Electricity–Appliances | GE | 38.4 | 11.7 | 5.6 | 29.8 |
| (Keirstead 2007) | Electricity All | UK | 2.6 | 4.2 | 0.5 | 2.4 |

Table 5. Potential effects on CO$_2$ emissions (MtCO$_2$/yr) from the load shifting presented in figure 2, per load and country. C1, C2, and C3 are the scenarios of carbon intensity of electricity presented in table 3. Empty cells are those for which no values were found in the literature. Values are rounded.

| Load | France | Germany | Sweden | UK |
|------|--------|---------|--------|----|
|      | C1     | C2     | C3     | C1  | C2 | C3 | C1 | C2 | C3 |
| Electricity All | −2.20 | 0.45 | −2.05 | 0.01 | 0.01 | 0.01 | 1.00 | 1.80 | 0.65 |
| El—Appliances wet | −1.60 | 0.35 | −1.50 | 0.00* | 0.00* | 0.01 | 1.15 | 2.90 | 0.40 |
| El—Appliances | 4.35 | 5.73 | 4.45 | 0.00* | 0.00* | 0.01 | 0.25 | 0.55 | 0.10 |
| El—Direct heating | −0.45 | 0.10 | −0.40 | 0.00* | 0.00* | 0.01 | 1.30 | 3.40 | 0.45 |
| El—Storage heating | −2.05 | 0.45 | −1.90 | 0.00* | 0.00* | 0.01 | 0.05 | 0.15 | 0.05 |
| EV | 0.00 | 0.00 | 0.00 | 0.00* | 0.01 | 0.04 | 1.15 | 3.00 | 0.40 |
| Heat pumps | 0.05 | 0.35 | 0.45 | 0.00* | 0.01 | 0.04 | 0.65 | 1.65 | 0.25 |
| Space heating—El | 0.05 | 0.75 | 1.05 | 0.00* | 0.01 | 0.04 | 1.15 | 3.00 | 0.40 |
| Space and water heating | −1.35 | 0.30 | −1.25 | 0.00* | 0.01 | 0.04 | 0.65 | 1.65 | 0.25 |

*Values smaller than 0.001 have been rounded to 0.00.

Figure 3 illustrates carbon emission reductions for various residential electrical loads in the studied references, given as a share of total annual emissions from residential electricity. These are the maximal mitigation potentials arising from scenario C2. Total annual emissions are calculated using data from the Odyssee database and Mata et al (2013a). See table A2 in the appendix for a compilation of the mitigation potentials obtained from all loads and scenarios.

3.1.3.2. Deployment of renewables

The potential carbon emission reductions presented in section 3.3.1 assume that peak loads are shifted from times of marginal electricity production to those of average electricity production. In this section, we discuss the potentials for shifting loads to maximize the use of RESs instead.

The growing renewable energy sector brings the challenge of highly fluctuating and unpredictable energy generation (e.g. from PV and wind). Because of the current inflexibility of demand for electricity, it is not always possible to match renewable energy generation and demand (Wolisz et al 2017). The rising share of wind and PV in the total energy portfolio will further aggravate that challenge in the upcoming years (Boßmann and Staffell 2015). Residential and commercial buildings can provide flexibility to counter supply and demand imbalances in the electrical grid (Le Dréau and Heiselberg 2016, Wolisz et al 2016). In PV-dominated regions, DSR and load shifting partially substitute short-term energy storage.
when PV generation is at its peak, allowing for even more penetration of non-wind-related renewable energy (Aryandoust and Lilliestam 2017). Therefore, here we assume that all loads are shifted from peak hours to hours with enough renewable electricity to cover demand.

Table 6 presents potential carbon emission reductions in residential electricity use under these assumptions. By assuming that renewable electricity is carbon neutral, the maximal carbon emission reductions in the table were obtained by multiplying the load shifted by the marginal carbon intensity of electricity production; Min, loads shifted from average carbon intensity of electricity production.

Table 6. CO₂ emission reduction potential [% of the total emissions of electricity in the residential sector of each country] from load shifting presented in figure 5. Empty cells are those for which no values were found in the literature. Max, loads shifted from marginal carbon intensity of electricity production; Min, loads shifted from average carbon intensity of electricity production.

| Load                  | France | Germany | Sweden | UK      |
|-----------------------|--------|---------|--------|---------|
|                       | Max    | Min     | Max    | Min     | Max     | Min     | Max     | Min     |
| Electricity All       | 18.3%  | 17.7%   | 2.5%   | 2.0%    | 10.5%   | 6.8%    |         |         |
| El—Appliances wet     | 13.3%  | 12.8%   | 19.0%  | 11.7%   |         |         |         |         |
| El—Appliances         | 17.7%  | 17.3%   | 0.2%   | 0.2%    | 3.5%    | 2.2%    |         |         |
| El—Direct heating     | 3.6%   | 3.5%    |        |         |         |         |         |         |
| El—storage heating    | 16.8%  | 16.2%   |        |         |         |         |         |         |
| EV                    |        |         |        |         | 22.3%   | 13.7%   |         |         |
| Heat pumps            | 0.0%   | 0.0%    |        |         | 0.9%    | 0.6%    |         |         |
| Space heating—El      | 6.7%   | 3.2%    | 4.2%   | 3.4%    | 19.6%   | 12.1%   |         |         |
| Space and water heating| 15.1%  | 7.2%    |        |         |         |         |         |         |
| Water heating         | 11.3%  | 11.0%   | 2.5%   |         | 10.3%   | 6.5%    |         |         |
minimal reductions assume that loads were shifted using the average carbon intensity of electricity production instead. The real potentials likely lie somewhere between the minimum and maximum values presented; however, our focus is not on accuracy but on the (comparative) sizes of potentials for different flexibility measures.

Our results indicate that carbon emissions from residential sector electricity could be reduced between 2.0% (in Sweden, corresponding to 0.05 MtCO2/yr as the Swedish energy system is already low emissive) and 18.3% (in Germany, corresponding to 13.5 MtCO2/yr) depending on the country. These mitigation potentials add up to a maximum of 23.8 MtCO2/yr for the four countries combined.

Implementing this potential depends on technical and energy political boundary conditions. For instance, technical challenges may arise from managing building energy demands (e.g. space and water heating), requiring greater automation of electricity-driven heating systems (e.g. heat pumps and direct electric heating) to effectively utilize the energy flexibility offered by buildings (Liljeblad 2016, Wolisz et al 2016). Greater acceptance of indoor temperature variations (Liljeblad 2016) is also required.

### 3.2. Trade-offs and feasibility

#### 3.2.1. Benefits

Apart from energy savings and carbon emissions reductions, the increased flexibility will improve system efficiency, increase utilization of renewable sources, and reduce costs (table 7). Technical system’s benefits include higher generation capacity, improved utilization of the transmission grid, and distribution network assets and operational efficiency as well as enhancing the balancing capability between demand and supply in systems with intermittent RES (Pudjianto and Strbac 2017). For instance, network capacity increased by 20% in this case study of EV integration (Qiao and Yang 2016). This shifting and its duration (i.e. energy) can potentially be used to facilitate variation management of intermittent power generation on the electricity supply side depending on the characteristics of the variability of the intermittent generation and on the grid voltage level (Nyholm et al 2016).

Short-term variations in load and a higher level of intermittent generation in the system cause imbalances between planned generation and load, which require regulating reserves. The heating load could possibly be used to supply some of these regulating reserves (Nyholm et al 2016). An interesting subset of appliances for DSR encompasses thermostatically controlled loads (TCLs), e.g. refrigerators. Individual customers or entities like aggregators or system operators may employ the intrinsic flexibility of these devices and benefit from their provision of a portfolio of frequency response services or realize energy arbitrage (Trovato et al 2016). Smart controlled refrigerators can provide system security and transmission constraint management services. TCLs can shift their energy consumption to reduce price spikes caused by peaking generators and reduce the impact of transmission constraints. In addition, the responsive devices participate in the provision of frequency services, thereby reducing the need to run generators part-loaded (Trovato et al 2015). These benefits are shown to increase with not only an increase in the extent of EV/EHP flexibility but also with an increase of EV/EHP penetration, thereby demonstrating the increased potential of demand flexibility in the future with wide electrification of transportation and heat sectors (Papadaskalopoulos et al 2013).

Economically, the adoption of DRS strategies creates a double dividend for consumers. They receive a lower bill for using electricity (Silva et al 2012, Bradley et al 2016, Nilsson et al 2017, Li and Pye 2018) and heating fuels (Kensby et al 2019) and may also may receive financial payments for the proportion of usage that is off-peak (Bradley et al 2016). With an extended system boundary that includes demand and storage in buildings as well as connections to the electrical and district heating grids, co-optimization can be

| Benefits                                                                 | Challenges                                                  |
|------------------------------------------------------------------------|--------------------------------------------------------------|
| Economic                                                               | Challenges                                                  |
| - Low initial investments for the individual                           | - High costs of advanced smart metering options              |
| - Lower energy costs for the consumer                                  | - Unclear business models                                     |
| - Effect and peak reduction yield lower generation costs               | - Disadvantageous current market models                       |
| Technical                                                              | Technical constraints for HPs                                |
| - Increased network capacity                                           | - Space heating flexibility is seasonal and unstable         |
| - Increased RES integration                                            |                                                             |
| - Increased penetration of EV and HP                                   |                                                             |
| - Improved utilization of transmission grid and distribution network   |                                                             |
| Behavioral                                                             | Heterogeneity of consumption patterns                        |
| - Behavioral changes towards lower/flexible energy consumption         | - Lack of information on consumers’ response to tariffs      |
| - Increased user awareness of energy consumption                       | - Lack of technical understanding of interface and hardware   |
| - Increased self sufficiency                                           | - Acceptance of comfort changes                              |
| - Triggers environmental motivations                                    | - Acceptance of increased automation                        |

Table 7. Summary of benefits and challenges. EV, Electric vehicles; HP, Heat pumps; RES, Renewable energy sources. Sources stated in the text of this sections 3.2.1 and 3.2.2.
performed that creates great value for the economy (Le Blond et al 2014, Kensby et al 2019).

Behavioral benefits are identified with respect to increasing the level of energy awareness of the users (Rehm et al 2018). Deliberate attempts of the consumers to reduce and/or shift their electricity usage were measured (Bradley et al 2016). Households that changed their time-of-use primarily did so to try and use their PV electricity in their homes. This is not only convenient but is also preferred by the electricity industry, partly because it results in electricity being utilized more efficiently (some losses will arise if the electricity is distributed to neighboring properties) (Keirstead 2007). Environmental motivations were also important for some participants in their shifting (Bradley et al 2016).

3.2.2. Challenges
A few challenges undermine effective implementation of the potentials presented above. At the outset, business models are unclear (i.e. TCLs may operate individually or may be managed by entities such as aggregators or system operators (Shivakumar et al 2018, Keirstead 2007, Trovato et al 2016)) and economic incentives are limited (Nyholm et al 2016, Romero Rodriguez et al 2019). In some cases, initial investments for the individual can be low (Nägèle et al 2017), but advanced smart metering options have high costs (Keirstead 2007, Torriti et al 2010, Shivakumar et al 2018). Uptake will be likely a function of the extent to which consumers can understand the contracts being offered (Platchkov and Pollitt 2011). In all the cases, it seems that the current regulatory framework would need to change to facilitate participation.

Technical constraints have been identified for heat pumps such as minimum running time or COP correlation to indoor–outdoor temperature (Papadaskalopoulos et al 2013). Space heating flexibility is seasonal and unstable because it depends on outdoor temperature (Liljeblad 2016, Nyholm et al 2016) and similar seasonality applies to cooling loads. Moreover, DR is not limited by the magnitude of shiftable capacity but by the maximum shift duration and the patterns of switching between positive and negative power demand, which makes DR useful for fast and short-term services but less useful for longer shifts (Aryandoust and Lilliestam 2017).

Human factors play an important role in DSM. Although different household types show different consumption patterns and thus individual availability of DSM capacity during the day (Fischer et al 2016), limited (Morris 2006, Shivakumar et al 2018) or inexistent (Drysdale et al 2015, Nilsson et al 2017) information of consumers’ response to ToU pricing exists, especially among those living in apartments (Bartusch and Alvez-Hag 2014). Consumers are shown to have a lack of awareness of real-time price information (Torriti et al 2010), inadequate technical understanding of interface, hardware (Sweetnam et al 2019), and tariffs (Fischer et al 2016), and resistance to accepting comfort changes (noise, overnight heating) and increased automation (Drysdale et al 2015, Bradley et al 2016, Sweetnam et al 2019).

Among the uncertainties identified, there is high agreement on the risks of higher peaks and congestions in low price-hours (Papadaskalopoulos and Strbac 2012, Fischer et al 2016, Nyholm et al 2016, Nägèle et al 2017, Pudjianto and Strbac 2017) with corresponding increases in aggregated demand and prices at those times (De Paola et al 2017) that would trigger a demand for new transmission capacity (Pudjianto and Strbac 2017). Risks in electricity tariffs include conflicts with CO2 intensity (Zhang et al 2016, Wolisz et al 2016, Nilsson et al 2017, Nyholm et al 2016) and instability in the entire electricity system caused by coupling to wholesale electricity pricing. Remote control of appliances raises issues of data security, confidence in the technology, and the availability of easy overrides (Platchkov and Pollitt 2011). Finally, a methodological issue exists on the manner of defining the consumer baseline, which is especially important when evaluating TSO and DSO products, because several member states still have no regulation concerning baseline measurement (Shivakumar et al 2018). All these potential conflicts must be carefully managed to obtain the maximum benefits of DSR. A summary of the identified benefits and challenges is shown in table 7.

4. Conclusions
The residential sector is responsible for 34% of global energy use, with most of the GHG emissions coming from electricity use in buildings. In the EU-28, the residential sector accounts for 28% of final energy consumption, with 24% corresponding to electricity use in residential buildings. A wider digitalization of the grid edge is expected to optimize demand and supply interactions and provide economic and environmental benefits such as reduced energy and peak demands and integration of a greater share of renewable energy.

We have performed a review of literature on the flexibility of residential electricity demand that could be achieved by a digitalization of the grid edge in four European countries (France, Germany, Sweden, and the UK). The resulting insights from the literature are summarized as answers to our initial research questions and are represented below.

- What definitions of digitalization of the grid edge does the literature offer in terms of taxonomies of flexibility measures?

The literature on digitalization of the grid edge refers to load shifting as well as energy saving. Load shifting is the practice of moving loads in time for reasons such as grid congestion, consumer cost optimization, or production optimization and is conducted during peak hours. Energy savings are the overall reductions in energy use taking place during any hour of the day, not
only during peak hours, and automation is used to improve the management and operation of buildings’ technical systems. The studies addressed a wide range of flexibility measures (i.e. price mechanisms, user-centered control strategies for space heating and water heating, automated shifting of appliances’ use, EV charging algorithms, and consumer feedback) and methods (i.e. simulations, trials, and interviews).

• What are the types of potentials reported in terms of both energy and CO₂ emissions? The literature reports a variation of technical and techno-economical potentials depending on the studies conducted, but the potentials are neither clearly categorized nor defined. They have been simply implied from the methodological approaches. A trial of a ToU tariff derives techno-economical potentials is one such example. However, simulation of automated scheduling of appliances for energy saving purposes naturally derives technical potentials. The potential flexibility for the total residential electricity load varied greatly among the countries investigated, with the largest potential found in Germany (6%–29%) and the lowest potential found in Sweden (1%–5%). The identified energy-saving potentials also vary, with simulation studies tending to find higher potentials than demonstration studies. Most of the studies focused on Germany and identified potential reductions of residential electricity demand of between 1% and 6%, using different measures and methods. This flexibility could reduce carbon emissions from electricity in the residential sector by up to 8.5% in the UK. This potential varies between 1% and 8.5% for the countries investigated because of differences among the national energy systems and adds up to a total of 10 MtCO₂/yr. The largest absolute potentials were found in countries that had electricity production with higher carbon intensity such as Germany and the UK, whereas the absolute mitigation potentials were lower in Sweden because of that country’s low electricity production carbon intensity. However, if loads were shifted to maximize the use of renewables, carbon emissions from residential electricity could be reduced by up to 22% in the UK, with a range from 4% to 22% in the countries investigated. This would add up to a total of 24 MtCO₂/yr in the four EU countries investigated. These potentials are highly dependent on the assumed carbon intensities of electricity production, which vary greatly for different types of methodological accounting of the average and marginal electricity production in terms of fuel mix, time resolution, and data sources.

• What is the feasibility of these potentials in terms of additional benefits and implementation challenges? The literature identifies substantial economic, technical, and behavioral benefits from implementing flexibility measures. In all the cases, it seems that the current regulatory framework would need to change to facilitate participation. Three types of challenges exist: economic challenges such as unclear business models and disadvantageous market models and high costs of advanced smart metering; technical challenges such as constraints for HPs (minimum running time, COP correlation to indoor–outdoor temperature) and seasonality of space heating demands; social challenges in which consumers seem to display a lack of awareness of real-time price information, inadequate technical understanding, and resistance to acceptance (change thermal comfort and operation). Risks identified include higher peaks and congestions in low price-hours and difficulties in designing electricity tariffs because of conflicts with CO₂ intensity, and potential instability in the entire electricity system cause by tariffs coupling to wholesale electricity pricing.

• What are the research trends and gaps?

Of the reviewed studies, 85% aimed to identify potentials for shifting electrical energy use in time, thereby decreasing peak electricity demand and 15% aimed to identify energy-saving potentials. Most of the data were found for German and British electrical systems. We identified a lack of standardized calculation approaches, linkages between modelling exercises with different goals (e.g. simultaneously addressing the economic and environmental value), and upscale estimates that synthesize the learnings from individual case studies into generally applicable knowledge.

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Data availability statement

Any data that support the findings of this study are included within the article.

Appendix
Table A1. (a) Germany: Summary of the flexibility potentials obtained in the literature for Germany, by type of load, flexibility measure, and methodological approach. (b) Sweden: Summary of the flexibility potentials obtained in the literature for Sweden, by type of load, flexibility measure, and methodological approach. (c) France: Summary of the flexibility potentials obtained in the literature for France, by type of load, flexibility measure, and methodological approach. (d) UK: Summary of the flexibility potentials obtained in the literature for the UK, by type of load, flexibility measure, and methodological approach.

| Reference          | Load                | Flexibility measures and method                                      | Identified flexibility potential |
|--------------------|---------------------|----------------------------------------------------------------------|---------------------------------|
|                     |                     |                                                                      | units as in the reference       |
| Fischer et al (2016)| Appliances          | DR to variable tariffs, simulation of 500 German SFDs                | 8% daily peak shifted per household on average |
| Belitz et al (2013) | Appliances          | ToU products and consumption-dependent products, test field for 700 households | 0.625 kWh per household and day |
| Bradley et al (2016)| HP and PV            | Modeled DR if saved electricity costs for cluster of 6 buildings in Germany with HP, PV, storage, and EV | DR participation as a cluster with the HP is not financially viable for the energy prices considered |
| Aryandoust and Lilliestam (2017) | Wet appliances | Modeled load shifted short term (max 30 min) | 16.5 TWh/yr |
| Aryandoust and Lilliestam (2017) | Big appliances | Modeled load shifted short term (max 30 min) | 44.7 TWh/yr |
| Aryandoust and Lilliestam (2017) | Water heating | Modeled load shifted short term (max 30 min) | 14.1 TWh/yr |
| Aryandoust and Lilliestam (2017) | El. direct heating | Modeled load shifted short term (max 30 min) | 4.5 TWh/yr |
| Aryandoust and Lilliestam (2017) | El. storage heating | Modeled load shifted short term (max 30 min) | 20.9 TWh/yr |
| Klobasa (2008)      | All residential electricity | Simulation of power plant operation and balancing capacity activation | 37.9 TWh/yr shiftable residential sector in Germany in 2008 |
| Stötzer et al (2012) | All residential electricity | Modeled optimization of load profiles and RES integration for a representative German region with 500k habitants | 21 GW shiftable capacity from residential sector in Germany by 2020 |
| Nilsson et al (2017) | All residential electricity | RTP visualization, for a test group and a reference group of 12 households | 3.7 W h m⁻² average daily peak shift during the test period |
| Bartusch and Alvehag (2014) | All residential electricity | Time of use-tariff implemented on pilot scale | 229 kWh/yr at most, shifted per household |
| Bartusch and Alvehag (2014) | Appliances | Time of use-tariff implemented on pilot scale | 36.8 kWh/yr shifted per household |
| Liljeblad (2016)    | All residential electricity | Estimated potential of demand flexibility in Swedish households | 2000 MW of flexible load available during 3 h/day |
| Chrysopoulos et al (2016) | All residential electricity | Monetary demand response scheme implemented on 32 apartments in Luleå | 16% of peak shifted on average per day and apartment |
| Nyholm et al (2016) | Electric space heating | Modeled shifted electricity, assuming a scenario with high electricity prices | 1.46 TWh/yr for all Swedish SFDs |
| Crossley (2008)     | Space heating, hot water | Tempo tariff | 450 MW peak reduced for 350 000 residential customers and 100 000 SMEs |
| Nguyen et al (2010) | Electric space heating | Real-time peak-control system tested in one apartment | 1000 power reduction in one MFD |
| POST (2014)         | All residential electricity | Trials of time of use tariffs | 10%–14% of peak demand shifted for typical UK domestic demand profile |
| Bradley et al (2016) | All residential electricity | Financial payments to avoid peak electricity use and detailed energy feedback, | Average peak shifted per household during 6 weeks of trials in 10 SFD households |
| Drysdale et al (2015) | Cold appliances | Estimate, method unclear | 13 000 GWh/yr flexible demand from cold appliances |
| Drysdale et al (2015) | Wet appliances | Estimate, method unclear | 15 000 GWh/yr flexible demand from wet appliances |
| Drysdale et al (2015) | Electric space heating | Estimate, method unclear | 24 000 GWh/yr flexible demand from space heating |
Table A1. (Continued.)

| Reference                        | Load       | Flexibility measures and method                          | Identified flexibility potential |
|----------------------------------|------------|----------------------------------------------------------|----------------------------------|
| Lampaditou and Leach 2005        | Appliances | Simulation of direct control load (turning off appliances)| 3500 MW peak reduction per household |
| Sweetnam et al (2019)            | Heat pumps | Trial study including 31 households, smart control of heat pumps | 0.012 kWh evening peak reduction |
| Boait et al (2017)               | Electric space heating | Combination of DSR interface and ToU tariff, for a trial of six dwellings with thermal storage heating | 26 kWh peak shifted during February |
| Papadaskalopoulos and Strbac (2012) | Wet appliances | Price-based simulation | 7 GW of peak load shifted for 4 h during a typical winter season day in whole UK electricity system |
| Navarro et al (2012)             | Appliances | Price-based simulation | 70 kW total simulated peak demand reduction for 100 households |
| Qiao and Yang (2016)             | EV         | Simulation of EV charging strategy | 100 kW for 4 h shifted off peak in a local distribution network with 292 households with one EV each |
| Papadaskalopoulos and Strbac (2012) | EV         | Price-based simulation | 10 GW can be shifted by charging (a completely electrified UK fleet of light and medium vehicles) flexibly |
| Qia et al (2018)                 | All residential electricity | Market simulation, consumers react to price signals | 1500 MWh/day for 30% of the UK electricity market |
| Drysdale et al (2015)            | Water heating | Estimate of theoretical flexible demand in the shape of water heating | 7000 GWh/yr total flexible demand from water heating |

Table A2. Potential effects on CO₂ emissions (% of the total emissions of electricity in the residential sector of each country) from load shifting presented in table 5. C1, C2, and C3 are presented in table 3. Empty cells are those for which no values were found in the review.

| Load                                      | France | Germany | Sweden | UK    |
|-------------------------------------------|--------|---------|--------|-------|
|                                           | C1     | C2      | C3     | C1    | C2    | C3     | C1    | C2    | C3     |
| Electricity All                           | −3.0   | 0.6     | −2.8   | 0.0   | 0.5   | 2.3    | 2.5   | 4.5   | 1.5    |
| El—Appliances wet                         | −2.2   | 0.4     | −2.0   | 0.0   | 0.0   | 0.2    | 0.5   | 1.4   | 0.2    |
| El—Appliances                             | 5.9    | 7.8     | 6.0    | 0.0   | 0.0   | 0.2    | 0.5   | 1.4   | 0.2    |
| El—Direct heating                         | −0.6   | 0.1     | −0.5   | 0.0   | 0.0   | 0.2    | 0.5   | 1.4   | 0.2    |
| El storage heating                        | −2.7   | 0.6     | −2.5   | 0.0   | 0.0   | 0.2    | 0.5   | 1.4   | 0.2    |
| EV                                        | 3.3    | 8.5     | 1.1    |       |       |        |       |       |        |
| HP and PV                                 | 0.0    | 0.0     | 0.0    | 0.0   | 0.8   | 4.0    | 2.9   | 7.5   | 1.0    |
| Space heating—El                          | 0.2    | 4.0     | 4.9    | 0.0   | 0.8   | 4.0    | 2.9   | 7.5   | 1.0    |
| Space and water heating                   | 0.5    | 8.0     | 10.9   | 0.5   | 2.3   | 1.5    | 4.0   | 4.0   | 0.5    |
| Water heating                             | −1.8   | 0.4     | −1.7   | 0.5   | 2.3   | 1.5    | 4.0   | 4.0   | 0.5    |

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