No. B 2348
April 2019

# Solid state breakers as climate solutions

Érika Mata, Jonas Ottosson and Johanna Nilsson

**In cooperation with** Blixt Tech AB

**Author:** Érika Mata, Jonas Ottosson and Johanna Nilsson (IVL Swedish Environmental Research Institute)
**Funded by:** Click and add text
**Report number** B 2348
**ISBN** 978-91-7883-051-0
**Edition** Only available as PDF for individual printing


IVL Swedish Environmental Research Institute Ltd.
P.O Box 210 60, S-100 31 Stockholm, Sweden
Phone +46-(0)10-7886500 // www.ivl.se

This report has been reviewed and approved in accordance with IVL's audited and approved management system.

# Preface

This report describes the work performed by IVL Swedish Environmental Research Institute (IVL) and co-funded by Stiftelsen Institutet för Vatten-och Luftvårdsforskning (SIVL) and Blixt Tech AB under SIVL's project number 3B:01/19 and is publicly available. Blixt Tech AB is a company that develops solutions for smart electric grids, including solid state circuit breakers. Their technologies allow for a wider digitalization of the grid edge which can reduce end use consumption and optimize the interaction between energy demand and supply, with implications for various sectors (industry, tertiary, residential). Blixt Tech wanted to understand the implications of their technologies as climate solutions. IVL has mapped the potential energy savings and load flexibility that can be achieved using solid-state breakers on a large scale as well as identified the associated environmental impact (in terms of carbon dioxide emissions). The analysis is grounded in the scientific literature and has been performed by IVL experts in the fields of energy system modelling, energy efficiency, climate change mitigation and sustainable development.

As required by the chosen methodological approach, the project progress has been discussed at three occasions with a reference group over the duration of the work (January – April 2019). The group consisted of: Magnus Backman (ABB), Cathy Crunelle (Engie), Dioni Franken (Eneco), Johan Holmqvist (IVL), Fredrik Martinsson (Energiforsk), Michel Muurmans (Eneco), Ulrich Seitz (Baywa) and Sean Stephenson (Centrica); they are gratefully acknowledged for their contributions and comments.

This report targets a broad range of interested actors and provides limited and concise explanations of the work performed. For the academic community, the content of this report will be presented in a scientific article, now under preparation. The scientific article shall therefore be considered the most updated and accurate reference when referring to the results of this work.

Gothenburg, April 2019

Érika Mata
Project leader, IVL Swedish Environmental Research Institute

# Table of contents

# Summary

Increased flexibility at the grid edge is required to achieve ambitious climate goals and can be provided by smart energy solutions. Such solutions are expected to support the ongoing shift on the supply side towards more renewable generation (both on grid and distributed) and to offer consumers the opportunity to reduce costs by demand shifting. In combination with better information and automation to optimize energy use, grid edge solutions can take customers a step forward to become prosumers.

Using a systematic review of the scientific literature, an overview – for France, Germany, UK and Sweden – is provided of the potential flexibility of different residential electrical loads. The potentials obtained from the literature have been upscaled to the national level, including the corresponding effects in terms of carbon dioxide ($CO_2$) emissions. The results show that between 2% and 18% of the electricity from the residential sector in the four countries could be shifted, resulting in total emissions reductions of 10 $MtCO_2$ from peak shaving, or 24 $MtCO_2$ per year if the flexibility would optimize the deployment of renewables. Additional incentives are needed, and changes are required in energy price mechanisms and tariffs to make flexibility economically feasible on the market.

# Sammanfattning

Ökad flexibilitet i elnätets utkant är nödvändigt för att uppnå ambitiöst satta klimatmål, en sådan ökad flexibilitet kan fås genom smarta energilösningar. Dessa lösningar förväntas vara en del av det pågående skiftet inom energiförsörjning, med ett större fokus på förnybar energi, både centralt och distribuerat i näten. Även genom att konsumenter ges möjlighet att minska sina energikostnader genom att flytta sin elförbrukning i tiden, ge bättre information kring och lösningar för att automatisera sin energiförbrukning och kan ta steg mot att bli prosumenter.

Genom en systematisk genomgång av vetenskaplig litteratur ges– för länderna Frankrike, Tyskland, Storbritannien och Sverige – en överblick av den potentiella flexibilitet som finns hos olika el-laster i bostadssektorn. Potentialerna har hämtats från litteratur och skalats upp homogent för att spegla den nationella potentialen, inklusive effekten som den potentiella flexibiliteten har på koldioxidutsläpp. Våra resultat visar att i de fyra EU-länderna kan mellan 2% och 18% av elanvändningen i bostadssektorn flyttas i tiden, vilket skulle resultera i att utsläpp mellan 10 och 28 Mton $CO_2$ per år kan undvikas till förmån för att maximera användandet av förnybara energikällor. Med dagens prismekanismer och tariffer för energianvändning är flexibilitet av denna typ inte ekonomiskt hållbar och det krävs förändringar.

# Nomenclature

$CO_2$, Carbon Dioxide
DSR, Demand Side Response
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)

# 1. Background

The residential sector is responsible for 34% [32.4PWh, year 2010] of the energy use globally, and most of the greenhouse gas (GHG) emissions [2.0 Gt, year 2010] come from electricity use in buildings. In the EU-28, the residential sector accounts for 28% [3311 TWh, year 2016] of the final energy consumption, of which 24% [808.3 TWh, year 2016] stems from electricity use in residential buildings.

To keep global warming at the 1.5°C target a 9-Gt reduction in carbon dioxide ($CO_2$) emissions is required from the global building sector. High-income regions need to take the lead in this mitigation effort (Wang et al, 2018). The buildings sector contribution to achieving this ambitious climate target includes high rates of energy-efficient renovations of buildings, increased electrification and deployment of decentralized Renewable Energy Sources (RES) (Eom et al. 2012; Chaturvedi et al. 2014; Zhou et al. 2014).

One possible pathway for achieving large scale reductions of $CO_2$ emissions from electricity use in the residential sector is found in the concept of Demand Side Response (DSR) and load shifting, which can be facilitated with Smart Energy Solutions (SES). Such solutions are also expected to offer consumers the opportunity to reduce costs by demand shifting, providing better information and automation to optimize energy use, bringing them a step forward to become prosumers (Shivakumar et al. 2018). Shivakumar et al. (2018) provide – for France, Switzerland, Ireland, UK and Sweden – an overview of the status of smart metering followed by a discussion of the demand response potential and how the estimation of this potential can be improved. The study concludes that SES can contribute to balancing the supply and demand of energy and consequently help Europe achieve its emission reduction targets and promote an increased use of RES.

Although the interest of the environmental effects of DSR has increased lately (Gyamfi and Krumdieck, 2011) and some recent pilot projects have included analyses of environmental impact of load shift as a secondary aim (e.g. Nilsson et al., 2017), previous studies have primarily focused on savings in peak electricity demand and costs. In Europe and for all sectors, the potential for DSR has been estimated to be of 26% of reduction of annual peak load and 172 GW of power decrease (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 their 'moderate' scenario) are provided by Capgemini et al (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 10- 20% reductions in peak power loads (Stötzer et al, 2015). In the UK (all sectors), a study that examines pathways for a green electricity system by 2050, finds that demand side measures, such as shifting demand a few hours, can reduce peak net demand by 10 GW (decrease by 13-25%) in three different scenarios (The Economist, 2014). More recently, another study focusing on the UK points out that the potential for load shifting depends on the time of day and time of year but states that 15-27 GW of all electricity loads (in all sectors) is available for short-term load shifting during evening hours (Aryandoust & Lilliestam, 2017).

The potential for DSR in residential electricity consumption has been evaluated in numerous studies, with focus on the impact of dynamic price tariffs and varying results (Nilsson et al., 2017). in Europe and U.S., a compilation of results from different real-time feedback studies identifies an average energy saving of 5–15% (Darby, 2006). Within Scandinavia, different demand response programs also show a wide variation in their results. For instance, in Norway, a pilot project including a distribution tariff of varying energy rates and demand charges showed a 5% reduction in demand during peak hours (Stokke et al., 2010). However, in Sweden, Zimmermann (2009) suggests that flexible load represents about 10% of the total electricity consumption. Whereas Bartusch and Alvehag (2014), including time-of-use-based electricity distribution tariffs, suggest a more modest result of 0–1% reductions in demand 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 & 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, including deployment of solid-state circuit breakers, affect the energy consumption and $CO_2$ emissions in the residential building sector in France, Germany, Sweden and the UK?*

# 2. Method

We have performed a literature review of previous assessments of the potential demand response in the four countries (Sweden, France, Germany and the UK). The main stages of the project are:

1. Literature search
2. Appraisal
3. Analysis and data extraction
4. Upscaling

Both scientific publications and grey literature are included. The resulting articles from the search have been appraised through a screening process to select the appropriate articles for inclusion. The selected articles have been analysed in depth and data on the amount of energy shifted or saved using different DSR measures has been extracted and summarized. Finally, the extracted data was upscaled to represent the total potential within each studied country. Each of the methodological steps is described in detail in upcoming sections.

The above-mentioned methodological steps follow a semi-systematic review methodology, which we have documented using the so-called ROSES support tools (Haddaway et al. 2017) that are 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 CEE guidelines (CEE 2018) in that we have conducted the search query in only one database (Scopus). We have set up a reference group, which has contributed to the method as described further down. The reference group contains a well-balanced combination of stakeholders with different interests and perspectives.

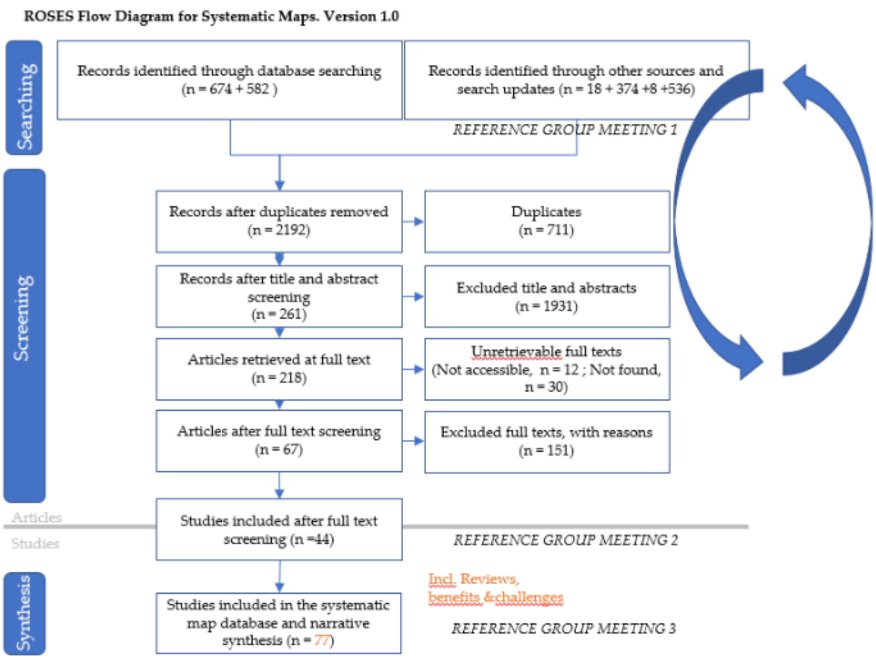


**Figure 1 Schematic summary of the method; n, amount of studies included in the different steps. Adapted from (Haddaway et al. 2017).**

Figure 1 schematically summarizes the method used, using the ROSES flow diagram to present the amount of references assessed in the different methodological stages. A detailed description of the overall stages of the project is presented in the following sections.

## 2.1. Search

We have identified key elements of our research question using a PICO approach. In environmental evidence, the most common question to answer is what type of impact a certain intervention or exposure has on the environment and generally four key elements need to be specified: which is the population (P) that is affected, 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: Flexibility measures and demand side response/management measures
- Comparator: Savings or changes compared to 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. Query 1 reflects aspects of grid edge digitalization which can be achieved by the implementation of 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 behaviour, digital communication interface, and current limit. Query 2 aims to capture all issues around the deployment of solid-state circuit breakers in the residential sector and includes all specific mentions to solid-state circuit breakers in relation to energy savings and mitigation potentials in the building sector. The searches have been conducted in English and encompass the four stated nations.

The search has been performed in the scientific database Scopus. The reference group has provided specific literature tips (26 studies) as well as suggestions on how to improve the search queries by using synonyms and additional terms to capture the targeted aspects of each query. The resulting amount of search results from Scopus is summarized in Table 1.

**Table 1 Summary of studies compiled from Scopus, by search query and stage of the process.**

| Query | Focus | Initial results in Scopus | Additional results in Scopus for the updated query | Total amount of documents from Scopus considered |
|---|---|---|---|---|
| 1 | Digitalization of grid edge | 674 | 374 | 1 048 |
| 2 | Solid-state circuit breakers | 582 | 536 | 1 118 |

# 2.2. Appraisal

The search results from Scopus (2166 studies) and the literature tips from the reference group (26 studies) have been imported for screening to the APSIS tool (MCC 2018). Criteria for inclusion and exclusion have been developed based on the PICO framework described earlier. The inclusion criteria are: relevant population (residential buildings), intervention (flexibility measure), comparator (reference or baseline clearly stated) and outcome (effects in energy demand or carbon emissions). Rejection criteria include: geographical scope other than the four countries investigated; not referring to end-use (e.g. to transmission networks), not referring to the residential sector, not referring to a flexibility measure along with wrong scientific field. Articles published prior to 2005 are not included. The number of excluded articles and reasons for exclusion at each stage have been documented.

Every title and abstract were screened by the project members and is either rejected or accepted for inclusion in the study based on a defined rejection/inclusion criterion. The rejection criterion should reflect the research question and put simply, decides if an article is deemed relevant for the research or not. For example, some of the search terms give results irrelevant to our search: the term "consumption" leads to studies focusing on food, the term "building" leads to studies focusing on building materials and the term "optimization" leads to studies focusing on all types of algorithms, many times related to indoor air quality, thermal comfort. At the same time, the defined geographical scope includes the author´s affiliation, and returns studies performed e.g. by French authors that however do not study French buildings.

A total of 261 documents have been selected for inclusion, of which 218 full texts could be retrieved (12 documents were not accessible and 30 were not found). The articles that were included based on abstract and title are retrieved in full text format, when possible. Reasons that articles are not accessible include, for example, that they are published in databases that the project group does not subscribe to. In other cases, the full text article is simply not published.

# 2.3. Analysis

We have developed additional criteria for inclusion and exclusion for the screening at full text level, along with a data extraction questionnaire. Inclusion criteria at this point are: clear quantification of an impact in terms of energy or emissions, clear population studied. We have excluded works which do not describe methods as well as review articles that cite other pieces of work without providing an appropriate context.

A total of 27 documents fulfill the inclusion criteria. The number of excluded articles and reasons for exclusion at each stage have been documented. For the selected documents, data has been extracted including:

- Quantified energy saving, flexibility or mitigation potential
- Geographical scope
- Stock unit/population for upscaling: Subsector (Single-Family Dwelling [SFD], Multifamily Dwelling [MFD]) or household type; end-use (electricity, space heating, hot water); load (lighting, appliances, photovoltaic panel [PV], electrical vehicle [EV]; see full list of loads in Figure 4)

- Type of flexibility measure studied
- Approach used (model, pilot, etc.)
- Other findings: benefits, challenges, trade-offs, costs (qualitative), effects in grid development and investments

The data-extraction matrix is documented and stored. The review articles not fulfilling the inclusion criteria (Shivakumar et al., 2018; Gyamfi & Krumdieck, 2011; Aryandoust & Lilistam, 2017; Gils, 2014; Capgemini, 2008; Darby, 2006; Stokke et al., 2010; Zimmerman, 2009), are presented in the Background section of this report, since they for example give overviews of the demand side management potential for an entire country but not specifically for the residential sector.

## 2.4. Upscaling

The selected studies and articles present data at varying levels of detail and for different types of electrical loads within the residential sector. One study could for example 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, the data on energy saving, flexibility and mitigation potentials has been upscaled to represent the entire country where needed. If the studies do 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 have been calculated.

### 2.4.1. Energy demand

The quantified energy saving, flexibility of mitigation potential, obtained from the studies has been upscaled based on stock description data (with the “stock” units being: subsector, typology, end-use, load) of the residential sector of the four countries investigated. An example of the upscaling process is given here, explaining how data from one article is analyzed and processed to represent the full potential for energy saving or load shifting in the residential sector of one country.

In this exemplary a pilot study (Belitz et al, 2013), 700 customers households in Germany were provided with smart meters, access to an online energy marketplace and automated household appliances. Several dynamic pricing tariffs with the aim of shifting loads from high demand hours to low demand hours were put in place and the electricity use patterns in the households were measured before and after the dynamic pricing tariff was in effect. The study found that, on average with one tariff structure, around 0.625 kWh of electricity was shifted per household and day from peak hours. To upscale this potential, it is assumed that the same amount of electricity can be shifted daily around the year in every SFD in Germany. The average heated area (HFA) of a SFD and the total HFA of all SFDs in Germany is taken from Mata et al. (2013a). From these assumptions and according to Equation 1 below, where $E$ denotes energy, it is estimated that the load shifting potential of electrical appliances in all German SFDs is 2.88 TWh/yr.

$$E_{shifted,Germany,SFD,year} = E_{shifted,household,day} * days\ per\ year * \frac{HFA\ per\ SFD}{Total\ HFA\ of\ all\ SFDs}$$

Data on fuel type, end use and floor areas are typically not available in national and international statistics (e.g. Eurostat, Odyssee, Building Stock Observatory) by building typology (SFD, MFD) and end use (space heating, hot water and electrical uses). Therefore, we have 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, the energy use per fuel type, end use and building typology as well as the HFAs and amount of buildings per typology have been obtained from Mata et al, (2013b, 2014). The $CO_2$ emissions of households, total $CO_2$ emissions of households (including electricity), and residential electricity consumption have been obtained from Odyssee database.

## 2.4.2. Associated emissions

To make an estimation of the effects in the carbon emissions from saved or shifted electrical load in each country, data on the electricity production mix for each country is needed. Marginal carbon intensity of electricity [$CIel_{marginal}$] production is associated with peak demand hours whereas average carbon intensity [$CIel_{average}$] reflect non-peak hours. The potential for reducing carbon emissions through shifting electric loads from peak hours to non-peak hours is estimated according to Equation 2 below.

$$CO2_{reduction,year} = E_{shifted,country,load,year} * \left(CIel_{marginal} - CIel_{average}\right)$$

Carbon intensities of electricity production have been compiled from the literature (Table 2). The compiled values, illustrated in Table 3, vary substantially depending on the fuel mix considered for electricity production as well as on the year for which the estimate is made. As for the marginal emissions, these additionally depend on the time resolution of the additional unit production, e.g. hourly or yearly. It can be noted, that several sources give for France and Germany marginal carbon intensities that are higher than the average carbon intensities, as in both countries the marginal hourly units are on average produced by hydropower to a large extent (ElectricityMap 2019; Tranberg et al, 2019).

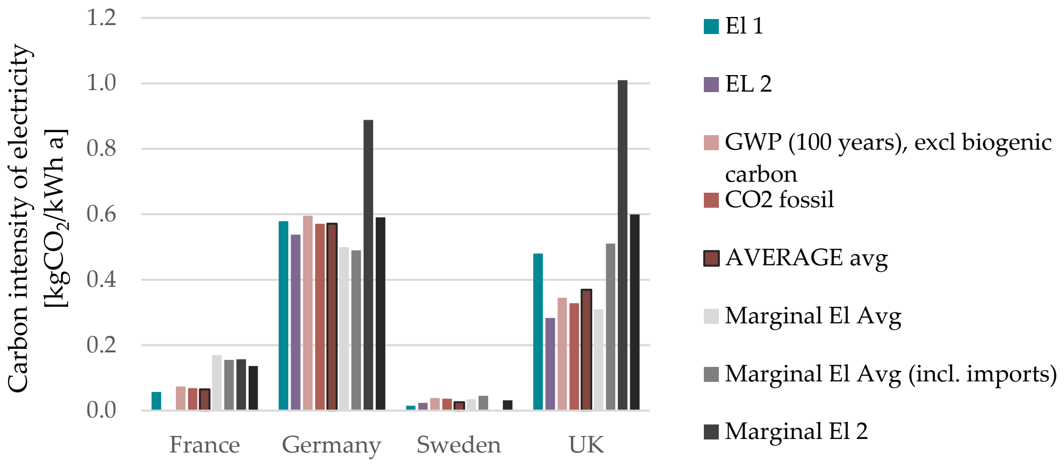


**Figure 3 Comparative illustration of varios estimates of average and marginal carbon intensities of electricity. Sources: see Table 2.**

**Table 2 Description of the 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 el al, 2018 |
| El 2 | Average carbon intensity from different sources and years | Germany: SKV, 2014; for Sweden 2013: Nilsson et al, 2017; for UK unknown year: DEFRA. |
| GWP | Global warming potential (100 years), excl biogenic carbon, for the annual fuel mix for electricity production in each country, derived for this report | IEA 2019, Thinksep2018 |
| CO2 fossil | Carbon intensity for the annual fuel mix for electricity production in each country, derived for this report | IEA 2019; Thinksep2018 |
| 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 | ElectricityMap 2019; IPCC, 2014 |
| Marginal El Avg (incl. imports) | Hourly marginal carbon intensity of electricity (including imports), average over 2 years | ElectricityMap 2019; IPCC, 2014 |
| 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; Thinksep2018 |
| Marginal El 2 | Marginal carbon intensity of electricity from different sources and years | From personal communications |
| AVERAGE Maginal | Average of all estimates above | |

Given the varying estimates of carbon intensity of electricity, we use three different combinations of carbon intensity of electricity production, as a form of sensitivity analysis in this project. The different scenarios are made up of combinations of emission data in Table 2 and are presented in Table 3 below.

**Table 3 Three different carbon intensity scenarios used. See full abbreviations and corresponding full descriptions in Table 2.**

| Combination | Average carbon intensity of electricity | Marginal carbon intensity of electricity |
|---|---|---|
| C1 | El 1 | Marginal El 1 Avg |
| C2 | AVERAGE avg | AVERAGE Marginal |
| C3 | El 1 | Marginal El Avg (incl. imports) |

# 3. Results

## 3.1. Load flexibility

Load shifting is the practice of moving loads in time for various reasons (grid congestion, consumer cost optimization, production optimization) and takes place during peak hours. 85% of the studies [23 in total: two for France (Crossley, 2008; Nguyen et al., 2010), five for Germany (Belitz et al., 2013; Bradley et al., 2016, Aryandoust and Lilliestam, 2017; Klobasa, 2008; Stötzer et al.; 2012), five for Sweden (Nilsson et al., 2017; Bartusch and Alvehag, 2014; IVA, 2016; Chrysopoulos et al., 2016; Nyholm et al., 2016) and eleven for the UK (POST, 2014; Bradley et al., 2016; Drysdale et al., 2015; Lampaditou and Leach, 2005; Sweetnam et al., 2019; Boait et al., 2017; Papadaskalopoulos and Strbac, 2012; Navarro et al., 2012; Qiao and Yang, 2016; Qiu et al., 2018; Drysdale et al., 2015) had the aim to identify potentials for shifting electrical energy use in time, thereby decreasing peak electricity demand. Most of the data has been found for the German and British electrical systems. This does not mean that there is a larger potential for load flexibility in Germany and the UK than in Sweden or France, only that our search method has returned fewer studies on the subject in for Sweden and France. It has been a condition for inclusion that the geographical scope of the work is clearly stated in the title or abstract, we may have therefore missed other studies that address one of the four investigated countries in the full text.

The studies address 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, electric vehicle charging algorithms, consumers' feedback) as well as methods (e.g. simulations, trials, 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 4 presents a summary of obtained flexibility potentials expressed as a percentage of the total corresponding load for each country, upscaled at country level. Wet appliances include dishwashers, washing machines and tumble dryers, whereas all appliances additionally refrigerators, freezers and cooking appliances. When several sources provide an estimate in a particular category, the average of the estimates is shown in the table. For instance, the figure presents that 11.7% of the load for wet appliances in the UK could be shifted. This estimate is an average of the based on 13.9% provided by Drysdale et al. (2015) and the 9.5% provided by Papadaskalopoulos and Strbac, (2012).

The potential flexibility for the total electricity load varies greatly among the countries investigated, with the largest potential found in Germany [17.7% as average of the estimates by Klobasa (2009) and Sötzer et al. (2012)] and the lowest potentials found in Sweden [1.9% as average of the estimates by Nilsson et al. (2017), Bartusch and Alvehag (2014), Chrysopoulos et al. (2016) and IVA (2016)].

For Germany, Klobasa (2009) have simulated power plant operation and balancing capacity activation and conclude that 29.4% of the electricity load could be shifted residential sector in 2008, corresponding to 37.9 TWh/yr of which 26.6 TWh/yr are for cooling and electrical heating and 11.3TWh/yr for households without electrical heating. More recently, Sötzer et al. (2012) have modelled optimization of load profiles and RES integration for a representative German region with 500k habitants and found a more modest potential of 6% of the electrical load from residential sector in Germany by 2020, corresponding to 21 GW shiftable capacity.

For Sweden, different types of price mechanisms including Real Time Price (RTP) visualization (Nilsson et al, 2017), 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) find 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 that real-time spot price visualization contributes to a reduction in overall household electricity consumption level could be found. The result of the load shift by households was a decrease in annual electricity costs of 1%, while the $CO_2$eq emissions increased approximately 3%. Estimates compiled by IVA (2016) are somewhat higher, amounting to 6% of the electrical domestic load. The flexibility in households comes mainly from heating and is very dependent on outdoor temperature and the variations in indoor temperature allowed. During summer, there may be no heating demand and therefore the energy use for heating cannot be decreased.

| **LOAD CATEGORY** | **FLEXIBILITY POTENTIAL** | | | |
|---|---|---|---|---|
| Load | France | Germany | Sweden | UK |
| Electricity all | – | 17.7% | 1.9% | 8.9% |
| Electricity: Appliances wet | – | 12.8% | – | 11.7% |
| Electricity: Appliances | – | 13.2% | 0.2% | 2.2% |
| Electricity: Direct heating | – | 3.5% | – | – |
| Electricity: Storage heating | – | 16.2% | – | – |
| Electric vehicles | – | – | – | 13.7% |
| Heat pumps | – | 0.0% | – | 0.6% |
| Space heating: Electricity | 3.2% | – | 3.4% | 12.1% |
| Space and water heating | 7.2% | – | – | – |
| Water heating | – | 11.0% | – | 6.5% |

**Figure 4 Summary of obtained flexibility potentials (share of the load that can be shifted) by type of load, upscaled at country level. Sources: See Table A1.**

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

See Table A1 in the Appendix for more details on the sources on which Figure 4 is based.

# 3.2. Energy savings

Energy savings are overall energy use reductions that take place during any hour of the day, not only during peak hours. These potential energy savings, presented in different units, are summarized in Table 5.

**Table 5 Summary of energy saving potentials found in the literature, including sources.**

| REF | Load | Country | Energy savings | | | |
|---|---|---|---|---|---|---|
| | | | TWh/yr | kWh/m² HFA | % of total residential energy consumption | % of total residential el-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) | El-Appliances | GE | 38.4 | 11.7 | 5.6% | 29.8% |
| (Keirstad, 2006) | Electricity All | UK | 2.6 | 4.2 | 0.5% | 2.4% |

Only 15% of the studies [4 in total] had the aim to identify potentials for energy saving. Most of the studies focus on Germany and implement different measures and methods. Simulation studies estimate higher potential savings; for instance, Alzate et al., (2015) have modelled the implementation of a home energy management system and find that 38 TWh of electricity from appliances can be saved annually in Germany. If all heating sources are included, 50 TWh/yr could be saved according to Nägele et al., (2017), who simulated the implementation of a state of the art, connected heating control system in MFDs in Germany. Nevertheless, a pilot study in which German households were equipped with smart home systems to control heating systems combined with programmable routines to automatically adjust the settings of the heating systems, indicates a more limited potential saving of around 9 TWh/yr in total in Germany (Rehm et al., 2018). The only study on the UK found that energy monitoring services to consumers, if scaled to a national level, could save up to 2.6 TWh/yr (Keirstad, 2006).

# 3.3. Mitigation potentials

## 3.3.1. Peak shaving

Table 6 presents the potential $CO_2$ emissions reductions from load shifting, calculated for the three carbon intensity scenarios presented in Table 3 following Eq.1. These are given for the different loads and countries. The annual potential carbon emission reductions range from close to zero in Sweden, where the electricity is already low emissive, to almost 6 $MtCO_2$/yr in Germany. A total of roughly 10 $MtCO_2$ / yr can be avoided through load shifting in France, Germany, Sweden and the UK.

**Table 6 Potential effects in $CO_2$ emissions [$MtCO_2$/yr] from the load shifting presented in Figure 4, per load and country. C1, C2, C3 are the scenarios of carbon intensity of electricity presented in Table 3. Empty cells are those for which no values have been found in the literature.**

| Load | France | | | Germany | | | Sweden | | | UK | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C1 | C2 | C3 | C1 | C2 | C3 | C1 | C2 | C3 | C1 | C2 | C3 |
| Electricity All | | | | -2.19 | 0.44 | -2.03 | 0.0003 | 0.0051 | 0.025 | 0.99 | 1.80 | 0.61 |
| El - Appliances wet | | | | -1.58 | 0.32 | -1.47 | | | | 1.11 | 2.90 | 0.38 |
| El- Appliances | | | | 4.33 | 5.72 | 4.42 | 0.0000 | 0.0005 | 0.003 | 0.21 | 0.54 | 0.07 |
| El -Direct heating | | | | -0.43 | 0.09 | -0.40 | | | | | | |
| EL. storage heating | | | | -2.01 | 0.41 | -1.86 | | | | | | |
| EV | | | | | | | | | | 1.30 | 3.40 | 0.44 |
| Heat pumps | | | | 0.00 | 0.00 | 0.00 | | | | 0.05 | 0.14 | 0.02 |
| Space heating - El | 0.02 | 0.33 | 0.45 | | | | 0.0004 | 0.01 | 0.04 | 1.15 | 3.00 | 0.39 |
| Space and water heating | 0.05 | 0.73 | 1.01 | | | | | | | | | |
| Water heating | | | | -1.35 | 0.27 | -1.25 | | | | 0.62 | 1.61 | 0.21 |

The effect of assumptions regarding carbon intensity in electricity production becomes evident here, as some of the resulting carbon emission reductions under C1 and C3 are negative, indicating increased emissions from load shifting. This is because the marginal carbon intensity is lower than the marginal in those scenarios, due to the use of hydropower to produce marginal units (Figure 3).

Our negative reduction results agree with the literature summarized in Nilsson et al, (2017). Whereas the 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 off peak hours (presented in Section 3.1) may give both reduced or increased carbon emissions as the carbon intensity of the electricity production varies over time. The possible carbon emissions increase from load shift is addressed by Stoll et al. (2013), which analyze the correlation between hourly dynamic price and hourly dynamic emissions for three different energy markets and find that the impact of load shift is strongly connected to the intraday variations in the electricity grid mix. In addition, Song et al. (2014) have simulated household consumption behavior under price and $CO_2$ emission signals in Sweden and found that carbon emissions may increase by roughly 3%, depending on the amount of load shift.

Figure 5 illustrates the carbon emission reductions for various residential electrical loads in the studied references, given as a share of the total annual emissions from residential electricity; these are the maximal mitigation potentials which arise from scenario C2. The total annual emissions are calculated by 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.

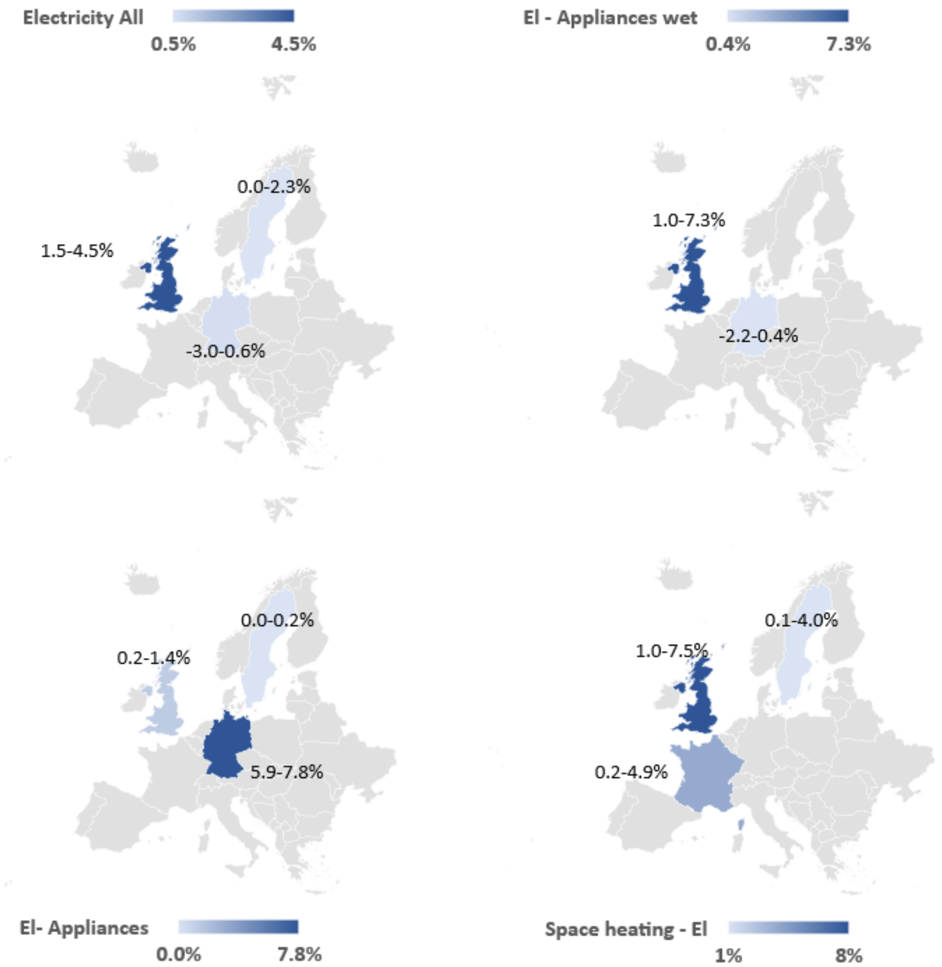


**Figure 5 Maximum carbon emission reductions [share of total emissions of electricity in the residential sector that could be avoided, scenario C2] for various residential electrical loads in the studied references.**

# 3.3.2. Deployment of renewables

The potential carbon emission reductions presented in Section 3.3.1 assume that peak loads are shifted from hours with marginal electricity production to hours with average electricity production. But what if the loads were shifted to maximize the use of renewable energy sources?

The growing renewable energy sector induces the challenge of highly fluctuating and unpredictable renewable energy generation (e. g. from PV and wind). Due to the current inflexibility of electricity demand, it is not always possible to match the renewable energy generation with the 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. & Staffell, 2015). Residential and commercial buildings can provide flexibility to counter these imbalances between supply and demand in the electrical grid (Wolisz et al., 2016; Le Dréau & Heiselberg, 2016). In PV-dominated regions, DSR and load shifting partially substitutes short-term energy storage when the PV generation is at its peak, allowing for even more renewable energy penetration that is not wind-related (Aryandoust & Lilliestam, 2017). Therefore, here we assume that all loads are shifted from peak hours to hours where there is enough renewable electricity to cover the electricity demand.

Table 8 presents the potential carbon emission reductions in the residential electricity use under these assumptions. By assuming that the renewable electricity is carbon neutral, the maximal carbon emission reductions in the table are obtained by multiplying the load shifted by the marginal carbon intensity of electricity, whereas the minimal reductions assume that loads are shifted from average carbon intensity of electricity production instead. The real potentials likely lie somewhere in between the minimum and maximum values presented.

**Table 8 $CO_2$ emissions reduction potential [% of the total emissions of electricity in the residential sector of each country] from the load shifting presented in Figure 4. Empty cells are those for which no values have been 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% | | 10.5% | 6.5% |

Our results indicate that carbon emissions from electricity in the residential sector could be reduced between 2.0% [in Sweden, corresponding to 0.05 $MtCO_2$/yr as the Swedish energy system is already low emissive] to 18.3% [in Germany, corresponding to 13.5 $MtCO_2$/yr] depending on the country. These mitigation potentials add up to a maximum of 23.8 $MtCO_2$/yr for the four countries together.

The implementation of this potential depends on technical and energy political boundary conditions. For instance, technical challenges may arise from managing the energy demand of buildings (space and water heating), requiring higher automation of electricity driven heating systems (e. g. heat pumps, direct electric heating) to effectively utilize energy flexibility offered by buildings (Wolisz et al., 2016; IVA, 2016). Higher acceptance of variations of indoor temperatures (IVA, 2016) is also required.

# 4. Conclusions

The residential sector is responsible for 34% of the energy use globally, and most of the GHG emissions come from electricity use in buildings. In the EU-28, the residential sector accounts for 28% of the final energy consumption, of which 24% corresponds to electricity use in residential buildings. A wider digitalization of the grid edge is expected to optimize the interaction of demand and supply, and to provide economic and environmental benefits such as reduced energy and peak demands, and integration of a higher share of renewable energy.

We have performed a literature review on the flexibility of residential electricity demand to be achieved from a digitalization of the grid edge in four European countries, namely France, Germany, Sweden and UK. 85% of the reviewed studies had the aim to identify potentials for shifting electrical energy use in time, thereby decreasing peak electricity demand. Most of the data has been found for the German and British electrical systems. The potential flexibility for the total residential electricity load varies greatly among the countries investigated, with the largest potential found in Germany (6-29%) and the lowest potential found in Sweden (1-5%). Only 15% of the studies had the aim to identify potentials for energy saving. Most of the studies focus on Germany and, using different measures and methods, identify potential reductions of residential electricity demand between 1% and 6%. The only study on the UK identifies a 0.5% potential reduction of residential electricity demand from implementing energy monitoring services in domestic consumers.

This flexibility could reduce carbon emissions from electricity in the residential sector by up to 8.5% (in the UK). The potential varies between 1% and 8.5% for the countries investigated, due the differences among the national energy systems, and adds to a total of 10 $MtCO_2$/yr. The largest absolute potentials are found in countries with higher carbon intensity of electricity production such as Germany and the UK, whereas in Sweden the absolute mitigation potentials are lower due to the low carbon intensity of electricity production. If the loads were shifted to maximize the use of renewables, carbon emissions from residential electricity could be reduced by up to 22% (in the UK, ranging from 4% to 22% for the countries investigated), and would add up to a total of 24$MtCO_2$/yr in the four EU countries investigated.

To make flexibility economically feasible on the market, would require higher automation, additional incitement as well as changes in energy price mechanisms and tariffs.

# Appendix

**Table A1a Germany: Summary of the flexibility potentials obtained in the literature for Germany, 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 | Modelled 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 | Modelled load shifted short term (max 30min) | 16.5 TWh/yr |
| Aryandoust and Lilliestam (2017) | Big appliances | Modelled load shifted short term (max 30min) | 44.7 TWh/yr |
| Aryandoust and Lilliestam (2017) | Water heating | Modelled load shifted short term (max 30min) | 14.1 TWh/yr |
| Aryandoust and Lilliestam (2017) | El. direct heating | Modelled load shifted short term (max 30min) | 4.5 TWh/yr |
| Aryandoust and Lilliestam (2017) | EL. storage heating | Modelled load shifted short term (max 30min) | 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 | Modelled 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 |

**Table A1b Sweden: Summary of the flexibility potentials obtained in the literature for Sweden, by type of load, flexibility measure and methodological approach.**

| Reference | Load | Flexibility measures and method | Flexibility potential [units as in the reference] |
|---|---|---|---|
| Nilsson et al. (2017) | All residential electricity | RTP visualization, for a test group and a reference group of 12 households | 3.7 W h/m² 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 |
| IVA (2016) | All residential electricity | Estimated potential of demand flexibility in Swedish households | 2000MW 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 | Modelled shifted electricity, assuming a scenario with high electricity prices | 1.46 TWh/yr for all Swedish SFDs |

**Table A1c France: Summary of the flexibility potentials obtained in the literature for France, by type of load, flexibility measure and methodological approach.**

| Reference | Load | Flexibility measures and method | Identified flexibility potential [units as in the reference] |
|---|---|---|---|
| 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 |

**Table A1d 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] |
|---|---|---|---|
| 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 | 13000 GWh/yr flexible demand from cold appliances |
| Drysdale et al. (2015) | Wet appliances | Estimate, method unclear | 15000 GWh/yr flexible demand from wet appliances |
| Drysdale et al. (2015) | Electric space heating | Estimate, method unclear | 24000 GWh/yr flexible demand from space heating |
| 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 hours 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 hours shifted off peak in a local distribution network with 292 households with one EV each |
| Papadaskalopoulos and Strbac (2012) | EV | Price based simulation | 10GW can be shifted by charging (a completely electrified UK fleet of light and medium vehicles) flexibly |
| Qiu 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 in $CO_2$ emissions [% of the total emissions of electricity in the residential sector of each country] from the load shifting presented in Table 6. C1, C2, C3 are presented in Table 3. Empty cells are those for which no values have been found in the review.**

| **Table text heading** | **France** | | | **Germany** | | | **Sweden** | | | **UK** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C1 | C2 | C3 | 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 | | | | 2.8 | 7.3 | 1.0 |
| 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 | | | | | | |
| EL. storage heating | | | | -2.7 | 0.6 | -2.5 | | | | | | |
| EV | | | | | | | | | | 3.3 | 8.5 | 1.1 |
| HP and PV | | | | 0.0 | 0.0 | 0.0 | | | | 0.1 | 0.3 | 0.0 |
| 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 | | | | | | | | | |
| Water heating | | | | -1.8 | 0.4 | -1.7 | | 0.5 | 2.3 | 1.5 | 4.0 | 0.5 |

# References

Alzate, E. B., Mallick, N. H. & Xie, J. 2015, A high-resolution smart home power demand model and future impact on load profile in Germany. In 2014 IEEE International Conference on Power and Energy (PECON) (pp. 53-58). IEEE.

Aryandoust, A. & Lilliestam, J. 2017, The potential and usefulness of demand response to provide electricity system services. Applied Energy, 204, 749-766.

Bartusch, C. & Alvehag, K. 2014, Further exploring the potential of residential demand response programs in electricity distribution. Applied Energy, 125, 39-59.

Belitz, H-J., Winter, S., Rehtanz, C. 2013, Load Shifting of The Households in the E-energy Project E-DeMa. In 2013 IEEE Grenoble Conference (pp. 1-6). IEEE.

Boait, P. J., Snape, J. R., Darby S. J., Hamilton, J. & Morris, R. J. R. 2017, Making legacy thermal storage heating fit for the smart grid. Energy and Buildings, 138, 630-640.

Boßmann, T. & Staffell, I. 2015, The shape of future electricity demand: Exploring load curves in 2050s Germany and Britain, Energy, Volume 90, October 2015, Pages 1317-1333,

Bradley, P., Coke, A. & Leach, M. 2016, Financial incentive approaches for reducing peak electricity demand, experience from pilot trials with a UK energy provider. Energy Policy, 98, 108-120.

Capgemini, 2008, Demand response: A decisive breakthrough for Europe.

CEE 2018 Guidelines and Standards for Evidence synthesis in Environmental Management Available at Link 181105

Chaturvedi V, Eom J, Clarke LE, Shukla PR, 2014. Long term building energy demand for India: disaggregating end use energy services in an integrated assessment modeling framework. Energy Policy; 64: 226–242.

Chrysopoulos, A., Diou, C., Symeonidis, A. L. & Mitkas, P. A. 2016, Response modeling of small-scale energy consumers for effective demand response applications. Electric Power Systems Research, 132, 78-93.

Crossley, D. 2008, Worldwide Survey of Network-driven Demand-side Management Projects. Task XV of the International Energy Agency Demand Side Management Programme, second edition. Energy Futures Australia Pty Ltd.

Darby, S. 2006, The Effectiveness of Feedback on Energy Consumption. A Review for DEFRA of the Literature on Metering, Billing, and Direct Displays. Environmental Change Institute, Oxford, UK.

Drysdale, B., Wu, J. & Jenkins, N. 2015, Flexible demand in the GB domestic electricity sector in 2030. Applied Energy, 139, 281-290.

ElectricityMap 2019, figures available on-line: https://medium.com/electricitymap/using-machine-learning-to-estimate-the-hourly-marginal-carbon-intensity-of-electricity-49eade43b421 and background data available on-line: https://github.com/tmrowco/electricitymap-contrib [Accessed 2019-03-27]

Eom J, Clarke L, Kim SH, Kyle P, Patel P., 2012, China's building energy demand: long-term implications from a detailed assessment. Energy 46(1): 405–419

Federal Ministry for Economic Affairs and Energy, 2016, Energy-data-and-forecasts, 01.01.2016. Available at: http://www.bmwi.de/EN/Topics/Energy/Energy-data-and-forecasts/energydata.html.

Fischer, D. et al. 2016, Modelling the Effects of Variable Tariffs on Domestic Electric Load Profiles by Use of Occupant Behavior Submodels. IEEE Transactions on Smart Grid, 8(6), (pp. 2685-2693). IEEE.

Gils, H. C. 2014, Assessment of the theoretical demand response potential in Europe. Energy, 67, 1-18.

Gyamfi, S. & Krumdieck, S. 2011, Price, environment and security: Exploring multi-modal motivation in voluntary residential peak demand response. Energy Policy, 39(5), 2993-3004.

Haddaway, N R., et al. 2017 ROSES for Systematic Review Protocols Version 1.0 [free on-line]. Available at Link 181105

IEA 2019, (International Energy agency Statistics, Statistics data browser, 2019)

IPCC, 2014; "IPCC Working Group III – Mitigation of Climate Change, Annex II Metrics and Methodology - Table A.III.2 (Emissions of selected electricity supply technologies (gCO 2eq/kWh))". pp. 14–31.

IVA 2016, Framtidens elanvändning En delrapport, IVA-projektet Vägval el. Kungl. Ingenjörsvetenskapsakademien (IVA)

James, K L., et al. 2016 A methodology for systematic mapping in environmental sciences Env. Evid., 5.1

Keirstad, J. 2007, Behavioural responses to photovoltaic systems in the UK domestic sector. PhD thesis, Environmental Change Institute University of Oxford.

Klobasa, M. 2008, Analysis of demand response and wind integration in Germany's electricity market. IET renewable power generation, 4(1), 55-63.

Lampaditou, E. and M. Leach 2005, Evaluating Participation of Residential Customers in Demand Response Programs in the UK. ECEEE 2005 Summer Study, France.

Le Dréau, J. & Heiselberg, P. 2016 Energy flexibility of residential buildings using short term heat storage in the thermal mass, Energy, 111, 991-1002,

Mata É, Sasic Kalagasidis A and Johnsson F, A Modelling Strategy for Energy, Carbon, and Cost Assessments of Building Stocks, Energy and Buildings (2013a) 56: 108 –116.

Mata É, Sasic Kalagasidis A and Johnsson F, Contributions of Building Retrofitting in Five Member States to EU Targets for Energy Savings, Renewable and Sustainable Energy Reviews (2018) 93: 759-774.

Mata, Érika, A. Sasic Kalagasidis, and Filip Johnsson. "Building-stock aggregation through archetype buildings: France, Germany, Spain and the UK." Building and Environment 81 (2014): 270-282.

Mata, Érika, Angela Sasic Kalagasidis, and Filip Johnsson. "Energy usage and technical potential for energy saving measures in the Swedish residential building stock." Energy Policy 55 (2013b): 404-414.

MCC 2018 APSIS tool [free on-line]

Nägele, F., Kasper, T., Girod, B. 2017 Turning up the heat on obsolete thermostats: A simulation-based comparison of intelligent control approaches for residential heating systems. Renewable and Sustainable Energy Reviews, 75, 1254-1268.

Navarro, A., Ochoa, L. F. & Mancarella, P. 2012, Learning from residential load data: Impacts on LV network planning and operation. In 2012 Sixth IEEE/PES Transmission and Distribution: Latin America Conference and Exposition (T&D-LA) (pp. 1-8). IEEE.

Nguyen, N-H., Tran, Q-T., Leger, J-M., Vuong, T-P. 2010, A Real-time Control Using Wireless Sensor Network for Intelligent Energy Management System in Buildings. In 2010 IEEE Workshop on Environmental Energy and Structural Monitoring Systems (pp. 87-92). IEEE.

Nilsson, A., Stoll, P. & Brandt, N. 2017, Assessing the impact of real-time price visualization on residential electricity consumption, costs, and carbon emissions. Resources, Conservation and Recycling 124 (2017): 152-161.

Nyholm, E., Puranik, S., Mata, E. et al 2016, Demand response potential of electrical space heating in Swedish single-family dwellings. Building and Environment, 96(1): 270-282

Oakley, A., et al. 2005 The politics of evidence and methodology: lessons from the EPPI-Centre Evid & Pol. 1.1

Papadaskalopoulos, D. and Strbac, G., 2012, October. Decentralized participation of electric vehicles in network-constrained market operation. In 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe) (pp. 1-8). IEEE.

Papadaskalopoulos, D. & Strbac, G. 2013, Decentralized optimization of flexible loads operation in electricity markets. In 2013 IEEE Grenoble Conference (pp. 1-6). IEEE.

Parliamentary Office of Science and Technology. 2014, Electricity Demand-side Response. POSTNOTE Number 452 Jan. 2014.

"Profitable Interruptions", The Economist, 10 May 2014. Available at: https://www.economist.com/business/2014/05/10/profitable-interruptions [Accessed 2019-05-07]

Peersman G. 1996 A descriptive mapping of health promotion in young people. London: EPPI-Centre Soc. Sci. Res. Un., Inst. of Ed., Univ. of London

Qiao, Z. & Yang, J. 2016, Electric Vehicle charging management algorithm for a UK low-voltage residential distribution network. In: 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC). IEEE, 2016. p. 156-160.

Qiu, D., Papadaskalopoulos, D., Ye, Y. & Strbac, G. 2018, Investigating the Impact of Demand Flexibility on Electricity Retailers. In 2018 Power Systems Computation Conference (PSCC) (pp. 1-7). IEEE.

Rehm, T., Schneiders, T., Strohm, C., Deimel, M. 2018, Smart Home Field Test – Investigation of Heating Energy Savings in Residential Buildings. In 2018 7th International Energy and Sustainability Conference (IESC) (pp. 1-8). IEEE.

Romero Rodríguez, L. et al. 2019, Heuristic optimization of clusters of heat pumps: A simulation and case study of residential frequency reserve. Applied energy, 233, 943-958.

Song, M., Alvehag, K., Widén, J., Parisio, A., 2014. Estimating the impacts of demand response by simulating household behaviours under price and CO2signals.Electric Power Syst. Res. 111, 103–114.

Stokke, A.V., Doorman, G.L., Ericson, T. 2010, An analysis of a demand charge electricity grid tariff in the residential sector. Energy Effic. 3, 267–282.

Stoll, P., Brandt, N., Nordström, L. 2013, Including dynamic CO2intensity with demand response. Energy Policy 65 (2014), 490–500.

Stötzer, M., Gronstedt, P., Styczynski, Z., Buchholz, B.M., Glaunsinger, W., Suslov, K.V. 2012, Demand side integration—A potential analysis for the German power system. In 2012 IEEE Power and Energy Society general meeting (pp. 1-8). IEEE.

Stötzer, M., Hauer, I., Richter, M. and Styczynski, Z.A., 2015. Potential of demand side integration to maximize use of renewable energy sources in Germany. *Applied Energy*, *146*, pp.344-352.

SVK, 2014. Elstatistik för hela Sverige. Svenska Kraftnät, available on-line: http://www.svk.se/Energimarknaden/El/Statistik/Elstatistik-for-hela-Sverige [Accessed 201-05-24]

Sweetnam, T., Fell, M., Oikonomou, E. & Oreszczyn, T. 2019, Domestic demand-side response with heat pumps: controls and tariffs. Building Research & Information, 47(4), 344-361.

Thinkstep 2018 (Gabi ts, program version 8.7.0.18. Database 8007)

Tranberg, B., Corradi, O., Lajoie, B., Gibon, T., Staffell, I. and Andresen, G.B., 2019. Real-time carbon accounting method for the European electricity markets. Energy Strategy Reviews, 26, p.100367

Wang H, Chen W, Shi J. Low carbon transition of global building sector under 2- and 1.5-degree targets. Appl Energy 2018; 222:148–157.

Wolisz, H., Punkenburg, C., Streblow, R. & Müller, D. 2016, Feasibility and potential of thermal demand side management in residential buildings considering different developments in the German energy market, Energy Conversion and Management Volume 107, January 2016, 86-95,

Wolisz, H., Schütz, T., Blanke, T., Hagenkamp, M., Kohrn, M., Wesseling, M. & Müller, D. 2017, Cost optimal sizing of smart buildings' energy system components considering changing end-consumer electricity markets, Energy, 137, 715-728.

Zhou Y, Clarke L, Eom J, Kyle P, Patel P, Kim SH, Dirks J, Jensen E, Liu Y, Rice J, Schmidt L, Seiple T. Modeling the effect of climate change on U.S. state-level buildings energy demands in an integrated assessment framework. Appl Energy 2014;113:1077–1088.

Zimmermann, J.P. 2009, End-use metering campaign in 400 households in Sweden. Assessment of the potential electricity savings. Enertech.

IVL Swedish Environmental Research Institute Ltd.
P.O. Box 210 60 // S-100 31 Stockholm // Sweden
Phone +46-(0)10-7886500 // www.ivl.se