Energy Feedback and Demand Response Strategies - Exploring Household Engagement and Response Using a Mixed Methods Approach

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Title: Energy Feedback and Demand Response Strategies - Exploring Household Engagement and Response Using a Mixed Methods Approach

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To Anna

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Anders Nilsson
Stockholm, November 2018.

Abstract

Real-time energy feedback (EF) and demand response using dynamic pricing tariffs (DR) have been suggested as effective intervention strategies to meet the need for increased energy efficiency and demand flexibility in the residential sector. Although previous studies provide some empirical support for the effectiveness of EF and DR, evaluation approaches used in practical experiments and field trials commonly suffer from several methodological shortcomings, preventing deeper of knowledge on the potential and barriers for EF and DR to influence household energy consumption.

This thesis explored the potential of employing a mixed methods approach for evaluation of household energy consumption to provide improved understanding on how and why households engage and respond to EF and DR strategies. Three research objectives were set: 1) Analysis of the potential for using high-resolution data from smart meters in evaluation of household energy consumption and response to DR strategies, 2) development of a conceptual framework for evaluation of household responses to EF and DR strategies and analysis of its potential to increase understanding of household responsiveness, and 3) identification and analysis of household motivations, perceptions, and obstacles to engaging in EF and DR strategies.

The work to achieve these objectives followed a mixed methods research methodology grounded on literature reviews and empirical studies in real-life settings in a single case study, an EF/DR field trial taking place in Stockholm Royal Seaport. A combination of quantitative and qualitative methods was used for data collection and analysis, comprising interviews, surveys, and statistical analysis of smart meter energy data.

The results suggest that the mixed methods approach addresses several of the limitations and challenges associated with previous evaluation approaches. As regards objective (1), it was found that high-resolution data from smart energy meters can provide evaluation outcomes with increased transparency and accuracy. Regarding objective (2), it was found that the proposed framework can increase understanding of variations in household responsiveness to EF and DR strategies and reveal the relationship between impacts on electricity use and factors influencing energy consumption behavior. As regards objective (3), several obstacles for households to engaging in EF and DR strategies were identified, primarily related to household-individual factors such as knowledge, sense of control, and personal values and attitudes. Based on these findings, key issues and areas for further research are proposed.

Key words: Energy feedback; demand response; household energy consumption; energy efficiency and conservation, demand flexibility; smart grids; smart homes

Sammanfattning

Realtidsfeedback på energianvändning (EF) och demand response baserat på användande av dynamiska elpristariffer (DR) anses utgöra effektiva strategier för att kunna möte behovet av ökad energieffektivitet och efterfrågeflexibilitet inom hushållssektorn. Även om tidigare studier ger visst empiriskt stöd för att EF and DR kan vara effektivt för detta ändamål, har utvärderingen av praktiska experiment och fältförsök ofta begränsats av metodologiska tillkortakommanden, vilket förhindrar djupare kunskap om potentialen för EF och DR att influera hushållens energianvändning samt hinder för detta.

Den här avhandlingen undersöker potentialen av att använda en ”mixed methods approach” för att skapa bättre förståelse för hur och varför hushåll engagerar sig och responderar till EF och DR strategier. Tre mål etablerades; 1) Att analysera potentialen av att använda högupplöst data från smarta elmätare för utvärdering av hushålls energianvändning och respons till DR strategier, 2) att utveckla ett ramverk för utvärdering av hushålls respons till EF och DR strategier samt att analysera dess potential till att skapa ökad kunskap om hushålls responsivitet, och 3) att identifiera och analysera hushålls motiv, uppfattningar och hinder för att engagera sig i EF och DR strategier.

Arbetet med att uppfylla dessa mål följde en ”mixed methods”-forskningsmetodik förankrad i litteraturstudier och empiriska studier i verkliga miljöer, där en fallstudie genomfördes på ett EF/DR-program i Norra Djurgårdsstaden i Stockholm. En kombination av kvantitativa och kvalitativa metoder för datainsamling och analys tillämpades, vilket involverade; djupintervjuer, enkätundersökningar och statistisk analys av energidata från smarta elmätare.

Resultaten indikerar att ett tillvägagångssätt baserat på en ”mixed methods approach” har potential att adressera flertalet av de begränsningar och utmaningar som förekommit i tidigare utvärderingar. Beträffande mål (1), visade forskningen på att användandet av högupplöst data från smarta elmätare kan möjliggöra utvärderingsresultat av ökad transparens och noggrannhet. Beträffande mål (2), visade forskningen på att det föreslagna utvärderingsramverket kan möjliggöra ökad förståelse för hur olika typer av hushåll responderar till EF och DR strategier genom att tydliggöra förhållandet mellan effekter på elanvändning och faktorer som påverkar hushållens energikonsumtionsbeteende. Beträffande mål (3), så identifierades ett flertal hinder som kan begränsa hushålls engagemang för EF och DR strategier, primärt kopplade till hushållsindividuella faktorer som: kunskap, känsla av kontroll och personliga värderingar och attityder. Med utgångspunkt från dessa resultat föreslås ett antal nyckelfrågor och områden för vidare forskning.

Nyckelord: Feedback på energianvändning; Demand response; Hushållens energianvändning; Energieffektivitet och energibesparing; Smarta elnät; Efterfrågeflexibilitet; Smarta hem

List of appended papers

Paper I: Holmstedt, L., **Nilsson, A.**, Brandt, N., Mäkivierikko, A., 2018. Stockholm Royal Seaport Moving towards the goals - potential and limitations of dynamic and high resolution evaluation data. *Energy and Buildings* 169: 388-396.

My contribution to this paper was: development of the research idea in cooperation with the co-authors, collection and analysis of data, and critically reviewing the paper.

Paper II: **Nilsson, A.**, Stoll, P., Brandt, N., 2015. Assessing the impact of real-time price visualization on residential electricity consumption, costs, and carbon emissions. *Resources, Conservation & Recycling* 124: 152-161.

My contribution to this paper was: development of the research idea, planning the study, collection and analysis of data, writing the paper, and corresponding author during publication.

Paper III: **Nilsson, A.**, Lazarevic, D., Brandt, N., Kordas, O., 2018. Household responsiveness to residential demand response strategies: Results and policy implications from a Swedish field study. *Energy Policy* 122: 273-286.

My contribution to this paper was: development of the research idea, planning the study, development of the survey questionnaire, conducting the surveys, collection and analysis of data, writing the paper, and corresponding author during publication.

Paper IV: **Nilsson, A.**, Wester, M., Lazarevic, D., Brandt, N., 2018. Smart homes, home energy management systems and real-time feedback: Lessons for influencing household energy consuming from a Swedish field study. *Energy and Buildings* 179: 15-25.

My contribution to this paper was: development of the research idea, planning the study, development of the interview guide, conducting the *interviews, collection and analysis of data, writing the paper, and corresponding author during publication.*

Relevant additional publications

Shahrokni, H., Årman, L., Lazarevic, D., Nilsson, A., Brandt, N., 2015. Implementing Smart Urban Metabolism in the Stockholm Royal Seaport: Smart City SRS. *Journal of Industrial Ecology* 19: 917-929.

AlSkaif, T., Guerrero Zapata, M., Bellalta, B., Nilsson, A., 2017. A distributed power sharing framework among households in microgrids: A repeated game approach. *Computing* 99: 23-37.

Nilsson, A., Brandt, N., 2017. Proposing an hourly dynamic wind signal as an environmental incentive for demand response. *Advances and New Trends in Environmental Informatics*: 153-164.

Nilsson, A., Lazarevic, D., Kordas, O., 2017. Influencing household energy consumption: The case of Stockholm Royal Seaport. *Biennial International Workshop Advances in Energy Studies*, Naples, Italy, September 2017.

Contents

1. Introduction

1.1 Research rationale

Due to rapid population growth and urbanization, more than half the world's population are now living in urban areas (United Nations, 2014). As an effect, cities are faced with some serious sustainability challenges. Major energy and resource use, climate change, land degradation, and waste generation constitute some of the most critical issues that put pressures on the urban environment (Metzger & Rader Olsson, 2013). Given the continuous urbanization trend, these challenges are expected to become even greater over the coming decades (Cohen, 2003). However, due to their compact and dense configuration and their resources of social and knowledge capital, cities have also been identified as a key arena to lead the transition towards a more sustainable world (Rees & Wackernagel, 1996; Niza et al., 2009).

Energy consumption within the residential sector accounts for a large share of urban energy flows world-wide. Today, household energy consumption represents approximately 25% of total global energy consumption (Global Energy Statistical Yearbook, 2017). Although the energy efficiency of electrical appliances has improved substantially over recent decades, the gains are negated by the growing number of home electrical appliances and applications, a phenomenon commonly referred to as the rebound effect (Bennich et al., 2009). Yet, there is still great potential for reduced energy consumption within the residential sector (BPIE, 2011). The European Commission (EC) estimates the technical potential for energy efficiency in the European Union (EU) building sector to be approximately 30% (EC, 2009a). However, the gap between the technical potential, i.e. the upper limit to what is theoretically possible given the best available technologies, and the market potential, also accounting for social and market barriers and obstacles, is wide (Jaffe & Stavins, 1994; Jochem et al., 2000). One of the main reasons for this gap is that households suffer from a serious information deficit (IPCC, 2007). Conventionally, the only information about energy consumption that households receive is accumulated values through monthly or quarterly energy bills, limiting consumers' understanding about energy use, costs, and its environmental consequences (Fischer, 2008; van Elburg, 2009).

The growing European deployment of advanced metering infrastructure, which is encouraged by the EC's Energy End-use Efficiency and Energy Services Directive (2006/32/EC) (EC, 2006) and Electricity Directive (2009/72/EC) (EC, 2009b), has great potential to meet the need for improved information about electricity consumption to residential consumers.

Advanced metering infrastructure, commonly referred to as 'smart meters'[1], facilitates real-time communication between end-users and utility companies, enabling provision of detailed feedback through in-home displays, mobile apps, and/or internet services (Fischer, 2008; Darby, 2010). The central assumption underlying the concept of *energy feedback* (EF) is that provision of more accurate and detailed information will lead to increased consumer awareness and activity, ultimately supporting consumers in reducing energy use, costs, and carbon emissions (EC, 2009b).

The importance of developing effective strategies and policies for influencing household energy consumption has been further emphasized with the recent emergence of smart grids involving demand response strategies. *Demand response* (DR), a key demand-side management strategy, is expected to bring to fruition the potential benefits of smart grids[2], defined as: *'Changes in electric usage by end-customers from their normal consumption pattern in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized'* (U.S. Department of Energy, 2006). The general concept of DR is based on the central assumption that it is more economically, technically, and environmentally efficient to intelligently influence consumer demand to adjust to existing power system conditions, rather than the conventional approach of expanding generation and/or distribution capacity (e.g., Gellings, 1985; Albadi & El-Saadany, 2008; Strbac, 2008). The EU Energy Efficiency Directive (2012/27/EU) also identifies DR as an important instrument for increased energy efficiency, suggesting that DR *'significantly increases the opportunities for consumers or third parties nominated by them to take action on consumption and billing information and thus provides a mechanism to reduce or shift consumption, resulting in energy savings in both final consumption and, through the more optimal use of networks and generation assets, in energy generation, transmission and distribution'*.

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[1] Sweden was one of the first countries in Europe to start a large-scale roll-out of smart meters, enacting legislation (2002/03:85) in 2003 that mandated monthly billing based on electricity meter readings for all Swedish consumers by 2009[1] (Swedish Parliament, 2003). By 2014, Sweden had achieved greater than 90% smart meter coverage, ranking the highest in the EU along with Finland and Italy (EC, 2014).

[2] Smart grids are expected to meet the future need for improved efficiency, reliability, safety, sustainability in the European electric power grid infrastructure, defined by the Smart Grids European Technology Platform for Electricity Networks of the Future (ETP Smart Grids, 2006) as *'An electrical network that can intelligently integrate the actions of all users connected to it generators, consumers and those that do both in order to efficiently deliver sustainable, economic and secure electricity supplies'*. For in-depth descriptions and reviews of the smart grid concept, see e.g., Amin & Wollenberg, 2005; Farhangi, 2010; Rahimi & Ipakchi; 2010; Clastres, 2011.

Over the past few decades, practical experiments and field studies have provided some empirical support for the effectiveness of EF and DR strategies in influencing household energy consumption. Studies have shown that EF and DR can lead to reductions in electricity peak demand and total household energy consumption (e.g., Darby, 2006; Fischer, 2008; Ehrhardt-Martinez et al., 2010; Bartusch & Alvehag, 2014), particularly when they are combined (e.g., Faruqui et al., 2010; Strömbäck et al., 2011). However, successful implementation of EF and DR strategies also struggles with some serious limitations. Most critically, by building on the assumption of consumers as rational decision-making agents, the effectiveness of DR and EF strategies is ultimately limited by household engagement and response, i.e., the extent to which households adapt to the strategies and change their actual energy consumption (e.g., Abrahamse et al., 2005; Ehrhardt-Martinez et al., 2010; O'Connell et al., 2014; Nolan & O'Malley, 2015; Paterakis et al., 2017). However, household energy consumption is seldom rational, but rather influenced by a wide range of behavioral and contextual factors, such as attitudes, values, social and moral norms, and daily habits and routines, that may conflict with households' willingness and ability to engage in EF and DR strategies (e.g., Stern, 1992; 2000; Lutzenhiser, 1993; Steg, 2008; Steg & Vlek, 2009).

The role of consumer behavior is gaining increasing interest among researchers and policy makers, suggesting a need for greater attention to the human dimension of energy consumption when evaluating the effectiveness of EF and DR (e.g., Hargreaves, 2010; Kim & Shcherbakova, 2011; Nolan & O'Malley, 2015). Indeed, despite challenges related to market regulations, technology infrastructure, and investment costs, improved understanding of household engagement and response has been pointed out as a key step in identification and refinement of targeted EF and DR strategies (e.g., Gyamfi & Krumdieck, 2011; Nolan & O'Malley, 2015; Nachreiner et al., 2015; Paterakis et al., 2017; Good et al., 2017). However, previous evaluation approaches applied to EF and DR strategies commonly suffer from several shortcomings, primarily related to lack of data availability and a mono-methodological approach, preventing acquisition of in-depth knowledge (e.g., Abrahamse et al., 2005; Delmas et al., 2013; Nolan & O'Malley, 2015; Karlin et al., 2015).

A mixed methods research approach has the potential to address several of the limitations of previous evaluation approaches. By combining quantitative and qualitative methods for collection and analysis of data, a mixed methods approach allows for increased breadth and corroboration in evaluation outcomes, providing fuller, deeper, and more comprehensive findings (Johnson & Onwuegbuzie, 2004). Recent studies adopting a mixed methods approach for evaluation of EF and DR strategies report that this approach has promise (e.g., Grønhøj & Thøgersen, 2011; Nilsson et al., 2014), but also emphasize the need for further investigation of its potential to provide improved understanding of household engagement and response to EF and DR strategies (see section 2.4).

1.2 Aim and objectives

The aim of this thesis was to explore the potential for employing a mixed methods approach in evaluation of household energy consumption to provide improved understanding of how and why households engage and respond to energy feedback and demand response strategies.

Specific objectives were to:

1) Study the potential for using high-resolution data from smart meters in evaluation of household energy consumption and response to demand response strategies (Papers I and II).

2) Develop a conceptual framework for evaluation of household response to energy feedback and demand response strategies, and analyze its potential to provide improve understanding of household responsiveness (Paper III).

3) Identify and analyze household motivations, perceptions, and obstacles to engaging in energy feedback and demand response strategies (Paper IV).

1.3 Scope

The research presented in this thesis was mainly carried out in the context of the *Active House* (AH) field trial, a Swedish research and development program in a Stockholm city district (Stockholm Royal Seaport) currently under development. Due to its location, scope, and wide actor network, the AH field trial provided a suitable opportunity for applied research, serving as single case study (for a further description of the AH field trial and its applicability for a case study, see section 3.2.1). Hence, the results and findings in this thesis are limited by the specific context of the AH field trial, in particular with regard to its time period, program design, implementation, and sample size and population characteristics (see further discussion of limitations to generalizability in section 4.5).

2. Background

2.1 Household energy consumption: Research perspectives and theories

In the search for effective ways to improve energy efficiency and promote energy conservation, during recent decades household energy consumption has been an area of research within several disciplines, including behavioral economics (Madden et al., 1992), social and environmental psychology (Rossi & Armstrong, 1999), and ecological economics (Bamberg, 2013). Although a wide range of theories and models aiming to explain household energy consumption behavior have been proposed, the vast majority of research efforts to date can be broadly divided into two major paradigms: economic, and social and behavioral (Vitali et al., 2015).

The basis to the economic research paradigm on household energy consumption is *Rational Choice Theory* (RCT), a neoclassical economics theory which suggests that people rationally seek the maximum benefit with minimum cost to maximize their expected utility (Elster & Hylland, 1986). In the context of household energy consumption, this means that, based on the information available, households are assumed to make a brief cost-benefit analysis of all their energy-related decisions and select the lowest-cost alternative to maximize utility (e.g., Hargreaves et al., 2010). Hence, earlier studies based on RCT have argued that households would take more informed decisions for energy efficiency and conservation if sufficient information were provided (e.g., Lutzenhiser, 1993).

Research grounded in social and behavioral theories has directed a substantial amount of criticism towards RCT (e.g., Thaler, 2000; Jackson, 2005; Hargreaves, 2011). Jackson (2005) identifies three main categories of criticism. First, criticism of the assumption that residential energy consumers are economically rational decision-making agents, with critics arguing that the general public have limited cognitive skills and that the burden of constantly processing information might lead to cognitive shortcuts and consumers falling back on well-established habits and routines (e.g., Jackson, 2005; Loock et al., 2013). Second, criticism of the assumption in RCT of an independent relationship between behavior and social context. Critics in this case argue that people do not solely act individualistically, and that interpersonal relations influence people's decision-making processes to a substantial degree (Jackson, 2005; Granovetter, 1985). Third, criticism of the fact that RCT does not account for moral considerations, since it has been suggested that people do not always act according to personal self-interest, but that altruistic concerns may also influence decisions and behavior (e.g., Schwartz, 1973). In the context of energy consumption, a substantial amount of previous research suggests that environmental attitudes and concerns may influence decisions and behavior (e.g., Brandon & Lewis, 1999; Poortinga et al., 2002; Steg, 2008; Steg & Vlek, 2009).

A wide range of studies within several research areas have attempted to address the recognized limitations of RCT by developing new theories and models. Some of the most prominent theories which have gained particular interest in the literature are the *Theory of Planned Behavior* (TPB) (Ajzen, 1991), the *Norm-Activation Model* (NAM) (Schwartz, 1973, 1977), and *Value-Belief-Norm* theory (VBN) (Stern, 2000). Overall, these theories suggest that energy consumption is influenced by a wide range of personal and psychological factors, including environmental attitudes, subjective and moral norms, perceived behavioral control, awareness and ascribed responsibility for energy consumption consequences, and personal values and beliefs (Ajzen, 1991; Schwartz, 1973, 1977; Stern, 2000).

Previous research also suggests that contextual factors, neither personal nor psychological, may influence household energy consumption behavior (e.g., Brandon & Lewis, 1999; Stern, 2000; Wilson & Dowlatabadi, 2007; Abrahamse & Steg, 2009; Thøgersen & Grønhøj, 2010). Contextual factors may further be divided into *individual* factors, i.e., variables that provide opportunities and constraints for household energy consumption, such as socio-demographic characteristics, and individual skills and resources (e.g., Gatersleben et al., 2002; Abrahamse & Steg, 2009; Thøgersen & Grønhøj, 2010), and *external* factors, i.e., external influences on energy consumption, such as regulations and policy measures, promotional and informational strategies, and social norms (e.g., Brandon & Lewis, 1999; Abrahamse et al., 2005, 2007; Fischer, 2008).

2.2 Policy instruments for influencing household energy consumption

Policy instruments are introduced with the aim of influencing development to reach pre-defined targets or to change the direction of a current negative development (e.g., Sterner, 2003). According to Lindén (2008), there are four major categories of policy instruments for influencing household energy consumption: 1) *informative*, such as feedback on energy consumption, marketing, and labeling, which aims to increase knowledge and awareness of energy consumption and its consequences; 2) *administrative*, such as laws and regulations, which aims to serve as an external restriction for an undesired type of energy consumption behavior; 3) *economic*, such as subsidies, discounts, taxing and pricing, which aims to serve as a financial incentive for changing energy consumption behavior; and 4) *physical*, such as technical innovation (i.e., smart meters and home energy management systems), which aims to serve as support for energy consumption behavior change. The effectiveness of achieving changes in energy consumption is highly dependent on choice of instruments, design of measures, and delimitation of the target group. As different types of instruments may vary significantly in the pace at which the desired effects potentially emerge (e.g., the effect of information may be considered relatively slow compared with regulations, which come into immediate effect), the effectiveness may be improved by a combination of several measures (e.g., Jordan et al., 2003).

Although administrative policy instruments are considered to be of great importance, previous research suggests that there is a substantial need to further explore the potential of non-governmental measures for influencing household energy consumption (Steg, 2008; Ek & Söderholm, 2010). To address this need, this thesis focused on market-based strategies applying informative, economic, and physical policy instruments to promote changes in household electricity use. Specific attention was devoted to energy feedback and demand response strategies, which are described in the following section.

2.3 Energy feedback and demand response strategies: Concepts, potentials, limitations

2.3.1 Energy feedback

In contrast to many other types of consumer goods, energy may be considered 'invisible', as it is untouchable, silent, and commonly purchased through automated payment and billing systems (Burgess & Nye, 2008; Westskog et al., 2015). Thus, energy use is rarely seen as a coherent field of consumption, but rather as an integral part of daily habits and routines, indirectly consumed via appliances and services (e.g., Hargreaves et al., 2010; Grønhøj & Thøgersen, 2011). A wide range of research efforts and practical studies have addressed the need for increased visibility of household energy consumption by providing various types of feedback. The approaches used in such studies have varied widely, from providing electricity bills with a higher level of detail (e.g., Wilhite & Ling, 1995) and advice on energy-saving measures via brochures, websites, and personal meetings (e.g., Brandon & Lewis, 1999; Darby, 2003; Abrahamse et al., 2007), to direct (i.e., real-time) feedback and information presented on in-home displays, mobile apps, or online services (e.g., Anderson & White, 2009; Grønhøj & Thøgersen, 2011; Chen et al., 2013; Gans et al., 2013; Schultz et al., 2015; Guerassimoff & Thomas, 2015; Skjølsvold et al., 2016; Burchell et al., 2016; Gölz, 2017). Regardless of the mechanism used for provision of energy feedback (ER), these studies are all based on the underlying assumption that increased feedback will lead to increased awareness and knowledge about energy consumption and its consequences, which in turn will lead to informed decisions among households to reduce consumption. This chain of cause and effect is explicitly described by Wilhite & Ling (1995) as:

> Increased feedback → Increase in awareness or knowledge → Changes in energy-use behavior → Decrease in consumption.

Over recent decades, the rationale for EF has gained some empirical support. A meta-review by Darby (2006), covering 21 studies involving direct EF carried out in Europe and the USA, concluded that the average reduction in electricity use is 5-15%. A later meta-review by Fischer (2008), covering five previous review studies and a substantial amount of primary source research, presented similar findings, suggesting average reductions in electricity use of 5-12%. An additional meta-review by Ehrhardt-Martinez et al. (2010), covering 57 US and European studies, reported a similar range of 4-12% average reduction in electricity use.

Among studies carried out in the Nordic countries to date, only a few have involved smart meters and direct EF through in-home displays. In general, these studies have obtained less optimistic results. A study by Bager & Mundaca (2015), covering 47 Danish households, reported average reductions in electricity use of 6.7%, while a study by Nilsson et al. (2014), covering 40 Swedish households, failed to find any statistically significant effect of feedback on electricity use at all. While these two studies suffer from small sample size (and hence less robust results), a large-scale field study by Uggmark (2013), covering more than 9000 Swedish households, reported an average reduction in electricity use of 2.2% compared with the control group, and 0.7% compared with historical use. Recent reviews of studies carried out in the USA and Europe also report more modest results. For example, a meta-review by McKerracher & Torriti (2013), covering 33 studies involving direct EF on in-home displays, suggested average reductions in electricity use of no more than 3-5%. Those authors claim that one reason for this lower figure is that the presence of smart grids and smart meters in more recent trials has allowed for less costly projects, and has thus enabled more representative samples. Another meta-review, by Delmas et al. (2013), covering 156 feedback studies conducted during 1975-2011, supports these findings, suggesting that the more optimistic results reported in previous EF trials stem from less robust studies.

Although EF has shown some potential for reducing energy consumption, the concept is associated with some serious limitations. Most critically, given its underlying assumption of consumers as rational decision-makers, the effectiveness of EF for reduced energy consumption is ultimately limited by household response, i.e., the extent to which households engage with feedback and actually reduce their consumption. Previous research suggests that household engagement may vary widely depending on the content and presentation of feedback (e.g., frequency, duration, metrics, aggregation, design, etc.). This raises several critical concerns, e.g., that feedback is often is perceived as difficult to interpret and relate to, that financial incentives for energy savings are commonly overemphasized, and that feedback may be associated with serious risks of rebound effects (e.g., Abrahamse et al., 2005; Darby, 2006; Fischer, 2008; Ehrhardt-Martinez et al., 2010; Delmas et al., 2013; Wilson et al., 2015; Karlin et al., 2015; Buchanan et al., 2015). This means that if feedback is perceived as too complex to understand and interpret, overwhelming, or simply irrelevant, there is a substantial risk that potential initial enthusiasm and interest in feedback will decrease over time, and that people will fall back into their well-established habits and routines. Hence, obtaining deeper insights into household motivations, attitudes, and perceived obstacles to engaging with EF, and linking these insights to actual changes in energy consumption, has been identified as a key component in the development of enhanced feedback strategies (e.g., Grønhøj & Thøgersen, 2011; Nachreiner et al., 2015; Gölz & Hahnel, 2016; Hargreaves, 2017).

2.3.2 Demand response

Demand response (DR), or in a broader sense, demand-side management[3], refers to '*all intentional adjustments in electricity consumption pattern by end-use customers that are intended to modify the timing, level of instantaneous demand, or total electricity consumption*' (IEA, 2003). The general concept of DR is based on the assumption that it is more economically, technically, and environmentally efficient to intelligently influence consumer demand to adjust to existing power system conditions, rather than, as conventionally, expanding generation and/or distribution capacity (e.g., Gellings, 1985; Albadi & El-Saadany, 2008; Strbac, 2008; Palensky & Dietrich, 2011). In doing so, DR strategies aim to bring the benefits of smart grids into fruition; reducing generation margins, improving investment and operation efficiency in transmission grids and distribution networks, and maintaining the balance of demand and supply in the system.

The potential benefits of DR strategies relate to several aspects of the power system. Participating customers can achieve cost savings by decreasing electricity usage during peak hours (e.g., Kirschen, 2003; Jazayeri et al., 2005; Albadi & El-Saadany, 2008). Market-wide benefits may be achieved and expressed as electricity price reduction, due to more efficient utilization of the available system infrastructure. DR may also lead to increased short-term capacity, thus resulting in avoided deferred capacity costs (e.g., US Dept. of Energy, 2006; Tan & Kirschen; 2010; Albadi & El-Saadany, 2008). Furthermore, the risk of power outages may be reduced due to decreased

[3] While demand-side management (DSM) is a broader concept including several techniques, demand response is considered as a key DSM strategy (Gellings, 1985; Albadi & El-Saadany, 2008).

demand during peak hours, and system operators will have more options and resources to maintain the reliability of the grid (e.g., Goel et al., 2006; Albadi & El-Saadany, 2008). In addition, DR may improve the overall electricity market performance, as customers will have more opportunity to affect retail competition through market-based or dynamic pricing programs. Another possible market effect is reduced price volatility in the spot market, as DR encourages flattening of the demand curve. In an environmental perspective, a flattened demand curve would also enable increased integration of electricity from intermittent renewable sources (e.g., Barbose et al., 2004; Spees & Lave, 2007; Albadi & El-Saadany, 2008; Siano, 2014).

Although DR may be deployed within a wide range of applications, DR programs can be broadly divided into two main categories; incentive-based and price-based (e.g., U.S. Department of Energy, 2006; Albadi & El-Saadany, 2008). Incentive-based programs refer to strategies where customers receive bill credits or discount rates for their participation, while price-based programs refer to strategies using dynamic pricing tariffs, such as time-of-use (ToU), critical peak pricing (CPP), and real-time pricing (RTP). The general intention of price-based programs is to stimulate consumers to flatten their demand curve over the day in response to dynamic price rates. For example, ToU tariffs, a particular focus in the present thesis, involve higher prices during peak periods and lower prices during off-peak periods (e.g., Albadi & El-Saadany, 2008; Siano, 2014).

Since the introduction of price-based DR programs using ToU tariffs, a number of follow-up studies have been undertaken during the past decade. An early study drawing on a state-wide trial in California during 2000 and 2001 suggested that ToU tariffs may lead to average peak load reductions of approximately 5% (Faruqui & George, 2005; Faruqui et al., 2009). Two following reviews by Faruqui & Sergici (2008, 2010), in total covering the 15 most recent DR programs in the USA at the time, provided similar results, i.e., average peak load reductions of 3-6%. Further support for these findings is provided by a more recent study by Woo et al. (2013), covering more than 1700 Canadian households, which determined average peak load reductions of between 3% and 9%, depending on the ratio between peak and off-peak price.

Studies carried out in the Nordic countries are typically smaller-scale and include less automation technologies than North American studies. A study by Bartusch & Alvehag (2014), covering the response of approximately 100 Swedish households to a demand-based ToU tariff over a six-year period, found average peak load reductions of approximately 4-12%, but varying substantially across type of housing tenure. A study by Stokke et al. (2010), covering more than 400 Norwegian households, identified an average reduction in peak demand of 5%, with a maximum reduction of 9%. Moreover, Stokke et al. (2010) claim that the observed reductions would probably have been even greater if customers had been provided with feedback on their electricity consumption.

An enhanced effect of combining EF and DR is reported by Strömbäck et al. (2011), who conducted a review of over 200 DR trials using TOU tariffs and found that programs involving some kind of EF achieved on average a 4% reduction in total energy consumption, compared with an average 1% reduction in programs without any feedback. They also found that the observed peak load reduction among the trials involving feedback was on average 40% higher than in those without any feedback. Similarly, a study by Faruqui et al. (2010), reviewing a dozen international programs involving EF on in-home displays, found that the effect of time-varying electricity price rates may be augmented by direct feedback from in-home displays.

Although DR shows promise, particularly when combined with EF, successful application of DR is associated with some serious limitations. Extensive reviews on the barriers and challenges to successful implementation of DR suggest that, apart from issues related to market regulations, technology infrastructure, and investment costs, the effectiveness of residential DR strategies is ultimately limited by household responsiveness, i.e., the extent to which households change their energy consumption according to the incentives provided (e.g., Kim & Shcherbakova, 2011; O'Connell et al., 2014; Nolan & O'Malley, 2015; Paterakis et al., 2017; Good et al., 2017).

Insufficient household response is primarily related to two factors. First, it is widely suggested that DR struggles with weak financial incentive models, as potential electricity bill savings are not sufficiently significant for households to change daily habits and routines (Clastres, 2011; Gyamfi & Krumdieck, 2011; Kim & Shcherbakova, 2011; O'Connell et al., 2014; Nolan & O'Malley, 2015). Indeed, in most European countries, electricity costs usually represent only a small fraction of households' total expenditure, implying that the potential savings from response to time-varying price tariffs can be considered almost negligible (Kim & Shcherbakova, 2011).

Second, DR is based on the assumption in RTC that consumers are economically rational decision-making agents. However, the consumption behavior of residential customers is seldom rational and, as acknowledged in section 2.1, may be influenced by a wide range of behavioral factors (Schwartz, 1973; Ajzen, 1991; Stern, 2000). Hence, limitations and challenges to DR are closely related to the issues affecting EF. To identify and allow for future development of effective DR strategies, previous research stresses the need for greater attention to the human dimension of household energy consumption; how households' act and respond to incentives provided, and how the effectiveness of DR strategies relates to factors influencing household energy consumption (Abrahamse et al., 2005; Kim & Shcherbakova, 2011; Nolan & O'Malley, 2015).

2.4 Evaluation of household response to energy feedback and demand response: Limitations and challenges

As noted in the above sections, the effectiveness of EF and DR to promote increased energy efficiency and/or demand flexibility is ultimately limited by a joint factor: household engagement and response. Hence, for identification and development of enhanced strategies and incentives, further investigation of how households adopt EF and DR strategies is needed. However, extensive reviews of EF and DR studies suggest that previous evaluation approaches are limited by several methodological shortcomings (e.g., Abrahamse et al., 2005; Delmas et al., 2013; Nolan & O'Malley, 2015; Karlin et al., 2015).

First, it is suggested that previous evaluation efforts commonly suffer from limitations in data collection, since data on energy consumption need to be collected at higher frequency and for longer periods to provide an increased level of detail on potential effects and ensure robust evaluation outcomes (e.g., Nolan & O'Malley, 2015; Karlin et al., 2015). While longer time periods may be considered highly dependent on the study-specific context, the growing emergence of smart meters has the potential to meet the need for data at higher frequency, allowing for collection of data at hourly (or even higher) resolution (EC, 2009b; Darby, 2010). In addition, the contribution of data from smart meters is not restricted to evaluation of household response to EF and DR strategies explicitly, but can serve to improve transparency and accuracy in analyses of energy consumption in buildings and households for several purposes (e.g., for evaluation of a building's energy performance, energy billing, etc.).

Second, evaluation efforts typically suffer from a mono-methodological approach. On the one hand, research within the energy field primarily adopts a strict quantitative approach, focusing on potential impacts in overall power demand explicitly, while rarely investigating underlying reasons for observed effects or variations across different types of households. On the other hand, research grounded in social and behavioral science commonly adopts a qualitative approach, focusing on potential effects on attitudes and motivation, but not necessarily accounting for actual changes in energy consumption (e.g., Abrahamse et al., 2005; O'Connell et al., 2014; Paterakis et al., 2017). This distinction into quantitative and qualitative analyses means that many studies fail to provide a complete picture of the underlying reasons for (insufficient) changes in energy consumption, accounting for how feedback and dynamic pricing tariffs are perceived and acted upon, to its resulting effects on energy consumption. Referring to the cause and effect chain suggested by Wilhite and Ling (1995) (see section 2.3.1), barriers and obstacles may occur in several of its stages, preventing the desired final outcome of reduced energy consumption. Increased information does not necessarily increase knowledge and awareness, and increased knowledge and awareness does not necessarily lead to changes in energy consumption behavior.

To meet the need for a more holistic evaluation approach, recent studies have employed a combination of quantitative and qualitative methods for collection and analysis of data (e.g., Grønhøj & Thøgersen, 2011; Nilsson et al., 2014). Through this, some of the limitations of mono-methodological approaches have been addressed, e.g., by linking quantitative effects (i.e., changes in energy consumption) to qualitative findings (i.e., household attitudes and motivations). However, these studies also stress the need for further investigation of the mixed methods approach, exploring its potential to increase understanding of household engagement and response to EF and DR strategies. In the following section, the mixed methods methodology employed in the present thesis is outlined.

3. Methodology

3.1 A mixed methods research approach

Mixed methods research has attracted increasing interest during the past few decades and has been recognized as the third major research paradigm, along with qualitative research and quantitative research (Johnson et al., 2007). Johnson and Onwuegbuzie (2004) define mixed methods research as: '*the class of research where the researcher mixes or combines quantitative and qualitative research techniques, methods, approaches, concepts or language into a single study*'. Mixed methods are primarily used in research for the purposes of improved breadth and/or corroboration, to provide a better, fuller, and deeper understanding of a certain phenomenon and to produce more comprehensive, consistent, and valid findings (e.g., Johnson et al., 2007). In particular, mixed methods approaches have been suggested as the preferred methodology when quantitative findings such as numbers and key figures need to be supplemented with words, pictures, and narratives in order to add meaning to the findings (Creswell et al., 2003; Johnson & Onwuegbuzie, 2004).

Although mixed methods research may be applied in a wide range of forms, there are two major categories of mixed methods research design, *mixed-model* and *mixed-method*. Mixed-model refers to research mixing qualitative and quantitative approaches within the stages of a research process (i.e., addressing the same objectives by quantitative and qualitative approaches). Mixed-methods, the approach used in this thesis, refers to research that includes a quantitative phase and a qualitative phase in an overall research study (i.e., addressing different objectives by quantitative and qualitative approaches carried out in parallel) (Johnson & Onwuegbuzie, 2004).

Given its benefits and flexible applicability, a mixed methods approach was considered suitable methodology in this thesis work to address several of the limitations and challenges in evaluation of EF and DR strategies listed in section 2.4. More explicitly, a mixed methods approach was employed with the purpose of providing a more detailed and comprehensive understanding of how and why households engage with, and respond to, EF and DR strategies. In this case, the qualitative findings addressed the 'why' question (i.e., household attitudes, motivations, and obstacles for engagement), to provide increased meaning to the quantitative results that addressed the 'how' questions (i.e., changes in energy consumption). Accordingly, a combination of quantitative and qualitative approaches was used for collection and analysis of data addressing the objectives of the thesis. The connections between research objectives, applied methods, and papers are shown in Table 1, followed by descriptions of the qualitative and quantitative methods used.

Table 1. Connections between research objectives, applied methods, and Papers I-IV in this thesis

Research objective	Research method	Paper
(1) Study the potential for using high-resolution data from smart meters in evaluation of household energy consumption and response to demand response strategies.	Literature review Statistical data analysis	I, II
(2) Develop a conceptual framework for evaluation of household response to energy feedback and demand response strategies, and analyze its potential to increase understanding of household responsiveness.	Literature review Statistical data analysis Case study research Household surveys	III
(3) Identify and analyze household motivations, perceptions, and obstacles to engaging in energy feedback and demand response strategies.	Literature review Statistical data analysis Case study research In-depth interviews	IV

3.2 Qualitative methods

Qualitative research methods are of significant value for obtaining deeper insights into topics for which limited knowledge exists when the primary research purpose is to explore how social and cultural contexts affect processes, decisions, and events (e.g., Liamputtong, 2009; Bryman, 2016). Hence, although a qualitative research approach may be criticized for its limited reliability and generalizability, it has the potential to provide an in-depth understanding of events and phenomena that would not be possible to achieve using a strictly quantitative approach. In this thesis, qualitative approaches were used to explore household attitudes, motivations, and obstacles to engagement and response to EF and DR strategies, hence, providing deeper meaning and increased understanding of quantitative effects on energy consumption.

3.2.1 Case study

Case study research, focusing on a particular case (e.g., an individual, a group, or an organization), is a preferred method to gain knowledge of a complex social issue, event, or object, and where multiple variables and interrelationships exist (Stake, 1995; Creswell, 2009). Conducted as single, multiple, or embedded cases, the approach may be considered an empirical inquiry that investigates a contemporary social phenomenon within its real-life context. This is an appropriate strategy for explorative research when the investigator has no or little control over events and when, how and why questions are posed (Eisenhardt, 1989; Yin, 2009, 2012).

A single case study was carried out to provide an in-depth understanding of how residential households engage with, and respond to, real-time feedback on energy consumption and dynamic pricing tariffs (Papers III and IV). The study was conducted on a residential EF/DR field trial called the *Active House* (AH), taking place in a new city district under current development, Stockholm Royal Seaport[4].

The AH program was considered well-suited to serve as a case study for several reasons. First, the purpose of the AH trial was to develop, implement, and evaluate the potential of EF and DR strategies. To do so, 154 residential households[5] were equipped with a home energy management system (HEMS) developed by the program, called *Tingco Home,* providing the residents with possibilities for increased monitoring and control of their energy consumption through direct feedback on energy consumption, smart home features, and economic and environmental incentives visualized in in-home displays[6]. The trial commenced on January 1, 2017 and ran for 15 months, to March 31, 2018. During that period, household-individual energy consumption in all participating households was measured by in-home smart energy meters at a high frequency (1-15 seconds). Hence, studying the AH trial was considered a valuable opportunity to collect the necessary quantitative and qualitative data to obtain deeper insights on household energy consumption behavior and consumer response to DR strategies, meeting the research objectives of this thesis.

Second, the population of Stockholm Royal Seaport consists of high-income and highly educated households, characteristics typical of so-called early adopters of technological innovations (possessing the required knowledge and

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[4] In 2009, the City of Stockholm decided that the Stockholm Royal Seaport district will serve as a test arena and international model for innovative energy solutions and sustainable urban planning, establishing challenging objectives for increased energy efficiency in an environmental and sustainability program (City of Stockholm, 2009, 2010).
[5] The households included in the trial were all apartments in newly built multi-dwelling buildings (completed during 2016) of varying sizes (1-5 rooms, 40-130 square meters), comprising 72 rental apartments and 82 apartments belonging to tenant-owned private housing cooperatives. All households were recruited through a broad agreement with the housing and property companies (body corporates) collaborating with the AH trial, where tenants signed participation agreements during acquisition of their apartments.
[6] See Papers III and IV for more details of the Tingco Home HEMS concept.

financial capital to engage with HEMS). Hence, studying this particular population segment could provide findings and experiences serving as valuable input for development and implementation of large-scale EF and DR programs in the near future.

3.2.2 In-depth interviews

The approach of using in-depth interviews is regarded as a valuable method for exploring in detail personal experiences, perceptions, and descriptions of a certain topic expressed in the words of the interviewee (e.g., Minichiello, 2008). In exploratory and qualitative-based research, a semi-structured interview approach is commonly preferred over structured interviews, allowing for a non-restricted process with the freedom to explore and probe emergent topics (e.g., Bryman, 2016). In the research for this thesis, in-depth, semi-structured interviews were conducted with 14 households that participated in the AH program, to explore their role as energy consumers in a smart home environment (Paper IV). The households were selected to be representative of the full population of the case study in terms of age, income, gender, educational level, family composition, household size, and type of housing tenure. The interview questions focused on: attitudes to program participation and energy savings, use and perceptions of the HEMS, perceived effects on knowledge and behavior, and perceived obstacles to energy consumption behavior change. The interviews lasted approximately 60 minutes and were conducted in the home, allowing interviewees to demonstrate their use and understanding of the HEMS. All interviews were digitally recorded and transcribed verbatim, and the transcripts were thematically analyzed to identify common themes across different households.

See Paper IV for more details of the interview study, including the recruitment process and socio-demographic descriptions of the households interviewed.

3.3 Quantitative methods

Quantitative research methods are used to determine the relationships between defined variables through statistical, mathematical, and computational techniques based on numerical data (e.g., Balnaves & Caputi, 2001). While providing less in-depth detail on the observed phenomena compared with qualitative methods, quantitative approaches are appropriate when seeking to generalize results from a large sample population (e.g., Carr, 1994). In the research for this thesis, quantitative methods were used to examine the effects of DR strategies on household energy consumption, and to identify links between observed effects and household-individual factors influencing energy consumption behavior.

3.3.1 Energy consumption data analysis

Statistical data analysis was used for evaluation of household energy use and to examine the effects of EF and DR strategies on energy consumption levels and patterns (Papers I-IV). To provide a summary of observed effects, descriptive statistics were used, including measures of important tendencies and data variability. Data at high temporal (i.e., time frequency of 5-15 seconds) and spatial (i.e., household-level) resolution, hereafter referred to as high-resolution data, collected on household-individual level through in-home smart energy meters, were used for the analyses.

In the analyses of potential changes in energy consumption (Papers II-IV), the households included in the studies were all apartments in newly constructed buildings, acquired and occupied just a few weeks prior to the commencement of the studies. Hence, it was not possible to establish any baselines based on historical consumption. The best available option was to use conventional households in neighboring buildings as control households. These control households were recruited and matched to the intervention households based on socio-demographics (e.g., age, income, household size, educational level, etc.) and physical characteristics that can impact energy consumption (e.g., building age, household size, district heating system, efficiency of installed appliances, etc.). Accordingly, data from both intervention households and control households were collected and analyzed.

See Paper I-IV for more details of the statistical data analyses undertaken for each study, including data characteristics, and key figures and indicators.

3.3.2 Household surveys

Household surveys are considered the preferred method to collect detailed data on household-level characteristics and gain a deeper theoretical understanding of factors facilitating and/or constraining household energy consumption (e.g., Painuly, 2001; Campbell et al., 2013). In this thesis, internet-based survey questionnaires were used to collect several types of information about the households that participated in the AH program (Paper III). Accounting for factors influencing household energy consumption, as suggested by previous research reported in section 2.1, the survey questions covered: socio-demographic characteristics, environmental and energy-saving attitudes, and perceived ability to change energy consumption behavior. Hence, data from the surveys provided the possibility to draw links between observed effects on energy use and household-individual factors influencing energy consumption behavior. Respondents were asked to account for the full household when completing the questionnaire. Depending on the character of the question/statement, several response options were given: single answers, multiple choices, or a five-degree Likert scale (i.e., respondents asked to indicate the extent to which they agreed with a certain statement using a scale range from 1 to 5).

See Paper III for more details of the survey, including survey questions and response rates.

4. Summary of results and discussion

4.1 The potential for using high-resolution data in evaluation of household energy consumption and response to demand response strategies (Papers I and II)

In Paper I, the potential for using high-resolution data in evaluation of energy consumption in buildings and households was explored. The study comprised analysis of energy consumption data from smart energy meters, covering 40 residential households in two multi-dwelling buildings in Stockholm Royal Seaport during 2016.

The results suggest that the use of data from individual metering of energy consumption streams (i.e., electricity, hot tapwater, and heating) enables differentiation of energy use related to diverse types of a building's energy performance. The possibility to distinguish between energy demand for hot tapwater use and heating purposes in multi-dwelling buildings may be considered of particular importance, as hot tapwater use is primarily a parameter of individual behavior by tenants, while heating demand reflects the energy performance of the building construction (i.e., insulation, size and location of windows, etc.). This means that hot tapwater use can be allocated to individual households based on actual consumption and not, as is conventionally done in Sweden, based on apartment area (e.g., Huovila et al., 2017).

As shown in Figure 1, energy consumption varied widely across the households covered by the study, with no signs of a linear relationship between consumption and apartment area (Paper I). Given the wide spread of consumption levels across household sizes, the results indicate that other factors (e.g. such as behavioral and contextual factors, see Section 2.1), instead influence household energy consumption to a larger extent than household area.

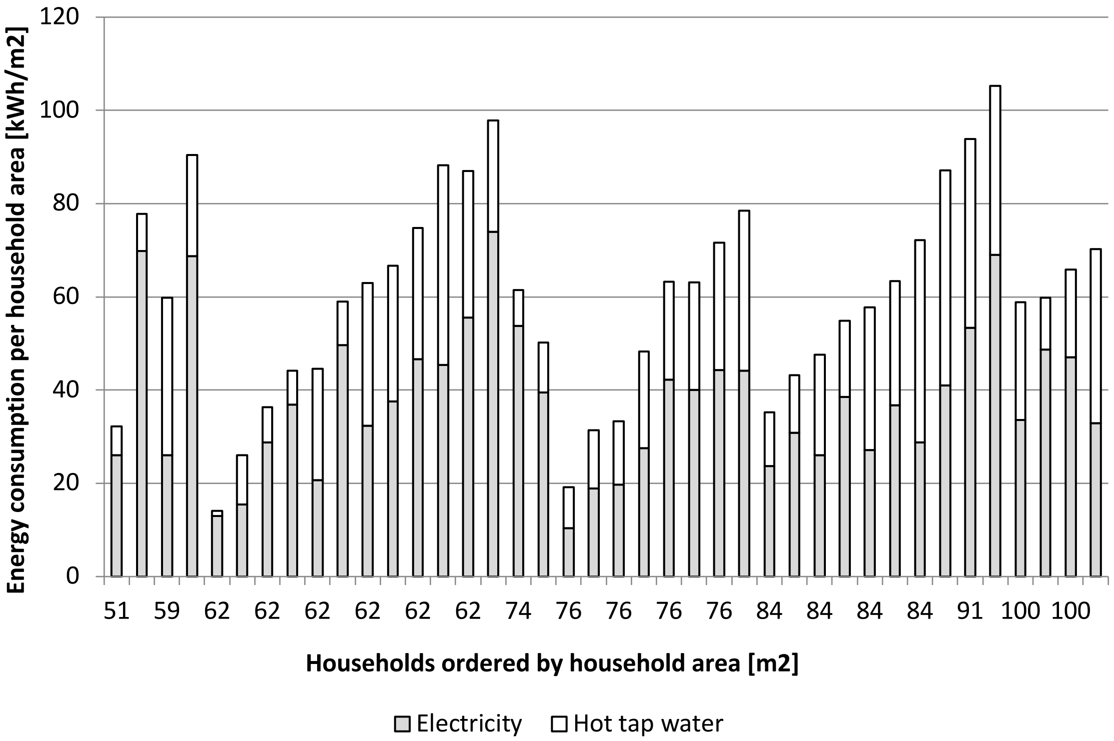

Figure 1. Electricity and hot tapwater use per unit household area [kWh/m^2] for individual households, ordered by household area [m^2], 2016 (Paper I).

Concerning the potential for using high-resolution data in evaluation of household response to DR strategies, Paper II investigated the impact of real-time price visualization on household electricity consumption (and the subsequent effects on costs and carbon emissions, which are discussed in the paper). The analysis was based on data from a small-scale field pilot, covering 12 households in a suburban area of Stockholm (Fagersjö), using high-resolution energy data for one year, 2013.

The mean change in electricity use and mean electricity spot price based on all hours of 2013 are illustrated in Figure 2. It shows that, in line with the overall purpose of DR strategies (see section 2.3.2), households on average increased their electricity use during off-peak hours with lower electricity prices and decreased their electricity use during peak hours with higher prices (Paper II). Moreover, it is clearly apparent that the largest share of the reduction occurred during working hours (i.e., 08.00-18.00 h), rather than during hours when most households are cooking dinner or watching TV (i.e., 18.00-22.00 h), although the fluctuations in price during these periods are relatively small (Paper II).

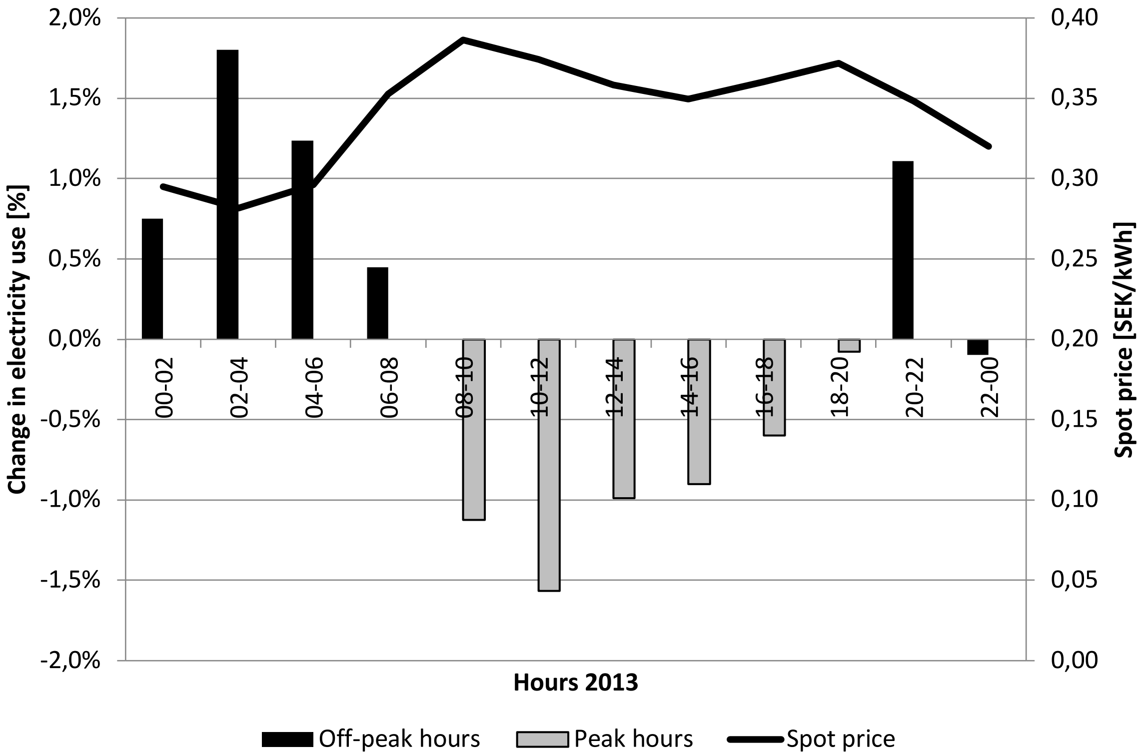

Figure 2. Mean two-hourly change in electricity use [%, left-hand axis] and mean two-hourly electricity spot price [SEK/kWh, right-hand axis] based on all hours of 2013 (Paper II).

Taken together, the results in Paper I and II suggest that the use of high-resolution data has the potential to provide evaluation outcomes of increased transparency and accuracy with regard to energy consumption in buildings and households. Therefore, high-resolution data provide possibilities for improved energy performance indicators (Paper I) and further understanding of how dynamic pricing may impact electricity consumption patterns (Paper II). Moreover, as data from smart meters allow for continuous analysis and evaluation, a 'real-time dynamic understanding' of household energy consumption may be achieved, where EF and DR strategies and incentives can be repetitively adjusted and improved based on consumer response.

Energy consumption behavior is a complex decision-making process influenced by a wide range of behavioral and contextual factors (see section 2.1). However, data from smart meters only provides information on the final outcome of this process (i.e., actual energy use). Hence, while Paper II shows that smart meter data may provide an answer to 'how' DR strategies impact energy consumption, it also emphasizes the need to combine energy consumption data analysis with qualitative approaches in order to investigate the 'why' question, i.e., underlying reasons and motivations for observed changes and/or barriers and obstacles for insufficient effects.

4.2 A conceptual framework for evaluation of household response to EF and DR strategies (Paper III)

In Paper III, a conceptual framework for evaluation of consumer response to EF and DR strategies was devised. As previous evaluation efforts have typically adopted a mono-disciplinary approach, as discussed in section 2.4, the framework was developed with the aim of gaining an increased understanding of variations in household responsiveness to EF and DR strategies, by exploring the relationship between impact on electricity use and influencing factors on energy consumption behavior. Drawing on previous research (see section 2.1), the approach was based on the assumption that key influencing factors (IFs) for energy consumption behavior fall within four main categories: socio-demographics, energy-saving attitudes, ability, and external factors (Paper III).

In practice, the framework developed in Paper III involves three main processes, as illustrated in Figure 3: i) Household-individual changes in electricity consumption are examined using smart meter data, ii) household-individual IFs are measured using quantitative data from survey questionnaires, and iii) households are aggregated based on co-existing characteristics in IF measures, providing evaluation outcomes illustrating the relationship between changes in energy consumption and IFs (as exemplified in Figure 3 by household size, environmental attitudes, and perceived control) (Paper III). The category of external factors influencing energy consumption is represented by the specific incentives used by the EF/DR program of study, and hence was treated as a fixed variable in the analysis.

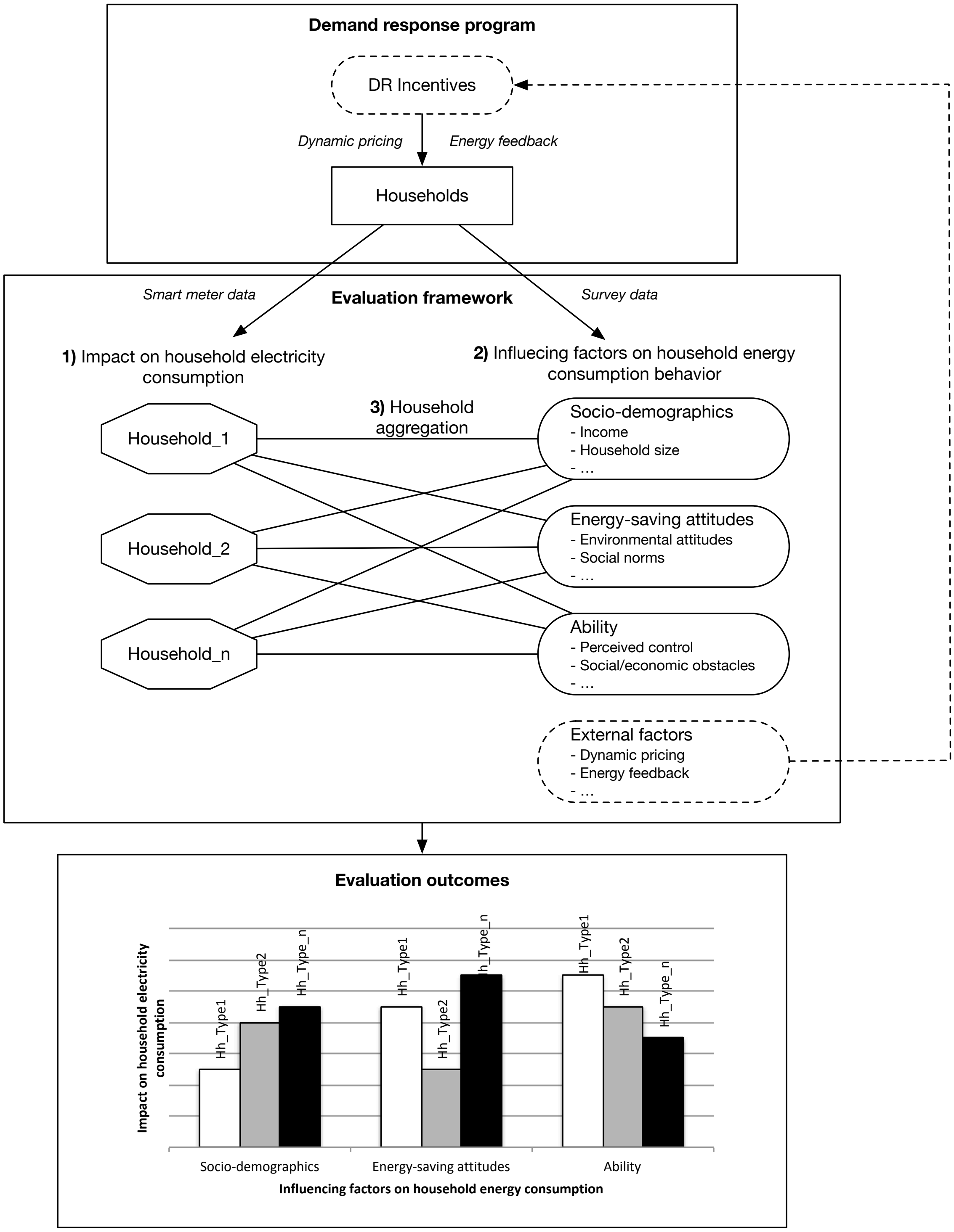

Figure 3. Overview of the conceptual framework for evaluation of consumer response to energy feedback (EF) and demand response (DR) strategies (Paper III).

To demonstrate its practical applicability and analyze its potential to increase understanding of how households respond to EF and DR strategies, the framework was used for evaluation of the *Active House* (AH) program in Stockholm Royal Seaport (Paper III). The AH program covered 154 smart home households (of which 136 households were included in Paper III) equipped with HEMS, which provided real-time feedback on energy consumption, smart home features, and price and environmental signal, during 2017[7].

Figure 4 shows an example of evaluation outcomes enabled by use of the framework (Figure 3), illustrating the impact on electricity use by household size, accounting for single, couple, and family households. Since a secondary aim of the study was to investigate the potential of environmental incentives, by comparing the effectiveness of price and environmental signals, each household category was further divided into subgroups of price and environmental signals. As shown in Figure 4, changes in electricity use varied widely across different types of households, with the most prominent differences arising between single households (reductions of 16.8% and 15.6% accounting for all hours) and family households (reductions of 6.7% and 3.7% accounting for all hours, 4.3% increase in electricity use during peak hours by households with environmental signals). Another notable finding was that reductions for households with price signals were greater than reductions for households with environmental signals across all household types, suggesting that the price signal was the more effective incentive for reducing consumption (Paper III).

[7] See section 3.2.1. and Paper III for further descriptions of the AH program. A detailed description of the HEMS concept used in the AH program is provided in Paper IV.

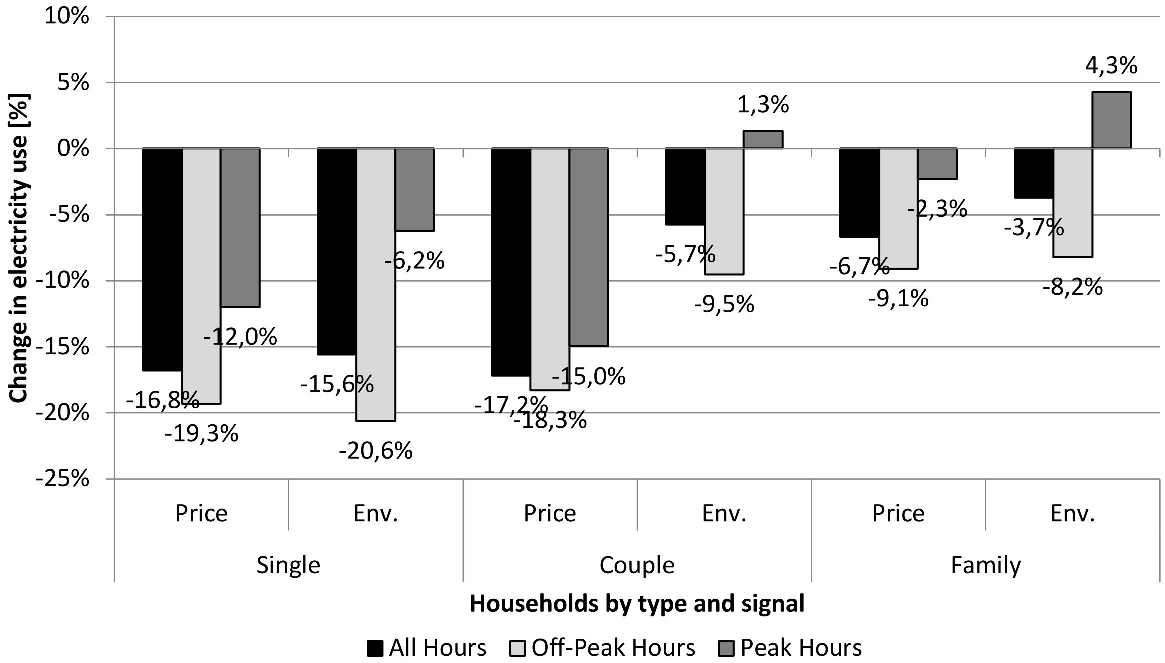

Figure 4. Mean change in electricity use [%] during all hours, off-peak hours, and peak hours by single, couple, and family households with price and environmental signals, respectively, in 2017 (Paper III).

By breaking down the effects of EF and DR on electricity use to household level, the framework produces evaluation outcomes with a higher level of detail, improving understanding of how the effectiveness of EF and DR strategies may vary across different types of households. Thus, outcomes may serve as a valuable input for the development of enhanced strategies, refining incentives and techniques to target specific consumer segments. However, in the context of this thesis, where a mixed methods evaluation approach was applied, the quantitative evaluation results provided by the framework may primarily serve as a starting point for qualitative approaches investigating reasons and motivations for observed effects and patterns (Paper III).

The study-specific context of the AH trial limited the analysis of potential contributions of the framework. Despite a 72% response rate to the survey questionnaire, the great majority of the households provided similar answers to questions regarding environmental and economic motivations and perceived ability and control[8]. Hence, while the framework allows for multivariate analysis, lack of variance in attitudinal and behavioral factors prevented such analysis in the case study. This outcome is considered to be strongly related to the specific population of the AH trial, rather than directly attributable to the framework itself (for a further discussion of the limitations of the case study, see section 4.5).

[8] See Paper III for details of responses to the survey.

The framework is also highly dependent on survey data, and thus limited by households' willingness to respond to questionnaires. The considerably high response rate achieved in the AH trial can never be guaranteed. Nonetheless, previous research suggests that response rates are highly dependent on the design of the survey, where short and clear questions, logical ordering of questions, and clear description of the purpose of the survey are proposed as important factors for increased survey response (e.g., Cook et al., 2000; Fan & Yan, 2010). In addition, as in the case of the AH trial, complementary data from additional sources (e.g., housing corporations, building companies) may be used to fill information gaps concerning characteristics of the actual apartments (e.g., apartment area, type of ownership, etc.).

4.3 Household motivations, perceptions, and obstacles to engaging in EF and DR strategies (Paper IV)

In Paper IV, household motivations, attitudes, and perceived obstacles to engaging in EF and DR strategies were explored by investigating the potential of HEMS, involving energy feedback, smart home features, and economic incentives[9], to influence household energy consumption. The study was based on data obtained in in-depth interviews with 14 householders who participated in the AH trial, selected to be representative for the full population of the trial in terms of household size, composition, age, and type of ownership[10]. In the following sections, key findings and outcomes are summarized and discussed.

Concerning attitudes and motivations for energy savings, two main motivational factors were identified, financial and environmental. Although both these reasons were mentioned by most interviewees, the vast majority of the interviewees stated that reduced climate and environmental impact was their main motivation for energy conservation efforts. In fact, many of these interviewees expressed significant environmental concerns, and reported that they had the intention to act in an environmentally friendly way in all their everyday routines, e.g., recycling waste, buying organic food and products, choosing bike over car, etc. Although only two interviewees reported cost savings as their strongest motivation for reducing energy consumption, all interviewees stated that the economic incentive would most likely gain greater relevance as a motivational factor if energy prices increase significantly from today's levels (Paper IV).

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[9] See Paper IV for a detailed description of the HEMS concept used in the Active House program.
[10] See Paper IV for further details of the households interviewed.

Concerning perceptions and use of the HEMS, several positive effects were identified. Interviewees reported increased understanding of consumption 'baseline levels', greater awareness of unnecessary energy use, and increased home comfort as welcome outcomes. Although the knowledge acquired in some cases was translated into energy-savings actions (e.g., switching off lamps in unoccupied rooms, being sparse with hot tapwater use), a number of obstacles that limited households' ability to change their energy consumption behavior were identified. Some clear links were apparent between the obstacles identified and the influencing factors on behavior suggested by previous research (see section 2.1), particularly related to knowledge, sense of control, and values and attitudes (Paper IV).

First, concerning knowledge, it was found that the energy feedback provided in the AH trial largely failed to support informed decisions on reduced consumption, since it lacked relevant information such as behavioral outcomes (e.g., economic and/or environmental effects of energy consumption) and potential behavioral alternatives (e.g., what specific actions to take to reduce consumption without markedly disturbing everyday routines). The criticism reported by the interviewees can be summarized into some general recommendations directly related to the feedback and features provided by HEMS: i) Energy feedback needs to be clear, relevant, relatable, and flexible, i.e., presented in a variety of metrics, formats, and aggregation levels, in order to help consumers make links between everyday practices and energy consumption and/or environmental/economic impact. ii) Smart home features need to be easy to understand and use, technically robust, self-learning, and contribute to increased comfort in order to support energy saving efforts. iii) Visual design of in-home displays needs to be appealing and intuitive for consumers to easily find, interpret, and navigate among different information and features (Paper IV).

Second, concerning sense of control, the majority of the interviewees perceived their electricity use as 'already low', without any room for further reductions. Major electricity-consuming activities such as cooking, laundry, and cleaning were considered basic necessities that could not be omitted or reduced without a significant negative impact on living standards. Hence, although households possess the required willingness and knowledge to change behavior, the step from intention to actual change relies on whether households perceive that there is a possibility to really act differently. When this not is the case, the findings in Paper IV confirm the risk of rebound effects suggested by previous research (e.g., Hargreaves et al., 2010). Through this, energy feedback may give rise to some anxiety and stress among households, in that they are constantly exposed to their own consumption, reminding them of environmental and financial impacts while they perceive that they cannot do anything about these (Paper IV).

Third, concerning values and attitudes, some specific activities were seen as justifiable and reasonable, i.e., a type of 'well-deserved' energy consumption important for comfort and 'value of life'. Interviewees mentioned different types of activities and appliances seen as non-negotiable, such as computers, sound systems, televisions, and baths and showers. Hence, although households are positive to energy-saving measures for economic and/or environmental reasons, their motivation for this may be trumped by conflicting values of higher personal priority (Paper IV).

In a similar manner, disagreements and differences in attitudes among household members may prevent potential energy savings, as household energy consumption to a large extent may be considered as a collective action. This means that although some household members have the ambition to reduce consumption, such attempts may be overridden by consumption considered justifiable by other household members (Paper IV).

In summary, the results raise concerns about the underlying assumption within EF strategies of a linear relationship between increased information and reduced energy consumption (see section 2.3.1). While such a simplified cause and effect chain may be appealing for policy-makers, the findings in Paper IV suggest that households in fact tend to act and respond highly individually to EF and DR strategies, not necessarily leading to changes in energy consumption.

4.4 Summary of research contributions

As shown in the above sections, this thesis contributes with insights and findings of relevance for several key actors and stakeholders within the field. Concerning empirical contributions, the case study research provides results and findings from one of the first field trials in Sweden involving real-time feedback on energy consumption, dynamic pricing tariffs, and HEMS. For researchers, insights from the trial add to the existing literature on EF and DR studies, where only a few field trials of similar scope have been carried out in Scandinavia to date (see section 2.3). For policy-makers, the results provide an indication of the potential of market-based policy instruments to foster increased energy efficiency and demand flexibility within the Swedish residential sector, serving as input for further policy development. For practitioners within the energy field, findings from the trial may assist in the design of future EF/DR programs, proving a basis for enhanced strategies and incentives.

Concerning methodological contributions, the results reported in this thesis demonstrate how quantitative and qualitative methods can be combined to increase understanding of household engagement and response to EF and DR strategies. By doing so, the thesis addresses some of the limitations of previous evaluations (see section 2.4), producing deeper and more comprehensive evaluation outcomes. The findings should be of relevance for researchers and energy companies seeking to investigate the effectiveness of EF and DR to promote increased energy efficiency and demand flexibility in the residential sector, providing a starting ground for further exploration of the potential for using a mixed methods approach.

4.5 Discussion of limitations

The quantitative and qualitative methods used in this thesis are all associated with some limitations and uncertainties, primarily related to objectivity, generalizability, and reliability. Regarding objectivity, it has been suggested that, due to the close distance between the investigator and the participants, biased results can be produced as interpretation of data is subject to the focus of the investigator (e.g., Benbasat et al., 1987; Bryman, 2016). Although complete objectivity can never be demonstrated, the data from interviews in Paper IV were analyzed as a group effort, interpreted and discussed by several researchers, hence reducing the risk of biased results.

Regarding generalizability, the case study described in the thesis was conducted in strict relation to the context of the AH field trial, bounded to its specific planning, design, and implementation (Papers III and IV). Thus, the results should only be generalized to a larger scale with great caution, considering in particular the small sample size, limited time period, and specifics of the study population (high-income, highly educated households, notably above the Swedish national average, see Paper IV). To improve understanding of the complexity of household energy consumption, behavior studies on larger scales, including larger sample sizes, longer time periods, and households with greater variation in socio-demographic characteristics, are needed (see further recommendations in Chapter 5).

Regarding reliability of results produced through quantitative approaches, lack of data availability was the most limiting factor. As mentioned in section 3.3.1, it was not possible to establish household-individual baselines based on historical consumption data, so the use of control households was considered the best available option. However, this option is associated with some uncertainties, as comparison of different households means comparisons of different people, and therefore the possibility of potential differences in non-measured factors between control households and intervention households affecting the accuracy of the results cannot be excluded. However, the use of control groups is a widely accepted scientific approach, frequently applied in studies assessing effects on energy consumption (e.g., Abrahamse et al., 2005; Darby, 2006; Ehrhardt- Martinez et al., 2010; Grønhøj & Thøgersen, 2011;

Schleich et al., 2013; Gölz, 2017). In addition, to reduce the risk of comparing 'apples and oranges', the control households were recruited and matched based on corresponding geographical, socio-demographic, and physical characteristics to the intervention households. Hence, although availability of historical consumption data would most likely have brought additional validity to the results, the findings can be considered not to be affected by the specific approach of using control households to any critical extent.

5. Further research

The research presented in this thesis only addresses a limited few of all the issues related to the potential of EF and DR strategies to influence household energy consumption. For instance, it has been widely suggested that EF and DR strategies involve a wide range of critical challenges within the technical, economic, and market domains (e.g., Delmas et al., 2013; O'Connell et al., 2014; Nolan & O'Malley, 2015; Karlin et al., 2015), areas which all merit dedicated research. However, the following sections focus solely on challenges closely related to the quantitative and qualitative approaches undertaken in this thesis, highlighting key issues and areas for further research.

First, and perhaps most important, future explorations of using a mixed methods approach for evaluation of household engagement and response to EF and DR strategies should involve case studies over longer time periods and on greater scales, including larger population sizes and households with varying socio-demographic characteristics. Such studies could address the need for deeper insights into the potential long-term effects of EF and DR strategies (e.g., Hargreaves, 2012) and allow for improved generalizability.

Second, the importance of reliable baselines when evaluating the effectiveness of EF and DR strategies has been widely stressed (e.g., Delmas et al., 2013; Nolan & O'Malley, 2015). However, given the study-specific context of the research presented in this thesis, household-individual baselines based on historical consumption data could not be established. Hence, for improved reliability in evaluation outcomes, future studies should secure such measurements, ideally using both control groups and historical consumption to examine potential impacts on energy consumption.

Third, but also related to energy consumption data, the analyses in this thesis were limited by using data on a total household level only. Future studies should strive to obtain energy consumption data on a room-specific or ideally an appliance-specific level, thus providing possibilities to link changes in consumption levels and patterns to specific energy-related activities, behavior, and appliances. Appliance-specific energy data would also enable provision of feedback on a higher level of detail, making it easier for households to link specific activities to their consequences and identify alternative consumption behaviors) (e.g., Fischer, 2008; Ehrhardt-Martinez et al., 2010).

Fourth, although a deeper analysis of potential effects of EF and DR strategies on underlying behavioral determinants was beyond the scope of this thesis, it is a subject with great potential for further research. Future studies will most likely gain from building on previous research efforts (e.g., Steg & Vlek, 2009; Abrahamse & Steg, 2009), adopting methods and tools from the sociopsychological field to improve understanding of the potential of EF and DR to influence behavioral factors such as personal values, beliefs, and moral norms. Through this, deeper insights into the relationship between the theories underlying the EF and DR concepts and practical implementation of these strategies could be achieved. Moreover, findings reported in this thesis (Paper IV) suggest that household energy consumption is largely integrated in everyday activities and routines involving several household members, rather than an individual action by a single consumer. Hence, future behavior-oriented research might gain from focusing more on the household collective, investigating household dynamics and cultures for joint energy conservation efforts.

Fifth, in line with previous studies (e.g., Fischer, 2008; Ehrhardt-Martinez et al., 2010), the findings in this thesis suggest that household perceptions and attitudes to EF are heavily dependent on the content and presentation of the feedback. Following several previous attempts (e.g., Karjalainen, 2011), future studies should try to articulate the most effective feedback strategies, accounting for metrics, frequency, comparisons, aggregational level, visual design, etc. Such efforts should also assess the way in which feedback is provided, comparing the effectiveness of the most recent techniques, e.g., in-home displays, mobile apps, and internet-based services.

Sixth, smart home technologies, i.e., smart home features that attempt to increase energy efficiency while also enhancing in-home comfort and convenience, such as smart washing machines, lighting controls, and home/away switches, are the subject of current research (e.g., Wilson et al., 2015; Hargreaves et al., 2017). It has been suggested that such technologies may be both technically and socially disruptive (e.g., Hargreaves et al., 2017) and that, due to enticing visions and high expectations, they could also normalize and intensify energy consumption (Nyborg & Røpke, 2013; Strengers, 2013). While this thesis briefly touched upon the subject (Paper IV), further exploration of how consumers use, perceive, and adopt smart home technologies is required. Further investigation of the potential of smart home technologies is of particular importance given that the smart home market is expected to grow dramatically in coming years (IEA, 2013), and given that some firms claim that these technologies can save up to 30% of energy costs, without compromising home comfort (Siemens, 2014).

Finally, the present thesis primarily focused on electricity, so future studies should build on previous efforts (e.g., Sønderlund et al., 2014; Liu et al., 2015) to further investigate the potential of EF and DR strategies to promote reductions in residential use of space heating and hot tapwater. Providing better knowledge about such approaches may be considered of particular relevance for Sweden, where heating and hot water consumption account for approximately 80% of total residential energy use (The Swedish Energy Agency, 2017).

6. Conclusions

This thesis explored the potential for using a mixed methods approach to provide improved understanding of household engagement and response to energy feedback and demand response strategies. The research comprised literature reviews and empirical studies in real-life settings, involving surveys, in-depth interviews, and smart meter energy data analysis. The results suggest that a mixed methods approach can address several of the limitations identified in previous evaluation efforts.

With regard to research objective (1), it was found that high-resolution data from smart meters can aid evaluation of household energy consumption and response to DR strategies, providing evaluation outcomes of improved transparency and accuracy (Papers I and II). It was also found that high-resolution data can increase the level of detail on different types of energy use (Paper I) and increase understanding of how dynamic pricing impacts electricity consumption patterns (Paper II).

With regard to objective (2), a conceptual framework for evaluation of household response to EF and DR strategies was developed and analyzed through application in a Swedish field trial (Paper III). It was found that the framework has the potential to overcome some of the limitations of conventional evaluation approaches, providing improved understanding of variations in household responsiveness to EF and DR strategies by exposing the relationship between impact on electricity use and factors influencing energy consumption behavior. This can yield better knowledge of how the effectiveness of EF and DR strategies varies across different types of households, enabling formulation of better strategies and incentives targeting specific consumer segments (Paper III).

With regard to objective (3), household motivations, perceptions, and obstacles to engaging in EF and DR strategies were identified, providing increased understanding of how home energy management systems (HEMS) involving energy feedback, smart home features, and economic incentives are perceived, used, acted upon, and the resulting effects on awareness, energy-related behavior, and consumption (Paper IV). It was found that, although several positive effects such as increased energy awareness and home comfort may be achieved, HEMS does not necessarily lead to changes in energy consumption. Several obstacles to energy consumption change were identified, primarily related to household-individual factors such as knowledge, sense of control, and personal values and attitudes. Hence, the findings raise concerns about the assumption of a linear relationship between increased information and reduced energy consumption, suggesting instead that households tend to perceive and respond to EF and DR strategies highly individually (Paper IV).

The thesis contributes with insights and findings of relevance for different key actors and stakeholders within the field. The demonstrated methodological contributions of a mixed methods evaluation approach and the empirical results from the case study research can serve as valuable input in the development of enhanced methods, strategies, and policies, assisting researchers, policy-makers, and practitioners within the energy field (see section 4.4).

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