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Revisiting household energy rebound: Perspectives from a multidisciplinary study

Bente Halvorsen¹, Bodil M. Larsen¹, Harold Wilhite² and Tanja Winther²

Abstract

In this paper, an interdisciplinary team of economists and anthropologists study the perplexing case of Norwegian households' heat pump ownership. The heat pump is a technology that has the potential to reduce electricity consumption by up to 25% compared to conventional electric heating, but, as we demonstrate in this study, when taken into use it results in little or no change in electricity consumption. To explain this large rebound effect, we use a quantitative economic analysis combined with qualitative interviews attuned towards examining the effect of heat pumps on people's everyday practices. We find that, on average, households with and without a heat pump use approximately the same amount of electricity. The main sources of rebound identified was higher indoor temperature and heated living space, less firewood and fuel oil use and less use of night-set-backs or reduced temperature while away from the home.

Keywords

Household energy consumption, Heat pump, Energy efficiency, Rebound effects, Multi-disciplinary

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Introduction

Despite the common assumption that introducing more energy-efficient technologies is a cheap and effective way of reducing energy consumption, empirical studies indicate that the implementation of energy efficiency technologies often results in unanticipated behavioural changes that reduce or eliminate the expected energy savings.^{1,2} However, the drivers and scope of these rebound effects are still not fully understood. Few studies have managed to adequately quantify the rebound in energy use; fewer yet have identified what households actually do that result in a rebound of their energy consumption or the rationales behind these changes in energy use.

In the economic literature, there are studies which quantify significant rebound effects.² This literature focuses mainly on price and income effects of increased energy efficiency.³ Little attention is given to changes in the daily activities and habits of households after adoption of an energy efficiency measure. As price and income effects of a necessity good such as electricity

are generally thought to be low, it is often argued that rebound effects ought to be small. Nonetheless, large rebound effects are observed in empirical analyses.^{1,2} However, due to a lack of information, it is often not possible to fully explain the rebound effects found in the analysis. To achieve a comprehensive explanation, one needs detailed information on the micro level of how the households adopt and use the new technology, which is normally not recorded in larger datasets.

To account for the factors that foster rebound, social psychologists have examined the role of changing attitudes, norms and social behaviour.⁴ Energy rebound has also been studied by sociologists and

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anthropologists.^{5,6} These studies use qualitative research designs and several studies apply social practice theory to an understanding of home energy consumption.^{7–9} A recent publication argues for the merit of combining qualitative data on the practices behind energy consumption with quantitative analyses.⁵ In such mixed methods research, qualitative data may be used in advance of surveys or the collection of other quantitative data, providing input on the themes to be explored in questionnaires. Alternatively, qualitative data may be used in the aftermath of quantitative surveys to help explain and elaborate on central observations.

In this paper, a mixed quantitative and qualitative analytical approach have been applied to understand the rebound effects of household heat pumps.⁵ Our study builds on two coordinated studies; one economic and one anthropological.^{10,6} As in Gram-Hanssen, the qualitative study is framed in a social practice theory perspective to generate insights on how heating practices have changed after heat pumps are installed, and on the reasons behind the observed changes in practices.⁵ However, in our paper, the quantitative approach is based on statistical economic modelling (econometrics) of household behaviour, which enables us to identify and quantify different behavioural causes of the observed rebound effects. As the quantitative study is not able to explain all causes of the observed rebound effect, the qualitative study use the results of the quantitative study to develop research questions on why and how households change their behaviour after investing in a heat pump, to better understand these unexplained sources of rebound found in the quantitative economic analysis. In addition, the qualitative study was designed to examine whether it would confirm the causes for rebound effects identified in the quantitative economic study. In this way, we are able to cross-check the robustness of the main results in both analyses, and discuss the extent to which the results from the two studies would complement, confirm or contradict each other.

Background

In Norway, one of the main uses of energy in households is for space heating. Depending on winter temperatures, energy prices and other factors, the proportion of energy used for heating homes varies from 40 to 50% of household stationary energy consumption.¹¹ Conventional electric heating (resistance ovens and heating cables) has been the most common heat source in Norwegian households, often in combination with wood stoves or fireplaces. Approximately 70% of Norwegian households have this combination of heat sources. During the last decade, we have seen a

tremendous increase in the number of households owning a heat pump. In the year 2000, less than one percent of Norwegian households owned a heat pump. In 2012, a quarter of the households owned a heat pump, of which approximately 90% are air-to-air heat pumps. Heat pumps are found in all types of households, but are more common in detached houses and in farm houses (<http://www.ssb.no/en/energi-og-industri/statistikker/husenergi>).

Compared with a conventional heating system, air-to-air heat pumps reduce the amount of electricity needed to achieve a given indoor temperature because they use ambient heat from outside air to produce indoor heat. Given the technical potential for electricity savings of the heat pump, the expected reduction in household electricity consumption from the installation of a heat pump should be significant, assuming that households do not change their heating behaviour in a significant way. However, when comparing electricity consumption before and after installing a heat pump, using data from the Norwegian Survey of Consumer Expenditure (SCE) for 2009, we do not see this reduction in average consumption.

To illustrate the distribution of the rebound effect associated with heat pump ownership among different households, we compare electricity consumption the year before the investment in the heat pump with their consumption after the investment (for which we chose the year 2009). In this year, an additional questionnaire on energy use was attached to the SCE, enabling us to do this comparison on an individual level. Information on household electricity consumption in the investment year and the reference year 2009 is collected from the household's electricity supplier and corrected for the differences in outdoor temperature between the years. The resulting electricity savings are sorted according to size and plotted in Figure 1. If the household uses less electricity after investing in the heat pump, electricity savings are positive. However, if the household increases its electricity consumption after investing in the pump, electricity savings is negative.

We see from the figure that some households use less electricity, whereas others (40%) use more electricity after investing in a pump. On average, the mean electricity savings do not differ significantly from zero. Bearing in mind that the heat pump is technically more energy efficient than ordinary electric heaters, this implies that on average, the rebound effect in electricity consumption appears to be approximately equal in size to the technical energy savings potential of the heat pump. Had we used the technical potential for savings to estimate the effect of installing a heat pump, the results would have been overestimated. For a discussion of how the use of technical performance as

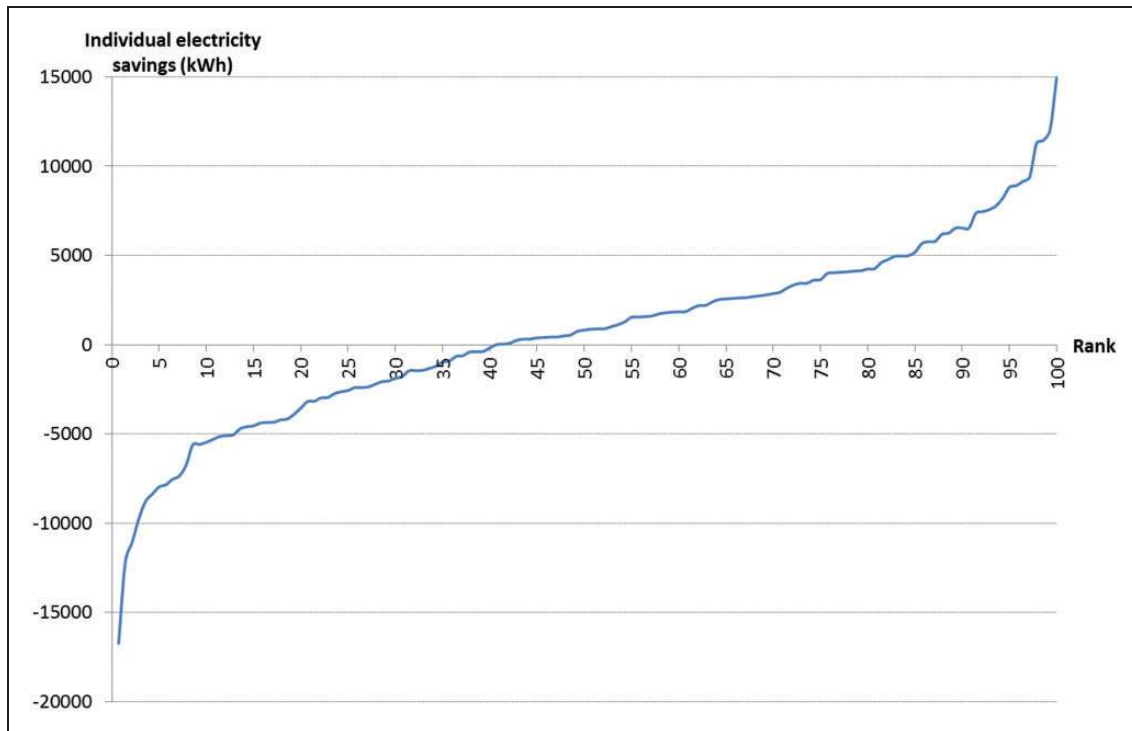


Figure 1. Household electricity savings (kWh) before and after the heat pump investment, corrected for differences in outdoor temperature ($N = 141$). Source: Norwegian survey of consumer expenditure 2009.

reference for predicting the effect of energy efficient technologies is likely to overestimate the potential for savings (preboud effects).^{12,13}

Surprised by the size of this rebound effect, we wanted to investigate the changes in heating practices behind this result and to explain why the savings differs so much across households. Could the investment in a heat pump really alter the way households use energy to the extent that the entire technical electricity savings potential embedded in the heat pump is completely offset by behavioural changes? Why do some households actually increase their electricity consumption after investing in a heat pump? These are the questions we set out to address using the combined result from both the economic and the anthropological study.

Methodological approach

In this section, we describe the methodological approach in both the economic and anthropological analyses, and discuss how they may be combined to synthesize the results.

The quantitative economic analysis

The quantitative economic study combines a micro-economic modelling of household behaviour in combination with a statistical regression analysis, often

referred to as micro econometrics. Data from observed household behaviour is used to identify the main drivers expected from economic theory, corrected for differences in characteristics among households and residences (heterogeneity). This correction for heterogeneity is important in order to correct for potential self-selection problems in the analysis, as, e.g., large households in large houses have a higher probability of owning a heat pump.

In economic theory, the main drivers for rebound effects of an energy efficiency measure are associated with the reduction in energy costs needed to produce the same amount of services, such as space heating and hot water.³ The first of these economic drivers is referred to as *price effects*. Price effects occur because a heat pump will make it cheaper to use electricity to heat a given space to a given temperature, thereby reducing the user price of electricity for heating. The user price of electricity for heating also becomes cheaper relative to the user prices of other energy sources. This will generate two types of price effects; an own-price effect and a substitution effect. As the price of electricity for heating is reduced as a result of increased energy efficiency, the demand for electricity is expected to increase, given that all other factors are equal (own-price effect). In addition, there will be a substitution effect among households that have the opportunity to use paraffin and/or firewood for space heating, as they

may choose to reduce the use of alternative heat sources when electricity has become relatively cheaper. As a consequence, they will use more electricity and less wood and fuel oils, compared to a situation with no change in relative user prices. The reduction in energy costs also means that households have more money available for other purposes after the energy bill is paid, referred to as *the income effect*. This income effect may increase both the consumption of energy goods and of other goods and services. In addition to having a direct effect on the consumption of all energy goods, these price and income effects may also affect the desired production of services at home, for instance lead to an increase in indoor temperature in order to achieve higher comfort. These behavioural changes increase electricity consumption and reduce the consumption of alternative fuels (all other equal), and may reduce actual savings relative to the technical potential embedded in the heat pump.

To quantify these behavioural effects on household energy consumption of investing in a heat pump, we use a data set of 1111 households from the Norwegian Survey of Consumer Expenditure (SCE) of 2009. The data are used to estimate a structural demand model. The estimation is corrected for potential self-selection biases that may occur as the probability of owning a heat pump may be correlated with characteristics of the household and residence. See Halvorsen and Larsen for more information on the econometric modelling, descriptive statistics and estimation results.¹⁰

The results for this estimation are used to predict the effects of heat pump ownership on indoor temperature, household consumption of all specified energy goods and on energy consumption as a whole. The structural modelling applied in this analysis enables us to decompose the total effect on the electricity consumption into various behavioural components, such as the effects on electricity consumption of changes in indoor temperature and changes in the consumption of alternative energy sources. However, we are only able to identify the effects of variables observed in the SCE. These do not provide detailed information on household energy habits and how these would change after installing a heat pump. Thus, in the estimations, we are not able to identify the drivers of a relatively large proportion of the observed rebound effect (see also Table 2). We are therefore not able to explain all differences in energy consumption between households with and without a heat pump, only the contribution from some main economic drivers.

The qualitative analysis

The qualitative study applies a practice theory approach to explain why rebound effects may occur

when households invest in a heat pump. Social practice theory has its roots in the work of Bourdieu and his concept of habitus, defined as a domain of dispositions for action, created and perpetuated through the repeated performance of actions in a given social and cultural space.^{14,15} These dispositions constitute a form for knowledge which influences subsequent performances of the same action.

Over the past decade, practice theory has been revisited and applied to the understanding of consumption. Recent work draws on the refinement of practice theory by Reckwitz, who defines

a practice as a routinized type of behaviour which consists of several elements, interconnected to one another: forms of bodily activities, forms of mental activities, 'things' and their use, a background knowledge in the form of understanding, know-how, states of emotion and motivational knowledge.¹⁶

Practice theory regards the totality of these elements as the unit of analysis, and investigates the interconnectedness between them. Consequently, to understand the changes caused by the introduction of heat pumps (and potential rebound effects), it is necessary to examine how the new 'thing' and the associated knowledge (e.g. expert advice, manuals) become integrated in various existing home practices (e.g. heating, cleaning, time management). Practice theory provides a basis for a more robust analysis than purpose-oriented (rational choice) and norm-oriented theories that have dominated the analysis of energy consumption.¹⁶ Practice theory opens a window for understanding why the expected rational response to an energy efficient technology (i.e. energy savings) does not always occur.

Qualitative methods involve data collection through personal (usually face-to-face) meetings between researcher and respondent, which enhances the understanding of respondents' own life worlds.¹⁷ In-depth interviews are the most common technique, often used in combination with observations, but there is a range of other possible means for collecting qualitative data, such as participatory observation, collecting diaries and life stories and taking photos.¹⁸ A social practice perspective directed attention in the interviews and observations to routinized behaviour, experiential knowledge, practical learning and people's interactions with the heat pump technology. In the qualitative analysis, we observed and asked people detailed questions in interviews on how and why they used the pump as they did, while also focusing on how they had heated (or cooled) their residence prior to acquiring the heat pump. We focused on the different types of knowledge people draw on when using and modifying their energy related behaviour, such as reflexive and practical

knowledge. We also paid attention to people's non-heating-related practices and their various concerns when organising and managing everyday life.

We conducted 28 in-depth interviews with Norwegian households owning a heat pump. The sample was drawn from the households in the counties of Oslo and Akershus that owned a heat pump in the 2012 Norwegian Survey of Consumer Expenditure. The in-depth interviews were conducted face-to-face with all household members in their homes. We used an interview guide to structure the conversations, focusing on people's motivation for purchasing the heat pump, how and from whom they had learned how to use it, and how they interacted with the heat pump in daily life. The questions for the qualitative study were based on the preliminary quantitative results and the need for deeper understanding of some of the specific findings. We asked how the heat pump was being used in combination with other heating sources and how heating practices were related to other home practices (e.g. time management and cleaning), as well as about people's perceptions of comfort and convenience. We also asked about their views on the potential economic gains from using heat pumps as compared to other heating devices. The interviews were open-ended, allowing for questions to be posed in a conversational flow, allowing us to follow up on what was said. Each interview lasted for 1–1½ h and was recorded and transcribed.

Table 1 summarizes the characteristics of the sample. Almost all of the families interviewed lived in a detached house. Each had a chimney and either a wood stove or wood-burning fireplace. Almost all of the houses had electric floor heating in bathrooms and, in a few cases, also in other rooms, and all houses were equipped with electric resistance ovens in several rooms. Of the 28 households, 12 had their heat pump installed from three to five years ago.

The mixed method approach

We have two main goals for the synthesis of results from the qualitative and quantitative analyses. The first is to corroborate the results from the two approaches. This is possible, as both studies study the same phenomenon for the same population. The second is to use the results in combination to paint a broader picture and obtain a better understanding of how heat pump ownership affects household energy consumption. This is important because the quantitative study alone is not able to explain all drivers of the observed rebound effects, whereas the qualitative study cannot quantify the effects or account for the relative importance of the various observed effects. To synthesize, we give a qualitative comparison of results from the two studies, comparing the effects observed by both studies

Table 1. Characteristics of the 28 families interviewed in the qualitative study.

		No. of households
Type of home/building	Detached	26
	Semi-detached	1
	Flat in detached house	1
Type of tenure	Own	27
	Rent	1
Time of installation, heat pump	About to be installed/just moved in	3
	1–2 years	8
	3–5 years	12
	6–15 years	5
Type of heat pump	Air-to-air	22
	Air-to-water	2
	Geo thermal, water-to-water	4
Family status (adults)	Only male	1
	Only female	2
	Both male and female	25
Adult respondents per interview	Male	4
	Female	8
	Both male and female	16
Age of respondents	20 s and 30 s	6
	40 s and 50 s	13
	60 s and 70 s	9
Children living at home	Yes	15
	No	13

Table 2. Decomposition of the predicted effect on electricity consumption of owning a heat pump, kWh, SCE 2009.

	Effect (kWh)
A. Direct effects of owning a heat pump	–764
Constant	2546
Stating that they use the heat pump for cooling during the summer (0, 1)	72
Stating that they may use the heat pump for heating the entire residence (0, 1)	274
Stating that they consume less fuel oils after installing the heat pump (0, 1)	59
Number of substitution possibilities (alternative heating sources)	–3714
B. Indirect effects of owning a heat pump	1058
Increased indoor temperature	484
Reduced consumption of fuel oil	204
Reduced consumption of firewood	370
C. Total effect of owning a heat pump	295

and complementing the unexplained rebound effects in the quantitative study with information on rebound effects found in the qualitative study. This synthesis is summed up in a table comparing the results from the two studies.

Results

Results from the economic study

Table 2 sums up the results from the economic study on how heat pump ownership affects household *electricity* consumption (measured in kWh).¹⁰ A positive sign indicates a rebound effect, whereas a negative sign indicates an energy savings effect of the efficiency measure. The results are separated into direct effects on electricity consumption of heat pump ownership (part A of the table) and indirect effects (part B) through changes in the consumption of alternative fuels and household production of heat, measured by indoor temperature.

We see from the table that all of the indirect effects increase electricity consumption, *ceteris paribus*, and thus contribute to the rebound effect. That means that a considerable reason for the observed rebound on electricity consumption is because the households use less wood and oil for heating, and because they maintain a higher indoor temperature. Together, these behavioural changes imply that heat pump owners who change their consumption of alternative energy sources and/or increase indoor temperature, on average use over one thousand kWh electricity more per year compared with heat pump owners who do not, all other things being equal.

If we turn to the direct effect of heat pump ownership, we can see from Table 2 that, on average, this effect (in total) implies a reduction in electricity consumption. That means that on average, the energy efficiency gains of the heat pump are higher than the rebound effects resulting from these causes. We have decomposed the direct effect into different drivers, some of which reduce and some of which increase electricity consumption, *ceteris paribus*. We find that heat pump owners using the heat pump for cooling use more electricity than other heat pump owners, all other things being equal. We also find that heat pump owners who heat the entire residence with the heat pump use more electricity than other households with a heat pump. We do not have information in the data to find the cause for this, but it may be that these households heat a larger share of the residence with electricity compared to households with a heat pump who do not have this opportunity. In the questionnaire, respondents with heat pumps were asked whether they use less fuel oil after they installed the heat pump. We find that households that answered yes to this question use significantly

more electricity than other heat pump owners. This effect comes in addition to the indirect effect of reduced wood and oil consumption (in section B of Table 2).

All of the direct effects discussed above increase electricity consumption (given that the household own a heat pump) and thus represent drivers for the rebound effect reducing the realization of the technical energy savings potential. We have only managed to identify one direct effect that implies reduced electricity consumption of heat pump ownership, and that is the effect of having the option to use several different energy sources for heating, measured by how many types of heating equipment the household possesses. We find that this variable has a large negative effect on the electricity consumption, implying that heat pump owners with alternative heating options save more electricity than those who have fewer options to the heat pump.

The biggest positive direct effect of heat pump ownership comes, however, through a large and highly significant constant term. This constant contains the effect of all behavioural differences (not specified by a separate variable in the econometric estimation) between households with and without a heat pump. Unfortunately, we do not have sufficient detailed description of household behaviour in this data to identify the sources of these drivers. We will thus use the results from the qualitative study to shed additional light on what sort of behavioural changes are behind this large rebound effect.

Even if the sum of all the direct effects is negative, the reductions in electricity consumption through these direct effects are not large enough to offset the large increase in consumption due to the indirect effects. In total, we find a small (and insignificant) increase in electricity consumption for households that own a heat pump compared with other households, which is consistent with what we found in Figure 1 comparing consumption before and after investing in a heat pump. We therefore conclude that the overall electricity savings potential, through the technically efficient heat pump, is offset by the reduced use of alternative fuels, increased indoor temperature and other behavioural changes.

While Table 2 sums up the effects of heat pump ownership on household *electricity* consumption, Table 3 shows the effect on *energy* consumption. Since households with a heat pump use less firewood and fuel oil than other households, yet have approximately the same electricity consumption, we would expect energy consumption to be reduced. This is also what we find, as the reductions in firewood and fuel oil consumption far exceeds the small increase in the use of electricity. This means that when all energy sources are accounted for, the introduction of heat pumps in Norwegian homes has increased the energy efficiency of heating. However, as documented, several mechanisms (direct and indirect

Table 3. Effects on household energy consumption of owning a heat pump, kWh, SCE 2009.

	Effect
Total energy consumption (kWh)	−2180
Consumption of electricity (kWh)	295
Consumption of fuel oils (kWh)	−693
Consumption of firewood (kWh)	−1782

effects) contribute to producing rebound effects, which implies that a large share of the potential for both electricity and energy savings is not realized when heat pumps are taken in use.

Results from the qualitative study

The rebound effects quantified in the econometric study suggest that households make many changes in how they heat their residences after investing in a heat pump. However, the econometric study was not able to identify all drivers for the observed rebound. In order to better understand how people use heat pumps and other energy sources, we have deployed the results from the qualitative study, that give more contextualized information on how households change their heating practices after acquiring a heat pump.

The qualitative study has sought to disentangle the motives and ways in which people acquire and take heat pumps in use. By this we mean the ways heat pumps form part of, and modify, the social practices into which they are integrated, whether related to heating, ventilating, cleaning, time management, or other activities and concerns. Far from observing energy savings as the main driver or the result when adapting heat pumps, the interaction between family members, with their knowledge, motives and expectations, and the technology, with its script for optimal heating comfort led to practices that increase electricity consumption. This may explain why the econometric analysis finds that the rebound effect offsets the technical electricity savings potential of the heat pump.

A first source of rebound found from the interview sample, which has also been observed in other studies, is that people had often purchased the heat pump in conjunction with changing in heating source, such as replacing the oil heater and when refurbishing and expanding the house.¹⁹ Only seven out of the 28 families in our sample had kept the existing structure of the house and simply added the heat pump to the existing heating system. For those who expanded the size of the house, the increase in the energy needed to heat the expanded space is an important explanation for the rebound effect, i.e. the reduction in the net decrease attributable to the heat pump.

The second source of rebound that we have identified is consistent with the findings from the econometric study: those with multiple heating sources tend to change the mix of energy sources used, using less wood and increasing their use of electricity. Some families had replaced oil burners and former extensive use of wood with the heat pump. Because heat pumps consume electricity, these families assumed that their electricity consumption had increased and that their fuel oil and wood expenses had gone down (though few actually monitored this). Other families had used only electricity for heating before obtaining the heat pump, and a few of these respondents said that electricity consumption (and costs) had decreased because of the heat pump. This finding points to the observation that households with previous use of oil heaters and extensive use of wood are likely to increase rather than reduce their electricity consumption after installing a heat pump. After acquiring the heat pump most families reported that they use the heat pump as their main heating source and that they only use the wood stove or fireplace during particularly cold periods or on special occasions, such as when hosting guests.

A third important source of rebound is related to increased comfort and convenience. The use of the heat pump eliminates the hard work of starting and maintaining a fire in the wood stove or fireplace. Respondents often highlighted how quickly the temperature can be adjusted with the heat pump's remote control, even though most families rarely changed the temperature setting. Many respondents said they were pleased that the heat pump provided an 'even temperature', which they maintained by keeping the heat pump running day and night, including when they were away from home for a weekend or for longer periods. 'You avoid the discomfort of coming home to a cold house and having to wait for the heat' was a typical statement, which reflects a lack of concern about using excessive energy and money in order to have instant comfort when returning from a trip, which reflects a wish to obtain thermal comfort and convenience at the same time. Interestingly, respondents claimed they did not raise the indoor temperature after obtaining the heat pump. However, their detailed accounts of how they modified their heating habits, e.g. by letting the heat pump run 24 h a day, 7 days a week instead of starting a fire in the morning, reflects that an increase in average temperature had indeed taken place. These changes in heating practices contribute to a change in perceptions of optimal thermal comfort.^{20–22}

The discussion above reflects an important result from the qualitative material: the heat pump leads to an expansion of *heating time*. The increased temperatures on cold mornings are a result of this expanded heating time. Another expansion is due to the

maintenance of higher temperatures at night and when the family is away from home for an extended period. A second dimension of the comfort rebound has to do with an *extension of the total space of the house that is heated*. In contrast to point sources such as electric resistance ovens or stoves, our respondents gave detailed accounts of how the pump distributes the heat to several rooms. In order to even out the temperature throughout the house and to avoid experiencing uncomfortable temperature differences in various parts of the house, many said they tended to keep the doors between various rooms open, allowing the heat to flow between rooms.

The factors explaining the extensions in heating time and heated space are not uniquely rooted in people's desire for more thermal comfort. The air-to-air heat pump is in fact designed to transport and circulate air in order to function optimally, thus this heating technology favours open solutions and invites a practice of keeping doors between rooms permanently open and heating larger volumes of space. This effect of the technology's design (or 'script', cf. Akrich) is strengthened through the advice and information provided by installers and matches people's preferences for an extension of comfort to more rooms in the house.²³ Many respondents referred to the installer's recommendation to let the heat pump run continuously and not 'mess with' the set temperature or turn it on and off, continuing with a practice they had used with their previous conventional heating. The technical advice encourages the practice of maintaining even temperatures

throughout the house and increasing comfort. The respondents often rationalized or legitimized their comfort increases by attributing them to 'expert' technical advice.

A fourth category of rebound is a residual of other adjustments. In our qualitative study, examples in this category including attending to children at night (keeping doors open to be able to hear them) and maintaining safety (no need to be careful about the fire) were also given as an advantage of heating with the heat pump. Finally, a concern for improved air quality (avoiding moisture) and co-joint practices, such as drying clothes (leaving the laundry to dry in front of the heat pump), were mentioned.

Summary of results

We have summarized the main findings from the two analyses in a qualitative illustration in Table 4, which shows the effects on the heat pump on electricity consumption. The sign "+" indicates that the specified variable leads to increased electricity consumption.

The results from the two analyses complement and supplement one another. Both studies find that people switch from fuel oils and firewood to electricity for heating, and that the temperature in the living room is increased, especially during cold winter mornings. The results from the qualitative study identify changes in heating practices which are not discernible in the data applied in the econometric study, and which thus end up in the constant term for the direct effects in

Table 4. Illustration of effects on electricity consumption of heat pump ownership.

	Quantitative study	Qualitative study
A. Direct effects of owning a heat pump	—	
Constant	+	
Expansion of heating time		+
Expansion of heated living space		+
Expanding the structure of the building		+
Improvement of air quality, att. to children, safety, dry clothes		+
Stating that they use the heat pump for cooling during summer	+	+
Stating that they can use the heat pump for heating the entire residence	+	+
Stating that they consume less fuel oils after installing the heat pump	+	+
Number of substitution possibilities (alternative heating sources)	—	
B. Indirect effects of owning a heat pump	+	
Increased indoor temperature	+	+
Reduced consumption of fuel oil	+	+
Reduced consumption of firewood	+	+
C. Total effect of owning a heat pump (electricity rebound)	+	+

Note: "+" indicates that the specified variable leads to increased electricity consumption and "—" that electricity consumption decreases. The signs shown for the qualitative study indicate the observed relevance and direction of factors observed among the interviewed households.

Table 4. This includes behaviour such as an increase in the size of heated living space, which was found to be a result of structural changes to the house and due to opening of doors to previously unheated areas. In addition, some of the comfort and convenience motives unveiled in the qualitative study, such as not having to build and maintain a fire, increased heating time and clothes drying may help explain the constant term of the econometric analysis.

Based on the responses from the interviews about changing practices, we find that some households reduced their electricity consumption and some most likely increased it. The latter is due to increases in heated living space and switching from fuel oils and firewood to electricity as their main heating source. This variation in how heat pump ownership affects energy consumption is also evident in the econometric analysis, as we find heterogeneity in both the rebound effects and electricity savings effect.

Conclusion

Over a period of 10 years, approximately a quarter of Norwegian households acquired a heat pump. This rapid development took place with almost no subsidies or other financial support from government policies. Households may apply for grants for the bigger heat pumps. In addition, there was an investment subsidy scheme for air-to-air pumps during the year 2003. However, the main body (between 80 and 90%) of heat pumps in Norwegian residences was acquired without any financial support by the government. We have not seen a similar structural change in heating technology in Norwegian homes since the transition from oil and wood to electricity in the 1970s and 1980s.

In this analysis, we have synthesized the findings from two coordinated studies, one quantitative micro econometric study and one qualitative study. Somewhat surprisingly, the data used in the econometric study showed that average electricity consumption does not differ significantly before and after acquiring a heat pump, but that there is a large variation in the savings among households. Nearly half of the households actually use more electricity after purchasing the heat pump than before, and very few achieve the technical savings potential embedded in the heat pump in the form of substantial reduced electricity consumption. This may seem like an anomaly, but the results from this triangulated analysis help us understand what goes on in Norwegian homes when they install a heat pump.

Both the qualitative and the quantitative study show that many households increase indoor temperature and change their main heating source from fuel oils and firewood to the heat pump, which runs on electricity. In addition, many households increase the size of the

spaces that are heated, reduce the use of night setbacks and do not reduce the heat while away from home. The reasons behind these changes are closely linked to people's concern for comfort, convenience and time management, and also their perception that heat pumps are less costly to use compared to other heating sources. From the face-to-face meetings with users of heat pumps, there is little doubt that many people appreciate the heat pump because it provides them with increased comfort. Changes in practices associated with heating comfort explain why households with a heat pump on average use approximately the same amount of electricity compared to households without a heat pump.

~~It is important to note that although~~ much of the energy savings potential of the pump is offset by behavioural changes, there is considerable variation in how households adapt and use the heat pump. This is a reflection of the heterogeneity among Norwegian households with respect to existing home practices, preferences and motivations for installing a heat pump. Our analysis ~~also~~ shows that while there is a rebound in the use of electricity after the installation of a heat pump, the overall energy efficiency has increased because, on average, the households consume less energy, even after the temperature and heated living space have increased.

Authors' contribution

HW and TW are responsible for the qualitative analysis, whereas BH and BML are responsible for the quantitative analysis. All authors are responsible for the synthesized results.

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