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Abstract:
Increased energy efficiency is often seen as the best way of reducing energy consumption. However, the cost reduction resulting from the efficiency increase can undermine the energy-saving potential of the efficiency measures. In this study, we develop a method for decomposing the behavioral responses to increased energy efficiency based on a conditional demand model applied to a household production framework. We find that the electricity savings potential of the increased use of heat pumps in Norwegian homes is completely offset by changes in consumption. Households with heat pumps maintain higher indoor temperatures, consume less alternative fuels and engage less in energy-saving behavior than other households. This analysis illustrates that subsidizing investments in new and more energy-efficient technology may not always be an effective means of reducing energy consumption.

Keywords: Household energy consumption, energy-saving technology, heat pump, rebound effects.

JEL classification: C31, C34, D12, D13, Q41

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Sammendrag

Økt energieffektivitet blir ofte sett på som den beste måten å redusere energiforbruket på. Kostnadsreduksjonen som følger av økt energieffektivitet kan imidlertid underminere energisparepotensialet av energieffektiviseringstiltaket. I denne studien utvikler vi en metode for å dekomponere adferdseffektene av økt energieffektvitet basert på en betinget etterspørselsmodell anvendt innenfor et husholdningsproduktfunksjonrammeverk. Vi finner at husholdninger med varmepumpe har om lag det samme elektrisitetsforbruket som andre husholdninger. Dette skyldes at husholdninger med varmepumpe tar ut energisparepotensialet i økt velferd, ved at de har høyere innetemperatur, bruker mindre ved og olje og gjennomfører færre energisparetiltak.

1. Introduction

Increasing energy efficiency has been one of the main strategies for combating the climate problem. Several policy measures have been introduced that focus on household production. It is often assumed that increased energy efficiency is a cheap and effective way of reducing energy consumption. However, the full energy-saving potential of an energy-efficiency measure, as measured by the reduction in energy needed to produce the same amount of goods and services, will only be reached if consumers or producers do not change their behavior when the new and more energy-efficient technology is introduced. This is often assumed in analyses of the energy-saving potential of various energy-efficiency measures (as in, e.g., Li et al. 2012a). Based on economic theory, however, we expect behavior to change since increased energy efficiency will reduce the unit cost of producing a good or a service. This will result in a partial increase in demand for the energy source that has become more efficient in use due to both substitution and income effects. The full energy-saving potential of an energy-efficiency measure will thus only be reached if the demand for energy does not respond to changes in the unit cost of production. Several empirical studies indicate, however, that such unwanted behavioral changes as a result of increased energy efficiency, or rebound effects, are noticeable in several cases (Li et al. 2012b, Gram-Hanssen et al., 2012, Frondell et al., 2008).

In Norway, one of the main uses of energy in household production is for space heating. Depending on winter temperatures, the proportion of energy used for heating varies from 40 to 50 percent of household stationary energy consumption (Larsen and Nesbakken, 2004). One of the major sources of increased energy efficiency in household space heating in recent times is the increased use of heat pumps in Norwegian homes during the last decade. In 2000, less than one percent of households owned a heat pump. In 2012, a quarter of Norwegian households owned a heat pump, approximately 90 percent of which are air-to-air heat pumps. The question is how this major change in heating technology has affected household electricity consumption and the mix of energy consumed in Norwegian households. What behavioral changes has this change in technology resulted in?

The extensive substitution possibilities that exist for space heating is interesting in the Norwegian case, since most households can use more that one type of heating equipment to heat their residence. Of the households in our data, 86% can use more than one type of heating equipment, and a combination of firewood and electricity is most common (75%), while 36% can use three or more heat sources, and 20% can use a combination of heat pumps, electric heaters and firewood. There are also extensive substitution possibilities in relation to electricity used for space heating purposes, as 24% can use heat pumps and electric heaters. This means that most households have bought a heat pump as an addition to the heating equipment they already have in their residence. One reason for this could be that, in the cold Norwegian winter, it is not sufficient to rely on an air-to-air heat pump for heating, as many of them stop working at temperatures below -15°C.[1]

All these substitution possibilities make it easy to switch between heat sources and energy carriers. As a result, we would expect to find large rebound effects of increased use of heat pumps in Norwegian homes. In this paper, we examine whether households that own a heat pump have lower average electricity consumption, *ceteris paribus*, or whether the energy-saving potential is eaten up by rebound effects. In the rebound literature on transportation, information about the energy efficiency of a vehicle is often available (e.g., Frondell et al. 2008). It is thus possible (under some assumptions) to infer the change in the unit cost of producing transport services that the energy-efficiency measure results in. This is much more difficult in the case of heat pumps, as the energy efficiency of a pump varies across time and households with outdoor temperature, humidity, installation and utilization of the pump. Thus, we are not able to observe the households' actual unit cost of using electricity for heating purposes in the case of heat pumps. The rebound effects will be reflected in various behavior changes, however, such as changes in the consumption of alternative fuels and indoor temperature, which are observable.

To quantify the rebound effects resulting from these behavioral changes, we develop a behavioral model based on a conditional demand model (Pollak 1969, Browning and Meghir 1991, Halvorsen et al. 2010) that is adapted to a household production framework (Becker 1991, Lancaster 1966, Halvorsen and Larsen 2001). This model is used to decompose the effects of owning a heat pump on household electricity consumption into different behavioral changes: Do households that own a heat pump maintain a different indoor temperature than other households, and/or has it changed their energy-saving behavior? It is also interesting to analyze whether they use less firewood and wood pellets than other households, since the government also aims to increase the use of bio-energy for space heating. This conditional demand model is estimated using a sample of 1111 households from the Norwegian Survey of Consumer Expenditure for 2009, with an additional questionnaire on energy consumption.

In the literature, we find studies that discuss investment decisions concerning heat pumps in Norwegian homes based on micro data (Sopha et al. 2010, Lillemo et al. 2013). The literature

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[1] Newer and more expensive air-to-air pumps will still work in cold temperatures, but in such case their energy efficiency is more like that of an ordinary electric heater.

(Bjørnstad 2012) also contains analyses of households' satisfaction with their heat pumps, based on preferences stated in a survey. To our knowledge, however, no study has attempted to identify rebound effects of heat pump ownership by tracing its effects through behavioral changes in household production and energy demand, and applying econometric analysis to observed micro demand data. This analysis helps us to understand how Norwegian households have adapted their habits and behavior when this new technology is introduced. Our results indicate that, in the case of increased use of heat pumps in Norwegian households, changes in consumption may have completely offset the energy-saving potential of the heat pump, since households with a heat pump have a lower consumption of firewood and fuel oils and a higher indoor temperature, and make less energy-saving efforts than other households.

2. Theoretical foundation

To analyze how households change their behavior after investing in a heat pump, we model household production as a conditional demand model. Here, we only give a brief description of the model. For a more detailed description, see Appendix A1.

2.1 The conditional demand model

In our model, we assume that households can use two different energy carriers, electricity (x_1) and alternative energy sources (x_2), to produce the household service space heating (z), depending on the capital stock (K): $z = z(x_1, x_2; K)$. This stock can involve different technologies producing the same service, using a different or the same energy carrier (e.g., heat pumps and electric heaters). In this model, we only look at the short-term problem of utilization, where the stock is given. Thus, we do not discuss investments in new equipment. We assume that the consumption of these energy carriers is decided simultaneously, given that consumers minimize their costs of producing a given service ($\bar{z}$):

$$\min_{x_1, x_2} \quad p_1 x_1 + p_2 x_2 \qquad s.t. \qquad \bar{z} \leq z(x_1, x_2; K), \tag{1}$$

This minimization problem yields the conditional demand for x_1 as a function of the demand for x_2 and the service production level $\bar{z}$, and the demand function for x_2^*. Inserting the demand function for alternatives to electricity for heating (x_2^*) into the conditional demand function for electricity gives the optimal demand for electricity from the minimization problem (x_1^*) as a function of prices, the capital stock, and the level of service production: $x_1^* = x_1\left(p_1, x_2\left(p_1, p_2, \bar{z}; K\right), \bar{z}; K\right) = x_1\left(p_1, p_2, \bar{z}; K\right)$.

To find the overall optimal demand for electricity (x_1^{**}), we need to find the optimal level of service production (z^*). This depends on the choice of producing services at home and other consumption, given household income and the prices of other consumption, and the cost of household production. Based on the minimization problem, we can calculate the total cost of producing z , given by: $c^* = C\left(p_1, p_2, z; K\right) / z = c\left(p_1, p_2, z; K\right)$. The household is then assumed to maximize its utility (U) from the consumption of services (*z*) and other goods (x_3), given that the expenditures are less or equal to household income (y) and given the prices of other consumption (p_3), the unit cost of household production in optimum (c^*), and characteristics of the household (a):

$$\max_{z, x_3} \; U = U(z, x_3; a) \qquad s.t. \qquad y \geq c\left(p_1, p_2, z; K\right)z + p_3 x_3 . \tag{2}$$

Assuming an internal solution, this utility maximization problem gives the optimal demand for other goods (x_3^*) and the optimal production of services (z^*) as a function of all prices (p_1, p_2, p_3), household characteristics (a), the stock of capital (K), and income (y). If we insert the function for the optimal production of household services z^* into the conditional demand function from the cost minimization problem (x_1^*), we get an expression for the conditional demand function that will equal the demand for electricity in the overall optimum, given by:

$$x_1^{**} = x_1\left(p_1, x_2\left(p_1, p_2, z\left(c^*, p_3, y; a, K\right); K\right), z\left(c^*, p_3, y; a, K\right); K\right) = x_1\left(p_1, p_2, p_3, y; a, K\right) \tag{3}$$

In both these optimization problems, we have assumed an internal solution. Corner solutions are normal, however, both with respect to the choice of heat production and demand for alternative energy goods to electricity. Thus, these functions give the demand for households with a positive consumption. For households choosing a corner solution, the consumption equals zero.

2.2 How does heat pump ownership affect household electricity demand?

By using the conditional demand function in Equation (3), we can decompose the effect of owning a heat pump dK as follows:

$$\frac{dx_1^{**}}{dK}=\frac{\partial x_1^{**}}{\partial K}+\frac{\partial x_1^{**}}{\partial x_2^*}\left(\frac{\partial x_2^*}{\partial K}+\frac{\partial x_2^*}{\partial z^*}\left(\frac{\partial z^*}{\partial K}+\frac{\partial z^*}{\partial c^*}\frac{\partial c^*}{\partial K}\right)\right)+\frac{\partial x_1^{**}}{\partial z^*}\left(\frac{\partial z^*}{\partial K}+\frac{\partial z^*}{\partial c^*}\frac{\partial c^*}{\partial K}\right) \tag{4}$$

We see from the conditional demand model that owning a heat pump can affect the optimal demand for electricity (x_1^{**}) in different ways. First, we have the direct effect on electricity consumption of the heat pump ($\frac{\partial x_1^{**}}{\partial K}$), as the fact that there are more possibilities will change consumption. Second, owning a heat pump will change relative prices of production of space heating, affecting the demand for alternative energy goods (x_2^*). This effect can arise either directly or indirectly through changes in how we produce the service (z^*), as it changes the unit cost of producing heat (electricity for space heating becomes cheaper with a heat pump). It is likely that the main effect resulting from changes in the consumption of other energy goods is the result of changes in relative energy prices for heat production. Third, there is an effect on electricity consumption as a result of changes in the chosen level of service production after acquiring a heat pump ($\frac{\partial x_1^{**}}{\partial z}$). These effects can also be direct, since a heat pump makes it possible to produce new types of services, such as cooling during the summer. Finally, owning a heat pump also has an effect on heat production as a result of changes in the unit cost ($\frac{\partial z^*}{\partial c^*}\frac{\partial c^*}{\partial K}$), since the cost reduction due to the energy efficiency of the heat pump may reduce energy-saving behavior. This may result in an increased indoor temperature and reduced use of night setback and other temperature regulation to save money and energy.

3. The data

In this analysis, we use data from the Norwegian Survey of Consumer Expenditures (SCE) for the year 2009, and data from an additional questionnaire concerning energy consumption. The data used in the analysis are from 1111 households constructed around individuals randomly drawn from the Norwegian population. We have information about household electricity consumption collected from the households' electricity supplier, household and residence characteristics, information about ownership of heating equipment and electrical appliances, and information about energy-saving behavior undertaken by the households. Unfortunately, we do not have information about household income in this data. We therefore use the household's total expenditure as a proxy for consumption opportunities.

The additional questionnaire also contains information about indoor temperature and the insulating quality of walls, windows and the roof of the house. Information about outdoor temperatures, measured in heating degree days, is collected by the Norwegian Meteorological Institute and merged with the household information by municipality.[2] As we do not know the exact energy efficiency of the individual heating equipment in each household, fuel prices are used as a proxy for the cost of utilizing the heating equipment. Prices of energy goods are calculated using information about expenditures and consumption from the SCE. Where consumption information is not available, e.g., because the household's energy bill is paid by the employer or is included in the rent, or we do not have information about the consumption for the entire 12-month period, the consumption is estimated based on the mean consumption of similar households. This predicted consumption is the basis for the calculation of energy prices for these households. In the estimations, we include correction variables to capture any systematic under- or over-prediction of consumption for these households.

Descriptive statistics of the main variables used in this analysis are provided in Table 1. This table shows that the main energy carrier in Norwegian homes is electricity, but the variation in electricity consumption is considerable. We also see that firewood is popular as well, and some households purchase quite a lot of firewood and fuel oils, and they may hold substantial stores of these energy goods. The mean reported living room temperature is slightly above 21 ^{o}C. With respect to the electricity price, we see that the mean price is 83 øre per kWh, but the price varies considerably. This is because it is calculated on the basis of respondents' electricity expenditures and consumption. Electricity bills often consist of a fixed and a variable charge (depending on consumption). The price per kWh will be high for households with this pricing structure and very low consumption. For households where the electricity bill is paid by others (e.g., government support), the price equals zero. We see the same pattern as regards variation in the price of other energy goods, as some have high fixed costs (e.g., due to freight charges) or get their energy goods free (chop their own firewood, gifts, etc.).

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[2] Heating degree days are calculated as the summarized deviation between the mean temperature during the last 24-hour period and 17^{o}C.

Table 1. Descriptive statistics, 1111 households 2009

	Mean	St. dev	Min	Max
Electricity consumption (kWh)	19 044	8 602	1 272	56 221
Firewood purchases (kWh)	4 186	5 888	0	42 000
Fuel oil purchases (kWh)	733	4 053	0	58 480
Indoor temperature (^{o}C) [3]	21.3	1.5	15.0	26.0
Electricity price (NOK/kWh)	0.83	0.39	0.002	5.16
Firewood price (NOK/sack)	67.18	24.61	8.33	312.50
Fuel oil price (NOK/liter)	10.30	5.69	4.67	60.00
Total expenditure (NOK)	482 934	295 569	68 108	2 876 670
Own a heat pump	0.248	0.432	0	1
Own a central heating system	0.055	0.002	0	1
Common central heating system	0.034	0.182	0	1
Own a pellets stove	0.005	0.073	0	1
Can use firewood for heating	0.818	0.386	0	1
Number of oil-burning stoves	0.07	0.43	0	10
Number of electric heaters	3.39	2.72	0	16
Number of wood-burning stoves	0.99	0.85	0	7
Own electric floor heating	0.753	0.432	0	1
Area with electric floor heating (m^2)	0.79	1.68	0	18
Use the pump for cooling during summer	0.062	0.242	0	1
Can use heat pump to heat the entire residence	0.164	0.370	0	1
Use less fuel oil after installing a heat pump	0.017	0.130	0	1
Number of substitution possibilities	2.28	0.76	1	5
Use of night setback	0.483	0.500	0	1
Own an economy shower	0.660	0.474	0	1
Number of layers in windows	2.20	0.76	1	9
The residence is well-insulated	0.072	0.259	0	1
Self-owned detached house	0.58	0.49	0	1
Farmhouse	0.08	0.27	0	1
Multifamily residence	0.09	0.29	0	1
Live in a block of flats	0.13	0.34	0	1
Net floor space (m^2)	141	64	8	480
Number of household members	2.96	1.38	1	8
Number of income contributors	1.48	0.88	0	4
Electricity bill paid by employer	0.009	0.095	0	1
Number of years in current residence	13	13	0	76

Source: Norwegian Survey of Consumer Expenditure, 2009.

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[3] Indoor temperature in this study is based on the answers to the question about indoor temperature in the living room on a cold winter day.

In our sample, approximately 25 percent of households own a heat pump. Along with electric heating (both panel heaters and electric floor heating) and wood-burning stoves, heat pumps are the most common types of heating equipment owned by Norwegian households. Water-distributed systems, such as self-owned and commonly owned central heating systems are relatively rare, as are stoves based on paraffin and pellets. The most common energy-saving behavior is the use of night setback and economy showers. Most Norwegian households live in detached houses, and the mean net floor space is 141 m^2.

4. Econometric specification

The data described above are used to estimate the conditional demand for electricity in Equation (3). The estimation is done in a three-stage process. First, the service production is estimated. The production of heating services by the household is approximated by a linear function, given by:

$$IT = \alpha_0 + \alpha_{HP} HP + \sum_{i=1}^{I} \alpha_i HC_i + \varepsilon \,. \tag{5}$$

In this estimation, we use information about the indoor temperature (*IT*) from the additional questionnaire as a proxy for the production of heating services. The stock of heating equipment is modeled as a set of dummies for whether the household owns the equipment or not. The dummy for heat pump ownership is separated (*HP*), whereas the other equipment ownership dummies are included in a vector of characteristics of the household and residence ($HC^I = HC_1, \ldots, HC_I$). Table 2 shows the complete list of variables. ε is the error term, which is assumed to be independently and identically distributed with a zero expectation and a constant variance.

The results from this estimation are then used to predict heat production for each household, which is used as an instrument for service production in the estimation of the consumption of alternative fuels to electricity (firewood and fuel oils). The demand for fuel oils and firewood is approximated by a linear function, given by:

$$AF^{FO} = \beta_0^{FO} + \beta_{HP}^{FO} HP + \beta_{IT}^{FO} \hat{IT} + \sum_{j=1}^{J} \beta_j^{FO} HC_j + \upsilon^{FO} \tag{6}$$

$$AF^{FW} = \beta_0^{FW} + \beta_{HP}^{FW} HP + \beta_{IT}^{FW} \hat{IT} + \sum_{m=1}^{M} \beta_m^{FW} HC_m + \upsilon^{FW} \tag{7}$$

where AF^{FO} is the household's demand for fuel oils, AF^{FW} is the household's demand for firewood, $I\hat{T}$ is the household's predicted indoor temperature from the first stage, HC^J and HC^M are vectors of characteristics of the household and residence for the demand for fuel oils and firewood, respectively, and υ^{FO} and υ^{FW} are error terms assumed to be independently and identically distributed with a zero expectation and a constant variance.

The results from these estimations are then used to predict the demand for firewood and fuel oils for each household, which are used as instruments in the estimation of the conditional demand for electricity, given in Equation (3). The conditional demand function for electricity is approximated by a linear function, given by:

$$EL = \gamma_0 + \left(\gamma_0^{HP} + \sum_j \gamma_j^{HP} D_j \right) HP + \gamma^{IT} I\hat{T} + \gamma^{FO} A\hat{F}^{FO} + \gamma^{FW} A\hat{F}^{FW} + \sum_{n=1}^{N} \gamma_n HC_n + \varpi \qquad (8)$$

where EL is the household's consumption of electricity, D_j represents different behavioral aspects conditional on owning a heat pump, such as use of the heat pump for cooling during the summer months, $A\hat{F}^{FO}$ is the predicted household demand for fuel oils, $A\hat{F}^{FW}$ is the predicted household demand for firewood, HC^N is a vector of characteristics of the household and residence in relation to the demand for electricity, and ϖ is the error term assumed to be independently and identically distributed with a zero expectation and a constant variance.[4]

Because the probability of owning a heat pump increases with electricity consumption, we could experience biased results if we do not account for this correlation in the data. Since equipment can only be utilized after it is bought, and this is a short-term model for a given stock of equipment, ownership of the heat pump will be exogenous in the estimation of the conditional demand function. As a result, this self-selection problem collapses to a problem of omitted variable bias (Lee 2001), which can be controlled by including all relevant exogenous variables in the estimation. For that reason, we include several characteristics of the household and residence in order to control for the self-selection bias. If we are able to correct the estimation for all relevant variables, the results from this estimation will have a behavioral interpretation. However, since we cannot exclude the possibility that some important variables in relation to explaining the decision to invest in a heat pump are

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[4] This recursive estimation of the conditional demand for electricity implicitly assumes that the error terms in the four equations are independently distributed.

omitted due to the lack of relevant information in the data, we will only interpret the results as comparing behavior in different sub-samples, with and without a heat pump.

We do not have information about the unit cost of producing heating services, because we cannot observe the energy efficiency of various heating equipment in individual homes. Thus, we are not able to estimate directly the rebound effects resulting from changes in the unit cost of heat production. However, we are able to identify the rebound effects indirectly through the sum of all effects associated with heat pump ownership: both directly and indirectly through the heat production and the demand for firewood and fuel oils. This implies that rebound effects of the increased energy efficiency of heat pumps will fall into the coefficients γ_0^{HP}, γ_j^{HP}, γ^{IT}, γ^{FO}, γ^{FW}, α_{HP}, β_{HP}^{FO} and β_{HP}^{FW}. The sum of all effects of heat pump ownership, both direct and indirect, yields the total effect of heat pump ownership on electricity consumption (see Equation 9 for how this is calculated).

5. Results

We have estimated the conditional demand model in Equations (5) to (8) recursively in order to analyze how heat pump ownership affects household energy consumption, correcting for possible omitted variable bias due to the self-selection problems in the data. The results from these estimations are presented in Tables 2 and 3. These estimation results are used to calculate the different behavioral components and obtain the overall effect on electricity consumption of heat pump ownership. The results from these calculations are reported in Table 4.

5.1 Indoor temperature and demand for fuel oils and firewood

The conditional demand model in Equation (8) is a function of the predicted heat production and the predicted demand for firewood and fuel oils. To assess the indirect effects of owning a heat pump, we first look at how it affects these factors. Due to an extensive number of zero observations for the demand for fuel oils and firewood, the demand functions for fuel oil and firewood are estimated using a discrete continuous likelihood function (Dubin and McFadden 1984, Cragg 1971) to distinguish between consumers with and without expenditures on these goods. A description of the likelihood function in this estimation is provided in Appendix A2. We assume that all dependent variables are normally distributed, that the expected demand functions are given by Equations (6) and (7), and that the expected net utility of consuming firewood and fuel oils are approximated by a linear function.

The results of the maximum likelihood estimation of the indoor temperature, and firewood and fuel oil demand are shown in Table 2. The first column of the table shows the results from an estimation of the indoor temperature, the second column shows the results for fuel oil demand, and the last column shows the results from the estimation of firewood demand. The estimation results for households with positive expenditure on fuel oil and firewood (the continuous part of the likelihood function) are shown in section A of Table 2, whereas the result for the estimation of the probability of having zero expenditures on fuel oil and firewood (the discrete part of the likelihood functions) is shown in section B of the table. Parameters included in the calculation of the effects of heat pump ownership on electricity consumption are marked in bold print.

Looking at the results from the estimation of indoor temperature, we see that households with a heat pump have a significantly higher indoor temperature than other households, almost 0.4 ^{o}C higher. The effect on fuel oil demand and firewood demand of owning a heat pump is twofold. First, there is a direct effect, which is negative in both cases, but only significant for firewood consumption. The second effect is the effect owning a heat pump has on indoor temperature, as predicted indoor temperature also has a significant effect on firewood and fuel oil demand. This effect is complex, as the temperature effect differs between different types of houses.[5]

With respect to the estimation of indoor temperature, we see that especially respondents who own a common central heating system together with other households have a significantly higher indoor temperature than others; almost one degree Celsius higher. This is also true for households where the employer pays the electricity bill, although this effect is somewhat smaller. This indicates that these households engage in less energy-saving behavior than households that pay the cost of their own heating and benefit from their savings directly. We also tested the effects on the indoor temperature of owning different types of equipment, and engaging in different types of energy-saving behavior. For instance, we see that a household with a well-insulated home that uses night setbacks maintains a significantly lower indoor temperature than other households. Moreover, indoor temperature fluctuates over the year, being colder in the winter and warmer in the summer.

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[5] The total predicted indirect effect of owning a heat pump on firewood and fuel oil demand, as a result of higher indoor temperature, is reported in Table 4.

Table 2. Maximum likelihood estimation of indoor temperature, and fuel oil and firewood demand. °C, kWh

Variable	Indoor temperature (°C)		Fuel oil demand (kWh)		Firewood demand (kWh)	
A. Continuous function						
Constant	46.5701	***	-133 466	*	17 648	
Own a heat pump (0, 1)	**0.3869**	*******	**-695**		**-1 781**	*******
Price of electricity (NOK per kWh)			1 386		-415	
Price of fuel oils (NOK per liter)			-163		48	*
Price of firewood (NOK per sack)			-0.8		-40	***
Total expenditures (NOK 10 000)			722	**	90	
Number of household members	0.0586	*				
Electricity as main energy carrier (0, 1)					-1 323	**
Central heating system (0, 1)			9 637	***		
Common central heating system (0, 1)	0.9565	***				
Number of oil-burning stoves			2 467	***		
Number of electric heaters			-716	*	-176	*
Number of firewood stoves					1 413	***
Electric floor heating (0, 1)					-873	*
Heating degree days in January	-0.0022	***			4.1	
Heating degree days in July	0.0037	***				
The residence is well-insulated (0, 1)	-0.2876	**				
Economy shower (0, 1)	-0.2233	**				
Three-layer windows (0, 1)	0.1138	**				
Electricity bill paid by employer (0, 1)	0.5968	*				
Number of years in current residence					59	***
The year of moving into the residence	-0.0123	***				
Mechanic air ventilator (0, 1)	0.5310	**				
Use of night setback (0, 1)	-0.1694	*				
Automatic system for night/day setback (0, 1)	-0.1826					
Self-owned detached house (0, 1)			209 762	**		
Live in a block of flats (0, 1)			-10 867	**		
Farmhouse (0, 1)			10 289	***	6 227	***
Semi-detached houses (0, 1)	-0.2788	*				
Predicted indoor temperature (°C)			**6 711**	*****	**-647**	
Predicted indoor temp. in detached houses (°C)			**-10 030**	******	**97**	******
Standard deviation	1.4816	***	5 789	***	5 227	***
B. Probability of zero demand						
Constant			2.8293	***	0.8192	***
Fuel oil as main energy carrier (0, 1)			-3.0503	***		
Firewood as main energy carrier (0, 1)					-1.0185	***
Heating degree days in February			-0.0020	**		
Number of household members					-0.1314	***
Number of firewood stoves					-0.6510	***

* Significant at 10%, ** significant at 5%, *** significant at 1%

With respect to the demand for firewood and fuel oils, we also see that characteristics of the residence and choice of heating system are of significant importance to demand. Price effects are particularly important for firewood, whereas income effects are more important to demand for fuel oils. From the discrete part of the estimation, we see that the probability of observing a zero demand for fuel oils and firewood varies significantly with the stock and utilization of the heating equipment, as well as with outdoor temperature.

5.2 Conditional demand for electricity

The estimation results presented in Table 2 are used to predict the indoor temperature and demand for firewood and fuel oils for each household, which are used as explanatory variables in the estimation of the conditional demand function for electricity. The results from a maximum likelihood estimation of Equation (15) are presented in Table 3. The estimated coefficients and their associated p-values are shown in the first and second columns. The effects on the constant term are shown in section A of the table. We include both variables describing the heterogeneity across households and variables correcting for measurement problems in the dependent variable. Price and income effects are reported in section B, the effects of ownership of heat pumps on electricity consumption are shown in section C, and, finally, sections D and E show the effects of the predicted indoor temperature and demand for firewood and fuel oil, and the estimated standard deviation.

We see from section D of the table that all the estimated coefficients for the predicted variables are significant. First, electricity consumption increases by more than a thousand kWh annually for each degree Celsius the indoor temperature is increased by. Also, for each kWh firewood and fuel oil demand is reduced by, electricity consumption increases by 0.2 and 0.3 kWh. This entails an increase in the overall energy efficiency of the households' energy consumption when using electricity for heating purposes.[6]

Focusing on the effects of owning a heat pump on household electricity consumption (se section C of the table), we find many significant effects. Interestingly, the effect of using the heat pump for cooling in the summer is not significant, but it has a large estimated coefficient. The reason for the lack of significance is probably because we have very few observations of the pump being used for cooling purposes during the summer (only six percent of the sample).

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[6] This is not the same as saying that using electricity is five times more energy efficient that, e.g., firewood, since consumption can change with the equipment: previously unheated areas can now be heated, temperature can be increased and be more stable over the day, and firewood can still be used.

Table 3. Maximum likelihood estimation of electricity consumption. kWh

Variables	**Coefficient**	**p-value**
A. Effects on the constant term		
Constant	-25 812	0.0968
Net floor space (m^2)	51	0.0000
Own a detached house (0, 1)	1 976	0.0005
Farmhouse (0, 1)	2 711	0.0089
Heating degree days in January	13	0.0000
Common central heating system (0, 1)	-3 148	0.0403
Own a pellets stove (0, 1)	-7 077	0.0879
Number of income contributors	807	0.0034
Number of electric heaters	368	0.0000
Area with electric floor heating (m^2)	206	0.0683
Number of tumble dryers	665	0.0863
Number of freezers	736	0.0104
Number of PC's	334	0.0408
Correction variables:		
Moved into current residence in current year (0, 1)	-1 369	0.0771
Can use firewood for heating (0, 1) [7]	1 326	0.0525
Electricity bill paid by the employer (0, 1)	-2 716	0.0809
Energy expenditures included in rent (0, 1)	-1 172	0.0481
B. Price and income effects		
Price of electricity (NOK per kWh)	-2 317	0.0000
Price of fuel oils (NOK per liter)	-74	0.0620
Price of firewood (NOK per sack)	-1	0.9153
Total expenditures (NOK 1000)	389	0.0000
C. Ownership of heat pumps		
Constant	**2 546**	**0.2837**
Use the pump for cooling during summer (0, 1)	**1 161**	**0.1784**
Can use heat pump to heat the entire residence (0, 1)	**1 671**	**0.0435**
Use less fuel oil after installing a heat pump (0, 1)	**3 438**	**0.0352**
Number of substitution possibilities	**-1 628**	**0.0231**
D. Predicted instruments		
Indoor temperature (°C)	**1 252**	**0.0756**
Fuel oil consumption (kWh)	**-0.2943**	**0.0000**
Firewood consumption (kWh)	**-0.2077**	**0.0038**
E. Standard deviation	**6 083**	**0.0000**

Being able to heat the entire residence using heat pumps alone increases electricity consumption by more than 1600 kWh compared to other households that own a heat pump. However, the biggest effect on electricity consumption of owning a heat pump is found in households that state that they use less fuel oil after acquiring the heat pump. These households use almost 3500 kWh more electricity than other households that own a heat pump. Since we have included the predicted fuel oil consumption as

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[7] We suspect that this result is due to heat leakages through the chimney when the fireplace in not in use. However, we do not have information at household level that allows us to test this hypothesis.

an explanatory variable in the estimation, this coefficient represents the additional effect of reduced fuel oil consumption for households who state that they have switched heat sources from fuel oils to a heat pump.

Finally, we see that households that have many substitution possibilities for heating their residence in addition to the heat pump use significantly less electricity than other households that own a heat pump. We believe that this is because these households can use alternatives to electricity for heating purposes in very cold periods during winter, when the energy efficiency of the pump is low or when it is so cold that the pump does not work at all. If the households do not have other substitution possibilities than electricity, there is little or no energy-efficiency gain of owning a heat pump during these periods.

5.3 Decomposition of the total effect

Our estimations illustrate different effects of owning a heat pump on household electricity consumption, both direct and indirect. To find the overall effect, we can sum up all the effects on the estimated conditional demand for electricity of owning a heat pump. The total effect of owning a heat pump, and the importance of the various components in Equation (4), is calculated as follows:

$$dEL = \left(\sum_j \hat{\gamma}_j^{HP} \overline{D}_j + \hat{\gamma}_{FO} \left(\hat{\beta}_{HP}^{FO} + \hat{\beta}_{IT}^{FO} \overline{IT} \hat{\alpha}_{HP} \right) + \hat{\gamma}_{FW} \left(\hat{\beta}_{HP}^{FW} + \hat{\beta}_{IT}^{FW} \overline{IT} \hat{\alpha}_{HP} \right) + \hat{\gamma}_{IT} \overline{IT} \hat{\alpha}_{HP} \right) dHP \qquad (9)$$

Using the estimated coefficients in bold print in Tables 2 and 3, and information about mean values from Table 1, we can calculate the effect on the electricity consumption of the mean household of owning a heat pump ($dHP = 1$).[8] These predicted effects are presented in Table 4.

Looking at the results, we find many strong rebound effects of owning a heat pump, including the indirect effects resulting from increased indoor temperature and reduced consumption of firewood and fuel oils. We also see that the main energy savings are made by households with many substitution possibilities in relation to heating their residence, since these households can adapt better to variations in outdoor temperature. The constant term will capture all other direct effects of owning a heat pump on electricity consumption, e.g., because of reduced energy-saving behavior and an increase in the proportion of the residence heated during the winter. We see that this effect is the largest direct rebound effect.

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[8] This is a hypothetical household with mean values for all explanatory variables.

Table 4. Decomposition of the predicted effect on electricity consumption of owning a heat pump for the mean household. kWh

	Effect on electricity consumption (kWh)
A. Direct effects of heat pump ownership	***-764***
Constant	2 546
Use the pump for cooling during summer (0, 1)	72
Can use heat pump to heat the entire residence (0, 1)	274
Use less fuel oil after installing a heat pump (0, 1)	59
Number of substitution possibilities	-3 714
B. Indirect effects of heat pump ownership	***1 058***
Indoor temperature	484
Fuel oil consumption	204
Firewood consumption	370
C. Total effect on electricity consumption of owning a heat pump	**295**

Summing up all direct and indirect effects, we find a small increase in electricity consumption for the mean household as a result of owning a heat pump. The effect is small compared to the uncertainty in the estimated coefficients, and we cannot therefore conclude that a household that owns a heat pump has an electricity consumption that differs from other households' consumption. This implies that there are considerable rebound effects and that the entire energy-saving potential in terms of electricity consumption embedded in the heat pump is eaten up by behavioral changes as a result of the reduced unit costs of producing heating services. However, the results also indicate that the switch from fuel oils and firewood to electricity for space heating as a result of heat pumps has increased the overall energy efficiency of household heat production.

6. Conclusions

In this analysis, we have used a micro econometric approach to examine whether heat pump ownership in Norwegian households has reduced electricity consumption, *ceteris paribus*, or whether the potential saving is eaten up by rebound effects. We find significant evidence that households that own a heat pump use less of other heating sources. In particular, households that have invested in a heat pump use significantly less firewood than other households. They also maintain a higher indoor temperature compared to other households. All these differences in heating behavior result in higher electricity consumption, *ceteris paribus*. We also find that, of households with heat pumps, it is only those that can use alternatives to electricity for heating purposes that are able to save a significant amount of electricity, *ceteris paribus*. If we summarize all our estimated effects on household electricity consumption of owning a heat pump, including the effects on indoor temperature and firewood and fuel oil demand, we find a small increase in household electricity consumption.

In this analysis we find that, for the mean household, the predicted rebound effects are as great as the energy-saving potential of the heat pump, so that the total electricity saving is close to zero. This is not necessarily a bad thing, as the energy efficiency of total heat production and the households' utility have risen. The results indicate that households with a heat pump have chosen to spend the money they save on heating costs on living more comfortably: raising the indoor temperature, reducing the labor involved in chopping and carrying wood, heating a larger part of their residence, and using air conditioning. This is clearly what the Norwegian public wants, as the proportion of households that own a heat pump has risen from virtually zero to approximately one quarter in only twelve years. This has occurred almost entirely without government subsidies.[9]

Note that, in this analysis, we only look at the initial rebound effects resulting from changes in household behavior. These behavioral responses could have additional rebound effects via the energy markets if the changes are large enough to shift aggregate energy demand. These macro rebound effects via the energy markets could change relative energy prices, and thus create an additional behavioral response in households. Although potentially important, such market effects are beyond the scope of this paper.

One important implication of the results of this analysis is that energy-efficiency measures are not always a cheap and effective way of combating the climate problem. Energy-efficiency measures trigger behavioral changes because they reduce the costs of producing goods and services. The size of the unwanted behavioral responses is an empirical question. Empirical analyses have shown that they can vary from case to case, and from country to country. It is also difficult to know beforehand how they will affect behavior, as most new technologies do not only change costs, but also result in new consumption opportunities and change habits and behavioral patterns. The rebound effects will increase in magnitude if investments in more energy-efficient technology are subsidized, as a subsidy will increase the income effects. It may be desirable to subsidize new technology for other reasons; either to compensate for positive externalities, or for industry policy or distribution reasons. However, the energy savings accomplished by such subsidies are far from clear.

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[9] There was a grant in 2003, but it only lasted one year. Now, there are only grants for large heat pumps. However, very few households choose these large pumps, and the proportion of households owning a heat pump other than an air-to-air pump is less than three percent in 2012.

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Appendix A1. The conditional demand function

We assume that households can use two different energy carriers (x_1, x_2) to produce household services (z) such as space heating: $z = z(x_1, x_2; K)$. Some households can only use one energy carrier, while others can use two or more,[10] depending on their capital stock (K). This stock can involve different technologies producing the same service, applying different energy carriers or the same energy carrier (e.g., heat pumps and electric heaters). In this model, we only look at the short-term problem of utilization, where the stock is given. Thus, we do not discuss investments in new equipment.

Since many households can use alternative technologies to produce the same service, as in the case of space heating, the consumption of a particular energy good (x_1), hereafter referred to as the good of interest, will depend on the degree of substitution, and thus on the consumption of alternative energy carriers (x_2), hereafter referred to as conditioning goods. Which energy carrier is chosen is determined by the unit price of using this energy carrier to produce a given amount of this service, depending on the different properties of the technology.

In our model, we assume that the consumption of these energy carriers is decided simultaneously, given that the consumers minimize their costs of producing a given service ($\bar{z}$):

$$\min_{x_1, x_2} \; p_1 x_1 + p_2 x_2 \qquad s.t. \qquad \bar{z} \leq z(x_1, x_2; K), \tag{A1}$$

where p_i is the price of energy good *i*. Assuming an internal solution to this problem, the conditional demand function is found by solving the first order conditions with respect to x_1. In combination with the budget constraint, this yields the demand for x_1 as a function of the demand for x_2 and the production of services $\bar{z}$, and the demand function for x_2^*:

$$x_1 = x_1(p_1, x_2, \bar{z}; K) \tag{A2}$$

$$x_2^* = x_2(p_1, p_2, \bar{z}; K) \quad . \tag{A3}$$

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[10] In our example, we include the consumption of all alternatives to electricity for heating in the variable x_2 .

Inserting the optimal demand function for the alternative energy carriers (x_2^*) in Equation (A3) into the conditional demand function for x_1 in (A2) yields the optimal demand for the good in question (x_1^*) as a function of prices and the capital stock, for a given level of production of services $\bar{z}$:

$$x_1^* = x_1\left(p_1, x_2\left(p_1, p_2, \bar{z}; K\right), \bar{z}; K\right) = x_1\left(p_1, p_2, \bar{z}; K\right). \tag{A4}$$

To find the overall optimal demand for the good in question (x_1^{**}) given optimal service production (z^*), we need to insert the optimal choice of production of services into Equation (A4). This depends on the choice of producing services at home and other consumption, given household income and the prices of other consumption and the cost of household production. Based on the minimization problem, we can calculate the total cost of producing z :

$$C^* = p_1 x_1\left(p_1, p_2, z; K\right) + p_2 x_2\left(p_1, p_2, z; K\right) = C\left(p_1, p_2, z; K\right). \tag{A5}$$

The unit cost of producing z is then given by $c^* = C\left(p_1, p_2, z; K\right) / z = c\left(p_1, p_2, z; K\right)$. This will be the cost of producing z in the utility maximization problem.

The household is assumed to maximize its utility (U) from the consumption of services (z) and other goods (x_3), given that the expenditures are less or equal to household income (y) and given the prices of other consumption (p_3), the unit cost of household production in optimum (c^*) and characteristics of the household (a):

$$\max_{z, x_3} \; U = U(z, x_3; a) \qquad s.t. \qquad y \geq c\left(p_1, p_2, z; K\right) z + p_3 x_3 . \tag{A6}$$

Assuming an internal solution, this utility maximization problem yields the optimal demand for other goods (x_3^*) and the optimal production of services (z^*) as a function of all prices (p_1, p_2, p_3), household characteristics (a), the stock of capital (K), and income (y). If we insert the function for the optimal production of household services z^* into the conditional demand function in Equation (A4), we get an expression for the conditional demand function that will equal the demand for the good in question in overall optimum, given by:

$$x_1^{**} = x_1\left(p_1, x_2\left(p_1, p_2, z\left(c^*, p_3, y; a, K\right); K\right), z\left(c^*, p_3, y; a, K\right); K\right) = x_1\left(p_1, p_2, p_3, y; a, K\right) \qquad \text{(A7)}$$

This function tells us how the demand for the good of interest in the overall optimum (x_1^{**}) is affected by the optimal consumption of alternatives in household production (x_2^*) and the chosen level of household production (z^*). The demand for the good of interest is also conditional on a vector of household characteristics (a_1), and variables indicating the present stock of heating equipment and durables (*K*).

Appendix A2. The likelihood function

Due to an extensive number of zero observations for the demand for fuel oils and firewood, the demand functions for fuel oil and firewood are estimated using a discrete continuous likelihood function (Cragg, 1971) to distinguish between consumers with and without expenditures on the good. In a discrete continuous model, the probability density is a mixture of consumers with positive expenditure and consumers with zero expenditure on a particular good:

$$f\left(AF_h^r\right)=\left[\begin{array}{ll} f_+\left(AF_h^r\right) & if\ \ AF_h^r>0 \\ f_0 & if\ \ AF_h^r=0 \end{array}\right., \tag{A8}$$

where AF_h^r is the household h's consumption of alternative fuel r (= fuel oils and firewood), the discrete component, f_0, is the probability mass measured at zero expenditure, and the continuous component, $f_+\left(AF_h^r\right)$, is the density for consumers with a positive expenditure (see, e.g., Cragg 1971, Smith 2002 or Garcia and Labeaga 1996). The probability of positive expenditure on good r is given by $P\left(AF_h^r>0\right)$, and the probability of zero expenditure (f_0) is given by $1-P\left(AF_h^r>0\right)$. The continuous part of the distribution is then given by: $f_+\left(AF_h^r\right)=f\left(AF_h^r\,|\,AF_h^r>0\right)P\left(AF_h^r>0\right)$, where $f\left(AF_h^r\,|\,AF_h^r>0\right)$ is the truncated density function of AF_h^r. Assuming expenditures to be independently and identically distributed, the likelihood function in the DH model is the product of all densities for all households, that is:

$$L=\prod_{h_+} f_+\left(AF_h^r\right)\prod_{h_0} f_0\ =\prod_{h_+} f\left(AF_h^r\,|\,AF_h^r>0\right)P\left(AF_h^r>0\right)\ \prod_{h_0}\left[1-P\left(AF_h^r>0\right)\right], \tag{A9}$$

The first part of the likelihood function calculates the properties of the demand for households with a positive consumption (h_+), whereas the last part estimates the properties of the probability of observing zero demand for households choosing a corner solution (h_0).

We express the probability of observing zero consumption of alternative energy good r for consumer h as a function of whether the indirect utility of consuming the good ($\Delta V_{AF_h^r}$) is greater or equal to zero:

$$P\left(AF_h^r = 0\right) = P\left(\Delta V_{AF_h^r} \geq 0\right) = \Phi\left(\underline{\psi_h^r}\right) \ , \qquad \text{(A10)}$$

where the indirect utility of consuming alternative energy good *r* is assumed to be a linear function of its expected value ($\mu_{\Delta V_{AF_h^r}}$) and a stochastic error term (ψ_h^r), which is assumed to be independent and identically distributed with a zero expectation and a constant variance, and $\underline{\psi_h^r}$ is the standardized error term. The indirect utility of consuming alternative energy good *r* is assumed to be given by $\Delta V_{AF_h^r} = \mu_{\Delta V_{AF_h^r}} + \psi_h^r$. This gives the following likelihood function to be estimated:

$$L_i = \prod_{AF_h^r > 0} \left[\frac{1}{\sigma_{\upsilon^r}} \phi\left(\frac{AF_h^r - \mu_{AF_h^r}}{\sigma_{\upsilon^r}} \right) \Phi\left(\underline{\psi_i^h}\right) \right] \times \prod_{AF_h^r = 0} \left[1 - \Phi\left(\underline{\psi_i^h}\right) \right] \qquad \text{(A11)}$$

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