Energy 222 (2021) 119879

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Identifying drivers for the direct rebound when energy efficiency is unknown. The importance of substitution and scale effects

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ARTICLE INFO

Article history:
Received 25 August 2020
Received in revised form
22 December 2020
Accepted 15 January 2021
Available online 25 January 2021

JEL classification:
C31
C34
D12
D13
Q41

Keywords:
Energy efficiency
Heat pump
Household energy consumption
Rebound effect

ABSTRACT

The cost reduction resulting from energy efficiency initiatives may induce behavioural changes, which may undermine the energy savings effort embedded in the initiative (referred to as rebound effects). We develop a novel empirical method for illustrating contributions to the direct rebound for cases where the energy efficiency of the equipment is unobservable. Our focus is on substitution and scale effects in cases where more than one type of equipment may be used to produce the same service. We apply the model on a random sample of 1111 households from the Norwegian Survey of Consumer Expenditure for the year 2009 to identify components of the energy savings and rebound effects of household heat pumps. The results show that the electricity savings are completely offset by the rebound effects due to changes in demand, including changes in the mix of energy goods consumed and increased service production. However, the overall energy efficiency has risen, and total energy consumption is reduced.

1. Introduction

Increasing energy efficiency has been one of the main strategies for combating the climate problem. However, the energy-saving potential of an energy efficiency initiative will only be reached if consumers do not change their behaviour because of the new technology. From economic theory, we expect behaviour to change, since increased energy efficiency will reduce the cost of e.g. heating or cooling the residence to a given temperature. These behavioural changes will undermine the energy savings potential embedded in the efficiency measure, and thus create a rebound effect.

Rebound effects may be direct or indirect, because of household behaviour or economy-wide. At the micro level, direct rebound effects capture the demand responses for the energy good that has become more efficient in use, whereas indirect rebound effects are changes in the consumption of all other goods through the effect on disposable income. In addition, we may experience economy-wide rebound effects through market clearing and transformational changes (see e.g. [1–5]).

Measuring the rebound effects are difficult as it requires a counterfactual analysis, which again requires data from controlled experiments [4]. However, in the case of a single energy source producing a single energy service, it can be shown that under certain conditions, the rebound effect may be expressed as a function of the own price elasticity of the demand for the energy source [3,6,7]. Chan and Gillingham [3] examine if this is also the case with multiple energy services and/or multiple energy sources. They show that in these more complicated cases, using the own price elasticity of demand to calculate the rebound effect may bias the results. They conclude that “*empirical researchers may be well advised to carefully consider fuel-switching behaviour in studies of household energy demand and the rebound effect, especially when there are undesirable consequences of such fuel-switching behaviour*”.

When looking at the case where multiple energy sources may be used to produce the same energy service, Chan and Gillingham [3] discuss the theoretical implications in the case of perfect substitutes, with a linear and additive service production function. We may, however, observe situations where a specific energy service may be produced by a mix of energy sources and/or multiple

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https://doi.org/10.1016/j.energy.2021.119879

equipment with different energy efficiency. Furthermore, the energy service produced may not be homogenous (e.g. heating from a fireplace and an electric oven may not give the same utility), nor are all costs monetary as the use of some energy carriers may involve labour costs (e.g. carrying firewood). An example of such a more complicated case is space heating in Norway, as most Norwegian residences have multiple heating equipment to heat the same space. It is common to use electric panel ovens and/or a heat pump as base heating and add firewood on particularly cold days when electric heating does not provide enough heat. In these cases, we need to find alternative methods to quantify how the behavioural responses of an energy efficiency measure affect demand and the main drivers for energy savings and rebound effects.

When the efficiency of the equipment is known, it is possible to estimate the rebound effect directly (see e.g. [8]) without using the own price demand elasticity to approximate the rebound effect. More common is the situation where we do not have information about the actual energy efficiency of the specific equipment when in use. However, it is, in many cases, possible to measure how an efficiency measure creates rebound effects indirectly by studying the effects of consumer behaviour. The existence of close substitutes producing the same energy service using different equipment and multiple energy sources complicate the analysis. This is because changes in the energy mix used to produce a service depend not only on the efficiency of the more efficient equipment and of the equipment it replaces, but also on the efficiency of alternative and supplementary equipment already installed. This implies that the efficiency measure does not only affect the consumption of the energy source now more efficient in use: we may also experience behavioural effects on the consumption of alternative and/or complementary energy sources as well as on total energy consumption. In some cases, the substitution opportunities may be extensive, and this may have a significant effect on the size of the rebound.

Several empirical studies indicate that behaviour may change significantly, see Frondel et al. [8]; Gram-Hanssen et al. [9]; Li et al. [10]; Davis et al. [11] and Borenstein [12]. Newer analyses have used the relationship with the own price elasticity shown by Khazzoom [6] to obtain an estimate of the direct rebound effect, see e.g. Zhang and Peng [13]; Belaïd et al. [14] and Han et al. [15]. The role of substitution for the rebound effect is, however, not discussed much in the empirical literature, as most of the existing empirical micro econometric literature on rebound effects look at situations with no close substitutes. This was noted by Davis et al. [11]; and it still seems to be relevant. With the upcoming new transportation technologies and increased electrification of transport services, the substitution effects may be of increased significance in many countries, both now and even more so in the future. It is important to include these behavioural changes, to be able to evaluate and plan current and new policies.

In this paper, we investigate empirically the importance of substitution and changes in the level of household production for the size of the rebound effect. Our case is the production of heating services in Norwegian homes, as the short-term substitution possibilities are extensive. Most Norwegians households can use several types of equipment in combination to heat their homes, often using different energy sources. When studying a sample of Norwegian households, using information about electricity consumption from the household's electricity supplier, we find that the mean electricity consumption did not differ significantly for households with and without a heat pump. This indicates that the rebound effect on the electricity consumption may be close to a 100% on average, which is sometimes called backfire in the literature (see [5] for a discussion).

To identify the main driving forces of the direct rebound effect, we extend the existing literature by developing an econometric approach based on a household production framework for identifying the main contributions to both the energy savings effect and the direct rebound in the case where we are unable to observe the efficiency of the equipment directly. Our theoretical model resembles the analysis of multiple fuels for each energy service in Chan and Gillingham [3]; but we allow for a more complex service production function.

We also show how to explore the model empirically. Our method is applied to a sample of households from the Norwegian Survey of Consumer Expenditure (SCE) for 2009 with an additional questionnaire on energy. The main aim is to provide a method for identifying the mechanisms driving the potentially large rebound effects in cases with a complicated demand structure and limited data. We use home heating in Norway as a case, but the method may be used for identifying the main drivers of energy savings and rebound effects in general. Examples of areas of multiple technologies producing the same service, and possible significant substitution effects, are transportation (electric vehicles, fossil vehicles, hybrids), home heating (ovens for gas, firewood, wood pellets, electricity, heat pumps, central heating), cooking (gas, electric stoves) and cooling (gas, electric refrigerators).

2. Theoretical foundation

Our point of departure is a household production framework [16,17], tracing the role of substitution and level of production by using a conditional demand model [18,19]. We modify these models to trace the contribution to the rebound of changes in behaviour due to an efficiency measure. This conditional demand model enables us to identify the contribution to the rebound effect on electricity consumption of changes in the consumption of alternative fuels (substitution effects) and in the level of heat production (scale effects). The substitution effect is important in cases when households have the possibility to use different types of energy equipment, as well as different heating equipment in combinations. For expository purposes, we formulate and discuss the theoretical model with home heating as an example.

2.1. The conditional demand model

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

We assume that the consumption of all energy carriers (x_1 and x_2) are decided simultaneously, given that the household minimizes its costs of producing the desired level of energy services:

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

where p_i is the price of utilizing energy good i (= 1, 2) in service production, which is assumed to be a function of the purchaser price of energy good i, denoted q_i, and the available capital stock: $p_i = p_i(q_i, K)$. The capital stock and the energy efficiency of this stock are both household specific, depending on type of equipment and utilization. In our data, we cannot observe the energy efficiency of the capital stock. Thus, we consider the energy efficiency of the capital stock, and thus also the utilization prices of service production, as unobservable in this model.

To study how electricity consumption depends on changes in the consumption of alternative energy goods and the level of service production, as well as the direct price effects on electricity consumption, we calculate the conditional demand for electricity by solving the first order conditions and the budget constraint with respect to x_1. This also gives the optimal demand for the alternative energy goods (x_2^*):

$$x_1 = x_1(p_1, x_2, z; K) \tag{2}$$

$$x_2^* = x_2(p_1,\ p_2, z; K) \tag{3}$$

Inserting Equation (3) into Equation (2) yields the optimal demand for electricity (x_1^*) as a function of utilization prices, capital stock, and the level of service production, and shows how optimal electricity consumption changes with the demand for alternative goods:

$$x_1^* = x_1(p_1, x_2(p_1, p_2, z; K), z; K) = x_1(p_1, p_2, z; K) \tag{4}$$

To find an expression for the optimal unit cost of service production, which is important to determine how the choice of service production affects electricity demand, we calculate the cost of producing z from the minimization problem in Equation (1):

$$C^* = p_1 x_1^*(p_1, p_2, z; K) + p_2 x_2^*(p_1, p_2, z; K) = C(p_1, p_2, z; K) \tag{5}$$

This gives the optimal unit cost of producing z, given by:

$$c^* = C(p_1, p_2, z; K)\,/\,z = c(p_1, p_2, z; K)$$

To find the overall optimal electricity demand, we need to find the optimal level of service production ($z = z^*$) and insert it into Equation (4). The optimal level of service production is found by maximizing utility (U) subject to 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 optimal unit cost of service production (c^*) and characteristics of the household (a):

$$\max_{z,\, x_3} U = U(z, x_3; a) \quad s.t. \quad y \geq c(p_1, p_2, z; K)z + p_3 x_3 \tag{6}$$

Assuming an interior solution, this utility maximization problem yields the optimal demand for other goods (x_3^*) and the optimal level of service production (z^*) as a function of all prices (p_1,p_2,p_3), household characteristics (a), the capital stock (K), and income (y): $x_3^* = x_3(c^*, p_3, y; a, K)$ and $z^* = z(c^*, p_3, y; a, K)$.

Inserting the function for z^* and x_2^* at the optimal level of service production, $x_2^{**} = x_2(p_1, p_2, z^*; K)$, into Equation (4), yields a relationship for how the electricity demand in overall optimum (x_1^{**}) is affected by the optimal consumption of alternative energy goods and the optimal level of service production, i.e.$x_1^{**} = x_1(p_1, x_2^{**}, z^*, y; K)$:

$$x_1^{**} = x_1(p_1, x_2(p_1, p_2, z(c^*, p_3, y; a, K); K), z(c^*, p_3, y; a, K), y; K) = x_1(p_1, p_2, p_3, y; a, K) \tag{7}$$

We use this relationship, and the fact that the conditional electricity demand function equals the demand for electricity in overall optimum, as the basis for the decomposition of the change in consumption due to the efficiency gains and the rebound effect of a heat pump.

2.2. *Main drivers of the energy savings and rebound effects*

To understand how a heat pump affects household energy consumption and the energy savings and rebound effects, we use the model described above to decompose the changes in demand on different drivers. We denote the possibility for using a heat pump for service production as a difference in the capital stock (dK). By using the conditional electricity demand function of Equation (7), and that the prices of utilizing energy goods depend on the capital stock, $p_i = p_i(q_i,K)$, we can decompose the change in electricity consumption due to a heat pump as follows:

$$\begin{aligned} \frac{dx_1^{**}}{dK} = {} & \frac{\partial x_1^{**}}{\partial p_1}\frac{\partial p_1}{\partial K} + \frac{\partial x_1^{**}}{\partial x_2^*}\left(\frac{\partial x_2^{**}}{\partial p_1}\frac{\partial p_1}{\partial K} + \frac{\partial x_2^*}{\partial z^*}\left(\frac{\partial z^*}{\partial K} + \frac{\partial z^*}{\partial c^*}\frac{\partial c^*}{\partial K}\right)\right) \\ & + \frac{\partial x_1^{**}}{\partial z^*}\left(\frac{\partial z^*}{\partial K} + \frac{\partial z^*}{\partial c^*}\frac{\partial c^*}{\partial K}\right) + \frac{\partial x_1^{**}}{\partial K} \end{aligned} \tag{8}$$

In Equation (8) we have assumed that $\frac{\partial p_2}{\partial K} = 0$, i.e. the heat pump affects the price of heating by use of electricity only. We have also assumed that $\frac{\partial x_2^*}{\partial K} = 0$, i.e. the heat pump can use electricity only and have no effects excess of price and income effects on the consumption of alternative energy goods.

We see from Equation (8) that a heat pump affects the optimal electricity demand in different ways. On the right-hand side of the equation, we have four terms. The first term is the effect through changes in the price of heating by use of electricity $\left(\frac{\partial x_1^{**}}{\partial p_1}\frac{\partial p_1}{\partial K}\right)$, which is what is most commonly referred to as the direct rebound effect in the literature. However, this is not the only rebound effect, as shown by the three last terms of Equation (8). The first of these emerges as a heat pump will change relative prices of using different energy sources for service production, and thus affect the demand for alternative energy goods $\left(\frac{\partial x_1^{**}}{\partial x_2^*}\right)$. These *substitution effects* can be through changes in relative prices, or through changes in the level of service production, as the unit cost of service production changes (the user cost of electricity for heating is lower with a heat pump due to its efficiency).[1] As shown in the third term, a heat pump may also affect electricity consumption through changes in the chosen level of service production $\left(\frac{\partial x_1^{**}}{\partial z^*}\right)$. This *scale*

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[1] These substitution effects are measured at the new point of consumption and will not equal the Slutsky effect.

effect is twofold[2]: The first effect occurs because a heat pump makes it possible to produce new types of services $\left(\frac{\partial z^*}{\partial K}\right)$, such as cooling during the summer. The second is a result of a reduction in the unit cost of service production $\left(\frac{\partial z^*}{\partial c^*}\frac{\partial c^*}{\partial K}\right)$, which may result in a reduction in energy-saving behaviour in heating (e.g. increased indoor temperature and reduced use of night setback). If there is a large extent of savings behaviour in producing residential heating services, this scale effect may be substantial. In addition, we have a direct effect on electricity consumption of having a heat pump $\left(\frac{\partial x_1^{**}}{\partial K}\right)$, shown in the last term of Equation (8). This effect will capture all savings resulting from the efficiency change, as well as direct effects not captured by substitution and scale effects (e.g., if feeling warm glow from contributing to a better environment by having a heat pump results in a reduction in other energy-saving behaviour).

We define these contributions to the energy efficiency gain and direct rebound of a heat pump on electricity consumption as either direct effects through changes in the user price $\left(\frac{\partial x_1^{**}}{\partial p_1}\right)$ and other direct effects $\left(\frac{\partial x_1^{**}}{\partial K}\right)$, or indirect effects through changes in the consumption of alternative goods $\left(\frac{\partial x_1^{**}}{\partial x_2^*}\right)$ and the scale of production $\left(\frac{\partial x_1^{**}}{\partial z^*}\right)$.

3. Data

We have seen a tremendous increase in the number of Norwegian homes with a heat pump: from almost non-existing at the turn of the century to a quarter of the households with air-to-air heat pumps in the SCE for 2009. Electric panel ovens are the most commonly used heating source in Norwegian residences and there is a large extent of substitution possibilities: three out of four households in our data may use both electric panel ovens and a firewood oven, and one third may use three or more different heat sources. Common alternatives to electric panel ovens and firewood ovens are: paraffin ovens, central heating systems (either based on fuel oil, electricity, firewood or a combination), electric floor heating, pellets stoves, gas fireplaces, district heating and air-to-air heat pumps (see Appendix 1, Table A1 for more information). The extensive substitution possibilities that exist for space heating are interesting in the Norwegian case. Of the households in our sample, 86% can use more than one type of heating equipment. A combination of firewood and electricity is most dominant (75%), while 36% can use three or more heating sources, and 20% can use a combination of heat pumps, electric heaters and firewood.

To analyse how heat pumps have affected household energy consumption in the Norwegian case, we use cross-sectional data from the Norwegian Survey of Consumer Expenditure (SCE) for the year 2009, which includes an additional questionnaire on energy. Out of a gross sample of 2200 households randomly drawn from the Norwegian population, 53% completed the entire SCE with all questionnaires, resulting in a net sample of 1156 households. Our estimations are based on data for the 1111 households in the net sample with no missing values on any of the variables used in our analysis. Descriptive statistics for variables in the estimation is given in Appendix 1 Table A1.

We have information about household electricity consumption collected from each households' electricity supplier, consumption of firewood and fuel oils, household and residence characteristics, heating equipment and electrical appliances, and energy-saving behaviour undertaken by the household. Furthermore, from the SCE 2009 we have information about the household's total expenditure. As we do not have income data, we use total expenditure as a proxy for income in our estimations. Electricity, firewood and fuel oils are the main fuel sources used in Norwegian homes. From the information about heating equipment, we derive the number of heating options, that is, how many types of heating equipment a household may use.

The additional energy questionnaire attached to the specific SCE for 2009 also contains information about indoor temperature (as reported by the household) and the insulation of walls, windows and roof. Information about outdoor temperatures, measured in heating degree days, is collected by the Norwegian Meteorological Institute and merged with the household information by municipality. Heating degree days are calculated as the monthly summarised deviation between the mean temperature during the last 24-h period and 17 °C. Household-specific prices of each of the energy goods are calculated using information about expenditures and consumption from the SCE.

For a small number of households there is no electricity consumption information. In the data set we received from Statistics Norway, consumption for these households is estimated based on the mean consumption of similar households. To account for potential biases these households may create in our analysis, we include variables to capture any systematic under- or over-prediction of consumption. Two such variables included in our estimations are dummy variables for "household's electricity bill paid by the employer" and "household moved into the residence less than 12 months ago" (so that the consumption period is shorter than for other households).

4. Econometric specification

Our main interest is to decompose the change in consumption that leads to the rebound with respect to electricity consumption and show how substitution possibilities and changes in the level of service production affect the size of the rebound. We are also interested in calculating the effects with respect to changes in the consumption of the alternative energy goods as well as total energy consumption. In our model, we assume four endogenous variables: heat production (measured by indoor temperature), consumption of electricity, consumption of firewood and consumption of fuel oils.

4.1. Estimation of service production

To find estimates for all components needed to calculate the effect of a heat pump on electricity consumption in Equation (8) we estimate the conditional demand model in a three-stage process. First, the production of heating services by the household is estimated. We have information about the indoor temperature (T) from the additional energy questionnaire and we use this as a proxy for the production of home heating services. The production of home heating services is approximated by a linear function:

$$T = \alpha_0 + \alpha_V V + \sum_{j=1}^{3} \alpha_j q_j + \alpha_I I + \sum_s \alpha_s H_s + \varepsilon, \tag{9}$$

where q_j is the observed purchaser price of energy good j = electricity, firewood, fuel oils and I is household total

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[2] Not to be confused with indirect rebound due to income effects, as this is a result of changes in the level of household service production.

expenditure (as a proxy for income). The stock of heating equipment is modelled as a set of dummies that indicate whether the equipment is installed in the residence. The dummy for heat pumps (V) is separated, whereas the other heating equipment dummies are included in a vector of characteristics of the household and residence (H). Appendix Table A1 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.

4.2. Estimation of demand for energy goods

The results from the estimation of service production (indoor temperature) are used to predict service production for each household, which then is used as an instrument in the estimation of the demand for alternative energy goods (A= firewood, fuel oils). The demand for fuel oils and firewood are approximated by linear functions:

$$F^A = \beta_0^A + \beta_V^A V + \sum_{j=1}^{3} \beta_j^A q_j + \beta_I^A I + \beta_T^A \widehat{T} + \sum_{k=1}^{K_k^A} \beta_k^A H_k^A + \upsilon^A, \tag{10}$$

where F^A is the household's demand for the alternative fuel A, $\widehat{T}$ is the household's predicted indoor temperature from the first stage, $H^A$is a vector of characteristics of the household and residence for the demand for fuel oils and firewood, respectively, and υ^A are error terms assumed to be independently and identically distributed with a zero expectation and a constant variance for households with the opportunity to consume fuel source A. We capture all substitution effects of heat pumps in one parameter (β_V^A), i.e., we do not decompose the substitution effect of heat pumps. To distinguish between households with and without expenditures on fuel oils and firewood, the demand functions for fuel oil and firewood are estimated using a discrete continuous likelihood function [20,21] adapted to our problem. The number of zero observations and a description of the likelihood function in these estimations are given in Appendix 2.

The results from these estimations are used to predict the demand for firewood and fuel oils for each household, which are used as instruments (along with the predictions for indoor temperature) in the estimation of the conditional electricity demand (approximated by a linear function):

$$E = \gamma_0 + \left(\gamma_0^V + \sum_d \gamma_d^V D_d + \delta_1^V q_1 \right) V + \sum_{j=1}^{3} \gamma_j q_j + \gamma_I I + \gamma^T \widehat{T} + \gamma^O \widehat{F}^O + \gamma^W \widehat{F}^W + \sum_n \gamma_n H_n + \varpi, \tag{11}$$

where E is household electricity consumption, D is a vector of variables for behavioural aspects conditional on having a heat pump (e.g. use the heat pump for cooling), $\widehat{F}^O$ is the predicted household demand for fuel oils, $\widehat{F}^W$is the predicted household demand for firewood, and H is a vector of characteristics of the household and residence in relation to the demand for electricity. To capture the direct effect of having a heat pump on changes in the electricity price, we use an additive term ($\delta_1^V q_1 V$). We assume that the heat pump equipment is exogenous in the estimation of the conditional demand function, i.e. we assume a short-term model for a given stock of equipment. ϖ is the error term, assumed to be independently and identically distributed with a zero expectation and a constant variance. We assume that the error terms in Equations (9)–(11) are independently distributed, and we estimate the parameters in Equations (9)–(11) recursively. To control for heterogeneity across households in the cross-sectional data, we include several characteristics of the household and residence in the estimations.

4.3. Decomposition of the heat pump effect

To calculate the effects on consumption associated with heat pumps, we use the results from the estimation of Equations (9)–(11) and Equation (8). This gives the total effect of a heat pump on electricity consumption, given by $\frac{dE}{dV} = \frac{\partial E}{\partial V} + \frac{\partial E}{\partial F^O}\frac{\partial F^O}{\partial V} + \frac{\partial E}{\partial F^W}\frac{\partial F^W}{\partial V} + \frac{\partial E}{\partial T}\frac{\partial T}{\partial V}$. The indirect effect on consumption through changes in indoor temperature $\left(\frac{\partial E}{\partial T}\frac{\partial T}{\partial V}\right)$is an estimate of the scale effect, whereas the substitution effects, i.e. effects through changes in the optimal energy mix, are calculated as the indirect effect on electricity consumption through changes in the consumption of alternative fuels $\left(\frac{\partial E}{\partial F^A}\frac{\partial F^A}{\partial V}\right)$. In addition to the scale and substitution effects, a heat pump may also affect electricity consumption directly $\left(\frac{\partial E}{\partial V}\right)$. This term captures the effect associated with the own price ($\delta_1^V q_1$), other changes in heating practices resulting from having a heat pump ($\sum_d \gamma_d^V D_d$), as well as a constant term (γ_0^V) capturing effects of not having variables in our data for identification (see Equation (11)).

The above relationship and the estimated coefficients are used to calculate the contribution of scale and substitution, as well as the direct effects on electricity consumption of a heat pump for the mean household (a hypothetical household with mean values for all explanatory variables):

$$\frac{dE}{dV} = \widehat{\gamma}_0^V + \sum_d \widehat{\gamma}_d^V \overline{D}_d + \widehat{\delta}_1^V \overline{q}_1 + \widehat{\gamma}^O \left(\widehat{\beta}_V^O + \widehat{\beta}_T^O \widehat{\alpha}_V \overline{T} \right) \overline{F}^O + \widehat{\gamma}^W \left(\widehat{\beta}_V^W + \widehat{\beta}_T^W \widehat{\alpha}_V \overline{T} \right) \overline{F}^W + \widehat{\gamma}^T \widehat{\alpha}_V \overline{T}, \tag{12}$$

Table 1
Maximum likelihood estimation of indoor temperature (°C), fuel oil and firewood demand (kWh).

Variable	Indoor temperature (°C)		Fuel oil demand (kWh)		Firewood demand (kWh)	
A. Continuous function						
Constant	46.5701	***	−133466	*	17648	
Heat pump (0, 1)	**0.3869**	***	**−695**		**−1781**	***
Price of electricity (NOK per kWh)			1386		−415	
Price of fuel oils (NOK per litre)			−163		48	*
Price of firewood (NOK per sack)			−0.8		−40	***
Total expenditures (NOK 10 000)			722	**	90	
Number of household members	0.0586	*				
Electric heaters as main system (0, 1)					−1323	**
Central heating system (0, 1)			9637	***		
Shared central heating system (0, 1)	0.9565	***				
Number of oil-burning stoves			2467	***		
Number of electric heaters			−716	*	−176	*
Number of firewood stoves					1413	***
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 poorly 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	**				
Manual night setback (0, 1)	−0.1694	*				
Automatic system for night/day setback (0, 1)	−0.1826					
Detached house (0, 1)			209762	**		
Block of flats (0, 1)			−10867	**		
Farmhouse (0, 1)			10289	***	6227	***
Semi-detached house (0, 1)	−0.2788	*				
Predicted indoor temperature (°C)			**6711**	*	**−647**	
Predicted difference in the effect of indoor temp. in detached houses compared to other houses (°C)			**−10030**	**	**97**	**
Standard deviation	1.4816	***	5789	***	5227	***
B. Probability of zero demand						
Constant			2.8293	***	0.8192	***
Fuel oil burner as main heat system (0, 1)			−3.0503	***		
Firewood stove as main heat system (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%.

where variables with a ‘bar’ denotes the arithmetic mean of the variable and ˆ denotes estimated parameters.

5. Results

The data described in section 3 are used to estimate heat production in Equation (9), the demand for alternatives to electricity for heating in Equation (10) and the conditional electricity demand in Equation (11).

5.1. Indoor temperature and demand for fuel oils and firewood

The results from the maximum likelihood estimation of indoor temperature, firewood demand and fuel oil demand are shown in Table 1. 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*, and the results for the estimation of the probability of having zero expenditures on fuel oil and firewood (the discrete parts of the likelihood functions) are shown in section *B* of the table. Parameters included in the calculation of the effects of a heat pump on electricity consumption in Equation (12) are marked in bold print.

We include explanatory variables describing the heterogeneity across households that are expected from economic theory to influence the fuel oil and firewood demand. We also include variables with a significant effect on the dependent variable and that are important regarding controlling for measurement problems. We have tested the sensitivity of the results for the inclusion/exclusion of variables. If the main mechanism for the correlation between energy consumption and a variable goes through the instrument, this correlation is taken care of by this instrument. If the main effect of an explanatory variable is through the electricity demand and including it in the estimation of the instruments destroys this correlation, the variable is included in the electricity demand only. The latter was the case for e.g. total expenditure in the instrument for heat production (indoor temperature).

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 °C higher. Households sharing a central heating system with other households also have a significantly higher indoor temperature than others (almost 1 °C higher). This is also true for households where the employer pays the electricity bill. These results indicate that such households engage in less energy-saving behaviour than households paying the cost themselves and benefit from their savings directly. We also tested the effects on the indoor temperature of having different types of equipment and engaging in different types of energy-saving behaviour. For instance, we see

Table 2
Maximum likelihood estimation of electricity demand, kWh.

Variable	Coefficient	p-value
A. Effects on the constant term (γ_0, γ_n)		
Constant	−25841	0.0974
Net floor space (m^2)	52	0.0000
Detached house (0, 1)	1903	0.0006
Farmhouse (0, 1)	2794	0.0070
Heating degree days in January	13	0.0000
Shared central heating system (0, 1)	−3262	0.0351
Pellets stove (0, 1)	−7176	0.0778
Number of income contributors	808	0.0033
Number of electric heaters	372	0.0000
Area with electric floor heating (m^2)	210	0.0639
Number of tumble dryers	641	0.0978
Number of freezers	762	0.0082
Number of PC's	331	0.0428
Moved into current residence in current year (0, 1)	−1297	0.0932
Can use firewood for heating (0, 1)[a]	1302	0.0575
Electricity bill paid by the employer (0, 1)	−2838	0.0683
House renter (do not own the residence) (0, 1)	−1378	0.0183
B. Price and income effects (γ_j, γ_I)		
Price of electricity (NOK per kWh)	−1879	0.0001
Price of fuel oils (NOK per litre)	−72	0.0712
Price of firewood (NOK per sack)	−1	0.9039
Total expenditures (NOK 1000)	394	0.0000
C. Heat pump $(\gamma_0^V, \gamma_d^V, \hat{\delta}_1^V)$		
Constant	**3367**	**0.1740**
Price of electricity (NOK per kWh)	**−1196**	**0.3039**
State that they use heat pump for cooling during summer (0, 1)	**1173**	**0.1861**
State that they can use heat pump to heat the entire residence (0, 1)	**1644**	**0.0472**
State that they use less fuel oil after installing a heat pump (0, 1)	**3382**	**0.0415**
Number of heating options (1, ..., 5)	**−1569**	**0.0281**
D. Predicted instruments $(\gamma^T, \gamma^O, \gamma^W)$		
Indoor temperature (°C)	**1237**	**0.0797**
Fuel oil demand (kWh)	**−0.3007**	**0.0000**
Firewood demand (kWh)	**−0.2214**	**0.0018**
E. Standard deviation	6091	0.0000

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

that households with a poorly insulated residence and households using night setback maintain a lower indoor temperature than other households.

The effect on fuel oil demand and firewood demand of having a heat pump is twofold. First, there is a direct effect, which is negative in both cases, but only significant for firewood demand. Second, we have an indirect effect of having a heat pump through the influence on indoor temperature. The indirect temperature effect (shown in bold at the bottom of section *A*) is parted in two, as the effect differs across different types of houses. The overall effect on the consumption of fuel oil and firewood of increased indoor temperature, calculated by the sum of its contributions, can be shown to be positive for the mean household.

We see that characteristics of the residence and heating system are significant for fuel oil and firewood demand. Price effects are particularly important for firewood demand, whereas income effects are more important for fuel oil demand. 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 1 are used to predict the indoor temperature and demand for firewood and fuel oils for each household, which then are used as explanatory variables in the estimation of the conditional demand for electricity. The results from a maximum likelihood estimation of Equation (11) are presented in Table 2. The effects on the constant term are shown in section *A* of the table. We include 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* and the direct effects of a heat pump on electricity consumption are shown in section *C*. Section *D* shows the contribution to the scale and substitution effects from the predicted indirect effects through changes in indoor temperature and demand for firewood and fuel oil. Section *E* shows the estimated standard deviation. Again, parameters included in the calculation of the effects of heat pumps on electricity consumption in Equation (12) are marked in bold print.

In section *A* of the table, we see many significant variables correcting the estimation for heterogeneity across households. For instance, households living in farm houses use more electricity, because in some cases, electricity for the residence and for e.g. cow barns and grain driers are attached to the same electricity meter. Most of these variables are included as correction factors (as the example above), but some are of interest. We see that cold weather (as measured by the number of heating degree days in January, which was the coldest month in 2009), leads to a significant increase in the use of electricity in heat pump households. This indicates that the efficiency of the heat pump decreases as temperatures fall.

We see from section *D* of the table that all the estimated coefficients for the predicted variables are significant. Each degree increase in the indoor temperature is associated with a 1237 kWh increase in annual electricity demand, which may be due to, e.g., cold climate and a high share of electricity consumption for heating

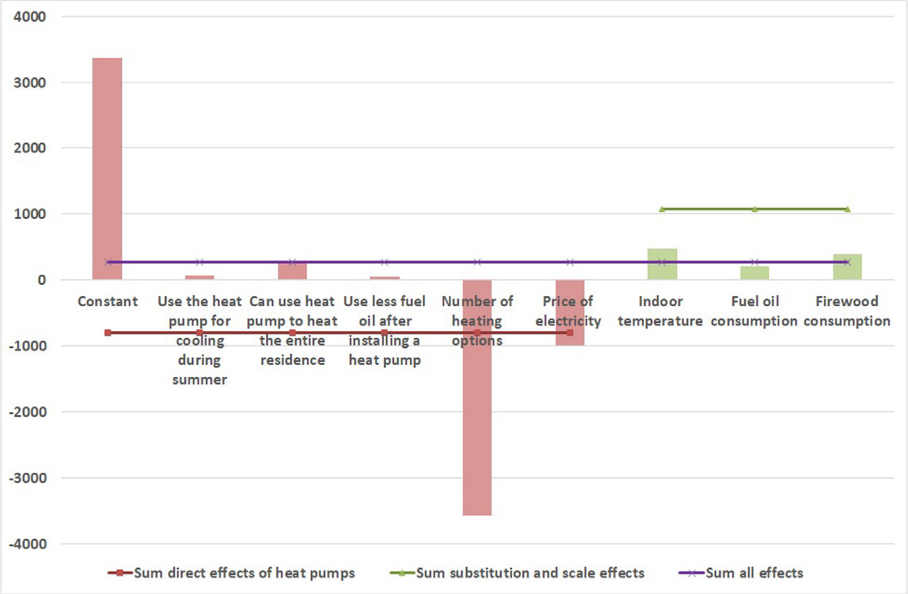

Fig. 1. Decomposition of the predicted effect on electricity consumption of having a heat pump, mean household, kWh.

in Norway. Also, for each kWh increase in firewood and fuel oil demand electricity demand is reduced by 0.2 and 0.3 kWh, respectively. This means that both the scale and substitution effect contribute significantly to electricity consumption and thus also to the rebound effect.

Focusing on the direct effects on household electricity demand of having a heat pump (section *C* of Table 2), we find several significant effects. Of the interaction effects, we see that being able to heat the entire residence using the heat pump alone increases electricity consumption by more than 1600 kWh compared to other households with heat pumps. However, the largest effect on electricity consumption of a heat pump is found for households that state that they use less fuel oil after installing the heat pump. These households use almost 3400 kWh more electricity than other households with a heat pump. This coefficient represents the additional effect of reduced fuel oil consumption for these households and indicates that households who replace their central heaters based on fuel oils with a heat pump save less electricity compared to other households with a heat pump. 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 few households state that they use the heat pump for cooling during the summer (only 6% of the sample). Finally, we see that households with heat pumps and many heating options use significantly less electricity than other households with a heat pump: they use 1569 kWh less electricity for each additional heat source they may use. This means that households with many heating options can save more electricity, compared to households with heat pumps without this opportunity for substitution. This may also increase the average energy efficiency of the heat pump, as alternatives can be used when the energy efficiency of the pump is low.

5.3. Decomposition of the effect of heat pump on electricity consumption

Our estimations illustrate different effects of a heat pump on household electricity consumption, both direct effects and indirect effects (scale and substitution effects). Using Equation (12) together with the estimated coefficients in bold print in Tables 1 and 2 and mean values from Appendix Table A1, we calculate the effect of heat pump ($dV = 1$) on electricity consumption for the mean household. These predicted effects are presented in Fig. 1. If the effect is negative, it constitutes an energy savings effect, whereas positive, it contributes to the rebound effect.

Looking at the results shown in Fig. 1, we find several contributions to the effect of a heat pump on household electricity consumption. Among these direct effects, some are positive, contributing to the rebound, whereas others are negative, indicating an energy saving. The sum of all direct contributions is negative, which implies that if there were no effects through changes in scale and the consumption of alternative energy goods, the overall result would be lower electricity consumption for households with a heat pump compared to other households, despite positive direct contributions to the rebound.

We see that the main reason why we find a negative sum of the direct effects is the number of options embedded in the households heating portfolio. These alternative heating opportunities make the households more flexible in their heating behaviour in cold periods when the energy efficiency of the heat pump is reduced. The constant term captures all unidentified direct effects of a heat pump on electricity consumption. This may be effects of changes in norms, reduced energy-saving behaviour and an increase in the proportion of the residence heated, which all create rebound effects. The scale and substitution effects are all contributing to increasing electricity consumption.

Summing up all effects of having a heat pump, we find a small increase in electricity consumption for the mean household. This effect is small compared to the uncertainty in the estimated coefficients, and we cannot conclude that households with a heat pump have an electricity consumption that differs from other households' consumption. This implies the existence of considerable rebound effects and that the entire electricity-saving potential of the heat pump on electricity consumption is offset by behavioural changes. We also see that a large proportion of these rebound effects are due to scale and substitution effects.

Another interesting question is the size of the effect on the consumption of firewood and fuel oils and on total energy consumption. This is shown in Fig. 2, which summarises the effects of heat pump on household energy consumption for the mean

Fig. 2. Effect on energy consumption of having a heat pump, mean household, kWh.

household. We see that households with a heat pump use less firewood and fuel oils than other households and that they use approximately the same amount of electricity. Thus, total energy consumption is lower for households with heat pump. The heat pumps in Norwegian homes imply an increase in energy efficiency due to a change in energy mix and because the use of electricity, especially for heat pumps, is more energy efficient than the use of firewood and fuel oils.

6. Conclusion

We have developed and used a micro econometric approach and Norwegian household data to examine the effect of heat pumps on electricity consumption and whether the potential electricity saving is offset by rebound effects. We also use this approach to study how the existence of close substitutes and changes in the chosen level of service production affect the rebound.

We find that the predicted contributions to the rebound effect is as great as the electricity-savings on average, so that the mean electricity savings of the heat pump is close to zero. This backfire may be taken as an argument for Jevons' Paradox, as the entire potential energy savings of heat pumps are offset by the rebound effect on electricity demand (see [5] for a discussion of Jevons' Paradox). However, this is not entirely true. We find evidence that households with a heat pump use less of heating sources alternative to electricity, especially firewood. As the reductions in the alternative energy sources are larger than the increase in electricity consumption, the overall energy consumption is reduced because of the energy efficiency measure. In addition, these are only the initial micro effects, and we do not know how this will affect the markets and consumption of other goods than energy goods at a micro level. Nor do we know how it will affect structural changes in the economy. Thus, we cannot conclude about Jevons' Paradox based on the results from this study only.

Households with a heat pump maintain a higher indoor temperature compared to other households. These substitution and scale effects result in higher electricity consumption, *ceteris paribus*, and contribute significantly to the result that the rebound effects outweigh the electricity savings. Thus, using a simple relationship between the rebound effect and the own price elasticity to calculate the direct rebound effect, as shown in Khazzoom [6], would more than likely bias our results. This is because production of heating services in Norwegian homes is a typical case of one energy service being produced by multiple heating sources with varying energy efficiency using multiple energy sources simultaneously. We also find that the direct energy savings resulting from the heat pump are higher among households with a heterogeneous heating portfolio. If we summarize all our estimated effects on household mean electricity consumption of having a heat pump, including the indirect effects on electricity consumption through increased indoor temperature and reduced firewood and fuel oil demand, we find a small increase.

Even if we find that the predicted contributions to the rebound effect is as great as the electricity-saving contributions of the heat pump on average, total energy consumption is reduced, and the energy efficiency of heat production has risen. Household welfare and utility has increased due to increased indoor temperature. The results indicate that households with a heat pump have chosen to spend the money they save on heating on living more comfortably: raising indoor temperature, reducing the labour involved in chopping and carrying firewood, heating a larger part of their residence and using air conditioning. Our results imply that the rebound effects are not only a phenomenon that affects the consumption of the energy source which have become more efficient in use, but it affects the consumption of close substitutes as well as heat production. Therefore, it is important to analyse all types of rebound effects in cases where close substitutes or complements are present.

Our results are similar to the findings in a Norwegian anthropological study of changes in household energy practices with the introduction of a heat pump [22]. They do not attempt to quantify the effects but find that the changes in behaviour are considerable after acquiring the heat pump: increasing indoor temperature, reducing the use of night set-backs, heating a larger part of the house, using less firewood and other alternative energy sources and using the pump for cooling in summer. Since the Norwegian winter is relatively cold and the Norwegian case of heat production is somewhat special with respect to the possibilities for substitution, comparing results to the international literature is difficult. However, Danish studies have indicated considerable rebound effects of heat pumps [9] even though the rebound effects are less than what we find for Norway. This is as expected since the possibility for substitution is considerably less in Danish residential heat production as well as the winter being milder (making the energy savings of a heat pump higher as the energy efficiency of the heat pump is significantly reduced when temperatures fall beneath −10 °C).

As illustrated by our analysis, it may be difficult to anticipate all behavioural effects beforehand in situations where there exist multiple alternative fuel sources. Most new technologies do not only change costs, but also result in new consumption opportunities and a change of habits. The services supplied by different equipment are thus not necessarily homogenous. The potentially large rebound effects make it problematic to rely on increased energy efficiency to reduce energy consumption, unless the prices of all energy goods are targeted to reduce the substitution and scale effects. Another aspect is that the rebound effect will increase in magnitude if investments in energy-efficient technology are subsidized, as a subsidy will increase the income effects. It may be desirable to subsidize new technology for other reasons, e.g. to compensate for positive externalities, or for industry or distributional reasons. However, the energy savings accomplished by such subsidies are ambiguous.

Credit author statement

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Declaration of competing interest

Acknowledgements

The authors are grateful to Terje Skjerpen and three anonymous referees of this journal for valuable comments on earlier drafts and for financial support from the Research Council of Norway through the Renergi program.

Appendix 1. Descriptive statistics

Table A1 shows that electricity is the main energy carrier in Norwegian homes. The variation in electricity consumption is considerable. We also see that firewood is popular. The mean reported indoor temperature is slightly above 21 °C. Indoor temperature is based on answers to the question about temperature in the living-room on a cold winter day. The electricity price is calculated using the respondents' electricity expenditures and consumption. Electricity bills consist of a fixed and a variable charge and the price per kWh will be high for households with very low consumption. For households where the electricity bill is paid by others (e.g., government support), the price equals zero. Approximately 25% of the households have a heat pump installed. Along with electric heaters, electric floor heating and wood-burning stoves, heat pump are the most common type of heating equipment. Central heating systems are relatively rare, and gas consumption is very small (no information about it in this sample).

Table A1
Descriptive statistics, 1111 households, 2009.

	Mean	St. dev	Min	Max
Electricity consumption (kWh)	19044	8602	1272	56221
Firewood purchases (kWh)	4186	5888	0	42000
Fuel oil purchases (kWh)	733	4053	0	58480
Indoor temperature (° C)	21.3	1.5	15.0	26.0
Electricity price (NOK/kWh)	0.83	0.39	0.002	5.2
Firewood price (NOK/sack)	67.2	24.6	8.3	312.5
Fuel oil price (NOK/litre)	10.3	5.7	4.7	60.0
Total expenditure (NOK)	482934	295569	68108	2876670
Heat pump	0.25	0.43	0	1
Central heating system	0.06	0.002	0	1
Common/shared central heating system	0.03	0.18	0	1
Pellets stove	0.01	0.07	0	1
Expenditure on firewood	0.62	0.49	0	1
Expenditure on fuel oils	0.08	0.27	0	1
Can use firewood for heating	0.82	0.39	0	1
Can use fuel oils for heating	0.19	0.39	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
Electric floor heating	0.75	0.43	0	1
Area with electric floor heating (m^2)	0.79	1.68	0	18
State that they use the heat pump for cooling during summer	0.06	0.24	0	1
State that they can use heat pump to heat the entire residence	0.16	0.37	0	1
State that they use less fuel oil after installing a heat pump	0.02	0.13	0	1
Number of heating options	2.28	0.76	1	5
Electric heaters as main system	0.41	0.49	0	1
Fuel oil burner as main system	0.04	0.19	0	1
Firewood stove as main system	0.20	0.40	0	1
Mechanic air ventilator	0.05	0.21	0	1
Manual night setback	0.48	0.50	0	1
Automatic system for night/day setback	0.14	0.34	0	1
Economy shower	0.66	0.47	0	1

Table A1 (*continued*)

	Mean	St. dev	Min	Max
Three-layer windows	0.07	0.26	0	1
Number of layers in windows	2.20	0.76	1	9
Number of tumble dryers	0.59	0.53	0	3
Number of freezers	1.01	0.74	0	5
Number of PC's	1.93	1.35	0	10
The residence is poorly insulated	0.08	0.28	0	1
Detached house	0.58	0.49	0	1
Semi-detached house	0.12	0.32	0	1
Farmhouse	0.08	0.27	0	1
Multifamily residence	0.09	0.29	0	1
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
Heating degree days in January	559	88	391	868
Heating degree days in February	584	91	426	991
Heating degree days in July	52	35	2	194
Electricity bill paid by employer	0.01	0.09	0	1
The year of moving into the residence	1996	13	1933	2009
Number of years in current residence	13	13	0	76
Moved into current residence in current year	0.08	0.28	0	1
House renter (do not own the residence)	0.29	0.45	0	1

Source: Statistics Norway, Norwegian Survey of Consumer Expenditure 2009.

Appendix 2. The likelihood function

Due to an extensive number of zero observations for the demand for fuel oils (1022 households) and firewood (422 households), the demand functions for fuel oil and firewood are estimated using a Double Hurdle (DH) model, with a discrete continuous likelihood function [20]. In a discrete continuous model, the probability density is a mixture of consumers with positive expenditure and consumers with zero expenditure on a good:

$$f\left(F_h^A\right) = \begin{bmatrix} f_+\left(F_h^A\right) \; if \; F_h^A > 0 \\ f_0 \quad if \; F_h^A = 0 \end{bmatrix}$$

where F_h^A is the household h's expenditures on alternative fuel A (= fuel oils and firewood). The discrete component, f_0, is the probability mass measured at zero expenditure, and the continuous component, $f_+(F_h^A)$, is the density for consumers with a positive expenditure (see [20,23,24]. The probability of positive expenditure for a good is given by$P(F_h^A > 0)$, and the probability of zero expenditure (f_0) is given by $1 - P(F_h^A > 0)$. The continuous part of the distribution is then given by:$f_+(F_h^A) = f(F_h^A \mid F_h^A > 0) P(F_h^A > 0)$, where $f(F_h^A \mid F_h^A > 0)$ is the truncated density function of F_h^A. Assuming expenditures to be independently and identically distributed, the likelihood function in the DH model is the product of all densities for all households:

$$L = \prod_{h_+} f_+\left(F_h^A\right) \prod_{h_0} f_0 = \prod_{h_+} f\left(F_h^A \middle| F_h^A > 0\right) P\left(F_h^A > 0\right) \prod_{h_0} \left[1 - P\left(F_h^A > 0\right)\right]$$

The first part of the likelihood function shows the properties of the demand for households with positive expenditures (h_+), whereas the last part shows the properties of the probability of observing zero expenditures (h_0).

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

$$P\left(F_h^A = 0\right) = P\left(\mathit{\Delta} V_{F_h^A} \geq 0\right) = \Phi\left(\underline{\upsilon_h^A}\right)$$

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

$$L_i = \prod_{F_h^A > 0} \left[\frac{1}{\sigma_{\upsilon^A}} \phi\left(\frac{F_h^A - \mu_{F_h^A}}{\sigma_{\upsilon^A}}\right) \Phi\left(\underline{\upsilon_h^A}\right)\right] \prod_{F_h^A = 0} \left[1 - \Phi\left(\underline{\upsilon_h^A}\right)\right]$$

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