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Quantifying the direct and indirect rebound effects for consumers as a response to energy-saving technologies in the EU-27

Keywords: Rebound effect, embodied energy, residential energy demand, energy efficiency, heat pumps, energy efficient lighting

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Quantifying the direct and indirect rebound effects for consumers as a response to energy-saving technologies in the EU-27

Jinxue Hu* and Evgueni Poliakov

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Abstract:

We estimate the rebound effect for residential space heating at the EU-27 level, which occurs when an improvement in energy efficiency results in additional energy consumption. Three types of rebound effects are distinguished, namely the direct effect, indirect effect and the embodied energy. We demonstrate that the magnitude of the direct rebound effect is highly dependent on the chosen estimation method and equation specification. The indirect rebound effect captures the effect at the macro level and is estimated using input output modeling. It includes the change in energy taxes received by the government. The results showed an estimated direct rebound effect in the range of six to 26 per cent depending on the method. The indirect effect was estimated at only one per cent. Finally, we apply the estimated values of rebound effects to heat pumps and energy efficient lighting in order to assess the impact of the diffusion of these energy saving technologies on energy consumption. We further translate the potential technical savings of these technologies into the actual expected energy savings, direct and indirect rebound effect and embodied energy.

JEL codes: D12, Q43, Q55

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1 Introduction

Improving energy efficiency in buildings is important to reduce greenhouse gas emissions and is therefore one of the priorities on the European policy agenda. A large number of technological innovations aimed at energy savings have been introduced in the built environment, which is necessary for a transition towards a more sustainable energy use system. The (final) energy intensity of the European economy has decreased significantly in the past years, due to the application of new energy-saving technologies. However, the effect of the successful diffusion of the energy-saving technologies was dampened by the behavioral response of the consumers (Brouwer and Klein Woolthuis, 2014). This was partly caused by the response of the consumers, who increased the comfort level. An example of such a behavior is consumers setting the thermostat to a higher temperature due to improved insulation. Moreover, in case there is still a net energy saving, the monetary savings from the energy bill can be used for purchasing other energy-intensive commodities, which increase the economy-wide use of energy. The production and implementation of an energy efficiency improvement requires energy use as well. The embodied energy demand of a certain technology will also be included in the estimation of the economy-wide net energy savings.

The goal of this paper is to elucidate econometrically the change in consumer behavior concerning energy consumption as a result of the diffusion of energy-saving technologies in the built environment and to estimate the economy-wide net energy savings. The increased energy consumption which partially offsets the energy savings arisen from improved energy efficiency is called the rebound effect. In this study, we quantified the direct and indirect component of this effect in regards to gas and electricity as well as embodied energy use and estimated the net economy-wide energy savings resulted from new technologies. We applied different methods for estimating the direct rebound effect to test the robustness of the results. The rebound effect model was applied to assess the impact of the diffusion of heat pumps and energy efficient lighting on energy consumption.

2 Theoretical framework

The concept of the rebound effect was introduced by Khazzoom (1980). The rebound effect is defined as an improvement in energy efficiency which leads to a decrease in the relative price for the energy service. As a response the demand for the energy service will increase. Several definitions of the rebound effect were used in broader contexts such as economy wide (Greening et al., 2000). Different labels are used in different studies describing the same types of effect. We will describe them based on the rebound effect typology as proposed by Sorrel (2007).

Figure 1: Rebound effect typology

<table>
<tr><td rowspan="4">Potential residential energy savings</td><td colspan="2">Net energy savings</td></tr>
<tr><td rowspan="3">Economy-wide rebound effect</td><td>Indirect rebound effect</td></tr>
<tr><td>Embodied energy</td></tr>
<tr><td>Direct rebound effect</td></tr>
</table>

The potential residential energy savings is the starting point, as illustrated with the figure above. The potential energy saving is the technical estimation of the energy savings demonstrated in the laboratory tests. However, the economy-wide rebound effects will reduce the actual energy savings. The total rebound effect is built up from three types of rebound effects.

The first effect that occurs from an energy efficiency improvement is a decrease in the energy bill for households. A decrease in the energy bill can be considered as a decrease in the relative energy price. If energy becomes cheaper demand for energy will increase. This effect is also called the own price effect or *direct rebound effect* (Berkhout et al., 2000; Sorrel, 2007).

The *indirect rebound effect* occurs when monetary savings on energy are spent on the consumption of other goods. This change in household expenditure is also referred to as the re-spending effect, secondary or indirect rebound effect (Berkhout et al., 2000; Greening et al., 2000; Gonzalez, 2007). The re-spending effect has repercussions throughout the whole economy. The households spend less on energy while consuming more of other products. The sectors providing these other products are affected by the change in final demand, which in turn affects other sectors as well, and so on. This mechanism can also be labeled as the economy-wide effect affecting the energy use in all sectors[1].

The *embodied energy* relates to the energy needed to achieve the energy efficiency improvement. This can be for instance the energy use related to the production of an innovation or its installation into the built environment. We limited embodied energy to the energy use related to the production. The embodied energy for the new technologies selected in this report is larger than

[1] In most cases, the implementation of an energy improvement requires an investment. The monetary savings and re-spending on the consumption of other products are reduced by capital requirements. Sufficient data, however, were not available to include this effect of the capital costs.

for the conventional technologies. This is not necessarily always the case. For instance, the production of eco boilers requires less input materials compared to the production of conventional boilers[2], and hence embodied energy is saved by implementing the new technology.

The discussion of the rebound effect can be traced back to the Industrial Revolution. The economist William Stanley Jevons observed that increased energy efficiency of steam engines led to increased coal use (Jevons, 1865; Nässén and Holmberg, 2009). The actual debate on the rebound effect was started by Khazzoom (1980) who introduced the rebound effect as it is used in the current literature. The debate was a response on the energy efficiency policies of the 1970's (Nässén and Holmberg, 2009). Since, many studies have quantified the direct rebound effect. This can be done using the quasi-experimental approach, by measuring the energy use before and after the introduction of an energy efficiency improvement, while controlling for other factors which could explain a change in energy use. However it is very difficult to collect large datasets necessary for the application of this method; in addition, the assembled data could be prone to selection bias (Sorrel at al., 2009). Another and more common way of quantifying the rebound effect is by applying econometric methods based on secondary data. Ideally one would estimate the elasticity between energy efficiency and the use of energy services (in our case heating). However no direct data are available for this estimation. Instead, we will use the price elasticity of the energy demand as a proxy for the rebound effect as shown below (Sorrel, 2007; Gonzáles, 2011).

$$\eta_{\varepsilon}(E) = -\eta_{P_E}(E) - 1$$

$\eta_{\varepsilon}(E)$ designates the energy efficiency elasticity of demand for energy and $\eta_{P_E}(E)$ the price elasticity of demand for energy. The price elasticity for demand of energy would be zero without rebound effect, leading to an efficiency elasticity for energy demand of -1. This means that an increase in energy efficiency leads to an equal reduction in energy use. This proxy is based on energy demand and energy prices for which good data is available. We will therefore use the energy price elasticity as proxy for the direct rebound effect. We assume symmetry meaning that agents react in the same way to an increase in energy efficiency as to a decrease in energy prices.

A considerable amount of studies exists on quantifying the direct rebound effect for residential space heating and have made overviews of existing estimates as well. From these papers we listed several studies estimating the direct rebound effect in a European country. The range of the direct rebound effect seems to be between nine and 60 per cent. Some studies distinguish between the short run and long run effect by removing the time trend from the long run effect.

[2] Source: the FP7 EMInInn project, www.emininn.eu

Table 1: Overview of estimations of the direct rebound effect for residential space heating

Author	Country	Rebound effect	Comments
Galvin (2014)	EU28	18.3%	Based on energy efficiency data from Odyssee
Freire-Gonzalez (2010)	Catalonia (Spain)	36% short run 49% long run	
Nässén and Holmberg (2009)	Sweden	9%	Taking into the role of account capital costs
Nesbakken (2001)	Norway	15-55% (average 21%)	Listed by Freire-Gonzales (2011)
Haas and Biermayr (2000)	Austria	20-30%	Listed by Nässén and Holmberg (2009)
Haas et al. (1998)	Austria	15-48%	Listed by Sorrel et al. (2009)
De Groot et al. (1998)	The Netherlands	5-15% short run 10-60% long run	Listed by Berkhout et al. (2000)
Steering Committee on regulating energy taxes (1992)	The Netherlands	20-30% electricity has lower rebound effect than gas	Summarized by Berkhout et al. (2000)

Some other conclusions are drawn in the literature as well. For instance, electricity typically has a lower rebound effect than natural gas as indicated by a number of studies that include both electricity and gas prices (Berkhout et al., 2000). Further, if the capital costs of the implementation of the technology are taken into account, the estimated rebound effects are somewhat lower (Nässén and Holmberg, 2009; Thomas and Azevedo, 2013). And lastly, there is evidence that the rebound effects in developing countries or countries with lower income are higher, since the energy use is far from satiation (Thomas and Azevedo, 2013).

A few studies estimate both the direct and indirect rebound effects, often through the input-output framework. Freire-Gonzáles (2011) shows that the direct plus indirect rebound effect is around 56 per cent in the short run and around 65 per cent in the long run. The direct rebound effect was estimated at 36 and 49 per cent, respectively, for the short and long run. However, a study by Nässén and Holmberg (2009) shows that the indirect rebound effect is -1 per cent (you actually save even more energy indirectly) and six per cent for two different scenarios assuming different capital costs.

3 Applied methodology

3.1 The direct rebound effect

To estimate the price elasticity of residential energy demand we need to apply a regression model where we control for other factors which also affect the residential energy use. We use the standard specification often present in the literature on rebound effects:

$$\ln E_{it} = \alpha + \beta_1 \ln HDD_{it} + \beta_2 \ln Y_{it} + \beta_3 \ln P_{it}^{ELEC} + \beta_4 \ln P_{it}^{GAS} + \varepsilon_{it}$$

where E_{it} stands for the energy use by country i and year t, HDD_{it}, for heating degree days, Y_{it}, for household income in constant prices, P_{it}^{ELEC}, for the electricity price deflated with the consumer price index, and P_{it}^{GAS}, for the deflated gas prices.

The specification includes income elasticity of demand for energy (β_2), and price elasticities of demand for energy for electricity and gas (β_3 and β_4, respectively). Different model specifications will be applied to ascertain if and how the specification influences the results. The specifications are described in the chapter on results.

We apply panel econometrics methods, since our data is a panel of 27 European countries over 17 years. One important consideration for choosing the specific estimation methods is the possible presence of heteroscedasticity in the variance-covariance matrix of the error term. The ordinary least squares method is inefficient in the presence of heteroscedasticity. For instance, Gonzales (2010) used the feasible generalized least squares to account for panel heteroscedasticity in his estimation of the direct rebound effects for electricity and gas. Therefore, we ran tests for the possibility of heteroskedastic structure of the error term. Firstly, we checked if the error variance-covariance matrix of the error had the panel-specific heteroskedastic variances on its diagonal. We applied the likelihood ratio test for the constrained (homoscedastic) and unconstrained (heteroskedastic) models for each equation specification. The tests invariably showed the presence of panel-specific heteroscedasticity. In order to test the presence of non-diagonal heteroscedasticity (autocorrelation), we applied the Wooldridge serial correlation test. The results showed that the error term is auto correlated in all model specifications.

Therefore, we applied appropriate estimation methods in order to account for the presence of heteroscedasticity and autocorrelation. One is the feasible generalized least squares model for panel data and the other is the ordinary least squares with the panel-specific error correction. While the feasible least squares estimator weights observation by the (inverse) standard deviation of the errors, the panel-corrected standard error method corrects the standard error of the parameter with the covariance of the estimated residuals.

There are some differences in opinion in the literature which method to use in our case. Thus Beck and Katz (1995) argued that for the case of time-series cross-section data where the number of panels and the number of time periods is small (both between 10 and 40; which is our case), the feasible generalized least squares procedure leads to overoptimistic estimates of the standard errors that are biased downwards. They favor the ordinary least squares estimator accompanied by panel-corrected standard errors. Their Monte-Carlo simulations showed that the standard errors obtained by the latter method perform better in small samples than the former procedure. We used both methods for the robustness of results.

Furthermore, two variations of each estimation method were used. One assumed a common autocorrelation coefficient in all panels while another assumed panel-specific autocorrelation coefficients. The resulting four sets of parameter estimates are compared and contrasted in the results chapter.

3.2 The indirect rebound effect

If the direct rebound effect is smaller than 100 per cent, the households will achieve a direct energy saving. Savings on the energy bill will be re-spent on the consumption of other goods. The re-spending of additional income over products is proportionate to the average spending on these products. This assumption is based on the Cobb-Douglas utility function.

The energy products typically have a higher tax rate than other products. The tax rates for the energy and non-energy products were, respectively, 30 and 10.5 per cent in EU-27 in 2009. A shift from expenditure on energy to other products will lead to a reduction in taxes. The change in taxes in our model was included through government expenditures.

To estimate the indirect effects as a result of the change in final expenditure, we will apply an input output model. The input output table includes all transactions between economic agents in an economy, including sectors and final demand categories. We will apply the Leontief input output framework based on backward linkages, which means that demand defines supply. This enables the estimation of the effect of a demand change on the rest of the economy. We will include energy intensities per sector to translate the effect in sector output into sector energy use.

By using the following equation we will estimate energy intensities, which indicate for each additional euro of final demand the amount of additional energy demand in the rest of the economy.

$$e_i X_i = (I - A)^{-1} Y_i$$

Where e_i stands for the amount energy used per unit of output in, expressed in GJ per euro, X_i stands for the output by sector, $(I - A)^{-1}$ for the Leontief inverse and Y_i for the final demand.

4 Data and results

We used 1996-2012 data on energy use, heating degree days, household income and consumer price indices. We use the input output data from 2009. All data was extracted from Eurostat in September 2014. For the application of the model on energy efficient lighting and heat pumps we used data on diffusion rates, potential energy savings and embodied energy from the EU FP-7 project EmInInn[2] project. This is supplemented with data on the diffusion for heat pumps from the biennial report from EurObserv'ER (EurObserv'ER, 2011).

4.1 The direct rebound effect

We are interested in the effect of energy prices on energy consumption for heating. Different energy types are used for space heating including gas, petroleum products, solid fuels, derived heat, electricity, waste and wood. Only energy prices for electricity and gas were available though. However, energy prices for the different energy types are correlated (European Union, 2014). Thus the change in the electricity and gas price can also affect energy use of other sources. The exception however is wood, the production and consumption of which has a more local character, with a price less correlated with the gas and electricity prices. Therefore we explored different specifications. The following five different specifications were applied, where the dependent variable includes one of the following:

1. All energy types
2. All energy types except wood
3. Gas and electricity
4. Electricity
5. Gas

In the model specification including only gas demand rather, the data issue arises that some countries don't use gas for space heating. Therefore, all countries with less than gas use lower than one per cent of the total residential energy use are not included.

In Table 2, we report the estimates and standard errors of the direct rebound effects for electricity and gas obtained with two estimation methods: feasible (iterative) generalized least squares (designated with FGLS in the table) and ordinary least squares with panel-corrected standard errors (PCSE). Two variants of each estimator were used: common autocorrelation coefficient for all panels (AR) and panel-specific autocorrelation coefficients (PSAR). We cannot unambiguously rule out any of these four methods. Thus four estimation methods and five specifications result in 20 estimates. A significant number of estimates strengthen the robustness of the results.

Results from the first specification are similar for all four estimation methods. The gas price elasticities are in all cases significant and have a comparable size. The estimates for electricity however are not significant.

The second specification produces almost the same results. Again elasticities for the gas price are significant for all methods but not for electricity. Only one estimate of the electricity price in model 2 shows a significant non-zero elasticity.

Results for the gas price in the specification based on gas and electricity are similar for the four estimation methods. In models 1, 3 and 4, the results are significant. The sizes of the elasticity are also similar. For the electricity price, significant results are found in models 1, 2, and 3. The magnitude of the elasticities is comparable.

The fourth specification exhibits differences between the FGLS and PSCE models. In the FGLS models gas price has significant estimates while the PSCE models give insignificant results. The last specification shows similar results. Model 2 is the only model with insignificant estimates for the electricity price.

Literature shows a vast variation of the magnitude of the direct rebound effects depending on the data and methods used. There is indeed some variation of results in this study depending on the application of one of the four estimation methods. Sometimes gas price elasticity is significant and electricity price elasticity is not and the other way around. Since gas and electricity prices can be correlated this does not seem too striking.

In general the estimates are comparable between the methods. Especially the estimates of the first two specifications are consistent. There are a few contradictions between the methods within a model specification. Also the size of the elasticities is relatively similar between methods within a specification. This gives us an indication that the results are quite robust.

We believe that both gas and electricity prices should affect the energy use of household. Therefore we would propose the elasticity from the specification using all energy except wood as our middle estimate. The upper and lower boundary of the elasticities can be derived from all results.

We observe that the size of these significant elasticities ranges between six to 17 per cent for Model 1, 14 to 26 per cent for Model 2, 10 to 21 per cent for Model 3 and 11 to 20 per cent for the last model. The chosen model specification for the middle level gave us an elasticity of 15.7 per cent for the FGLS models, which is within all ranges. Based on the above, we can conclude that the gas price elasticity on energy demand is robust and the elasticity of 15.7 per cent is consistent across the different specifications and methods.

When looking at the electricity price, we observed that the size of the significant elasticities ranges between seven to 18 per cent for Model 1, between 13 to 21 per cent for Model 2, nine per cent for Model 3 and 15 to 17 per cent for the last model. From the preferred specification we obtained an elasticity of 12.5 per cent. The elasticity of the chosen specification for the middle estimation was more or less within these ranges or was at least close to the estimations from the PCSE model. We can conclude that the results for the electricity price are less conclusive than for gas price. This could be caused by the fact that electricity use also applies on a variety of end-uses not related to space heating.

Table 2: Regression results for residential energy use in EU-27

Energy use definition	Parameters	Model 1 FGLS PSAR Coefficient		Std. err.	Model 2 FGLS AR Coefficient		Std. err.	Model 3 PCSE PSAR Coefficient		Std. err.	Model 4 PCSE AR Coefficient		Std. err.
All energy types	$\ln HDD$	0.726	***	0.023	0.520	***	0.029	0.823	***	0.053	0.612	***	0.057
obs: 418	$\ln Y$	0.764	***	0.014	0.861	***	0.013	0.834	***	0.017	0.811	***	0.014
	$\ln P^{GAS}$	-0.096	***	0.034	-0.141	***	0.041	-0.179	***	0.068	-0.162	**	0.073
	$\ln P^{ELEC}$	-0.040		0.049	-0.044		0.059	-0.066		0.095	-0.127		0.100
	α	1.401	***	0.198	2.242	***	0.258	0.131		0.331	1.996	***	0.476
All energy types except wood	$\ln HDD$	0.691	***	0.023	0.551	***	0.031	0.714	***	0.046	0.540	***	0.053
obs: 418	$\ln Y$	0.847	***	0.011	0.861	***	0.015	0.862	***	0.013	0.839	***	0.018
	$\ln P^{GAS}$	-0.157	***	0.035	-0.157	***	0.042	-0.213	***	0.071	-0.198	***	0.071
	$\ln P^{ELEC}$	-0.058		0.050	-0.125	**	0.058	-0.092		0.088	-0.154	*	0.086
	α	0.951	***	0.180	1.923	***	0.281	0.671	**	0.300	2.192	***	0.449
Gas and electricity	$\ln HDD$	0.437	***	0.025	0.364	***	0.029	0.426	***	0.041	0.401	***	0.040
obs: 418	$\ln Y$	0.990	***	0.009	1.014	***	0.013	0.995	***	0.013	0.935	***	0.022
	$\ln P^{GAS}$	-0.057	*	0.033	-0.056		0.040	-0.103	*	0.061	-0.114	*	0.064
	$\ln P^{ELEC}$	-0.175	***	0.050	-0.212	***	0.061	-0.110		0.069	-0.168	**	0.079
	α	1.355	***	0.213	1.660	***	0.244	1.429	***	0.327	2.018	***	0.348
Gas	$\ln HDD$	0.821	***	0.045	0.545	***	0.067	1.346	***	0.180	1.191	***	0.166
obs: 286 (excl. countries with less	$\ln Y$	1.006	***	0.010	0.944	***	0.021	1.021	***	0.015	1.018	***	0.030
than 10% gas use, which are EE,	$\ln P^{GAS}$	-0.171	***	0.050	-0.260	***	0.071	-0.032		0.116	-0.165		0.133
LV, LT, GR, BG, SE, FI, CY and MT)	α	-2.361	***	0.373	0.562		0.574	-6.689	***	1.468	-5.376	***	1.426
Electricity	$\ln HDD$	0.163	***	0.017	0.152	***	0.021	0.198	***	0.029	0.218	***	0.034
obs: 418	$\ln Y$	0.874	***	0.007	0.825	***	0.010	0.863	***	0.009	0.842	***	0.016
	$\ln P^{ELEC}$	-0.065	*	0.036	-0.048		0.041	-0.092	*	0.048	-0.155	***	0.056
	α	3.543	***	0.143	3.849	***	0.184	3.377	***	0.231	3.364	***	0.288

* Significant at 10 per cent confidence level; ** Significant at five per cent confidence level; *** Significant at one per cent confidence level

In conclusion we would propose to use the elasticities shown in the table below. The direct rebound effect for gas use was between 5.7 and 26 per cent and for electricity use this was between 6.5 and 21.2 per cent. These results were in line with results from literature.

Table 3: Range of estimated direct rebound effect, based on different models

	Gas	Electricity
Lower boundary	5.7%	6.5%
Middle estimate	15.7%	12.5%
Upper boundary	26.0%	21.2%

4.2 The indirect rebound effect

The re-spending pattern of the monetary savings stemming from improved energy efficiency was estimated in order to estimate the indirect rebound effect. The re-spending of €1,000 by 65 types of products is shown below. The monetary savings were mostly spent on “Imputed rents of owner-occupied dwellings”, “Accommodation and food services” and “Retail trade services”. Note that this was based on prices excluding tax or trade and transport margins.

The energy intensity was needed to estimate the indirect effect on energy demand. It is expressed as the amount of energy required in all sectors for each additional euro of final demand. Land and air transport had the highest energy intensities. Other products with high intensities were metal products, non-metallic mineral products and paper products.

The reduced government income from energy taxes is taken into account by reducing the government expenditure. We can conclude that the average household expenditure requires more indirect energy use compared to the average government expenditure. The government consumes mostly “Public administration and defense services”, “Education services” and “Human health services”. These services have a very low energy intensity of 1.3 to 1.5 MJ per euro. Households consume much more of energy-intensive products such as “Food products, beverages and tobacco products” which has an intensity of 4.8 MJ per euro.

Table 4: Average household expenditure, multiplier and energy intensity by product type, 2009

CPA code	Product type	Average household expenditure	Average government expenditure	Energy intensity (MJ/€)
CPA_A01	Products of agriculture, hunting and related services	€ 15	€ 0.48	5.3
CPA_A02	Products of forestry, logging and related services	€ 1	€ 0.03	4.7
CPA_A03	Fish and other fishing products	€ 1	€ 0	5.4
CPA_B	Mining and quarrying	€ 1	€ 0.16	3.0
CPA_C10-C12	Food products, beverages and tobacco products	€ 86	€ 0.14	4.8
CPA_C13-C15	Textiles, wearing apparel and leather products	€ 16	€ 0.04	3.6
CPA_C16	Wood and of products of wood and cork	€ 1	€ 0	6.7
CPA_C17	Paper and paper products	€ 3	€ 0.04	10.4
CPA_C18	Printing and recording services	€ 1	€ 0	9.5
CPA_C19	Coke and refined petroleum products	€ 13	€ 0.03	4.4
CPA_C20	Chemicals and chemical products	€ 9	€ 0.43	5.9
CPA_C21	Pharmaceutical products	€ 4	€ 14	4.6
CPA_C22	Rubber and plastics products	€ 4	€ 0.01	3.8
CPA_C23	Other non-metallic mineral products	€ 2	€ 0	11.8
CPA_C24	Basic metals	€ 0.05	€ 0	13.0
CPA_C25	Fabricated metal products	€ 3	€ 0.04	4.2
CPA_C26	Computer, electronic and optical products	€ 6	€ 0.26	2.7
CPA_C27	Electrical equipment	€ 5	€ 0.03	3.5
CPA_C28	Machinery and equipment n.e.c.	€ 1	€ 0	3.5
CPA_C29	Motor vehicles, trailers and semi-trailers	€ 30	€ 0.02	3.9
CPA_C30	Other transport equipment	€ 2	€ 0.19	3.0
CPA_C31_C32	Furniture and other manufactured goods	€ 12	€ 0.92	3.5
CPA_C33	Repair and installation services of machinery and equipment	€ 1	€ 0.04	2.8
CPA_D35	Electricity, gas, steam and air-conditioning	€ 32	€ 0.32	2.9
CPA_E36	Natural water, water treatment and supply services	€ 4	€ 0.20	1.9
CPA_E37-E39	Sewerage, waste collection, treatment and disposal activities	€ 9	€ 4	2.5
CPA_F	Construction	€ 10	€ 1	2.5
CPA_G45	Wholesale and retail trade and repair services of motor vehicles	€ 34	€ 0.64	2.2
CPA_G46	Wholesale trade services, except of motor vehicles	€ 54	€ 6	2.9
CPA_G47	Retail trade services, except of motor vehicles and motorcycles	€ 90	€ 10	1.8
CPA_H49	Land transport services and transport services via pipelines	€ 27	€ 5	27.3
CPA_H50	Water transport services	€ 3	€ 0.08	4.5
CPA_H51	Air transport services	€ 8	€ 0.13	22.3
CPA_H52	Warehousing and support services for transportation	€ 4	€ 8	4.4
CPA_H53	Postal and courier services	€ 2	€ 0	1.9
CPA_I	Accommodation and food services	€ 91	€ 0.96	2.0
CPA_J58	Publishing services	€ 10	€ 0.19	2.8
CPA_J59_J60	Motion picture, video and television programme production	€ 8	€ 3	2.2
CPA_J61	Telecommunications services	€ 25	€ 0.16	1.6
CPA_J62_J63	Computer programming, consultancy and related services	€ 0.35	€ 0.23	1.5
CPA_K64	Financial services	€ 30	€ 0.03	1.1
CPA_K65	Insurance, reinsurance and pension funding services	€ 29	€ 0.01	1.6

CPA code	Product type	Average household expenditure	Average government expenditure	Energy intensity (MJ/€)
CPA_K66	Services auxiliary to financial services and insurance services	€ 2	€ 0.02	1.3
CPA_L68B	Real estate services (excl imputed rents)	€ 85	€ 8	0.9
CPA_L68A	Of which: imputed rents of owner-occupied dwellings	€ 96	€ 0	1.5
CPA_M69_M70	Legal and accounting services	€ 3	€ 0.58	1.5
CPA_M71	Architectural and engineering services	€ 1	€ 0.45	1.8
CPA_M72	Scientific research and development services	€ 0.09	€ 11	2.0
CPA_M73	Advertising and market research services	€ 0.12	€ 0	2.2
CPA_M74_M75	Other professional, scientific and technical services	€ 3	€ 0.57	1.8
CPA_N77	Rental and leasing services	€ 4	€ 0.21	1.8
CPA_N78	Employment services	€ 0.23	€ 0.57	1.1
CPA_N79	Travel agency, tour operator and other reservation services	€ 6	€ 0.31	4.7
CPA_N80-N82	Other business support services	€ 3	€ 0.63	1.8
CPA_O84	Public administration and defense services	€ 5	€ 374	1.5
CPA_P85	Education services	€ 17	€ 195	1.3
CPA_Q86	Human health services	€ 26	€ 246	1.4
CPA_Q87_Q88	Social work services	€ 13	€ 81	1.3
CPA_R90-R92	Creative, arts and entertainment services	€ 13	€ 13	1.6
CPA_R93	Sporting services and amusement and recreation services	€ 6	€ 7	1.9
CPA_S94	Services furnished by membership organizations	€ 1	€ 3	1.7
CPA_S95	Repair services of computers and personal and household goods	€ 3	€ 0	1.8
CPA_S96	Other personal services	€ 18	€ 0.20	1.3
CPA_T	Services of households as employers	€ 8	€ 0.25	0.6
CPA_U	Services provided by extraterritorial organizations and bodies	€ 0.02	€ 0	3.9
	Total	€ 1,000	€ 1,000	

5 Case study

The estimated parameters for the direct and indirect rebound effect were translated into the percentages presented in table 5. The direct rebound effect of gas and electricity are combined into one rebound effect by using the ratio between electricity and gas consumption for residential space heating. The energy savings after the direct rebound effect were then translated into monetary savings of the households by using energy prices. A composite energy price is calculated using again the ratio between electricity and gas consumption for residential space heating. The percentage energy used for embodied energy depends on the technology to be considered. Assuming that the embodied energy is larger than zero the net energy savings will be smaller than 84 per cent in the middle estimate.

Table 5: Range of size of rebound effects for EU-27 for 2010

	Technical estimation of energy savings			
	Economy-wide rebound effect			Actual energy savings
	Direct rebound effect	Embodied energy	Indirect rebound effect	
Lower boundary	5.8%		1.0%	<93%
Middle level	15.3%		0.9%	<84%
Upper boundary	25.4%		0.8%	<74%

The rebound effect model was applied to two cases: heat pumps and energy-efficient lighting. We used the results from the FP7 project EMInInn, which focused on innovations at the micro level and linked it with macro level environmental indicators. For each of the innovations the diffusion rate, potential technical energy savings and embodied energy demand was estimated or collected in this project[3]. The embodied energy use was expressed as the cumulated energy demand (CED). This is the cumulative energy use needed for the production of the materials used for the innovation. All additional CED and energy savings are estimated compared to the alternative technology. For the energy-efficient lighting, this means that the CED and energy savings are relative to the use of conventional light bulbs.

[3] The simulation software VIP Energy was used to estimate the technical energy savings at the micro level. The calculation covered many aspects for the energy balance of the building such as heat storage, air infiltration, solar energy and transmission through the ground. The model was validated by the IEA (International Energy Agency Building Energy Simulation Test and Diagnostic Method). The embodied energy was estimated using Ecoinvent data.

5.1 Heat pumps

Table 6: Technical savings, embodied energy use and diffusion for heat pumps

Annual technical savings per households	
North and Central Europe	49,493 MJ
West Europe	31,488 MJ
South Europe	14,147 MJ
Embodied energy demand for the production of the technology	
Production costs (CED)	42,067 MJ
Production costs alternative (CED)	33,130 MJ
Lifetime	15 years
Annualized net embodied energy use (CED)	596 MJ
Diffusion of technologies	
Diffusion in 2009	0.98% in North and Central Europe 0.30% in West Europe 0.03% in South Europe (0.46% in EU-27)
Diffusion in 2010	1.03% in North and Central Europe 0.33% in West Europe 0.03% in South Europe (0.49% in EU-27)

Source: EMInInn project and EurObserv'ER.

In table 6 heat pump data on technical energy savings, embodied energy and diffusion are summarized. The potential annual savings for heat pumps are 42,378 MJ per household, when weighing for the diffusion per climate zone which can be seen from table 7. We estimated the direct and indirect rebound effect, which are six to 25 per cent and around one per cent respectively. The annualized net embodied energy use of one per cent is also included. This means that according to this model the net energy savings of heat pumps is 82 per cent (middle estimate) of the technical estimation of the savings, which is still relatively high.

Table 7: Lower and upper boundaries of net savings and rebound effects per household for heat pumps, 2010

	Technical estimation of energy savings 42,378 MJ (100%)			
	Economy-wide rebound effect			Actual energy savings
	Direct rebound effect	Embodied energy	Indirect rebound effect	
Lower boundary	2,442 MJ (5.8%)	596 MJ (1.4%)	428 MJ (1.0%)	38,911 MJ (91.8%)
Middle level	6,481 MJ (15.3%)	596 MJ (1.4%)	385 MJ (0.9%)	34,916 MJ (82.4%)
Upper boundary	10,764MJ(25.4%)	596 MJ (1.4%)	339 MJ (0.8%)	30,679 MJ (72.4%)

The higher the direct rebound effect is, the lower the direct savings for the households are. When households have less direct savings they will have less to re-spend on the consumption of other products, resulting in a lower indirect rebound effect for the rest in the economy. However the direct rebound effect has a larger negative effect on energy savings than the indirect effect. This means that a lower direct rebound effect will also lead to a higher net energy saving economy-wide.

The savings for heat pumps per household was scaled up to macro level by using the diffusion data. The additional diffusion of heat pumps in 2010 compared to 2009, was 0.03 per cent at EU-27 level. This is equivalent to 58,443 households. This gives us a total potential annual saving of 2,477 TJ at the EU-27 level. This potential annual saving amounts to about 0.02 per cent of the total EU-27 residential energy use and can be seen from table 8. We can conclude that the net energy savings of the 58,443 households which had heat pumps since 2010, result in a net energy saving of 1,793 – 2,274 TJ in 2010 at the EU-27 level. This equals a saving of 0.015 to 0.019 per cent of the total EU-27 residential energy use (12,019 PJ).

Table 8: Lower and upper boundaries of net savings and rebound effects for heat pumps, in TJ and % of total residential energy use EU-27 2010

	Technical estimation of energy savings 2,477 TJ (0.02%)			
	Economy-wide rebound effect			Actual energy savings
	Direct rebound effect	Embodied energy	Indirect rebound effect	
Lower boundary	143 TJ (0.001%)	35 TJ (0.000%)	25 TJ (0.000%)	2,274 TJ (0.019%)
Middle level	379 TJ (0.003%)	35 TJ (0.000%)	22 TJ (0.000%)	2,041 TJ (0.017%)
Upper boundary	629 TJ (0.005%)	35 TJ (0.000%)	20 TJ (0.000%)	1,793 TJ (0.015%)

5.2 Energy efficient lighting

Energy efficient lighting includes LED and energy-saving light bulbs. The data on potential annual energy savings, annualized embodied energy and diffusion are summarized in the table below. The application of the rebound effect model on energy efficient lighting is different from heat pumps. Energy efficient lighting had an effect on electricity use rather than total energy use. This means that the rebound effect was solely based on the electricity price elasticity; hence the electricity price was used instead of the weighted energy price.

Table 9: Technical savings, embodied energy use and diffusion for energy efficient lighting

Annual technical savings per households	
North and Central Europe	2,077 MJ
West Europe	2,400 MJ
South Europe	3,314 MJ
Embodied energy demand for the production of the technology	
Production costs (CED)	514 MJ
Production costs alternative (CED)	77 MJ
Lifetime	10 years
Annualized net embodied energy use (CED)	44 MJ
Diffusion of technologies	
Diffusion in 2009	5.6% in NL, 21.8% in UK
Diffusion in 2010	5.9% in NL, 33.8% in UK

Source: EMInInn project

Diffusion data on energy efficient lighting was only available for the United Kingdom and the Netherlands. The additional diffusion in 2010 compared to 2009 was 4.8 per cent of the households in West Europe[4] which equals 3,292,605 households. The direct and indirect rebound effects are shown in the table below. The savings per household were much smaller than those for heat pumps. A smaller direct rebound effect leads to more monetary savings to be re-spent. This resulted in a higher indirect rebound effect. Indeed, the direct rebound effect was lower compared to heat pumps and the indirect effect was higher. This was caused by the fact that the electricity prices were much higher than gas prices. With higher energy prices, households had higher monetary savings to re-spend.

Table 10: Lower and upper boundaries of savings and rebound effects per household for energy efficient lighting, 2010

	Technical estimation of energy savings 2,400 MJ (100%)			
	Economy-wide rebound effect			Actual energy savings
	Direct rebound effect	Embodied energy	Indirect rebound effect	
Lower boundary	156 MJ (6.5%)	44 MJ (1.8%)	60 MJ (2.5%)	2,140 MJ (89.2%)
Middle level	300 MJ (12.5%)	44 MJ (1.8%)	56 MJ (2.3%)	2,000 MJ (83.3%)
Upper boundary	508 MJ (21.2%)	44 MJ (1.8%)	50 MJ (2.1%)	1,797 MJ (74.9%)

The (scaled-up) effect at EU-27 level of the additional diffusion in United Kingdom and the Netherlands is shown in the table below. The annual energy savings per household were much smaller compared to heat pumps and moreover we are considering only the diffusion in the Netherlands and United Kingdom. However, the effect at the EU-27 level is still much higher because the diffusion is higher. This illustrates the importance of a successful diffusion to achieve energy savings.

Given the lower and upper boundaries the following ranges of the direct and indirect rebound effects are produced. The net savings of additional diffusion of 4.8 per cent in West Europe (or 3,293,000 households) in 2010 leads to an annual net energy savings in

[4] West Europe consists here of Belgium, Luxembourg, Ireland, Netherlands, United Kingdom and France

the EU-27 in 2010 of 5,916-7,047 TJ which equals 0.049 to 0.059 per cent of EU-27 residential energy use (12,019 PJ) for the middle estimate.

Table 11: Lower and upper boundaries of rebound effects for energy efficient lighting, in TJ and % of total residential energy use EU-27

	Technical estimation of energy savings 7,901 TJ (0.07%)			
	Economy-wide rebound effect			Actual energy savings
	Direct rebound effect	Embodied energy	Indirect rebound effect	
Lower boundary	513 TJ (0.004%)	144 TJ (0.001%)	197 TJ (0.002%)	7,047 TJ (0.059%)
Middle level	988 TJ (0.008%)	144 TJ (0.001%)	185 TJ (0.002%)	6,584 TJ (0.055%)
Upper boundary	1,674 TJ(0.014%)	144 TJ (0.001%)	166 TJ (0.001%)	5,916 TJ (0.049%)

6 Conclusions

In this study we have developed a generic rebound effect model and applied it on heat pumps and energy efficient lighting. This model can be used to evaluate the total energy savings due to the diffusion of a specific energy-saving technology in the built environment. It estimates the net energy savings at the EU-27 level while taking into account the direct and indirect rebound effects.

Different studies show a wide range of estimations on the direct rebound effect for electricity and gas ranging from five to 60 per cent. We have illustrated that the size of the direct rebound effect is highly dependent on the chosen model and data specification. The estimated direct rebound effect in this study range between six to 26 per cent and between six and 21 per cent for gas and electricity, respectively. This could explain the wide range from the literature.

The indirect rebound effect is estimated at around one per cent for gas and electricity together and around two per cent for electricity. These effects are much smaller compared to the direct rebound effect, which is in line with the literature.

The negative effect of embodied energy was found to be between one and two per cent for heat pumps and energy efficient lighting. For these two case studies, the effect was very small in comparison to the potential energy savings. This effect however depends highly on the considered energy saving technology.

We applied the model on heat pumps and energy efficient lighting. We have illustrated the importance of the diffusion rate to achieve energy savings at the macro level. Heat pumps save a lot of energy at the household level while energy efficient lighting saves only a small amount of energy. However the impact of energy efficient lighting is much higher at the macro level.

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Vitae

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