Quantifying the energy efficiency gap for space and water heating in the residential sector in Sweden

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Abstract

Two different methodologies, one top-down and one bottom-up, are presented for estimating potential future energy demand for space and water heating in the existing building stock of the residential sector to 2030. Two future price scenarios are used as inputs. The work is tested using data for the existing Swedish residential building stock. Compared to 2005 levels of energy use (74 TWh) the bottom-up model shows reductions to 52 TWh and 50 TWh for the two price scenarios, respectively. Results from the top-down model are 11 % (8 TWh) and 7 % (5 TWh) higher than those of the bottom-up model for the two price scenarios. This suggests that the price mechanism alone will not be sufficient to achieve the full techno-economic potential for energy efficiency.

Introduction

Engineers often point at major potentials for cost-efficient energy efficiency measures while economists on the other hand often claim the cost-efficient potential to be low. One reason for these opposing viewpoints is *ceteris paribus* that bottom-up engineering calculations and top-down econometric calculations would calculate different estimates of future energy use with the *bottom-up* prognosis being lower than the *top-down* result. Such issues have been discussed in the past by Wilson and Swisher, (1993) and more recently by Jaffe et al., (2004), and Persson et al., (2008) in the context of the so called energy efficiency gap. The orthodox economic view put forward by Jaffe et al., (2004) for the difference in results is that there are certain intrinsic parameters which make the results obtained from bottom-up models unrealistic. These include hidden costs associated with technical change which are not captured by bottom-up models, the fact that the diffusion of new, economically superior technologies is never instantaneous but follows the pattern of Schumpeter's S-Curve, and that real private discount rates for investments may be as high as 25 %. Sorrell et al., (2004) on the other hand refute these arguments and state that the intrinsic parameters put forward by economists amount to market barriers which can be addressed by policy intervention.

Despite a large number of papers on the subject, papers focusing on the modelling work necessary to examine these opposing viewpoints are limited (SOU 2008:125). The aim of this paper is to provide such an examination by means of studying space and water heating in the existing Swedish residential sector to 2030 by using a top-down econometric model (hereafter referred to as TD) and a bottom-up simulation model (hereafter referred to as BU). Results from the two methodologies are discussed in the context of the different future energy price scenarios used.

Methodology

This work is conducted for the Swedish residential housing stock that existed in 2005, i.e. dwellings constructed from 2006 on are neglected. The analysis in this work compares a top-down energy savings potential for the existing stock using decomposition and econometrics with a bottom-up estimation of energy savings made using a building physics-based model for assessing the effects and costs of various energy efficiency measures.

TOP-DOWN METHODOLOGY

The top-down energy savings potential for the existing stock to 2030 is calculated using decomposition and econometrics as follows. Energy demand for space and water heating, E_t is decomposed into three sub-components (IEA,1997, Appendix 1):

$$E_t = A_t S_t I_t \qquad (1)$$

E is final use of energy for space and water heating measured in TWh.
A is population in millions.
S is residential sector floor area per capita measured in m^2.
I is unit consumption of energy for space and water heating measured in kWh/m^2.
t is time.

To estimate, E_t for the existing stock to 2030, A_t and S_t are locked at 2005 levels while future estimations of It to 2030 are used. The unit consumption for energy use for space and water heating, I_t, is calculated as:

$$ln\,(I_t) = ln(P_t)\,\alpha + ln(I_{t-1})\,\beta + (HDD_t)\gamma + (t)\delta + C \qquad (2)$$

where:
P is a weighted average price for energy for a year in Euro/MWh, HDD is heating degree days, α is short term price elasticity of demand of *I* (Pindyck and Rubinfeld, 1998), β is a coefficient of the previous year's *I* (lagged demand), γ is a coefficient of heating degree days, δ is an exponential time trend coefficient and *C* is a constant.
α, β, γ and δ are calculated from time series data from 1970 to 2005 using regression software. The use of the log-log regression form means that α is the price elasticity of demand of *I*. The use of the exponential trend means that δ times 100 is the percentage change per year in unit consumption due to factors such as autonomous technological development, imposition of regulations and other variables not captured by price, lag and *HDD*.

Changes in future energy demand for space and water heating in the existing stock will occur because of changes in unit consumption, *I*. *I* is an established indicator of progress with energy efficiency although the effects of fuel switching, conservation, changing habits and the climate obviously also cause it to change. Increases in energy prices, *P*, (whether from market developments or the imposition of carbon taxes) should in theory lead to decreases in unit consumption. In practice, this means that if energy prices increase and a home owner or tenant wants to reduce their energy bill, they can decrease the indoor temperature, shorten the duration of home heating or reduce their use of hot water. These are short term responses to price changes and are captured by, α, the short term price elasticity. Decreasing the indoor temperature may however not be an option if there are no controlling devices on radiators or if a dwelling is already being heated to the minimal level needed for health and comfort. In addition, energy prices may increase for a specific energy carrier, say oil, and not another, say biomass, which suggests that a home owner should switch from oil to biomass heating when this occurs rather than changing heating habits. Given the investment and temporary disruption that changing heating systems would necessitate, fuel switching would probably not occur very often and then only if there was long-term evidence that one energy carrier would remain cheaper than another. Factors such as these would cause a delayed or lagged reaction to price changes, but price increases should over a longer term lead to investments which improve efficiency, encourage conservation and lead to fuel switching. The coefficient of the lag operator I_{t-1}, β, when combined with α produces the long term price elasticity ($\alpha/(1-\beta)$), (Pindyck and Rubinfeld, 1998), which reflects these effects. To calculate I_t for 2006, I_{t-1}, which is I_t for 2005, should be used. However as I_{t-} for 2005 acts like a seed for Equation (2) and influences future outputs its value is normalised for climatic influences first. γ is a coefficient that accounts for the long term historic influence of climate (as represented by *HDD*) on demand. As future climate patterns are unknown a constant value of *HDD* (Odyssee, 2009) is used for forecasts and, therefore, the term, (HDD_t) γ, in Equation (2) acts like a constant. In the long run, there are inevitable technical improvements to building thermal efficiency and heating systems, which improve the efficiency of energy use and thereby lower the unit consumption, regardless of price dynamics. These technical improvements occur not only as a result of stricter efficiency standards, but also due to autonomous technical breakthroughs. As these improvements are typically implemented in a buildings renovation cycle, they only happen in a fraction of the building stock in any given year. Nonetheless, these trends are important in the long term, and thus are the fourth and final parameter incorporated into Equation (2). In practice, long-term technical trends are represented by the time variable, *t*, and this variable also includes the influence of other variables not captured by prices, the lag and *HDD*. To summarise, combining energy prices, *P*, the lag of unit consumption, I_{t-1}, the influence of weather, *HDD*, a linear trend that signifies technological development, *t*, and their respective regression coefficients, produces the relationship shown in Equation (2) for unit consumption, which reflects macroeconomic influences and technical trends, as well as the reality of the somewhat restricted user options available for the particular case of space and water heating.

As a next step, the same top-down exercise is performed, but, E_t, in Equation (1) is replaced by useful energy. This removes the historic influence of fuel switching on the elasticities calculated. This is necessary to do to make the TD results comparable to those of BU calculations. Useful energy is calculated by multiplying final energy use for each individual energy carrier by their respective conversion efficiencies. Conversion efficiencies have been published by Boverket (2009) for the existing residential stock in Sweden. Due to a lack of data on how these conversion efficiencies have changed over recent decades the same rates are assumed for the entire time series (1970 to 2005) for each energy carrier except for electricity for space heating. The efficiency of this carrier is assumed to increase from 1997 and on, due to the introduction of heat pumps.

BOTTOM-UP METHODOLOGY

The bottom-up estimation of energy savings between 2005 and 2030 is made using the ECCABS model (Energy, Carbon and Costs Assessment for Building Stocks), which is a building physics-based model for assessing the effects and costs of various energy efficiency measures. The model is a bottom-up engineering model, i.e. the energy demand of individual buildings is calculated based on the physical properties of the buildings and their energy use. The building stock is described by sample buildings and the results are then scaled-up to represent a country's building stock. Details on the model are provided by Mata et al., (2010).

The ECCABS model estimates direct costs (i.e. investment and operation and maintenance) for 10 energy efficiency measures, listed in Table 3, for the building stock considered and then, based on modelling the effect on the thermal performance of the stock, calculates the cost for reducing energy use. The total energy saving potential per measure – the parameter *ES* in Equation (3) – is the same for all scenarios examined and is given in Table 3 based on findings by Mata et al., (2011).

In the model, a measure is considered cost-effective when the cost saving obtained from applying a measure exceeds the total cost for the measure. The energy saving cost, $Cost_E$, is written:

$$Cost_E = {}^{NAC}\!/_{ES} \tag{3}$$

NAC is net annual cost of the efficiency measure in Euro/yr.
ES is energy saved in one year due to the application of the measure in kWh/yr .

The net annual costs are:

$$NAC = EAC - S \tag{4}$$

$$EAC = \left({}^{C \cdot r}\!/_{1 - (1+r)^{-n}} \right) + M \tag{5}$$

EAC is equivalent annual cost in Euro/year (i.e. the annual cost of the investment required to apply the measure over its entire life).
S is annual cost of the energy saved in Euro/yr, based on the energy saved, *ES* (see Table 3), and on the energy prices for the different scenarios and time periods (see Table 1).
C is direct cost of the measure (i.e. material, labour, installation) in Euro, including taxes (i.e. consumer prices, excluding VAT).
r is discount rate (0–1). A value of 0.04 (4 %) has been assumed.
n is lifetime of the measure over which the annual cost saving is supplied, in years.
M is extra maintenance cost of the efficient alternative in Euro/yr, including taxes (i.e. consumer prices, excluding VAT).

The costs are only related to the implementation of the energy efficiency measure. This means that most of the measures are assumed to be applied at the same time with normal renovation, such as façade or roof renovation, and, therefore, only the extra costs for energy saving measures are taken into account. Thus, if, for example, the façade is to be renovated, the insulating material is taken into account, but not the scaffolding.

When running the cost calculations according to Equation (3), the energy saving cost is calculated in the model for every 10 year period using the inputs shown in Table 1. For example, the costs for year 2010 are average values of the period 2005–2015. Thus, the energy saving cost given (Equation 3) represents the amount of money that one would invest (if the resulting cost is positive) or earn (if the resulting cost is negative), when applying the measure in any of the years of the considered 10 year period. Since it is not known when in time the investments will occur, the costs per kWh energy saved are calculated as average values for the whole period 2005–2030 according to:

$$Cost_E = \frac{1}{n} \sum_{2010}^{2030} Cost_E \tag{6}$$

where *n* is the number of time periods considered (2 in this case).

DATA SERIES USED

The time series data used to calculate the price elasticity, *α*, and the coefficient of HDD, *γ*,are obtained from the IEA (2009a), Odyssee database (2009), and other sources. Future estimations of energy price levels are also needed to calculate the unit consumption, *I*, in Equation (2) and the cost of energy saved in the ECCABS model, *S*, in Equation (4). The actual prices chosen are described next.

FUTURE ENERGY PRICES

The IEA WEO 2009 "450[1]" scenario (IEA, 2009b) is used to obtain future oil, natural gas and coal prices for 2020 and 2030. This scenario has an oil price of $90 a barrel in 2020 and 2030. This price is lower than the WEO 2009 baseline scenario price of $115 due to supposed increased greenhouse gas mitigation efforts resulting in a reduced demand for oil. A CO_2 tax which reaches 85 Euro a tonne by 2030 (Axelsson and Harvey, 2010) is added to fossil fuel prices in the "450" scenario.

A second price scenario is also employed. This uses the same WEO "450" fossil fuel prices but with a CO_2 tax that remains at today's rate until 2030. This second scenario is one where no increased mitigation of greenhouse gases occurs. Despite the IEA baseline scenario suggesting that demand would rise and thus prices would increase in a low mitigation scenario, it could also happen that at $90 a barrel a ceiling would be put on oil prices by an increased supply of coal to liquids. Thus, an oil price of $90 a barrel is also used for the second scenario as opposed to $115. For 2005 to 2010, actual market prices are used (OPEC, 2010, BAFA, 2010). A price model ENPAC (Axelsson and Harveys, 2010) which produces industrial wholesale prices, is used to calculate electricity, district heating (DH) and biomass prices. Distribution charges which are added to the ENPAC outputs are taken to be an average of the historic difference between Industrial energy prices without taxes and household energy prices without taxes (IEA, 2009a). Current VAT and excise tax rates are then added. The resulting input prices are listed in Table 1.

CALIBRATING TOP-DOWN AND BOTTOM-UP METHODOLOGIES

The top-down and bottom-up approaches have the same value of final energy demand for space and water heating in 2005, 74 TWh. This value is obtained from the ECCABS model (Mata et al., 2010) and is similar to the measured value of 72 TWh

1. As the name suggests the 450 scenario is one where the concentration of greenhouse gasses in the atmosphere is stabilised at 450 parts per million of Carbon Dioxide equivalent by 2030.

Table 1: Energy prices for residential sector customers to 2030, used in this work.

Future Prices	Unit	2010 Baseline	2020 Baseline	2030 Baseline	2020 450	2030 450
Light Fuel Oil	Euro/MWh	113	123	123	130	145
Natural Gas	Euro/MWh	83	95	95	101	112
Electricity	Euro/MWh	139	126	116	154	162
Biomass	Euro/MWh	32	36	37	44	61
District Heat	Euro/MWh	100	113	113	122	141

Table 2 : Regression results for unit consumption (final and useful energy) for space and water heating on the components of Equation (2). Serial correlation has not been found to be present in either case using the Durban Watson h statistic test.

Final Energy (1970 – 2005)						Useful Energy (1970 – 2005)				
Variable	Lag (β)	Trend (δ)	Price (α)	HDD (γ)	C	Lag (β)	Trend (δ)	Price (α)	HDD (γ)	C
Coefficient	0.49	-0.005	-0.14	0.00008	14.1	0.59	-0.003	-0.13	0.00007	8.64
t-statistic	(3.66)	(2.44)	(2.85)	(3.34)		(4.62)	(1.45)	(2.62)	(3.03)	
r^2					0.98					0.97
Adjusted r^2					0.98					0.97
F - statistic					314					234
Degrees of freedom					30					30
Durban Watson h statistic					0.50					0.09
Long run price elasticity					-0.27					-0.32

Table 3 : Cost-effective potential saving per measure (TWh/yr), for the period 2010-2030 for the Swedish dwelling stock. Rightmost column shows the total technical potential Energy Saved (ES) for space heating and hot water for each measure (% of the baseline consumption).

Measure description	Cost-effective potential Baseline	450 (TWh)	ES (%)
Total	22.5	24.1	83.0
Change of U-value of cellars/basements	0.4	0.5	7.2
Change of U-value of façades	0.8	1.0	9.7
Change of U-value of attics/roofs	0.9	1.0	3.6
Replacement of windows (U-value)	1.1	1.4	8.8
Ventilation with heat recovery, Single Family Dwellings (SFD)	5.4	6.1	17.1
Ventilation with heat recovery, Multi Family Dwellings (MFD)	0.5	0.6	12.6
Reduction of power used for the production of hot water to 0.80 W/m2(SFD)	1.0	1.1	3.5
Reduction of power used for the production of hot water to 1.10 W/m2(MFD)	0.1	0.2	2.8
Use of thermostats to reduce indoor air temperature by 1.2ºC down to 20ºC	12.1	12.2	17.6

(Odyssee Network, 2008). Energy prices, year 2005 demand and calculating the elasticities of the TD model with useful energy are the three features used to ensure that results from the TD and BU approach are directly comparable. For the year 2006 calculation in the TD model, I_{2005} for final energy demand is used as the lag component, regardless of whether price elasticities of useful or final energy demand are being used. This is to ensure that final energy demand is being calculated in both cases.

Results

The top-down calculation shows that energy use in 2030 in the baseline scenario will be 19 TWh lower than in 2005 while in the 450 scenario it is 23 TWh lower. Removing the influence of fuel switching from the scenario shows that energy use in 2030 in the baseline scenario will be 14 TWh lower than in 2005 while in the 450 scenario it is 19 TWh lower. Results for the baseline and 450 scenarios are predicated on the price elasticity of demand calculated (α) and the coefficients calculated for the lag, *HDD* and trend components (β, γ and δ). These are given in the coefficient row of Table 2 which shows results for the regression of both final energy demand and useful energy demand on the four parameters in Equation (2).

For both regressions listed in Table 2, all coefficients are found to have good significance (2.5 %) apart from δ in the regression of useful energy demand, which is only significant at the 10 % (See t-statistic row). An α (price elasticity) of -0,14 or -0.13 is relatively low and inelastic. This is the short run price elasticity (Pindyck and Rubinfeld, 1998). The long run elasticity is -0.27 (final energy demand) and -0.32 (useful energy demand) and is calculated by taking the effect of the lag (β) into consideration.

Elasticities calculated are somewhat similar to those obtained by Nässen et al., (2008) and Haas and Schipper (1998). Nässen et al., (2008) found short run price elasticities of -0.07 for multifamily dwellings and -0.21 for one and two family dwellings for Sweden between 1970 and 2002. The -0.14 calculated in this work for the entire stock of dwellings lies exactly between these

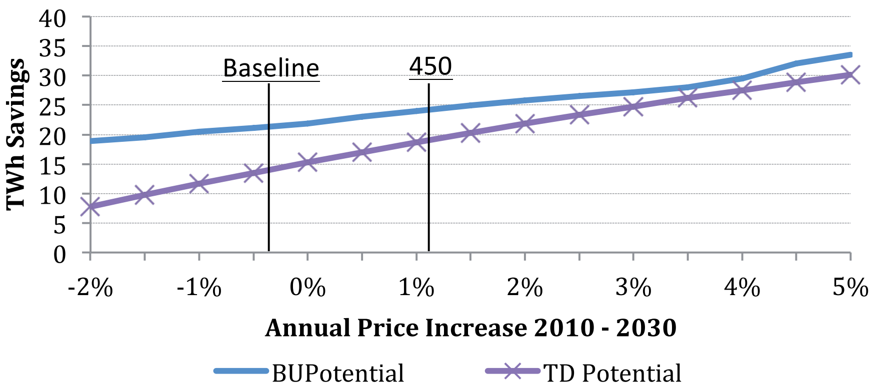

Figure 1: Resulting potential savings obtained in the sensitivity analysis for both models, in 2030 under price change scenarios from an annual decrease of 2 % to an annual increase of 5 %. Average annual price increases for baseline and 450 scenarios are also indicated.

figures. Haas and Schipper (1998) calculated a short run price elasticity of -0.11 for the period 1970 to 1993. Their work was for all energy use in households. The slightly lower value they obtained may be explained by electricity use for appliances (not included in present study) being less sensitive to price changes than energy for space and water heating.

The bottom-up model calculates a savings potential of 22 TWh for the baseline scenario and 24 TWh for the 450 scenario in the year 2030 compared to 2005 levels. This is the total cost-effective savings as a result of the implementation of the 10 measures listed in Table 3.

Fuel switching is not a measure examined in the BU work. Therefore, to compare results from the TD work with that of the BU work the impact of future price change on final energy demand is calculated using price elasticities of useful energy demand. Thus subtracting results for 2030 from the TD work from the BU results reveals a gap of 8 TWh in the baseline scenario and 5 TWh in the 450 scenario.

Discussion

Using the same future energy price scenarios, the two models have given results for 2030 that differ by between 5 TWh and 8 TWh.

A sensitivity analysis has been run for both models with price change scenarios from 2010 to 2030 in 0.5 % increments from -2 % per annum to 5 % per annum. The justification for this price range is that the baseline price scenario in Table 1 shows an actual price decrease (the baseline has an annual weighted average decrease of -0.3 % while the 450 scenario has a weighted average increase of 1.1 %) while the largest five year energy price increase seen over the period 1970 to 2005 was 8 %. Figure 1 presents the results of the analysis for 2030 and shows an efficiency gap between results from the BU and TD models which decreases from 11 TWh at an annual decrease of -2 % in energy prices to 3 TWh at an annual increase of 4 % in energy prices. This is probably due to the fact that there are many measures in the BU model which are already cost effective at current (or even lower) energy prices, while the TD model indicates that prices have a greater influence as they rise.

It should be commented here that our estimates of the market potential (the TD approach) is based on historical trends which may not be valid in the future. It is not necessarily so that future price elasticities will be same as the historical ones. However, it can be noted that Nässen et al., (2008) found that the price elasticities were almost identical between two different periods with increasing prices (1970–1985 and 1988–2002). Another issue here is that the TD calculations are based on the energy intensity trend of the entire stock of residential buildings, which in addition to energy efficiency improvements in existing buildings has also been affected by the addition of new buildings with higher energy efficiency than the average stock between 1970 and 2005. This may result in an overestimation (primarily in the autonomous time trend) of the market potential given by the TD calculation. Hence our estimate of the energy efficiency gap may also be slightly underestimated.

In a public enquiry published in 2008 (SOU:2008 125), the Swedish Ministry of Enterprise estimated an energy efficiency gap of 13 TWh for 2016 for space and water heating in dwellings. This is calculated from the difference between a profitable savings potential of 17 TWh and savings of 4 TWh due to autonomous technical progress that are expected if no new policies and measures are introduced. The 4 TWh of autonomous technical progress is an estimate based on the amount of cost effective savings potential that has been realised between 1995 and 2008. The work carried out for this paper on the other hand calculates a TD energy savings potential for 2016 of 11 TWh in the baseline scenario although this calculation is based on elasticities calculated from 1970 to 2005 and an alternative future price scenario. Although the 17 TWh profitable savings potential calculated by the enquiry for 2016 is of the same order as the bottom-up potential of 22 TWh calculated in the baseline scenario for this paper, this 22 TWh is estimated for 2030. Apart from the target years being different the profitable savings potential calculated in the enquiry is based on the energy calculations from BFR (1996), updated with an estimated realistic development of energy prices. Also a different description of the building stock (from 1995 as opposed to 2005) is used and a different discount rate (6 % instead of 4 %). The differences in results and methodology between the enquiry and this work highlight the difficulties that exist with making such comparisons and that further work is required to find a way to do so.

Conclusions

This work has used a top-down and a bottom-up model to calculate energy use in 2030 for space and water heating in existing Swedish residential buildings. The work has described both models in detail and thus presented a methodology for calculating future energy demand from two different perspectives – that of the economist and that of the engineer. Compared to 2005 levels of energy use (74 TWh), results of the bottom-up model have shown reductions to 52 TWh and 50 TWh for a baseline and a "450" price scenario respectively. Corresponding results from the top-down model are 11 % (8 TWh) and 7 % (5 TWh) higher than those of the bottom-up model for the same two price scenarios.

Even though the difference in results from both models and hence the energy efficiency gap for 2030 is a fairly moderate estimate, it indicates that there are seemingly cost-effective measures that may not be realized for various reasons. This also suggests that the price mechanism alone will not be sufficient to achieve the full techno-economic potential for energy efficiency.

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