Cost-effective retrofitting of Swedish residential buildings: effects of energy price developments and discount rates

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Abstract

This paper investigates how the cost-effectiveness of different energy saving measures (ESMs) in buildings is dependent upon energy prices and discount rates. A bottom-up modelling methodology is used to assess the profitability of different ESMs for Swedish residential buildings. The cost-effectiveness and total techno-economical potential for energy saving of each ESM are calculated for three different scenarios of energy prices up to Year 2050 and for different discount rates, including an estimate of the market potentials derived by applying the implicit discount rates given in the literature.

The three energy-price scenarios give similar techno-economical reductions of delivered energy (by 31%–42%), as well as a similar ranking for the investigated cost-effective ESMs. This means that there are cost-efficient opportunities for energy reductions in Swedish households for any future developments of the energy prices investigated in this work. The energy price developments have lower impacts than interest rates on the techno-economical potentials of the different ESMs. Thus, increasing energy prices cannot be expected to promote significantly the adoption of ESMs, whereas facilitating the financing of investments in ESMs and reducing other consumer barriers should play key roles in the implementation of ESMs. The importance of allaying stakeholders´ reservations is further stressed by the fact that the estimated market potentials for the ESMs are significantly lower than the techno-economical potentials, underscoring the need for policy actions that accelerate the achievement of the identified techno-economical potentials.

Keywords
Swedish existing buildings, cost assessment, energy saving measure, cost-effective retrofitting, energy prices, discount rates

1. Introduction

One of the greatest challenges facing efforts to reduce energy use and carbon dioxide (CO_2) emissions in the building sector is the definition of economically feasible strategies for retrofitting existing buildings. The economic feasibility of retrofitting measures is typically calculated from the investment associated to the measure, and the changes in the operating costs resulting from the measure such as reduced running costs (including operational costs and costs of the unused energy). The calculation can be done by either annualizing the initial investment cost and comparing it with the future annual operating costs, or by calculating the net present value of future running cost savings and comparing it with the initial investment; either way a discount rate has to be assumed. Therefore, the cost-effectiveness depends on the assumptions on the investment cost, the saved costs for the unused energy (determined by the amount of energy saved and the future energy prices) and the interest rates.

An approach that is commonly employed in the literature is to account exclusively for so-called *direct costs*, which can lead to the identification of large energy saving potentials (for a review of potentials worldwide, see Levine et al. 2007[1]). Direct costs represent the costs to the consumer that can be completely attributed to an energy retrofitting measure, i.e., those for the materials and labour associated with installation, maintenance, and operation. Direct costs are also referred to in the literature as the *tangible* or *techno-economical cost* (MKJA, 2002; Ürge-Vorsatz and Novikova, 2008) or *real private cost* (EC, 2012b). Therefore, in this paper, the *techno-economical potential* is the part of the *technical potential*[2] that is cost-effective with market costs, using *societal discount rates* and with carbon prices included in the energy prices. The societal discount rate is that used by society to give a relative weighting to social consumption or income accruing at different points in time (Price, 1988). As justifications for discounting as part of public decisions mainly rely on the opportunity cost of the capital, they are assumed to be equal to the market rate agreed by a lender[3]. This rate, which is generally used in the life-cycle cost analysis of capital investment for public projects, ranges from 2% to 10%[4]. The techno-economical potential is a saving calculated by including direct costs; as such, it is only an indicator of what would be realised if the public was entirely economically rational and should not be interpreted as realisable. Furthermore, such techno-economical

[1] As the literature on this topic is extensive, we cite here the 4th IPCC report, which contains a compilation of the estimates from bottom-up studies conducted worldwide.

[2] The *technical potential* is the amount by which it is possible to reduce energy use and CO_2 emissions by implementing already demonstrated technologies and practices without specific reference to costs (definition adapted from Levine et al., 2007 and Ürge-Vorsatz and Novikova, 2008).

[3] In this paper, a simplified interpretation of the societal discount rate is used, which is based on the standardised procedures for economic evaluation of energy systems in buildings (EC 2012a,b; EN 15459, 2007; Rushing et al., 2010). A broader environmental interpretation, not used in this paper, is the focus of an unsettled debate about discounting as intergenerational equity and linked to the theoretical concept of sustainability (as reviewed in Price and Nair, 1985; IPCC, 1995; Almansa Sáez and Calatrava Requena, 2007; Sterner and Persson, 2008).

[4] According to a review of what different European countries propose for the life-cycle cost assessment of their public projects (Cruz Rambaud and Muñoz Torrecillas, 2005), and in line with the key reference rates set by the European Central Bank and national central bank, which for the period 2001–2012 were in the range of 1.5%–5.0% (EC, 2010a).

estimates disregard *indirect costs*. Indirect costs are any costs (other than direct costs) that are incurred while adopting an ESM, and they include implementation costs, intangible capital costs, perceived private costs, and transaction costs. While the definitions of these costs overlap, in this paper they are collectively referred to as indirect costs.

In contrast, *market potentials* are taken to represent the potentials that are expected to be implemented[5]. For energy conservation programs, *private discount rates* are used to predict penetration rates or levels of investments in conservation, in other words, to estimate market potentials (Train, 1985). The private discount rate is also referred to in the literature as the *implicit discount rate,* as it represents consumer decision making. In making decisions that involve discounting over time, individuals behave in a manner that implies a much higher discount rate than can be explained in terms of the opportunity costs of the funds available in credit markets.

Energy price development influences the cost of the energy saved, with higher energy prices leading to increased profitability being associated with the ESMs. To answer the question as to what extent a certain (reasonable) increase in energy prices influence the profitability of a typical ESM, scenarios for fuel and electricity price developments can be used, e.g., with fuel price development data from the World Energy Outlook (IEA, 2012) or the EU Energy Trends to 2030 (EC, 2010).

The European Union (EU) has identified the importance of having a uniform assessment of the cost-effectiveness of the potential energy savings of the buildings of all Member States (MSs). In this context, the recent recast of the Energy Performance of Buildings Directive (EPBD) (EC, 2012a) provides a standard methodology for identifying cost-optimal energy performance requirements for buildings. The methodology includes: (1) the establishment of reference buildings; (2) the identification of energy saving measures (ESMs); (3) calculation of the delivered[6] and primary energy demands; and (4) calculation of the global cost, using a so-called *financial calculation* (i.e., including investment, running and disposal costs, and a residual value, including taxes and subsidies) and what EPBD refers to as *macroeconomic calculation* (which in addition includes the cost of emitting greenhouse gas emissions [GHGs] and excludes taxes and subsidies). In addition, the EPBD recommends the use of a sensitivity analysis to evaluate the impact of the discount rates and the different energy price developments.The purpose of this paper is to explore how the cost-effectiveness of different ESMs in buildings is dependent upon assumptions of energy prices and discount rates. The Swedish residential building stock is used as a case study, representative of a North-European country in terms of climate, building tradition and energy fuels. The authors have already performed an analysis of the current and future energy use of Swedish households (Mata et

[5] Adapted from the 4th IPCC Report (Levine et al., 2007), which defines the market potential as the level of GHG mitigation that occurs under forecast market conditions, including policies and measures based on private unit costs and discount rates.
[6] Given the geographical and regulatory scope of this work, energy performance related definitions are taken from the EPBD (EC, 2012b) as: primary energy, delivered energy, energy use and energy need. In the literature, delivered energy is also referred to as *final energy* or *secondary energy* .

al., 2013b) which serves as a basis for the present work. Although the techno-economic potentials are a focus here, the corresponding market potentials are estimated by including private discount rates, as given in the literature, to represent all the above-mentioned barriers in terms of indirect costs.

The Swedish residential sector accounts for 21% of the country's overall delivered energy demand, a value that is slightly below the average of 26% for EU-28 countries (EC, 2011) and has remained almost constant over the past 20 years (cf. Figure 1 in Mata et al., 2013b). This annual delivered energy (97.7 TWh) consists of 70% for space heating (SH) demand, 10% for hot water (HW) demand, and 20% for electricity for lighting and appliances (LA). SH shares for electricity, oil, biomass, and district heating of 28%, 2%, 17%, and 45%, respectively; for HW these are respectively, of 27%, 3%, 10%, and 54%.

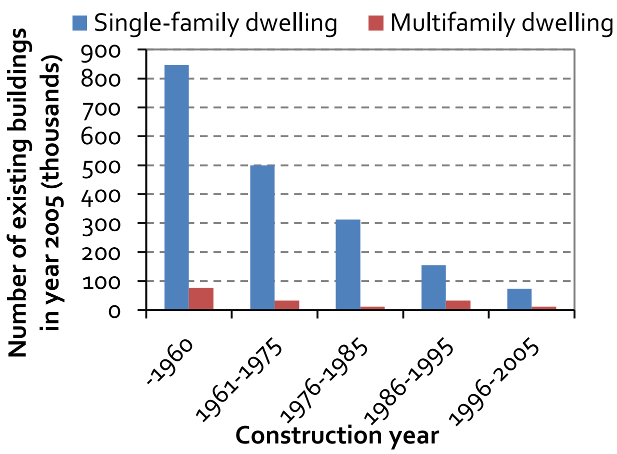

Figure 1. Number of Swedish residential buildings existing in year 2005, by building type and contruction year. Data from NBHBP(2009).

In year 2005 there were in Sweden about 2050 thousand residential buildings and a total of 538 Mm^2, with the distribution of single-family dwellings (SFDs) and multifamily dwellings (MFDs) and construction periods depicted in Figure 1. The average floor area of an SFD is 160 m^2 and the average floor area of an MFD is 84 m^2 (NBHBP, 2009), which gives an average floor area of 114 m^2 for a Swedish dwelling.

The annual CO_2 emissions in Year 2005 from the Swedish residential stock were 4.92 $MtCO_2$, of which 2.62 $MtCO_2$ were attributed to SFDs and 2.29 $MtCO_2$ to MFDs. This represents 10% of the 47.0 $MtCO_2$ reported as the total annual emissions of the country (Enerdata, 2010) owing to the characteristics of the Swedish energy system. With 46% of the electricity produced from hydro power and 45% from nuclear power, CO_2 emissions from electricity generation in Sweden are very low (SEA, 2011a). In addition, district heating is mostly produced from biomass and waste combustion (59%), heat pumps (12%), and waste heat (11%) (SEA, 2011a). An average Swedish SFD emits 1.39 tCO_2/yr, while an average Swedish MFD emits 0.81 tCO_2/yr and an average residential dwelling emits 1.05 tCO_2/yr.

2. Methodology

The present work is linked to the project Pathways to Sustainable European Energy Systems (the *Pathways Project*, Johnsson 2011), which studies the ways in which the European energy system might be transformed so as to become more sustainable, with a special focus on meeting targets for energy efficiency, reductions in CO_2 emissions, and increased use of renewable energy. For this purpose, a building-stock modelling methodology has been developed that can be used to analyse the current energy usage and CO_2 emissions of the building stock of a country, as well as to assess technical reduction potentials achieved by applying different ESMs[7] (Mata et al., 2013a). The modelling methodology follows the EPBD methodological recommendations, in that it uses reference buildings, identifies ESMs, and applies a bottom-up modelling methodology to yield the energy use and delivered energy demands, as well as the costs of ESMs using financial calculations. Macroeconomic calculations are considered outside the scope of the present work, although taxes levied on CO_2 emissions are included in the estimated future energy prices.

2.1. Model

The analysis is performed using the ECCABS model (Energy, Carbon and Costs Assessment for Building Stocks)(Mata et al., 2013a), which is a modelling framework that can be used to assess the effects and costs of different ESMs with respect to energy savings and associated reductions in CO_2 emissions for an existing building stock (i.e., construction and demolition rates are not considered). The energy demands of individual buildings are calculated based on simplified input data related to the physical properties of the buildings, their energy use patterns, and the demands for thermal comfort in the buildings. Furthermore, the building energy model is capable of time-dependent simulations of the indoor temperature (typically, hour-by-hour), which allows determinations of the heating demands at various times of the day or season. Input parameters required for the modelling include the building geometry (e.g., heated floor area, surface of the envelope) and properties of the construction materials (e.g., effective volumetric heat capacity, U-values), characteristics of the building technical systems (efficiencies and fuels used), and the required maximum and minimum indoor air temperatures. Finally, the model is readily adaptable to any building stock or set of buildings.

When modelling the net energy demand in a building stock, the calculations are performed for representative buildings in a building stock, with the results being scaled-up to represent the entire stock. The calculated net energy demand for end-uses is converted into delivered energy and associated CO_2 emissions using the efficiency and carbon intensity factors for the fuels used. For the latter, a proportion of different energy carriers should be defined in the model. A comparative method is applied when assessing the outcomes related to the renovation. This means that the potential reductions are calculated with respect to the state of

[7]Other work conducted by the authors also assesses efficiency improvements in the building technical systems and the supply from on-site renewable energy sources. Thus, in that work (Mata et al., 2014), we denoted these measures and the ESMs applied in the present work as 'Energy Conservation Measures' (ECMs).

the existing buildings before retrofitting, which is indicated in the work as the starting year (for example, Year 2005 in the present work). Further details about the capability of the energy model and its validations are given in Mata et al. (2013a).

The cost for reducing energy use and associated CO_2 emissions is calculated based on the investment costs that are provided as inputs, together with the modelled technical potential energy reductions to be achieved by implementing the ESMs. Since the energy savings (ES) and their corresponding saved costs (C_e) are calculated on an annual basis, the investment cost is also derived as an equivalent annual cost or annuity.

The net annual costs *NAC* are calculated as:

$$NAC_i = EAC + C_{r_i} \qquad (1)$$

where C_r represents the annual running costs in *i* decade (€$_{2005}$/yr), and EAC is the equivalent annual cost (i.e., the constant yearly cost of the investment required to apply the measure over its entire lifetime; €$_{2005}$/yr) given as:

$$EAC = {C_I \cdot R} \Big/ {1 - (1 + R/100)^{-n}} \qquad (2)$$

where C_I is the initial investment cost of the measure (€$_{2005}$), which can be expressed as € per heated floor area, € per envelope surface to be retrofitted or € per dwelling (for the heated floor areas, envelope surfaces, and number of dwellings specified as inputs), R is the discount rate (0–1), and n is the lifespan of the considered measure (years). Both the investments and the savings are annualised, such that Eq. (1) implies a continuous investment perspective. A continuous investment perspective means that if the lifespan of the ESM is shorter than the calculation period there will be a re-investment in the same measure to maintain the reduced energy use, and if the lifespan of the ESM is longer than the calculation period the remaining value at the end of the calculation period is disregarded (i.e., becomes sunk cost). The annual running costs C_r are:

$$C_r = C_m + C_o + C_e \qquad (3)$$

where C_m is the maintenance cost, C_o the operational cost, and C_e the energy cost (EN 15459, 2007), calculated as the annual cost of the energy saved ES based on the energy prices for the different scenarios and time periods applied; usually there is an economic gain. C_m, C_o and C_e are assumed to be constant over the life-span of the investment perspective, although C_e takes different values for different energy prices.

A measure is considered to be cost-effective when its net annual cost is negative, i.e., when the achieved cost saving from applying a measure, exceeds the investment cost for the measure. The cost-effectiveness is thus given by the net unit cost of conserved energy, NCCE (€$_{2005}$/kWh saved), for the calculation period considered (2010–2050):

$$NCCE = \sum_{i=2010}^{i=2050} \left(\frac{NAC_i}{ES}\right) / D \qquad (4)$$

where NAC_i is the average net annual cost of the ESM in the i decade of the calculation period (€/yr) defined in Eq. (1). Thus, the NCCE is calculated as an average for 10-year periods, using the inputs listed in Table 2. For example, the values for year 2010 are the average values for the period 2005–2015. ES is the energy saved annually resulting from the application of the measure (kWh/yr). The latter is the same for all the time periods, since no changes in the climate data are considered, and no system improvements at the moment of replacement are taken into account. Finally, D is the number of decades in the calculation period (D=4 in the calculation period of 2010–2050).

It should be noted that the NCCE is distinct from the so-called cost of conserved energy [CCE, defined by Meier (1982), recently used in Garg et al. (2011) and McNeil and Bojda (2012)], in that NCCE also includes the saved cost of the unused energy. Inclusion of the saved cost of the unused energy is a prerequisite in the present work for assessing the effects of energy price developments.

2.2. Building-stock description in the model

A set of input parameters was obtained from the BETSI project (Tolstoy, 2011). These correspond to 1400 residential buildings chosen by the Swedish National Board of Housing, Building and Planning [*Boverket*, in Swedish] in cooperation with Statistics Sweden [*Statistiska centralbyrån* (SCB), in Swedish] as being statistically representative of the Swedish existing building stock in Year 2005. The building data used for the descriptions of the reference buildings were gathered from surveys and measurements and correspond to actual buildings, i.e., all the building data refer to the buildings in their present state, which means that the effects of renovations are included (i.e., renovation rates do not need to be assumed). The number of buildings corresponds to 300 categories with respect to combinations of type, age and location (Hjortsberg, 2011) and includes both SFDs and MFDs. The buildings are divided into the following five age groups, classified according to the changes that have occurred over time in the building codes and building techniques: prior to 1960; 1961–1975; 1976–1985; 1986–1995; and 1996–2005 (cf. Figure 1). The buildings constructed after 2005 are not considered in the analysis, and construction and demolition rates are neglected. The buildings were chosen from 30 different municipalities based on population and geographical location, so as ensure a representative distribution of municipalities of different sizes and within different climate regions[8]. The meteorological data used in the modelling were generated by Meteonorm (Meteotest, 2009). The hourly values required in the model for an entire year are: outdoor temperature (ºC); global radiation on horizontal surfaces (W/m^2); diffuse radiation on horizontal surfaces (W/m^2); and normal direct radiation (W/m^2). Further details of the BETSI project are available elsewhere (NBHBP, 2009).

[8] According to the Swedish building energy code, there are three distinct climate regions in Sweden, with the number of degree days ranging from approximately 3500 in the southern regions to 6000 in the northern regions.

In addition, the input parameters describing the average electricity demand for hot water production and the average electricity demand for lighting and appliances are taken from the Swedish Energy Agency (SEA 2009a, 2011).

2.3. Costs of the energy saving measures

In total, twelve types of ESMs (Table 1) are assessed (Mata el al. 2013b):

- retrofitting of the different parts of the building envelope, i.e., basement, façade or roof (ESMs 1, 2 and 3, respectively)[9], and replacement of windows (ESM 4);
- installing ventilation systems with heat recovery for SFDs (ESM 5) and for MFDs (ESM 6);
- using energy efficient lighting and appliances (ESMs 7 and 8, respectively). Here, these technologies are assumed to be 50% more efficient than the current technologies. The investment cost is considered to be zero, based on the assumption that energy-efficient equipment will dominate the market, since new policy standards will only allow energy efficient options[10].
- reducing the use of hot water in SFDs (ESM 9) and in MFDs (ESM 10) through the substitution of existing water taps with aerator taps;
- reducing the electricity consumption of pumps for waterborne heating systems (ESM 11) through the replacement of existing water pumps with more efficient equipment;
- reducing the indoor temperature to 20°C through the installation of room thermostats for SFDs with individual heating systems, or the installation of thermostatic radiator valves for centralised systems (ESM 12). Measurements prove that in Sweden, the average indoor temperatures are 21.2°C for SFDs and 22.3°C for MFDs (NBHBP, 2009), and that these temperature are also almost constant 24 hours a day during the heating period (Mata et al., 2013b). The cost assigned is indicative, as some dwellings may already have thermostats. This ESM assumes acceptance of the change by the occupants and that the thermostats will be used in the appropriate manner.

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[9] Although only the averaged U-values of the building envelope are used as input to the model, the detailed knowledge of the sample buildings allows differentiation between several types of retrofitting strategies for cellars (floor above crawlspace, flat floor on ground, floor above unheated basements, basement wall above ground, basement wall below ground), facades (ventilated walls with different cover materials, brick facades) and roofs (attic joists, knee walls, sloped roof, flat roof) (for a detailed description, see NBHBP, 2009 and Mattsson, 2011).

[10] The production of different types of incandescent light bulbs has been gradually phased out during the period 2009–2012. The incandescent light bulbs still in stock will be sold (SEA, 2011b).

Table 1. Inputs to the modelling of the costs for the ESMs assessed in present work.

ESM No.	ESM Description	Life span (yr)	Maintenance and operational costs	Investment cost
1	Improved U-value of cellar/basement (different types)	40	0	104.4(b)
2	Improved U-value of facades (different types)	40	0	120.6(b)
3	Improved U-value of attics/roofs (different types)	40	0	32.8(b)
4	Replacement of windows	40	0.7	262.8(b)
5	Upgrade of ventilation systems with heat recovery, for SFDs	20	100	4149.9(c)
6	Upgrade of ventilation systems with heat recovery, for MFDs	20	100	4465.1(c)
7	Reduction by 50% of power for lighting	1	0	0
8	Reduction by 50% of power for appliances	1	0	0
9	Reduction in power used for the production of hot water to 0.80 W/m^2, for SFDs	15	0	1256.4(c)
10	Reduction in power used for the production of hot water to 1.10 W/m^2, for MFDs	15	0	753.8 (c)
11	Replacement of water pumps with more efficient ones	20	0	1628.0 (c)
12	Lowering the indoor air temperature to 20°C	10	0	3.4 (a)

The initial investment cost depending on the specific measure is given as: (a) € per heated floor area; (b) € per surface to be retrofitted; or (c) € per dwelling. SFD, Single-family dwelling; MFD, Multi-family dwelling.

For the reference cost calculations of the technical potentials, it is assumed that the potentials of the ESMs are fully achieved. Some of the measures (ESMs 1–4) will primarily require replacement of a part of the building or its systems with a more energy-efficient component/system (and once this replacement is executed, no further action is required by the tenant). However, most of the ESMs (ESMs 5–12) involve specific behavioural changes and adequate operation of the newly installed technologies by the building occupants. It is assumed that the installed technologies will be operated properly by the occupants.

The costs considered (C_I, C_m and C_o) comprise the costs for materials and labour for work related to the implementation of the ESM, i.e., consumer prices, including VAT. VAT is included because the owners of residential buildings cannot deduct this tax from their building costs, as the rent that the residential tenants pay does not include VAT (Mattsson, 2011). The costs are taken from NBHBP (2009) and EN 15459 (2007). As most of the ESMs are assumed to be implemented simultaneously with routine renovation, e.g., of the facade and roof, only supplementary or marginal costs for implementing the ESMs are taken into account. For example, if the façade is to be renovated, the cost of the insulating material is taken into account, but not the cost of the scaffolding.

Finally, the discount rate is set at 4% for all the ESMs (Mattsson, 2011). The considered life-span depends on the measure studied, based on data from the NBHBP (2009) and EN 15459 (2007). The residual value and extra disposal costs are assumed to be zero.

2.4. Energy price development scenarios

We define a scenario as a description of a possible future development of the energy system in terms of energy prices for the different energy carriers used in the buildings. Therefore, these scenarios should not be seen as an attempt to predict the future development of the energy market, but rather as a tool to investigate the possibilities and costs for transforming the building stock, given different future outlooks. Three price scenarios (fuels and electricity) are investigated: a Baseline scenario (BA), which assumes that the current trends in energy prices will continue; a high price-increase (HPI) scenario; and a low price-increase (LPI) scenario.

The development of electricity prices under the different scenarios for Sweden is taken from Johnsson (2011), while the prices of the other energy carriers are based on the average EU values reported by Axelsson and Harvey (2010). Data on distribution costs and excise taxes are taken from the IEA (2009), and VAT rates for the residential sector are based on current rates (EC, 2010). For a further explanation of the rationale behind the assumptions, see Johnsson (2011). The reason that there is a decrease in the biomass price in the Baseline scenario after Year 2020 is that this scenario is a reference scenario that was originally developed to represent a complete lack of climate mitigation policy instruments after Year 2020 (Johnsson, 2011).

Table 2. Inputs to the modelling, i.e., assumptions made regarding the average consumer energy prices (EP) of energy carriers used in the buildings (in €2005cents/kWh), given as the average value for each 10-year period.

Year	Scenario	EPel	EPo	EPg	EPbw	EPdh
2010	All	11.6	9.7	8.0	7.8	8.4
2020	BA	12.3	9.7	8.1	5.4	8.4
2030	BA	12.8	9.9	8.4	3.9	8.5
2040	BA	12.6	10.1	8.4	3.9	8.5
2050	BA	12.4	10.1	8.4	3.9	8.6
2020	HPI	13.6	10.8	8.8	8.5	9.2
2030	HPI	14.0	11.7	9.7	9.6	9.8
2040	HPI	14.3	12.2	10.0	10.3	10.2
2050	HPI	15.2	12.9	10.6	11.4	10.8
2020	LPI	12.4	10.7	8.7	8.5	9.1
2030	LPI	11.6	11.0	9.1	9.2	9.2
2040	LPI	12.1	11.4	9.4	10.3	9.6
2050	LPI	12.1	12.0	9.9	11.7	10.1

BA, Baseline; LPI, low price-increase scenario; HPI, high price-increase scenario; el, electricity; o, oil; g, gas; bw, biomass/waste; dh, district heating.

Table 2 lists the energy prices for the different scenarios. The annual weighted average increases in energy prices are assumed to be 0.37%, 0.47%, and 0.44% for the Baseline, HPI, and LPI scenarios, respectively. From Table 2 it is clear that the increase differs across energy carriers. The above average increases yield energy prices for the HPI and LPI scenarios in Year 2050 that are, on average, respectively, 40% and 28% higher than in the Baseline scenario.

3. Results

Before considering the cost-effectiveness of the ESMs, the investment costs required to implement the ESMs studied, as obtained previously by the authors (Johnsson, 2011), are briefly presented. Investments amounting to €5.7 billion are required to achieve the technical potential saving, which is 51.0 TWh per year (assuming that all ESMs assessed in the present study are implemented). This represents a 53% reduction in energy use in the Swedish residential sector, which in Year 2005 was 97.7 TWh (Mata et al. 2013b). These investment figures are similar to those given in NBHBP (2009) and Mattsson (2011). Figure 2 illustrates the different investment levels required to achieve such a potential saving in delivered energy demand; the curve represents all the ESMs for all archetype buildings, applied in order of increasing cost. These investments can be related to the current goals for reducing the specific energy use level in Sweden: a 20% reduction in Year 2020 and a 50% reduction in Year 2050, as compared to the energy use level in 1995. Energy use in Year 1995 (99.9 TWh EC, 2010) was very similar to the level of energy use in Year 2005 (97.7[11] TWh); thus, the energy reductions are calculated as compared to Year 2005 (Mata et al., 2013b; Mattson, 2011).

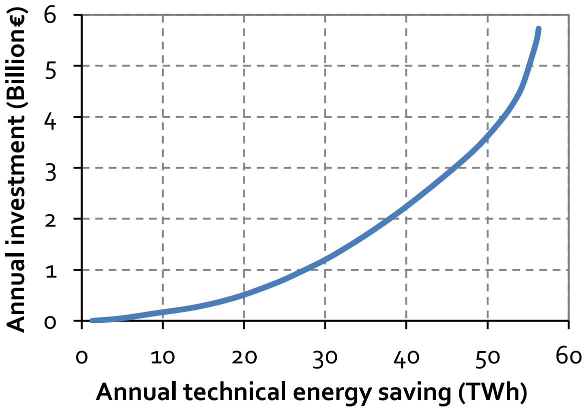

Figure 2. Correlation between technical potential energy savings in the Swedish residential building stock and annual investment levels, as obtained from the modelling of this work. The curve represents all ESMs for all archetype buildings, applied in the order of increasing cost (Johnsson, 2011[12]).

As shown in Figure 2, an annual investment of €0.5 billion[13] is required to meet the Swedish target for Year 2020 (i.e., a reduction of 20 TWh), and €3.5 billion would have to be invested annually to achieve the 2050 target of 50% reduction (i.e., 50 TWh). These investments represent, respectively, 0.2% and 1.2% of Sweden´s GDP, which in Year 2005 was €298 billion (EC, 2010a). For the 2020 target, the investment would correspond to €2 per m^2 and year, which means that for a dwelling of 100 m^2, €200 would have to be invested annually

[11] This includes the 5.4 TWh required to increase ventilation rates in SFDs to meet what the Swedish Ministry of Health recommends as the level needed to ensure adequate indoor quality (Mata et al., 2013b; Mattsson, 2011). It should be noted that measurements have proven that Swedish SFDs currently have substandard ventilation rates (NBHBP, 2009).

[12] The original figure appears in Chapter 45 of Johnsson (2011) and is modified here in that the axes have been switched.

[13] ‘Billion’ is used in the sense of 10^9. The exchange rate used is 1 € = 10 SEK.

until the Year 2020. For the 2050 target and for the same dwelling, €1000 would have to be invested annually from now until 2050.

3.1. Effects of energy price developments

Table 3 lists the net unit costs of conserved energy (NCCE; as given in Eq. 4) as the weighted averages for the ESMs in the three price scenarios for an average Swedish residential building. The NCCE for each of the 1400 representative buildings is thus different from the costs presented in Table 3. Table 3 ranks the costs according to decreasing cost-effectiveness (i.e., with the most cost-effective ESM in the first row of the table). The left-most column in Table 3 shows the total technical potential (i.e., for the entire country) for the ES for each measure (in starting Year 2005, as given by Mata et al. 2013b). The corresponding average NCCE for such energy saving potentials are given in the middle columns, and the right-most columns give the techno-economical potential energy savings (ES_{TE}), together with the associated costs (*Avg.* $NCCE_{TE}$).

Table 3. Average annual net costs of conserved energy (NCCE), per building[14], of the ESMs as obtained for the three scenarios, with the corresponding techno-economical potential energy saving (ES_{TE}) and average annual net cost ($NCCE_{TE}$) for the period 2010–2050. The total technical potential energy saving (ES) values for the ESMs are taken from Mata et al. (2013b). The ESMs are listed by number in order of decreasing cost-effectiveness; see Table 1 for a full description of the different ESMs.

	ES	*NCCE (€$_{2005}$/kWh)*			*ES_{TE}* (TWh/yr)			*$NCCE_{TE}$ (€$_{2005}$/kWh)*		
ESM No.	*(TWh/yr)*	*BA*	*HPI*	*LPI*	BA	HPI	LPI	BA	HPI	LPI
8	*1.0*	-0.158	-0.149	-0.135	1.0	1.0	0.9	-0.021	-0.019	-0.017
7	*0.3*	-0.153	-0.144	-0.131	0.3	0.3	0.3	-0.016	-0.015	-0.017
12	*13.3*	-0.036	-0.040	-0.039	13.2	13.3	13.3	-0.021	-0.020	-0.021
5	*12.0*	-0.006	-0.010	-0.009	7.4	9.2	9.0	-0.014	-0.013	-0.013
9	*2.6*	0.001	-0.003	-0.002	1.4	1.8	1.8	-0.018	-0.017	-0.017
10	*2.1*	0.008	0.003	0.003	0.2	1.0	1.0	-0.010	-0.009	-0.012
6	*9.6*	0.010	0.005	0.005	1.4	5.3	5.1	-0.161	-0.147	-0.147
4	*6.5*	0.011	0.007	0.008	1.7	3.1	3.0	-0.168	-0.153	-0.153
3	*2.7*	0.052	0.048	0.049	1.3	1.7	1.6	-0.017	-0.015	-0.015
11	*0.6*	0.099	0.096	0.099	0.2	0.2	0.2	-0.015	-0.014	-0.016
1	*5.3*	0.124	0.119	0.120	0.7	1.2	1.1	-0.025	-0.023	-0.023
2	*7.2*	0.159	0.155	0.156	1.9	2.9	2.8	-0.036	-0.034	-0.034
All ESMs	*63.2**	-0.014	-0.014	-0.010	30.6*	41.0*	40.3*	-0.086	-0.079	-0.081

(*)The values shown are only indicative; the individual potentials of ESMs cannot be summed because when several ESMs are applied as a package the ESMs influence each other.
BA, Baseline scenario; HPI, high price-increase scenario; LPI, low price-increase scenario.

The resulting ranking of the ESMs is similar for all the scenarios, as illustrated in Figure 3. Energy-efficient lighting (ESM 7) and energy-efficient appliances (ESM 8) are at the top of the ranking and appear as profitable ESMs (negative costs) because the investment cost is considered to be zero (*cf.* the right-most column in Table 1), in spite of having limited energy

[14] The average Swedish SFD has an area of 160 m^2, whereas the average Swedish MFD has an area of 1486 m^2 and contains 17 dwellings (NBHBP, 2009).

saving potential (0.3–1.0 TWh reduction in energy use; *cf.* the right-most column in Table 3). Furthermore, the energy saving potential could be difficult to attain, since the lifespan of these ESMs is only 1–3 years and the operation of lighting and appliances is subject to user preference. It is also profitable to reduce the indoor temperature (ESM 12), as the investment cost of the thermostats is rather low (3.4 €$_{2005}$/m^2) and there is a large potential for energy saving from this measure (13.3 TWh/yr). In addition, implementing heat recovery is profitable for SFDs (ESM 5) in spite of the high investment and maintenance costs, as the energy saving potential is high in these dwellings, which normally lack heat recovery systems. At the bottom of the ranking lie the measures related to retrofitting of the building envelope (i.e., attics, basements and facades; ESMs 1-3). While these are the least cost-efficient ESMs, they are associated with a substantial potential for energy savings (2.7–7.2 TWh/yr).

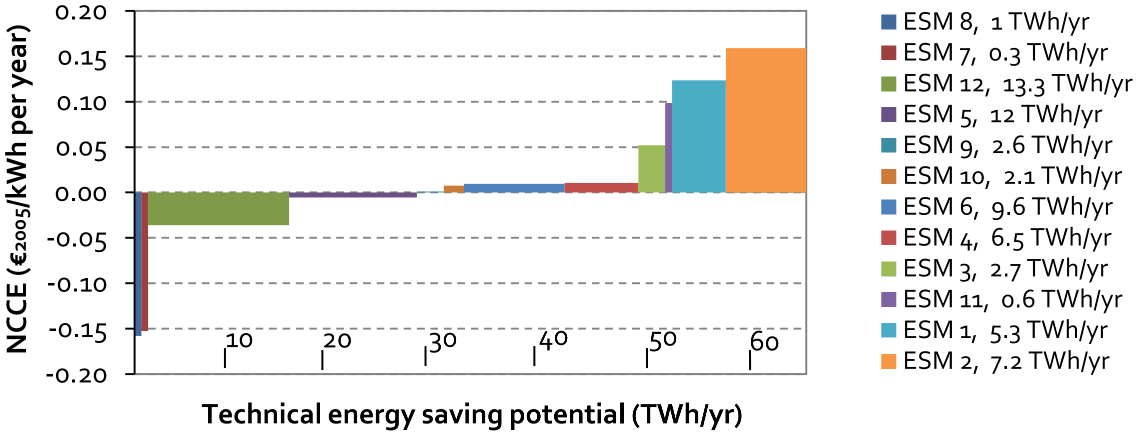

Figure 3. Net unit cost of conserved energy (NCCE) for the ESMs in the Baseline scenario. The results shown in the figure are based on the application of each ESM individually, which means that the potentials listed on the *x*-axis cannot be added to calculate a total potential.

Comparing the technical and techno-economical potentials for the most profitable measures (ESMs 7, 8 and 12), all or most of the technical potential saving is cost-effective, whereas for the remaining ESMs, not all of the potential savings are cost-effective. As indicated above, retrofitting of the building envelope (ESMs 1–4) has the highest average NCCE (0.011–0.159 €$_{2005}$/kWh). Nevertheless, depending on the ESM, 1.2– 3.1 TWh/yr of the total potential saving can be implemented in a cost-efficient way (negative cost) at -0.014 to -0.021 €$_{2005}$ /kWh. Furthermore, the window of opportunity is a key issue here when retrofitting the building envelop. Since the 30–40-year lifespan of ESMs 1–4 is the longest of the ESMs analysed, the technical potential savings may be lost if energy requirements are not considered when the building undergoes refurbishment. In the Baseline scenario, a total techno-economical potential of 30.6 TWh is identified, and the implementation of such a profitable potential would result in an average gain of 0.086 €$_{2005}$/kWh/yr. It should be borne in mind that the total potentials given in this paper are only indicative, since the ESMs are applied individually in the modelling and the potential energy savings from multiple ESMs cannot be summed, given that ESMs influence each other (*cf.* Mata et al., 2014).

The cost-effectiveness rankings of the investigated ESMs, the average NCCE of the ESMs, and the techno-economical potential energy savings are similar for the three different scenarios. The techno-economical potentials up to Year 2050 for reduced energy demand in the Swedish housing sector amount to 41.0 TWh in the HPI scenario and 40.3 TWh in the LPI scenario, as compared to the baseline annual demand of 97.7 TWh. Therefore, the techno-economical potential is almost the same in the HPI and LPI scenarios, despite the energy prices being on average 10% higher in Year 2050 in the HPI scenario than in the LPI scenario. However, the HPI scenario results in higher profitability, i.e., the average NCCE over the period 2010–2050 is -0.014 $€_{2005}$/kWh for the HPI scenario and -0.010 $€_{2005}$/kWh for the LPI scenario. In general, the measures are more profitable in the HPI scenario than in the Baseline and LPI scenarios, with some exceptions owing to the influences of the energy prices of the different fuels. The first exception is that the average NCCE is the same in the Baseline and HPI scenarios (-0.014 $€_{2005}$ /kWh/yr), although the energy prices in Year 2050 are on average 40% higher in the HPI scenario than in the Baseline scenario. This discrepancy is due to the discounting of the value of the energy saved in the future. The second exception is that, ESMs that reduce electricity consumption (ESMs 8 and 9) are the most profitable in the Baseline scenario, since the electricity price is higher in the Baseline than in the LPI scenario, and some measures influence simultaneously the electricity demand and the demand for space heating (ESMs 5–9). In short, there are cost-effective opportunities for all ESMs and energy price scenarios.

Table 4 presents the average annual reductions per building in delivered energy demand for the different energy carriers. The values are weighted averages derived from the results with the objective of representing an average residential building in Sweden. In Table 4, a value with a negative sign reflects an increase in energy demand. For example, the upgrading of a ventilation system with heat recovery reduces the demand for space heating but may increase or reduce the demand for electricity depending on the current ventilation installed in the building. For Swedish SFDs, which generally lack a mechanical ventilation system (NBHBP, 2009), the installation of heat recovery systems (ESM 5) results in a 12.7 TWh annual reduction in net energy demand for space heating (44 kWh/m^2 a), with a concomitant annual increase of 0.7 TWh in electricity demand (3 kWh/m^2 a), resulting in a net annual decrease of 12.0 TWh (as presented in the right-most column of Table 3). For the MFDs, the upgrading of a ventilation system with heat recovery (ESM 6) implies an annual reduction of 9.4 TWh (42 kWh/m^2 a) in net energy demand for space heating and a decrease of 0.25 TWh/yr (1 kWh/m^2 a) in electricity demand, yielding a net decrease of 9.65 TWh/yr (Mata et al. 2013b). The reduction in electricity demand in MFDs is due to substitution of the old exhaust-only ventilation systems already installed in the buildings with more efficient new ventilation systems that incorporate heat recovery (NBHBP, 2009). Reducing electricity consumption for lighting (ESM7) and appliances (ESM 8) increases space heating demand, which compensates for the loss of indirect heating from lighting and appliances (Mata et al. 2013b).

Table 4. Annual reductions in the delivered energy demand (kWh) for an average* building for the different energy carriers used in the buildings, derived from the modelling analysis in this work for different ESMs.**

ESM No.	Reduction in delivered energy demand (kWh/yr)						
	el	g	o	bw	dh	other	*Total*
5	2041	47	312	1470	1743	389	*6001*
6	5950	1693	1132	174	50124	534	*59606*
7	690	-14	-23	-78	-348	-23	*205*
8	2055	-41	-69	-234	-1052	-70	*590*

el, Electricity; o, oil; g, gas; bw, biomass/waste; dh, district heating.
*These values do not correspond to any of the building archetypes. They are weighted average values that are meant to represent an average residential building in Sweden.
**Coal does not appear as an energy carrier because it is not used in the Swedish residential sector.

The above results have been compared to the results of previous studies of the Swedish building stock. However, such comparisons are not straightforward, since the assumptions, ESM options, and approaches used in the modelling processes differ across the studies. Our resulting techno-economical potential saving is 10%–50% lower than the values reported by BFR (1996), Dalenbäck et al. (2005), and Göransson and Pettersson (2008). These discrepancies may be due to, first, that there are several definitions of energy saving potentials; in Sweden, the definitions are generally related to the so-called *cost savings*[15] (GB, 1977). Cost savings are defined as the sum of the investment and the present value of the annual maintenance cost of the efficient alternative, divided by the present value of the cost of the annual energy savings. In the present paper, the cost of the annual energy savings is subtracted from the investment and maintenance costs (*cf.* Eqs. 2 and 3). Second, the number of measures studied obviously influences the total potential (e.g., some studies do not include reduced indoor temperature as an energy-saving option). Third, the choice of data used for the description of the building stock influences the results. Specifically, BFR (1996) reported potential savings of 30–45 TWh/yr, reflecting the assumptions made (versus 30.6 TWh/yr in the present study). Dalenbäck et al. (2005) updated the energy prices and assumptions from BFR and reported a total potential saving of 26.0 TWh/yr, while Göransson and Pettersson (2008), in a further update of the energy prices and assumptions from BFR, reported a total techno-economical potential saving of 41.0 TWh/yr (i.e. similar to the 30.6 to 41.0 TWh/yr reported here). These three studies have all applied the above-mentioned cost savings (GB, 1977) and used a discount rate that is different from the one used in the present work (6% versus 4%, respectively). In addition, those previous studies are based on the description of the Swedish buildings as they were in 1995 (NBHBP, 1995), while the present work is based

[15] *Cost savings* were used as the basis for the first Swedish energy-saving plan and have subsequently been used in all Swedish energy efficiency assessments.

on the Swedish buildings as they were in 2005. The most recent report on optimal costs for energy retrofitting in Swedish buildings (NBHBP, 2013), which is based on Year 2005 descriptions of the buildings (as in the present work), applies discount rates of 3% and 6% to the financial calculations, and investigates a 20% variation in energy prices until Year 2040. However, the results are presented on an archetype basis rather than on a country level, which makes it impossible to compare the results with those of the present work. In the NBHBP report, it is concluded that most of the ESMs investigated are not cost-effective, which is in disagreement with the average NCCE reported herein (i.e. gains which range from 0.014 to 0.010 $€_{2005}$/kWh for the different scenarios assessed). The NBHBP report does not elaborate on this conclusion, so it is not entirely clear what they use as the basis for this result.

In a sensitivity analysis, we assessed the effects of typical increases in energy prices on the net annual costs (NAC in Eq. 1) of the ESMs. The justification for this price range is that the largest five-year energy price increase seen over the period 1970–2005 was 8%. Figure 4 shows the NAC per heated floor area, which enables the comparison of SFDs and MFDs. The net annual costs exhibit very low sensitivity to changes in energy prices. Thus, an increase in energy price is not sufficient to increase significantly the adoption of ESMs, at least for the range of historical price increases. This outcome is in agreement with the findings of Ó Broin et al. (2013) who concluded that increasing energy prices *per se* will not lead to significant savings in space and water heating demand for Swedish households.

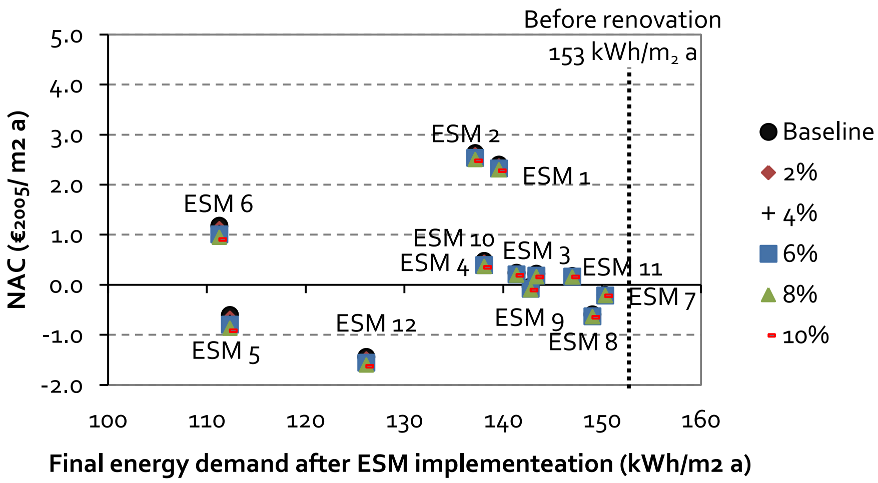

Figure 4. Sensitivity analysis of the effects of increases in energy prices (2%, 4%, 6%, 8%, and 10% above the baseline energy prices) on the net annual costs (NAC; *x*-axis) and the delivered energy demand (*y*-axis) after implementation of each of the ESMs investigated in this work, for Swedish residential buildings.

3.2. Effects of discount rates

Figure 5 presents the sensitivity analysis of the effects of different discount rates on the net annual costs of ESMs, applying discount rates of 1% to 6%. The lower rates represent policy actions that facilitate ESMs investments by offering low interest loans, while 6% is the additional discount rate[16] that the EC recommends for the financial calculations in the EPBD-related reporting of the cost-optimal levels of energy performance (NBHBP, 2013). It is clear from the figure that discount rates have significant effects on the net annual costs of the ESMs. Therefore, policy actions that facilitate the financing of ESM investments can increase the adoption of ESMs.

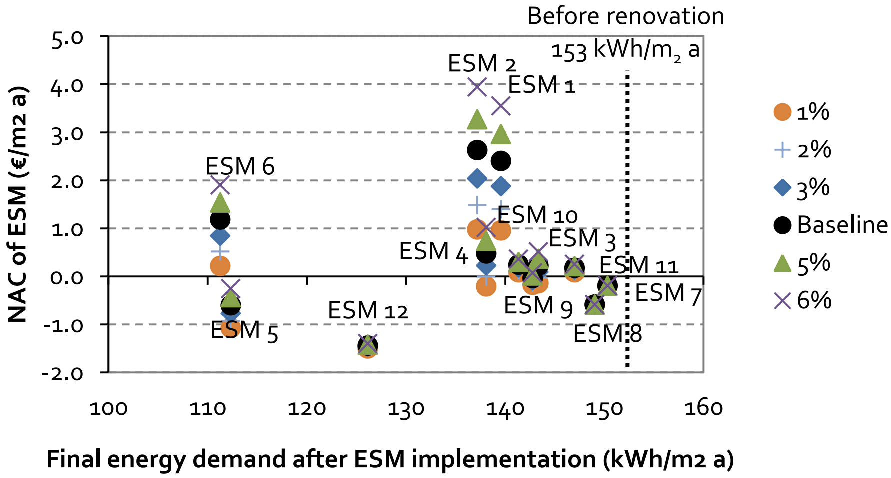

Figure 5. Sensitivity analysis of the effects of different discount rates (1%, 2%, 3%, 5%, and 6%; the Baseline rate is 4%) on the net annual costs (NAC; *x*-axis) and the delivered energy demand (*y*-axis) after implementation of each of the ESMs investigated in this work, for Swedish residential buildings.

Figure 6 provides an estimate of the market potentials (left *y*-axis) by applying a range of implicit discount rates derived from the literature, as well as their NCCE (right *y*-axis). It should be noted that the latter unit cost is actually (i.e., by definition) an economic gain, since it refers to the cost-effective potential. According to the literature, data on implicit discount rates that include consumer preferences reflect their willingness to make investments related to ESMs in their homes; these rates have been variously reported as: 18%–308% (Newlon and Weitzel, 1991); 50%–80% (Bailie et al., 1996); 20%–65% (EMG,1998); and 34.7% (Jaccard, 2009). Therefore, Figure 6 includes discount rates up to 80% (neglecting the highest value of 308%, which applies to clock thermostats only). The annual market potentials (in the grey area in the figure) can be expected to be substantially lower than the techno-economical potentials. The average unit cost for energy saving of all ESMs[17] will increase almost linearly from -0.011 $€_{2005}$/kWh (at a discount rate of 4%) to 0.731 $€_{2005}$/kWh over the range of discount rates investigated.

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[16] In addition to the 4% used in the Baseline calculations in this paper.

[17] For the entire energy saving potential of all the ESMs, not only that of the profitable part of the potential of each ESM.

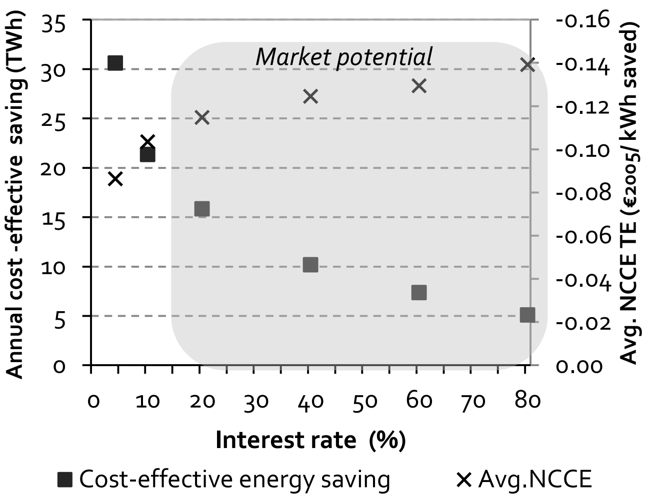

Figure 6. Estimates of the market potentials using private discount rates of 20%–80% (grey area) derived from the literature. The graph gives the total annual potential[18] energy saving *vs* the average net unit cost of conserved energy (*Avg. NCCE*). The techno-economical potentials obtained in the present work (4%) are shown for comparison.

4. Discussion

In this work, VAT is not included in the investment costs [C_I in Eq. (2)], although VAT, excise taxes, and distribution costs are included in the energy prices. We have made these assumptions to be in line with what we interpret as the flexibility of the EPDB specifications. In this context, the EPDB recast states that for the financial calculations (as defined in Section 1) the relevant prices to be taken into account are the prices paid by the customer including all applicable taxes, including VAT and charges. Ideally, subsidies available for different ESMs should be included in the calculation. However, according to the EPBD, MS can choose to leave subsidies aside, while still ensuring that all subsidies and support schemes for technologies, including existing subsidies on energy prices, are excluded (EC, 2012). Further work is needed to clarify the effects that the inclusion of taxes, VAT, charges and subsidies have on the cost-effectiveness of the energy saving potentials presented here.

In this work, the projected prices per tonne of CO_2 equivalent (tCO_2eq) of GHGs emission are implicit in the expected prices of the different energy carriers (*cf.* Section 2.4). However, the EPBD states that the cumulative carbon cost of ESMs should be calculated over the period studied by multiplying the sum of the annual GHG emissions by the expected prices per tCO_2eq of GHG emission allowances in every year issued. This raises the question as to how to avoid counting twice the effects of the carbon prices (i.e., in the energy prices and as carbon costs). In the scenarios applied in the present work, the required allowance price starts at 10 €/tonne CO_2 and increases to 25 €/tCO_2eq by 2030, followed by a steady increase to about 50 €/tCO_2eq by 2050 in the HPI scenario, and a somewhat higher level in the LPI scenario. These price levels are slightly lower than the prices suggested by the EPBD (in

[18] These are indicative values obtained by adding the potentials obtained by applying the individual ESMs, as commented above.

which the lower boundaries should be: initially, at least 20 €/tCO_2eq until 2025; 35 €/tCO_2eq until 2030; and 50 €/tCO_2eq beyond 2030; in line with current carbon price scenarios projected by the EU Commission in the emissions trading system; EC, 2010).

As mentioned above, the literature reports that consumers would apply an implicit discount rate of 20%–308% when deciding on energy-related home retrofitting. These values are substantially higher than the discount rate of 16% found our recent study (Ó Broin et al. 2014). The 16% value was that required by the (ECCABS) model used in the present work to yield the same results as were obtained using a top-down econometric model that estimated future price sensitivity based on historical data. However, the top-down analysis gives potentials that assume a continuation of historical trends, and thereby include the combined effects of indirect costs and policy instruments. However, it is not known to what extent the implicit discount rates reported in the literature include other factors that influence consumers, such as existing policies and subsidies. In addition, the work conducted by Ó Broin et al. (2014) applies only to space and water heating demand up to Year 2020, while in the present study, demand for electrical end-use is included, as well as the time period up to Year 2050. Therefore, further research is required to understand the relationships between implicit discount rates applied by consumers and other factors, such as the impacts of policies and support mechanisms for investments in ESMs.

More work is also required to elucidate additional parameters that influence the implementation of the different ESMs, especially for the ESMs that were identified in the present work as being cost-effective (ESMs 5–8, 12). For instance, it is well-known that decreasing the indoor temperature (ESM 12), despite its high cost-effectiveness and potential for energy savings, is difficult to implement in less-energy-efficient houses in which a high air temperature compensates for other factors in the operative temperature (i.e., high air velocity due to infiltrations or low radiation temperatures from the envelope surfaces). Glad (2012) has provided some insights into how occupants experience the installation of thermostats, and has concluded that occupants do not use them as intended, which lowers performance and increases occupants' general dissatisfaction with their indoor climate.

5. Conclusions

The cost-effectiveness of different ESMs in buildings is investigated with respect to energy prices and discount rates for the ESM investments. A bottom-up modelling methodology is used to assess the profitability of implementing ESMs until Year 2050 in Swedish residential buildings.

The three energy price scenarios investigated give similar techno-economical potential energy savings for the Swedish residential buildings over the period 2010– 2050, as well as a similar ranking for the investigated cost-effective ESMs. This means that there are cost-efficient opportunities for energy reductions in Swedish households for any future developments of the energy prices investigated in this work. The most profitable measures identified for all the scenarios are: application of energy-efficient lighting and appliances; reduction of the indoor temperature to 20°C through improved control systems; and installation of ventilation systems with heat recovery. These ESMs affect demand for both space heating and electricity and before any final conclusions are drawn, they should be assessed comprehensively in terms of delivered energy and associated CO_2 emissions, as well as in relation to implementation issues.

The sensitivity analysis reveals that energy prices have less impact than interest rates on the techno-economical potentials. Thus, increasing energy prices by itself cannot be expected to increase significantly the adoption of ESMs. Clearly, facilitating the financing of investments in ESMs and reducing other barriers in consumers' perspective or allaying consumers' reservations should also play key roles in the implementation of ESMs. The market potentials identified by applying implicit discount rates typical of households, as listed in the literature, are significantly lower than the techno-economical potentials. This indicates that more intensive policy actions than those executed in recent years will be needed to ensure the achievement of the identified techno-economical potentials.

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