Assessment of retrofit measures for reduced energy use in residential building stocks– Simplified costs calculation

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INTRODUCTION

Worldwide residential sector consumes 16-50% of total energy use, while the corresponding figure in Europe is 40%, although lower in Northern Europe (e.g. 31% in the UK, 21% in Norway and 19% in Sweden) (1). In developed countries turnover in building stock is low and the greatest challenge to successful reduction of energy consumption in the building sector over the next decades is to find effective strategies for retrofitting existing buildings. Yet, significant improvements are possible from applying available technologies and measures of which many are cost effective (2-4). To develop energy efficiency strategies for building stocks, there is a need of simplified methodologies and tools to assess the best steps to take according to the characteristics of the stock analyzed. Swan and Ugursal (5) reviewed available models for assessing the effect of energy efficiency measures in the residential sector and concluded that, so called bottom-up modeling of the buildings is required to determine the impact of new technologies. Such modeling is based on calculation of the energy consumption of an individual building or groups of houses and the results are then extrapolated to represent an entire region.

Literature gives a number of bottom-up methodologies to assess potential reductions of energy consumption in buildings and CO_2 emissions from buildings (5, 6-12). These methodologies apply models designed to get a comprehensive thermal performance of one building at any stage of its design. The models are based on a detailed description of a building with extensive input requirements and typically show long computational times (partly since they also often provide detailed graphical illustration of the results). Swan and Ugursal (5) give high requirements of detailed data and the computational intensity as the main negative attributes of bottom-up engineering models.

There are only a few examples of work available, where developed methodologies assess energy efficiency and CO_2 mitigation strategies for an entire building stock. Clinch et al. (3) and Balaras et al. (13) provide results, but their methodologies are not described in detail. Hinnels et al. (14) and Shorrock et al. (15) report details on their simplified models which they apply to the UK building stock. Hinnels et al. use the UKDCM2 model and Shorrock et al. the BREDEM-12 model. These authors developed a methodology where the calculated amount of energy saved by implementing energy efficiency measures is converted to carbon emission savings, using carbon intensity factors for fuels. They calculate the cost saving for each measure and the results are expressed as cost-effectiveness on a net annual cost basis. SGSR (16) have recently developed a carbon assessment model called DEMScot, which is applied to assist the Scottish Government in investigating the impact of different policy measures aimed at reducing CO_2 emissions from the housing sector. Although the three above works give valuable information on how to evaluate energy efficiency measures for a building stock, the models and methodologies are tailored specifically to the region for which they were developed (UK and Scotland), and therefore it is difficult to apply these models to other regions and building stocks. In summary, there are bottom-up methodologies that use complex models not developed for an entire building stock and the few methodologies reported which can handle building stocks, are either not readily available or were developed for a specific region.

The authors of the present work recently presented a simplified methodology to assess energy efficiency and CO_2 mitigation strategies for building stocks (17) using a sample of 1 400 buildings which are selected as representatives of the Swedish residential building stock. The modeling was developed as part of an energy assessment performed within the framework of a Swedish project initiated by Boverket (the Swedish National Board of Housing, Building and Planning) within the so called BETSI program (18). Different energy efficiency measures were presented as potentials and costs for increased energy efficiency and reduction in CO_2 emissions. Although the methodology applied in (17) is based on a simplified engineering bottom-up model, the calculation of the costs of the energy savings was based on data of equivalent annual costs collected in the field study. Such data may not be generally available and therefore, the aim of the work presented in this paper is to modify the costs calculation as to calculate the costs according to a simple set of data for a limited list of energy saving measures for each building. This modification will allow the model to be used with input data from available databases in literature and from aggregated statistics.

This paper is organized so that it first gives a general description of the energy calculations in the methodology of the previous work (17) and then gives an explanation of the basis for the costs calculation of the different energy efficiency measures applied. The original cost calculation (i.e. equivalent annual costs and costs per energy/CO_2 emissions saved) in the previous work (17) is described so it can be compared with corresponding upgraded cost calculations using a simple set of data for each measure. The upgrading also includes a reduced grouping of the measures studied, as to limit the number of input required. Finally, the results obtained in the previous work are compared with the results obtained in the present work, in order to verify that similar conclusions can be drawn from the results from both approaches.

METHODOLOGY

The methodology presented in (17) was developed to meet the following objectives:

- be simple both in respect to the description of the buildings and the model complexity in order to reduce computational time and amount of input data,
- to allow modeling of a building stock of an entire region or country on a level which allows aggregation to Europe as a whole,
- to allow assessment of the effects of different energy efficiency measures,
- to allow assessment of the costs per energy and CO_2 saved (meeting certain criteria, e.g. discount rate, baseline year, target year) and, finally
- to allow easy and quick change of inputs and assumptions in the model.

To accomplish these objectives, the complexity of the model has to be limited in order to use inputs from available databases and to facilitate low calculation time. In addition, reducing input data will make it more likely that efforts will be made to gather data in regions where these are lacking. The model is a bottom-up engineering model, i.e. the calculation of energy consumption of a sample of individual buildings is based on the physical properties of the building and the energy use, and the results are scaled-up to represent a region, i.e. an existing building stock. The energy consumption is calculated for the existing stock in a reference year (2005, for this case study) and then compared with corresponding calculations, for which various energy efficiency measures are applied such as corresponding to a certain target for reduced energy efficiency (e.g. the European target of reducing energy consumption by 20% until 2020). In addition, the analysis includes estimates of costs and carbon intensities of fuels and the estimated capital costs for the efficiency measures. Only existing buildings are studied, and the growth in the stock is not considered (i.e. renovation and demolition rates are not considered).

Assessing the energy use in the building stock

This section provides a brief description of the energy balance model (see (17) for details). The simulation of the energy consumption for the sample of reference buildings for the baseline year serves as a large-scale validation of the model. As indicated above, the building stock is represented by 1 400 buildings chosen to be representative of the Swedish housing stock (i.e. commercial buildings are not included). The restricted number of parameters used to define the basic feature of the energy use in these buildings is summarized in Table 1 and includes: building geometry and properties of the construction materials as well as energy characteristics of the sub-systems and required indoor temperature. Data of the 1 400 buildings were provided by Boverket (19) and were obtained from measurements and surveys. See (19) for details. The data can be divided into two categories: single family houses (hereafter referred to as “S-houses”) and multifamily apartment buildings (hereafter referred to as “F-apartments”). Regarding the year when the buildings were built, they can be divided into five age groups (according to changes in building codes and building techniques). The buildings were chosen from 30 different municipalities according to their population and geographical location in order to have a good distribution of municipalities of different sizes and from different climate regions. Meteorological data is generated by Meteonorm (20) as average for the period 1996-2005. The hourly values required in the model for all the year are outdoor temperature (C), global radiation on horizontal surface (W/m^2), diffuse radiation on horizontal surface (W/m^2) and normal direct radiation (W/m^2). Effects of possible anthropogenic climate change have not been considered.

Table 1. Model parameters used to characterize the energy use in the 1 400 buildings modeled. Parameters marked with “” are given per m^2 of heated floor area.*

Description	Unit
Area of heated floor space	m^2
Total external surfaces of the building	m^2
Total window surface area of the building	m^2
Shading coefficient of the window	%
Frame coefficient of the window	%
Effective volumetric heat capacity of a heated space (whole building)	J/K
Coefficient of solar transmission of the window	%
Average U value of the building envelope	W/ m^{2}C
Response capacity of the heating system	-
Maximum power rating of the heating system	W
Heat losses of the fan to the indoor air*	W/m^2
Specific fan power	W/l /s
Efficiency of the heat recovery system	%
Electricity consumption of hydro pumps*	W/m^2
Minimum indoor temperature	C
Indoor temperature above which opening windows/natural ventilation is assumed to occur	C
Initial indoor temperature	C
Minimum ventilation flow rate (sanitary ventilation)*	(l/s)/m^2
Natural ventilation flow rate*	(l/s)/m^2
Average constant gain due to people in the building*	W/m^2
Average power demand for hot water production*	W/m^2

The building is modeled as one thermal zone (21). The thermal inertia of the building is represented by its effective internal heat capacity, C according to ISO 13790 (21), which is determined by summing the volumetric heat capacities of the building elements in direct contact with the internal air, such as internal layers of exterior walls, internal walls and middle floors. It is assumed that the indoor air temperature and the temperature of all internal layers are the same. Therefore, the change of indoor air temperature is found from the differential energy balance equation:

$$C \cdot \frac{d\, T_{int}(t)}{dt} = q_t(t) + q_v(t) + q_r(t) + q_{int}(t) \qquad (1)$$

where C is the effective internal heat capacity of the building (J/K), T_{int} is the indoor air temperature (C), q_t are the transmission heat losses through the building envelope (W), q_v are the ventilation heat losses including sanitary and natural (W), q_r are the solar radiation gains through windows, represented by one horizontal window (W) and q_{int} are the total internal heat gains, including lighting, appliances, occupancy and heat released to the indoor air by other building systems, e.g. fans (W).

Transmission heat losses are calculated for the average thermal transmittance of the total surface of the building envelope. Ventilation flow rate is composed of sanitary ventilation and natural ventilation. While the sanitary ventilation stands for the minimum ventilation flow rate required to assure a healthy indoor environment in buildings, the natural ventilation assumes that the occupants will open the windows when the indoor air temperature exceeds some upper comfort limit, T_v. Thus, the natural ventilation occurs normally in summer. In buildings without heat recovery from exhaust air, the temperature of the supply air equals outdoor air temperature. If a heat recovery system is present, the supply air is preheated by the exhaust air. Cooling of the building by natural ventilation is used whenever the indoor temperature exceeds the set point temperature for natural ventilation, T_v. Since the aim of the simplified model is to be used for representative buildings, no specific orientation of windows is considered. The model treats the window area as one horizontal area, corresponding to the total area of all windows on the building. The difference in solar irradiation on differently oriented facades is compensated for by a constant, which for the case of Sweden is approximated to 0.65 (22). Internal heat gains include heat generated in the building by internal sources other than the space heating system, i.e. metabolic gains from occupants and the heat released by the appliances, lighting devices and ventilation fans.

Heat demand is defined as the heating power required to maintain the indoor air temperature at a given level. A “dead-band” control system is used in the model, i.e. the heating system is turned ON if the indoor air temperature is lower than a minimum indoor temperature, Tr_{min}. Otherwise, the heating is OFF. The value for Tr_{min} used in this study is 21.2C, according to the results of the measurements within the BETSI program given in Boverket (19). The heating system is characterized by a finite power and response time. Cooling demand is calculated in a similar way. In buildings with mechanical supply-exhaust ventilation system or exhaust air heat pump, the part of the heating demand for the sanitary ventilation losses recovered in a heat exchanger is also taken into account. Additional details on the modeling and its implementation are given by Mata and Sasic Kalagasidis (22).

Baseline energy use is the energy demand for heating and electricity use in the entire Swedish residential building stock, as it was in year 2005. This energy use is compared with the modeling by weighting (up-scaling) of the calculated heating, hot water and electricity demand in the sample buildings. Each of the buildings investigated represents a number of buildings on a national level, according to the number of buildings in each category, based on statistical data about the number of buildings in the country. As an example, if the stock of the country consists of 20 000 apartment buildings of certain age and in a certain climate region and 25 of them were selected to be investigated, the weighting coefficient is 20 000/25= 800. The baseline result obtained in the calculations, as well as results of potential energy savings given in this work refer to the energy demand (i.e. not energy delivered). However, the results obtained from the calculations are compared to data available in the official statistics, which are given as delivered energy. Thus, the energy delivered is obtained by applying the assumptions given by Boverket (19) to the energy use obtained in the calculations, for the efficiencies of the heat and electricity systems according to the characteristics of the housing stock (i.e. percentages of oil, gas, pellets, wood, electricity and district heating in heating and hot water demand). Application of the model has been compared with detailed multi-zone modeling and the agreement was generally good as discussed in (17).

Costs for energy savings and CO_2 emission reductions

With respect to the costs related to implementation of the energy efficiency measures applied, these are here expressed as the cost for reducing energy use and the cost to reduce CO_2 emissions. These costs are defined as the incremental cost of implementing the energy efficiency measures compared to the baseline case and are given in € per energy (kWh) saved and in € per ton of CO_2 emissions avoided on a yearly basis. As indicated above, the baseline is taken for the Swedish residential building stock as it was in year 2005. The cost represents the pure "project cost" (i.e. upfront investment) to apply (i.e. install and operate) the energy efficiency measures. Capital availability is not considered a constraint. Thus, energy saving cost is written (15):

$$Cost_E = {}^{NAC_{EA} - NAC_0}\!/_{ES} \qquad (2)$$

where NAC_{EA} is the net annual cost of the efficient alternative (€/yr), NAC_0 is the net annual cost of the reference case (year 2005) and ES is the energy saved due to the application of the measure (kWh/yr). Since the reference case is the existing building stock NAC_0 is considered equal to zero and NAC_{EA} is written (15):

$$NAC_{EA} = EAC - S \qquad (3)$$

where EAC is the equivalent annual cost or annuity (i.e. the annual cost of the investment required to apply the measure over its entire life) (€/yr) and S is the annual cost of the energy saved (€/yr).

In (17), the equivalent annual costs, EAC, were provided by Boverket for each building and measure, with interest rate of 4% and lifetimes as given in (19). The data required to calculate EAC were collected in the field studies through detailed inspections of building envelopes and building services. For instance, the field study provided exact number of water circuits and corresponding hydro-pumps that can be replaced, together with their technical characteristics. Resulting costs for energy savings and CO_2 emissions obtained with such detailed description of the costs are hereafter referred to as "detailed costs" (see Table 4).

However, such detailed data will not always be available. Therefore, the corresponding equivalent annual costs of the energy saving measures applied in this work is calculated as:

$$EAC = {}^{C \cdot r}\!/_{1 - (1+r)^{-n}} + M \qquad (4)$$

using the set of input data for describing the measures and buildings which are given in Table 2.

It is also interesting to discuss how the parameters in the equation are defined when the cost refers to "measures for building retrofit" (as compared to a business investment point of view). Thus, in the present work C is the cost of the measure (€), r is the discount rate (rate of return that could be earned on an investment in the financial markets with similar risk, given in %), n is depreciation time (considered equal to the lifetime of the measure over which the annual cost saving is supplied, given in years) and M is the extra maintenance cost of the efficient alternative (€/yr). The cost of the measure, C, can be provided in € per heated area (improvements on lighting and appliances and use of thermostats are commonly given in such way) or in € per surface to be retrofitted (improvements on the building envelope are commonly given in such way). The cost can also be given in € per dwelling (improvements on the ventilation systems are commonly given in such way). When applying the costs given per dwelling to a multifamily apartment building, the number or dwellings within the building is found using the average surface of an apartment dwelling given in Boverket (19). These data, summarized in Table 2, have also to be provided in the model as inputs, besides the inputs already listed in Table 1.

Table 2. Model parameters used to calculate the cost of the energy saving measures

Description	Unit	To be provided
Interest rate	%	Per measure
Lifetime of the measure over which the annual cost saving is supplied	years	Per measure
Cost per heated area	€/m^2	Per measure
Cost per surface below ground to be retrofitted (basements)	€/m^2	Per measure
Cost per surface above ground to be retrofitted (facades)	€/m^2	Per measure
Cost per surface of roof/attic to be retrofitted	€/m^2	Per measure
Unitary cost	€/unit	Per measure
Average surface of an apartment dwelling	m^2	Per building
Surface of the building envelope below ground (basements)	m^2	Per building
Surface of the building envelope above ground (facades)	m^2	Per building
Surface of the building envelope corresponding to roof /attic	m^2	Per building

The costs applied consist of the cost of material and labor for work related to implementation of the energy efficiency measure, including taxes (i.e. consumer prices, excluding VAT). This means that most of the actions are assumed to be taken simultaneously, such as facades or roofs renovation, and therefore only extra costs for energy savings 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, as recommended by Hermelink (23). Costs for planning, information retrieval and other client costs are not included (i.e. transaction costs are excluded), although costs for moisture safety planning and costs to conservation issues and aesthetic issues can increase the cost of an energy-saving measure. Discount rates and lifetimes considered are based on the same data, from (19), than the "detailed costs" used. This, since the aim is to eventually compare the resulting costs for reducing energy use and CO_2 emissions (expressed in cent€/kWh or tCO_2/kWh)obtained in this work with the "detailed costs", to verify that they lead so similar conclusions. Discount rate is set to 4% for all the measures. Lifetime considered depends on the measure, being between 10 years (for the thermostats needed to reduce indoor air temperature by 1.2C down to 20 C) and 40 years (for the retrofitting of basements, facades and roofs, and for windows replacement), according to data from (19). The annual maintenance costs, when such are present, are assumed to be the same each year.

Carbon intensities ($kgCO_2e$/kWh) for the energy sources have been assumed constant over the years.

The consumer energy prices (exclusive of VAT, but including all other taxes) for the period from 2005 to 2007, are based on data from Göransson and Pettersson (24). The estimated consumer energy prices for the period from 2008 to 2020 are based on data from Nilson et al. (25). Those data are further developed by Profu (26), including prices for electricity, district heating, oil, natural gas and biomass.

Energy saving measures considered

A total of 23 types of measures, outlined in Table 3 and henceforth referred to as "23 measures", were assessed. The list of measures was suggested by Boverket in the frame of the above mentioned cooperation within the BETSI program. Measures 1 to 17 and measure 22 are technical, that is, they only require replacement of a part of the building or its systems by a more energy efficient component/system. The remaining measures involve behavioral changes, and therefore they are applied by changing the assumptions of certain input parameters. For instance, a reduction of the use of hot water is considered to correspond to substitution of the existing taps and WCs with aerator taps and dual flow WCs, but also requires an adequate operation by the occupants. Measures 1 to 5 consist of the retrofitting of the parts of the building envelope below the ground (i.e. cellars and basements), each of them refer to different types of existing constructive solutions for the parts of the building envelope below ground (floor above crawlspace, flat floor on ground, floor above unheated basements, basement wall above ground, basement wall below ground). Measures 6 to 8 consist of the retrofitting of the parts of the building envelope above the ground (i.e. facades), each of them refer to a different type of existing constructive solutions for facades (ventilated walls with different cover materials, brick facades). Measures 9 to 14 consist of the retrofitting of attics and roofs and each of them refer to a different part of the attic/roof and/or a different type of existing constructive solutions (attic joists, knee walls, slope roof, flat roof).

Table 3. Relation between the two grouping of energy saving measures assessed in present work

Measures		Description
23	12	
1	1	Change of U-value of floors above crawlspaces
2	1	Change of U-value of flat floor on ground
3	1	Change of U-value of floor above unheated basements
4	1	Change of U-value of basement wall above ground
5	1	Change of U-value of basement wall below ground
6	2	Change of U-value of facades (curtain wall, outer layer)
7	2	Change of U-value of facades (outer layer covering brick facade)
8	2	Change of U-value of facades (intermediate layer, new brick facade)
9	3	Change of U-value of attic joists, from the inner side
10	3	Change of U-value of attic joists, replacement of the roof
11	3	Change of U-value of attic joists, from top side (400mm)
12	3	Change of U-value of attic joists, from top side (300mm)
13	3	Change of U-value of knee walls
14	3	Change of U-value of slope roofs
15	4	Replacement of windows
16	5	Upgrade of ventilation systems with heat recovery, for S- houses
17	6	Upgrade of ventilation systems with heat recovery, for F-apartments
18	7	50% reduction of power for lighting
19	8	50% reduction of power for appliances
20	9	Reduction of power used for the production of hot water to 0.80 W/m^2, S- houses
21	10	Reduction of power used for the production of hot water to 1.10 W/m^2, F-apartments
22	11	Change of electrical power to hydro pumps
23	12	1.2C reduction of indoor air temperature down to 20 C

Such detailed division is possible because the work with sample buildings can provide such level of detail in the description of the buildings and therefore in the input data. But since the aim of this work is to further develop the methodology to reduce the number of input required for the energy saving measures, measures 1 to 5 have been grouped into a general “retrofit of basement/cellars”, measures 6 to 8 have been grouped into a general “retrofit of facades” and measures 9 to 14 have been grouped into a general “retrofit of attics/roofs”. Thus, after the grouping the list of measures is reduced to 12 measures, which are shown in the second leftmost column of Table 3 and will be henceforth referred to as “12 measures”.

The potential energy saving can be calculated in two ways: by applying the measures one by one or by applying several measures at once. The results of the first analysis will here be referred to as “simple”. As effects of one measure might influence another, a summation of these simple potentials will probably overestimate the overall energy saving. Yet, in the present work, the “simple” approach is applied but only to serve the purpose of a first assessment of the cost efficiency of each of the measures investigated. To group the measures so as to take into account their influence on each other is not straight forward and is outside the scope of this work (see, however (17) for an initial discussion on this).

RESULTS AND DISCUSSION

Before we report on the costs it can be of interest to summarize the results from the energy calculations presented in (17). They show that the simple technical potential for energy savings in the Swedish residential sector is about 66 TWh/yr, corresponding to 68% of the energy use in the baseline year. A reduction in indoor temperature down to 20^{o}C reduces the annual energy consumption with 13.6TWh, while upgrading of the ventilation with heat recovery systems reduces the annual consumption by 11.9 TWh for a single family house and by 9.6 TWh for the apartment buildings. The upgrading of the U-values of cellar/basement and facades, and the replacement of windows provide a saving of about 7 TWh/yr each.

The total potential for CO_2 reduction is 3.6MtCO_2e/yr, which is a reduction by 60% of the emissions of the Swedish building sector. Yet, it should be noted that the CO_2 emissions from the Swedish building sector is already very low. Details on the potential energy and CO_2 savings are discussed in detail in Mata et al. (17).

Costs for energy savings and CO_2 emission reductions

Table 4 compares the costs obtained for the energy efficiency measures in the present work (for “12 measures” (12M) and for “23 measures” (23M)) with the “detailed costs” (DC) as applied in the previous work (17). As a validation of the modifications in the costs calculation, the equivalent annual costs obtained with Equation (4) have been compared to the ‘detailed’ equivalent annual costs from (17). In addition, the costs for energy and CO_2 savings based on the equivalent annual costs obtained with Equation (4) are calculated on the reduced number of energy saving measures, grouped in 12 categories as shown in Table 3, and the results are compared to the results obtained for 23 measures.

Table 4. Comparison of the costs obtained in present work for “12 measures” (12M) and for “23 measures” (23M) with “detailed costs” (DC), for the measures assessed. EAC for DC, marked with “”, is not calculated from Eq. (4) but was provided as input by Boverket.*

	Average Cost (from Eq. (2))						EAC (from Eq. (4))		
Measures	cent€/kWh per year			€/tCO_2e per year			€/yr		
	DC	23M	12M	DC	23M	12M	DC*	23M	12M
Lighting	-7.6	-7.2	-7.2	-2932	-2803	-2803	0	0	0
Appliances	-7.6	-7.2	-7.2	-2888	-2803	-2803	0	0	0
Reduction of Tint	-6.3	-5.7	-5.7	-2574	-2236	-2316	129	546	546
Heat recovery-S houses	0.5	0.1	0.1	-478	-417	-417	445	405	409
Hot Water -S houses	1.7	2.0	2.0	-101	219	219	113	113	113
Retrofit Attics/roofs	2.8	8.7	7.6	2346	2394	1876	455	648	492
Hot Water -F apartments	3.2	4.6	4.7	1424	747	747	199	240	240
Heat recovery-F apartments	6.8	5.3	5.4	1639	882	882	108	116	116
Windows replacement	7.5	3.7	3.7	1778	898	898	295	211	211
Hydro pumps replacement	11.0	24.3	24.3	2686	7937	7938	115	120	120
Retrofit Basements/cellars	11.6	15.5	21.0	2955	3796	5637	203	201	342
Retrofit Facades	26.8	28.4	33.3	7344	8987	10629	313	312	338

As can be seen in the third and second rightmost columns of Table 4, the ranking of equivalent annual costs, EAC, obtained from Equation (4) is in agreement with the ranking obtained with the equivalent annual costs used in the “detailed costs”. The equivalent annual costs obtained for the reduction of indoor temperature and for the retrofitting of attics/roofs are, however, higher than the values used in the “detailed costs”. For the reduction of indoor temperature, this is due to the difficulty in defining the reference unit - it could be per dwelling or per heated area. For example, this cost includes the cost of the thermostats, with the number of thermostats depending on the number of rooms or heating elements, but also on the characteristics of the heating system. In the present work the cost of thermostats is related to the heated area. For attics/roofs, the equivalent annual costs obtained are higher than the values used in the "detailed costs" due to the groping of the 6 types of measures for attic/roof retrofit (see Table 3) into average values for surfaces and costs in the costs calculation. For the windows, a constant relationship of 0.7 is found between the equivalent annual costs used in the "detailed costs" and the net annuals costs obtained in the present work. The reason for the deviation is not known, since the assumptions behind the equivalent annual costs used in the "detailed costs" taken from Boverket are not known.

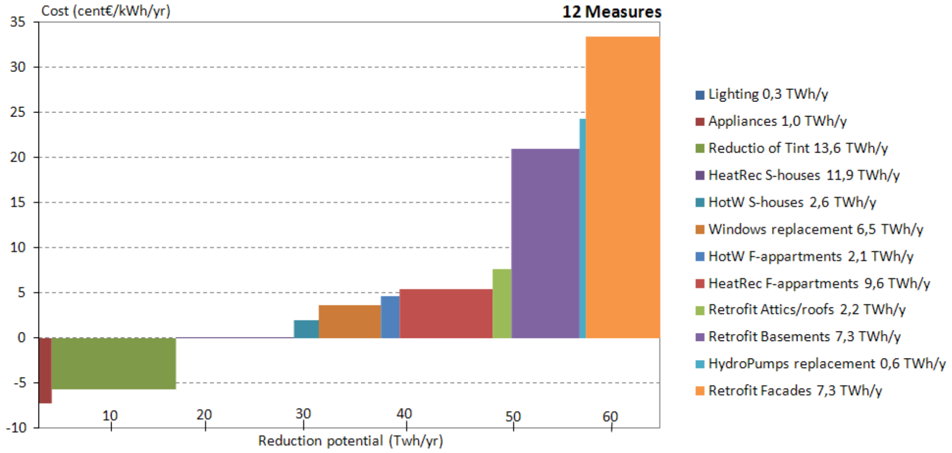

Figure 1. Cost per energy saved for the energy efficiency measures as obtained from simulations in this work using the "12 measures" division for the costs of efficiency measures.

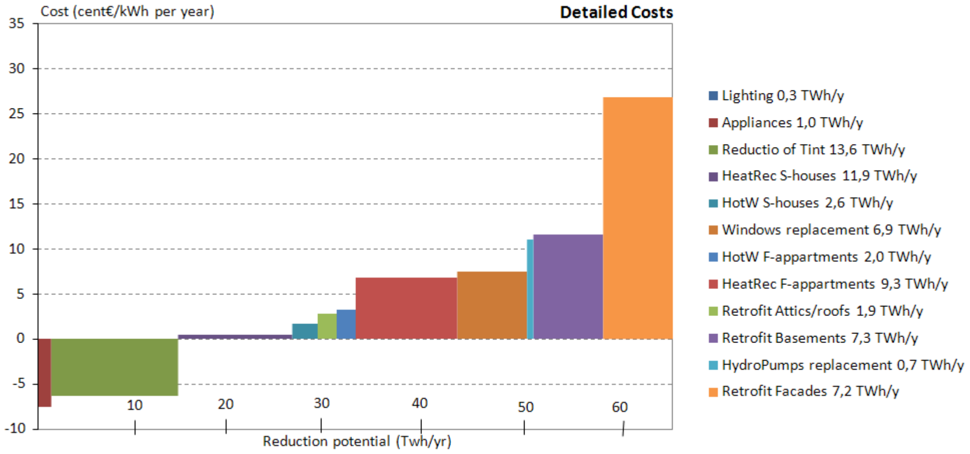

Figure 2. Detailed costs for energy efficiency measures as obtained from simulations in (17), i.e. using the "Detailed costs" division of costs for energy efficiency measures.

The comparison of the resulting costs per energy saved for a reduced grouping of "12 measures" with the results obtained for all the measures (both "detailed costs" and "23 measures") is shown in the three leftmost columns of Table 4. The results are also illustrated in Figures 1 and 2. As can be seen, the incremental cost increase obtained with the simple cost division (Figures 1) is in agreement with the ranking obtained with the "detailed costs" (Figure 2). The costs for energy savings obtained for the retrofitting of the envelope differ somewhat between the three different divisions as basis for cost calculation shown in Table 4 ("DC", "12 measures", "23 measures"). Yet, Table 4 and Figures 1 and 2 show that, overall, the results are similar for the three cost calculations. For cellars, facades and attics, there is a difference in costs between the simplified divisions and the detailed costs which shows that for these measures a simplification is not straight forward. The differences for windows replacement are likely due to the above mentioned unknown assumptions taken from Boverket (19) in the definition of the equivalent annual cost for this measure. Similar difficulties as those found for the reduction of indoor temperature with the definition of the costs are found for the reduction of the power used for the production of hot water and for the replacement of hydro pumps. For the latter measure the cost per energy saving obtained is much higher that the “detailed cost”. Thus, the definition of the cost might need to be improved in further stages of this work, according to the characteristics of the buildings and data availability for other regions.

The comparison of the resulting costs per CO_2 emissions avoided for a reduced grouping of “12 measures” with the results obtained for the longer lists of measures (both “detailed costs” and “23 measures”) is shown in the three middle columns of Table 4. As expected the incremental increase in CO_2 emissions avoidance cost is similar to the incremental increase in cost of the energy efficiency measures. Consequently, also the differences between the cost calculations (“DC”, “12 measures”, “23 measures”) are similar to those found for the energy efficiency measures. As mentioned previously, the average CO_2 abatement cost obtained is high due to that the Swedish building sector already is close to CO_2 free.

CONCLUSIONS

A simplified costs calculation is applied to a modeling methodology previously developed by the authors with the aim to assess the cost and potential of retrofit measures for reduced energy use in residential buildings. The simplified methodology includes the calculation of the equivalent annual costs according to a simple set of data for a limited list of energy saving measures for each building. The simplification also includes a grouping of the measures studied, as to reduce the number of input required.

Equivalent annual costs obtained and resulting costs for reduced energy consumption and CO_2 emissions for a reduced grouping of energy efficiency measures have been verified against the previous work. In general the agreement is good. For the calculation of the equivalent annual costs, the investment costs of implementing (i.e. install and operate) the energy savings can be provided as a function of the heated floor area, the surface affected by the retrofit or per dwelling. However, the costs of some of the measures are difficult to describe (the reduction of the power used for the production of hot water, the reduction of indoor temperature down to 20ºC and the replacement of hydro pumps), due to the different possibilities of the design.

For some of the measures with lifetime set to 40 years, the house owner may in practice have considerable higher requirement on pay-off time for the investment. Thus, a study which would have the aim to investigate the likelihood of if measures are to be implemented should take into account other (i.e. shorter) depreciation times and not only put these equal to the technical lifetime of the investment. In addition, since the depreciation time strongly influences the equivalent annual cost (see Eq. (4)), in order to be able to compare results from different bottom-up studies it might be necessary to agree on limiting the maximum lifetime of the measure to the extension of the period analyzed or the target year, as suggested in (2) and (4). As an example, in the present work the potential savings are calculated over the period 2005-2020. Thus, the maximum lifetime of the measures considered in this work should be 15 years. However, in the present work lifetimes considered are based on the same data as used in the “detailed cost” case (19), since the aim is to compare the resulting costs obtained in this work with the “detailed costs”.

At this stage, the modeling methodology is ready to be used with data available in literature and from aggregated statistics. As a first step, this can be done for Sweden as a test case, and the results compared with corresponding results in (17) based on data from sample buildings. Then, the building stocks of other European countries will be analyzed. Further simplifications on the methodology might be required due to difficulties due to limitations in data availability for other European countries.

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