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Contributions of building retrofitting in five member states to EU targets for energy savings

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ABSTRACT

To benchmark the contributions of building retrofits to the National Energy Efficiency Action Plans (NEEAPs) of the Member States (MS) of the European Union (EU) and to identify potential improvements to the general EU methodology, this paper presents homogenous mapping of the potential for energy savings and associated effects on CO_2 emissions for the building stocks of five selected MS: France, Germany, Spain, Sweden, and the United Kingdom. The mapping is created using a verified building stock modeling methodology, and includes results related to technical and techno-economical improvements for ten energy conservation measures (ECMs) and six ECM packages. These results are compared to the corresponding estimates in the NEEAPs, as well as those in the literature.

Although both our results and those in the literature show high variability for the cost-efficiency of the ECMs between the five national building stocks, the potential application of complete ECM packages generally appears to be more profitable than the application of individual ECMs. Certain challenges must be overcome before this potential can be realized. The energy savings for Year 2020 projected in the NEEAPs appear to be overly optimistic when one considers the efficiency trends, current regulatory framework, and techno-economical potential detailed in this study. Furthermore, the NEEAPs are not in full compliance with the requirements of the EU Energy Efficiency Directive. These requirements could be defined more specifically, so as to address the identified information gaps, thereby facilitating the implementation and monitoring of energy savings in existing buildings.

1. Introduction

It has been argued that the energy renovation of existing buildings is a ‘win-win’ option for the EU economy as a whole [1]. However, there is currently no single solution for the cost-effective renovation of existing buildings owing to substantial differences in size, construction, age, and energy standards, as well as regional climate and energy supply characteristics.

The EU methodological framework for the assessment of energy-saving building renovations (the Energy Performance of Buildings Directive (EPBD) [2] and the Energy Efficiency Directive (EED) [3]) is general and applicable to all Member States (MS) and is provided with distinct elements (i.e., the five parts of the EED Article 4, to be presented below). Nevertheless, the calculation procedure and input data used for the assessments are basically derived using free choice; such choosing of assumptions significantly influences the results. Table 1 presents the key methodological assumptions underlying the NEEAPs of the MS investigated, as well as in the literature. The NEEAPs for Year 2014 required for the transposition of EED Article 4 have been used in this paper to compare the modeling results, since the NEEAPs are the most up to date and comprehensive summaries of the potential improvements and costs of energy savings in buildings. The NEEAPs should include: a statistically representative description of the national buildings; an approximation of the potential energy savings for different relevant building segments (e.g., climate and usage type), including costs and co-benefits; and a proposed strategy for cost-effectively retrofitting these buildings. These elements are provided to a various extents by the NEEAPs of the five countries studied, apply different modeling approaches, and consider various relevant parameters, such as baseline year, number of ECMs, cost data, and discount rate.

Based on the key assumptions given in Table 1, it can be concluded

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Nomenclature

EC	The European Commission
ECM	Energy Conservation Measure
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
MFD	Multifamily Dwelling
MS	Member State
NCCA	Net Cost of CO_2 Avoided
NCCE	Net Cost of Conserved Energy
NR	Non-residential
of ECMs	Package P
R	Residential
SFD	Single-Family Dwelling

that the NEEAPs have followed the EU modeling framework but used different methodologies in the estimation of energy savings, and that they have not given all the information necessary to compare energy conservation estimates of all the MS. A description of the building stock for representative building types is presented in all the NEEAPs, but only a few buildings may be modeled for which a full set of resulting energy saving improvements and corresponding costs are available or for which the savings can be estimated from indicators based on aggregated statistics. The standards of the efficiency options considered also differ between the countries. Data for Non-residential (NR) buildings are generally scarce.

Although the final energy consumption has increased since Year 1990, a shift in trends is apparent. Fig. 1 shows that most of the MS decreased their primary and final energy consumption levels between Year 2005 and Year 2013 (at a rate higher than is required to meet the primary and final energy goals by Year 2020) [4]. In the Residential (R) sector, final energy consumption in Year 2013 decreased by 3% in absolute terms compared to the Year 2005 level; in the NR sector, an increase of 6% was observed with an added value of 11% over the same period, yielding a 4% decrease in energy intensity. As further growth in final energy consumption is expected for the NR sector and in the very last years an upward trend has been observed, efforts will have to be made across the EU to guarantee this downward trajectory for energy intensity [13]. It is in any case difficult to understand the component of the downward trend in energy demand that is linked to the actual renovation of existing buildings.

In addition to the abovementioned EU regulations, efforts have been made recently to increase our understanding of the potential for energy efficiency in EU buildings, including: the EU Tabula project, which has produced potential savings for two types of refurbishments of typology buildings in 21 European countries [14]; and Episcope, which has performed scenario analyses of energy efficiency in R building stocks at the local [15], regional and national levels [16]. At the same time, these projects have revealed some information gaps concerning the actual state of, and trends in, thermal insulation and efficient / renewable heating systems in EU buildings. EU databases, such as the open data hub[2] of the Building Performance Institute Europe, hold promise as a basis for assessing the transformation of the EU building stock, although they are still under development. Furthermore, in global assessments such as those conducted by the International Energy Agency [17] and the Intergovernmental Panel on Climate Change [18], the EU is treated as a single world region, being usually clustered with OECD countries.

The scientific literature contains several studies with varying geographic and sectorial scope regarding the potential for energy and CO_2 reductions in EU buildings: these studies investigate either the entire EU [18-20] or only a single MS [21–30]. In addition, various types of energy-saving measures have been studied, including measures that reduce only the energy use with [22,23] or without [20,21,24,25] on-site renewable energy sources (RES), and measures that also target the building technical systems by increasing their efficiency [22,23,26–31]. Several studies have assessed individual measures [19,22,24–28], whereas others [19,21,23,30,31] have investigated several measures aggregated into packages. Finally, the assessments may refer to the technical potential for energy savings or CO_2 emission reductions or include an economic evaluation thereof.

In summary, the information in the literature mostly relates to R buildings and is complex and far from homogeneous. It is also difficult to monitor the actual renovation of existing buildings within the projected energy savings. Thus, additional studies are needed to generate a systematic overview of energy saving options, their contributions to reduced energy usage, and the CO_2 emissions for existing R and NR buildings in the EU. Therefore, the primary aim of the present study is to provide homogenous mapping of the potential for energy savings in EU buildings, which will serve as the basis for further analyses of costs, associated benefits, and suitable policy measures designed to accelerate improvements in the energy performance of EU buildings. A secondary goal of the study is to benchmark the available NEEAPs for the five countries, thereby identifying the potential for improvement of the general EU methodology. The MS investigated are the United Kingdom, Sweden, Spain, Germany, and France, which together accounted for 54% of the final energy demand (Year 2015) and 52% of the CO_2 emissions (Year 2014) of the EU-28 buildings. Together, they cover all the climate zones of the EU [32,33].

The novelty of this paper lies in that it performs a five-country comparison of the potentials for energy efficiency improvements and their associated costs and CO_2 emission reductions, using the same modeling methodology. The results are compared to the corresponding values in the NEEAPs and in the literature. The comparisons are discussed in the context of the EU targets for energy efficiency and CO_2 emission reductions, as well as in relation to benchmarking the NEEAPs.

2. Methodology

2.1. Modeling procedure

We use the Energy, Carbon and Cost Assessment for Building Stock (ECCABS) model to calculate the energy performance of a set of *representative buildings* (samples or archetypes) [34] for each of the five countries investigated. The number of representative archetypal buildings is determined using a combination of building type, climate zone, period of construction, and type of heating system [35–37]. Specifically, the building stock of France is represented by 99 archetypes (54R, 45 NR), the R building stock of Germany by 122 archetypes, the building stock of Spain by 120 archetypes (40R, 80 NR), the building stock of Sweden by 1384R sample buildings and 336 NR archetypes, and the building stock of the UK is represented by 252 archetypes (168R, 84 NR).

Table 2 presents the weighted averages of the key characteristics of the representative buildings of the five MS investigated. For the sample buildings, i.e., R buildings in Sweden, data collection was based on surveys and measurements [36]. For the archetypal buildings, data were collected from national statistics, regulations, standards, and market surveys [35,37]. The parameters in the higher part of the table are based on national standards. For instance, the thermal transmittance of the envelope and windows is given in the national building standards and clearly reflects climate severity. The various electrical demands, although they are also based on design standards, show greater variability. As for the average efficiency of the new boilers, our

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[2] The data hub contains a parameter called "*Historical Renovation by Building Type and Year*" for which no data are available.

Table 1
Key assumptions made in the estimation of energy savings attained through the NEEAPs of the MS investigated and in the literature, as compared to the assumptions made in the modeling in this paper. R, Residential; NR; Non-residential.

	France		Germany		Spain	Sweden	UK	All 5 MS
Key issues	[4]	[5]	[6]	[7]	[8]	[9]	[10]	Modeling in this paper
Building stock description	R: 6 types/vintages, 6 occupancy types, 7 heating fuels, 7 performance levels; NR: 7 activities, surfaces, vintages	R: 22 administrative regions, 5 ages, 2 types, 20 heating systems; NR: 9 types, 2 ownerships	R: 5 ages, 5 types	R: 3 sizes, 3 ages; NR: 6 uses, 2 ages	R: 10 clusters types/ vintages, 3 performance bands within each cluster; NR: 8 types.	R: 2 types, 8 vintages, 3 climate zones; NR: 8 vintages	R: 5 house types, 4 tenures, 3 ages, 3 sizes, 4 fuel types, 3 wall constructions, 2 levels of efficiency; NR: 3 vintages,10 uses, 8 levels of performance***	R: archetypes and sample buildings; NR: archetypes (cf. Section 2.1)
Baseline year	2009	2010	2009	2012	2011	2011	2012	2009–2012 (cf. Table 2)
Type of calculation method	Not specified, although follows guideline 244/2012	Based on a simplification of the ENERTER model	Not given	R: DIN 4108–6:2003–06, DIN EN 832, DIN V 4701–10:2003–08; NR: DIN V 18599:2011	R: Yearly steady-state, radiation disregarded; NR: assumed % savings per subsector based on literature review	Seven indicators based on statistical aggregated annual data	R: Monthly quasi-steady-state following ISO 13790; NR: analysis of administrative data	R and NR: Hourly and dynamic following ISO 13790
Energy efficiency options	Three renovation scenarios: thermal system; envelope and thermal system; and deep	Two scenarios: existing measures; and supplementary measures	Unspecified, as it is included in the policy actions listed in the Plan	Three standards of thermal insulation, 5 (R) and 4 (NR) types of heating	R: envelope renovation; efficient heating installations; efficient lighting; new buildings and renovation of existing buildings with a high energy rating; efficiency in existing data centers; efficient appliances; efficient district heating and cooling networks	Insulation, window replacement, ventilation recovery or heat pump, circulation pump replacement, water conservation measures, hot water recovery from waste water, controls and regulators	Insulation, draught proofing, reduced infiltration, boiler upgrade, heating controls, efficient hot water production, efficient lighting, smart meters**	Ten individual ECMs and 6 ECM packages (cf. Tables 3, 4)
Cost	Global cost as in EPBD, for the 3 building types and scenarios	Annual cost of the measures for different actors	Not given	Building owner's perspective	R: Detailed description of the investments assumptions and costs per cluster and scenario	Not given	R: include all the cost of materials, labor costs and VAT, plus any transaction costs associated with finding the lead and marketing; exclude the value of grants/ subsidies and hidden or hassle costs	Direct cost following EPBD, building owner's perspective
Discount rate	4%	Not given	Not given	Not given	R: 8.2% − 5%; NR: not given	Not given	R: 3.5%; NR: not given	4%
Calculation period	15 and 30 years	Until Year 2035	Not given	Until Year 2050	Until Year 2030	Until Year 2050	R: Lifetime of ECMs; NR: not given	Continuous annual investment during the lifetimes of the ECMs (lifetimes from EN 15459)
Comments	Limited extrapolation to the national level				Quantifies associated job creation. Based on [11].	Approximates renovation actions taken in the period 2001–2011.	Methodology very similar to that in this work. Based on [12].	For the potentials in Year 2020 or Year 2050, a constant implementation rate is assumed (cf. Section 4).

** The ECMs have been grouped into themes; a full list is available elsewhere [12].

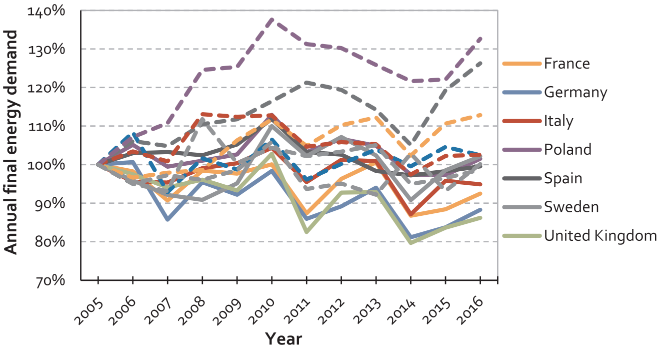

Fig. 1. Evolution of annual final building energy consumption level of selected MS over the period 2005–2016. The percentages are given with respect to the total final energy consumption for each MS in Year 1990. NR buildings are plotted as dashed lines. Data from the Odyssee database.

market survey shows marked national differences in the market penetrations of efficient gas boilers.

The parameters in the lower part of the table reflect building traditions and culture. These are apparent, for instance, in that 83% of R buildings in the UK have gas boilers but only 3% of Swedish residences have a gas boiler (district heating and electricity are the main energy choices in Sweden). Similarly, the average R building is much smaller in the UK than in Sweden; and the national typologies present different compactness and window sizes. Comfort levels are derived by the difference between the outdoor and indoor temperatures, calculated from the outdoor air temperatures listed in the climate datasets used in this paper (retrieved from Meteonorm) and the indoor temperatures modeled. The distribution of the average annual indoor temperatures modeled in the MSs is shown elsewhere [26]. As the locations and corresponding outdoor temperatures remain the same for the R and NR buildings in each MS, the differential variant temperature is due to our assumpion of the minimum indoor temperatures being different in R and NR buildings. In the UK, recent evidence [29] shows that the average number of hours that a house is typically heated and the length of the heating season are less than what assumed in the modeling in this paper. The same source reports that the average temperature setting is below the 21.3∘C for the living room and 20.3∘C for other rooms as generally assumed in previous studies. Combined, these factors imply that less energy is currently used in the average UK house than had previously been assumed.

2.2. Energy saving renovations

In the ECCABS model, potential energy savings and CO_2 emissions for energy-efficient renovations or ECMs are simulated by comparison to the above described energy demands and CO_2 emissions in the baseline year. In particular, the **technical potential** is defined in this paper as the reductions in energy usage (for space heating and hot water) and associated CO_2 emissions that could be achieved by implementing each ECM without any cost considerations. In addition, the **techno-economical potential** is defined as the portion of the technical potential that is cost-effective in relation to market costs using societal discount rates and given that all CO_2 taxes are included in the energy prices. An ECM is considered to be cost-effective when the annual cost of the energy not used due to the implementation of the ECM exceeds the total cost of the ECM. This cost-effectiveness is defined as the Net Cost for Conserved Energy (NCCE, in €/kWh saved per year) and the Net Cost for CO_2 Abatement[3] (NCCA, in €/tCO_2 emissions avoided per year) [30].

Table 3 lists the ECM measures and packages investigated in this study, whereas Table 4 summarizes the key modeling assumptions for ECM implementation.

ECMs 1–4 entail improvements to the building envelope through the addition of insulation to meet the standard building regulation in each MS [39–42].[4] The U-values for the different parts of the building envelope after retrofitting are listed in Table 4. For Sweden, the assessments of the optimum level of insulation have been performed for each sample R building by the National Board of Housing Building and Planning (*Boverket*) (cf. Table 3.3 in [43]). For NR buildings, an additional insulation layer of 300 mm is assumed.

For all MS, it is assumed that the effective volumetric heat capacity is the same before and after the retrofitting of the buildings. Although this assumption increases the thermal time constants of the buildings when ECMs 1–4 are applied, it should have no significant impacts on the results, given that the normalized sensitivity coefficient for the effective volumetric heat capacity of the space heated is rather low [35].

ECM 5 refers to the installation of ventilation with heat recovery. A review of the literature suggests that the technologies currently used in the different countries are not the same. This is reflected by the different efficiencies of the systems and Specific Fan Power values shown in Table 4.

ECMs 6 and 7 entail the installation of efficient lighting and appliances. If no particular national guidelines is identified, a reduction of 50% is assumed for both types of equipment. For France, the existing lighting equipment is replaced by more-efficient equipment according to the RT 2012 regulation [44]. The existing appliances are replaced with appliances that have A+ standards, which are on average 42% more efficient [45] for all R and NR subsectors, with the exceptions of the Educational and SCL (sport, culture and leisure) subsectors for which no data were found. For Spain, existing light bulbs are replaced with low-consumption light bulbs (75% more efficient), and existing appliances are replaced with A++ appliances (70% more efficient) [46].

ECMs 8 and 9 result in increased use of RES. For Spain, solar collectors (ECM 8) are installed to provide hot water to R and NR buildings according to the requirements of the current building code CTE [41]. For the other countries, 50% of the hot water from solar panels is assumed to be for R and NR buildings. In all cases, solar panels proportionally replace the existing systems for hot water production. In addition, for all MS and sectors, existing gas and oil boilers are replaced by biomass boilers (ECM 9) with efficiencies that, according to the national sources, differ depending on the MS investigated (cf. Table 4). For all MS, ECM 10 implies that existing gas and oil boilers are replaced with new boilers that have an efficiency of 90%.

Table 5 summarizes the costs for all ECMs and MS: investment costs are assumed be in accordance with EC Regulation No. 244/2012; lifetime, maintenance, operation and disposal costs are derived from EN 15459 [47]; and the interest rate is 4%. No residual value is assumed. The costs of the packages have been accounted for by summing the costs of the individual measures contained in each package.

2.3. Description of the National Energy Systems

In the ECCABS model, the energy system, to which the building-stock model is connected, has to be characterized with respect to the carbon emission factors and consumer prices for the different energy carriers used to supply energy to the buildings. Table 6 presents the carbon intensities of the various carriers considered in this study for the different MS. The averaged values have been retrieved from the literature. While we acknowledge that other assumptions would have

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[3] Termed "*unit cost for CO_2 abatement*" in Eq. 10 in [38].

[4] The French thermal regulation RT 2012 no longer uses the U-value parameter but only takes into account the insulation of the building envelope. Instead, the new regulation replaces the U-values with a parameter termed "Bbio". Bbio is a point system that rates the energy efficiency of a building in terms of heating, cooling, lighting, insulation, solar transmission, and air tightness.

Table 2
Descriptions of the key parameters of the building stock of the five countries in the baseline year, based on the datasets used in this study. All the values shown are weighted averages of the corresponding values for the different building types within each sector. Um, Average thermal transmittance of the building envelope; Uwindow, thermal transmittance of the windows; HFA, heated floor area; S, total envelope surface; Swindows, total surface area of windows; Swall, total surface area of external walls; Tout-Tint, difference between the outdoor and indoor temperatures.

	France		Germany	Spain		Sweden		United Kingdom	
	R	NR	R	R	NR	R	NR	R	NR
Um [W/m^2 K]	1.1	1.3	1.2	1.9	1.9	0.5	0.8	1.2	1.2
Uwindow [W/m^2 K]	3.2	4.0	2.7	3.9	2.7	2.2	2.3	3.5	3.5
Ventilation rate [l/s/m^{2}HFA]	0.4	0.8	0.7	0.2	0.4	0.4	0.4	0.2	0.3
Lighting load [W/m^2 HFA]	1.7	9.7	0.8	1.5	20.6	0.7	10.3	1.0	7.3
Appliances load [W/m^2 HFA]	2.2	2.4	1.9	1.2	1.5	2.2	6.2	4.2	2.9
Hot water demand [W/m^2 HFA]	2.8	2.1	1.4	2.2	0.4	1.8	1.9	5.0	1.3
Efficiency of oil boilers [%]	85	85	85	87	87	85	85	84	84
Efficiency of gas boilers[%]	80	80	90	87	87	90	90	82	82
Buildings with oil boilers [%]	23	12	33	36	14	3	0.7	4	10
Buildings with gas boilers [%]	27	25	52	25	8	1	0.3	83	56
HFA/building [m^2]	150	570	190	165	155	260	1515	90	310
S/HFA	2.2	2.0	1.2	2.5	2.5	2.6	1.3	2.4	2.1
Swindows/Swall	0.14	0.29	0.24	0.10	0.07	0.06	0.08	0.09	0.08
Tout-Tint [°C]	7.4	8.9	10.7	6.3	4.5	15.5	14.3	5.1	5.6

Table 3
Energy Conservation Measures (ECMs) and Packages (P) studied in this work.

ECM no.	Description
ECM 1	Increased insulation of cellar/basement
ECM 2	Increased insulation of facades
ECM 3	Increased insulation of attics/roofs
ECM 4	Replacement of windows
ECM 5	Upgrade of ventilation systems with heat recovery
ECM 6	Installation of efficient lighting equipment
ECM 7	Installation of efficient appliances
ECM 8	Hot water production with solar panels
ECM 9	Replacement of oil and gas boilers with biomass boilers
ECM 10	Replacement of boilers with more-efficient oil and gas boilers
P 1	Improved envelope (ECMs 1–4)
P 2	Improved ventilation (ECMs 4 and 5)
P 3	Reduced electricity use (ECMs 6 and 7)
P 4	Reduced energy need (ECMs 1–7)
P 5	Renewable energy supply (ECMs 8 and 9)
P 6	All ECMs (ECMs 1–9)

significant impacts on the NCCAs of the ECMs, it is outside the scope of the present paper to evaluate such impacts (i.e., methodological choices for the calculation of the carbon emission factors). The reason for the large differences in carbon intensities between electricity and district heating in the five MS is that there are substantial differences in the energy supply mix between the five countries. Table 6 shows variations in the carbon intensities for fossil fuels, the reason for which is unknown.

Table 7 summarizes the prices, including taxes, of the different fuels considered in this paper for the different MS. For all MS, energy prices are assumed to be the same for R and NR buildings.

2.4. Methodological assumptions in the literature review

Below, we explain how the different assumptions in the literature are handled in this paper, when possible for unification purposes, to allow for comparisons. The estimates reviewed refer to different sectors (i.e., R, NR or all buildings) and year (e.g., the German NEEAP reports savings for Year 2016 and Year 2020 in comparison to Year 2007, and for both R and NR buildings). To allow comparisons with the results presented in this paper, the literature estimates are converted to the sectors and reference years used in this paper (e.g., R buildings in Year 2009 alone for Germany) based on consumption data obtained from the Eurostat database, since the Eurostat database contains data for all years disaggregated into R and NR buildings.

In the French plan [4], existing R and NR buildings in Year 2009 are classified according to type, year of construction, occupancy, fuel use and performance level. Nevertheless, the analysis of potential improvements and costs for energy renovations (described by the key parameters in Table 7) is provided for only three building types (SFD built during the period 1950–1975, MFD built during the period

Table 4
Modeling inputs assumed for the ECMs, after retrofitting R and NR buildings in the five MS studied.

Input parameter [unit]	France		Germany	Spain		Sweden		United Kingdom		ECMs and Packages affected
	R	NR	R	R	NR	R	NR	R	NR	
U-value cellar [W/m^2 K]	0.27–0.36[a]	0.27–0.36[a]	0.35	0.62–0.69[a]	0.62–0.69[a]	0.10	0.10	0.40	0.40	ECM 1, P1, P4, P6
U-value wall [W/m^2 K]	0.36–0.4[a]	0.36–0.4[a]	0.28	1.2–1.7[a]	1.2–1.7[a]	0.10	0.10	0.25	0.25	ECM 2, P1, P4, P6
U-value roof [W/m^2 K]	0.20–0.25[a]	0.20–0.25[a]	0.20	0.46–0.65[a]	0.46–0.65[a]	0.09	0.09	0.18	0.18	ECM 3, P1, P4, P6
U-value window [W/m^2 K]	1.80–2.30[a]	1.80–2.30[a]	1.30	3.10–5.70[a]	3.10–5.70[a]	1.1	1.1	1.6	1.6	ECM 4, P1, P4, P6
Heat recovery efficiency [%]	50	50	70	84	90	75	85	70	70	ECM 5, P2, P4, P6
Specific Fan Power [kW/(m^3 s)]	0.75	0.75	1.0	0.6	0.6	1.5	1.5	1.5	1.5	ECM 5, P2, P4, P6
Consumption by lighting and appliances [% reduction[b]]	42	42; 50[c]	50	25 and 30	25 and 30	50	50	50	30	ECMs 6 and 7, P3, P4, P6
Hot water demand met by solar collectors [%]	50	50	50	50	70	50	50	50	50	ECM 8, P5, P6
Efficiency of new biomass boilers [%]	85	85	85	90	90	85	85	90	90	ECM 9, P5, P6

[a] Range depends on the climate zone.

[b] Reduction with respect to the existing equipment.

[c] Educational and Sport, Culture and Leisure (SCL) subsectors.

Table 5

Initial investment costs for the ECMs considered in this paper given as: (a) € per heated floor area; (b) € per surface to be retrofitted; (c) € per dwelling; and (d) €/kWh of demand.

Source: 1, [48]; 2, [45]; 3, [49]; 4, market survey of different providers; 5, [50]; 6, [51]; 7, [43]; 8, [52].

	France		Germany[5]	Spain[6]		Sweden*		United Kingdom[8]**	
ECM no	R	NR	R	R	NR	R	NR	R	NR
ECM 1	$30^{(b)1}$	$30^{(b)1}$	$30^{(b)}$	$4^{(b)}$	$4^{(b)}$	$130^{(b)7}$	$130^{(b)7}$	$32^{(b)}$	$32^{(b)}$
ECM 2	$45^{(b)1}$	$45^{(b)1}$	$35^{(b)}$	$6^{(b)}$	$6^{(b)}$	$150^{(b)7}$	$150^{(b)7}$	$11^{(b)}$	$11^{(b)}$
ECM 3	$120^{(b)2}$	$120^{(b)2}$	$25^{(b)}$	$11^{(b)}$	$11^{(b)}$	$41^{(b)7}$	$41^{(b)7}$	$23^{(b)}$	$23^{(b)}$
ECM 4	$500^{(b)1}$	$500^{(b)1}$	$105^{(b)}$	$200^{(b)}$	$200^{(b)}$	$260^{(b)7}$	$260^{(b)7}$	$317^{(b)}$	$317^{(b)}$
ECM 5	$2050^{(c)\ 4}$	$2050^{(c)\ 4}$	$60^{(a)}$	$190^{(c)}$	$1500^{(c)}$	$15^{(a)7}$	$15^{(a)7}$	$2440^{(c)}$	$27.2^{(a)}$
ECM 6	$1^{(a)4}$	$1^{(a)4}$	0	$1^{(a)}$	$0.1^{(d)}$	$0.7^{(a)}$	0	0	0
ECM 7	$6^{(a)4}$	$6^{(a)4}$	0	$1000^{(c)}$	$1.5^{(d)}$	$6^{(a)}$	0	0	0
ECM 8	$14^{(d)4}$	$14^{(d)4}$	$7500^{(c)}$	$1600^{(c)}$	$3^{(d)}$	$0.45^{(d)\ 4}$	$0.45^{(d)\ 4}$	$2050^{(c)}$	$0.50^{(d)}$
ECM 9	$33^{(a)1}$	$33^{(a)1}$	$9000^{(c)}$	$1600^{(c)}$	$3^{(d)}$	$0.53^{(d)\ 4}$	$0.53^{(d)\ 4}$	$12,250^{(c)}$	$2.15^{(d)}$
ECM 10	$33^{(a)1}$	$33^{(a)1}$	$9000^{(c)}$	$2100^{(c)}$	$14^{(d)}$	$0.32^{(d)\ 4}$	$0.32^{(d)\ 4}$	$4000^{(c)}$	$0.70^{(d)}$

*Exchange rate: 1 SEK = 0.10 € (average for Year 2010).

** Exchange rate: 1 GBP = 1.22 € (average for Year 2012).

Table 6

Carbon intensities of the different energy carriers (gCO_2/kWh) considered in this paper for the different MS. "Other" is calculated as the weighted average of the values for the other carriers. The "Weighted average" is calculated based on the mix of energy carriers used in the building sector of each MS. n.u., Not used.

Fuel	France	Germany [55]	Spain [56]	Sweden [36]	UK [57]
Electricity	57 [53][a]	579	649	15	480
Oil	300 [54]	314	287	280	270
Gas	230 [54]	245	210	210	170
Biomass/waste	13 [54]	91	0	10	21[c]
Coal	342 [54]	330	n.u.	n.u.	n.u.
District heating	172 [54][b]	251	n.u.	73	n.u.
Other (Avg.)	176	290	380	116	234
Weighted average	147	337	389	43	267

[a] Calculated from the total levels of production and emissions reported in the statistics of the Union of the Electricity Industry (Eurelectric).

[b] An average value for carbon intensity has been calculated based on the values provided for each French region (Appendix 7) in [54].

[c] Average for the different solid fuels, i.e., Wood Logs, Wood Chips, Wood Pellets, and Grasses/Straw, as given previously [58].

1975–1990, and offices built during the period 1985–2000) and has limited generalizability to the entire building stock. Therefore, the projected evolution of the final energy demand used for the comparison in Section 4 is taken from a latter publication [5].

The German NEEAP [6] describes R buildings in Year 2009 in terms of types and vintage. However, in agreement with our own findings [7,35], there is no reliable information available for NR buildings. While potential energy savings for the building sector are provided, they are unquantified with respect to most of the key parameters included in the table and make no reference to costs. Estimates of potential improvements and costs for various renovation scenarios from a more recent study commissioned by the German Environment Agency [7] will be used for the comparisons to the results of our own modeling in Section 4. The study subdivides R buildings into three size classes (single- and double-family houses, small and medium-sized MFDs, and large MFDs), each containing three age groups ("until 1948″, "1949–1994″. and "from 1995 onwards"). For NR buildings, there are six different usage types (R buildings with mixed use; education, office and administration buildings; commerce and industry; trade/services; hotels, restaurants and hospitals; and sports and cultural), of which four are subdivided into two age classes ("up until 1983″ and "from 1984 onwards"). The energy need and final energy demand are calculated according to DIN 4108–6:2003–06 and DIN EN 832 in connection with DIN V 4701–10:2003–08 (R buildings), as well as DIN V 18599:2011 (NR buildings). The ECMs include three standards of thermal insulation (EnEV in Year 2009 for newly built buildings with a 25% increase in that standard; passive house standard) and five and four types of heating technologies (gas condensing boilers; wood/pellet condensing boilers; electric heat pumps; gas combined heat and power units; district heating) for R and NR buildings, respectively.

The Spanish NEEAP [8] presents a classification into clusters that matches the segmentation used in this paper to classify R and NR buildings. The average final energy demand for space heating has been derived from the final energy consumption reported in the statistics by province and by distinguishing urban from rural areas, and each cluster has been disaggregated into three so-called "*bands* of consumption". The energy savings potential of each band is calculated as being steady-state with an annual resolution, disregarding solar radiation. There is a detailed description of the investment assumptions and costs per cluster and scenario. Energy savings and costs for NR buildings have been estimated from the literature and ESCO's experience.

The third Swedish NEEAP [9] presents the R and NR buildings according to type, vintage, and climate zone. Expected savings are calculated for Years 2016, 2020, and 2050 for a so-called reference option assuming that existing measures continue until Year 2050. There is scant information about the key parameters used in the calculations, especially for NR buildings, and no cost data are provided.

The UK NEEAP [10] presents a segmentation of R and NR buildings according to type, vintage, and performance level, with the savings calculated using the Standard Assessment Procedure used by the Housing Energy Model (HEM). The HEM model of the R buildings in the UK uses representative building types, for which the technical potential of a comprehensive list of ECMs is estimated. These potential improvements are then adjusted with coefficients to capture in-use, comfort, and inaccessibility. The number of R buildings for which each measure is applicable is taken from a previous report [12]. The costs have been assigned solely in relation to the sizes of the R buildings, with the typical proportions retrieved from BRE Standard Dwellings for Energy Modeling. Therefore, the data presented in the NEEAP are similar in terms of assumptions made and results obtained to the modeling in the present study, and will be directly used for comparison in Sections 3 and 4 (currency exchange rate: 1 GBP = 1.17 €).

3. Results

3.1. Potential energy savings

Fig. 2 presents the potential technical reductions in energy demand for the ECMs and packages investigated, as obtained from the modeling in this paper. Table 8 presents the total energy demands and CO_2

Table 7
Average annual prices of the energy carriers (€/kWh) considered in this paper for the different MS. "Other" is calculated as the weighted average of the values for the other carriers.

Fuel	France	Germany [50]	Spain [60]	Sweden [38]	UK [61,62]
Electricity	0.098 [59]	0.234	0.109	0.139	0.136
Oil	0.086 [45]	0.070	0.080	0.113	0.063
Gas	0.053 [55]	0.060	0.055	0.083	0.035
Biomass	0.035 [45]	0.050	0.034[a]	0.032	0.033
Coal	0.065 [45]	0.050	n.u.	n.u.	n.u.
District heating	0.075 [45]	0.080	n.u.	0.100	n.u.
Other (Avg.)	0.069	0.100	0.070	0.078	0.107

[a] The price for biomass considered as the energy price of pellets.

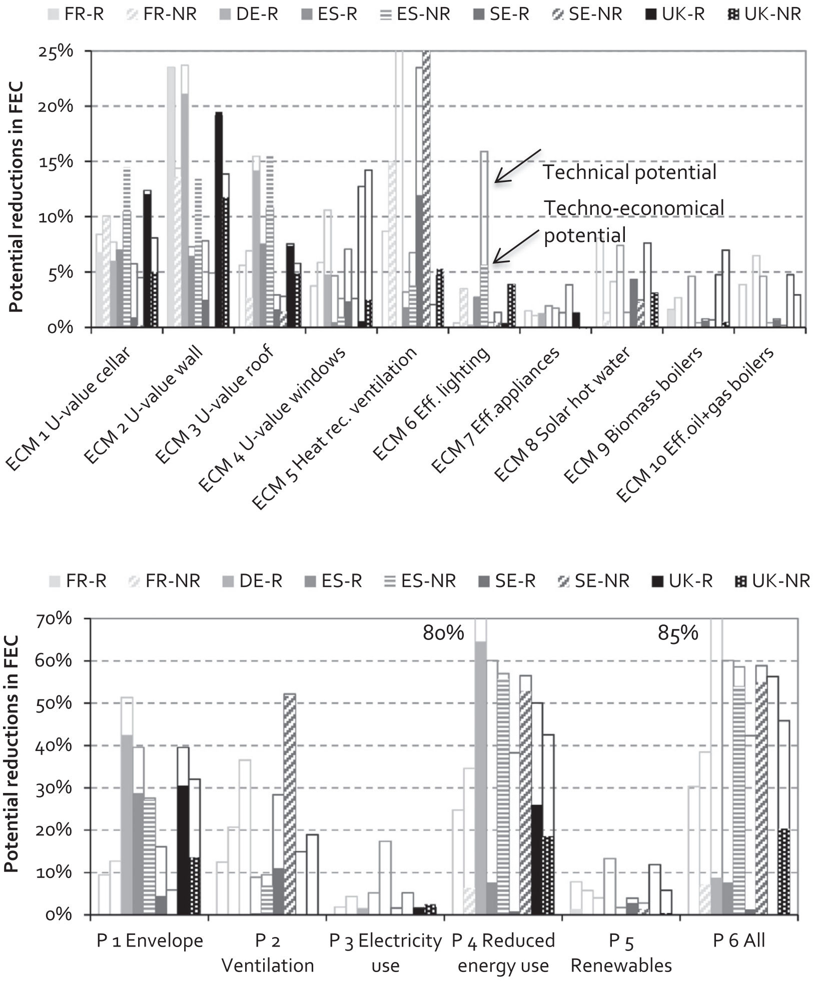

Fig. 2. Technical and techno-economical potential reductions in Final Energy Consumption (FEC) in terms of the percentage of the demand for each MS and sector in the reference year, as obtained in this study per sector and MS, for the different ECMs and packages investigated. The techno-economical potential is shown as the pattern-filling part of the technical potential. Top: For individual ECMs; bottom: for packages of ECMs.

emissions of R and NR buildings in each MS. Separate retrofitting of the different parts of the building envelope (ECMs 1–4 in Fig. 2) can generate reductions of at least 5–10% in all countries and sectors, with a higher improvement potential (up to 24%) for specific ECMs in France, Germany and the UK. Our estimates of demand reductions for R buildings in the UK are slightly higher than those reported previously [12].[5] This difference may be attributable to the fact that the latter source assumes, in agreement with recent DECC estimates, that over 60% of the cavity walls but only 5% of the solid walls have already been insulated (the insulation standard was not given).

Generally, our derived energy conservation potential is higher (in terms of %) for R buildings than for NR buildings due to the larger window surfaces of the latter (cf. Table 1). The potential improvements associated with the building envelope (average reductions of 31% and 20% for R and NR buildings, respectively, for Package 1, which includes ECMs 1–4; see Fig. 2) can, accordingly, vary substantially, corresponding to the combinations of existing insulation levels, desired indoor temperature, and climate, and the requirements of the regulation in force. The latter highlights the importance of strict building codes that govern the installation of additional insulation when the envelope is being renovated. In addition, ECMs that make strong contributions to

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[5] The summed savings from fossil fuels and electricity depicted in Figure 11 [12] are around 3%, 10%, 1%, and 4% for floor, wall, loft, and double-glazing, respectively.

Table 8

Final energy consumption and CO_2 emissions of the building stocks of the five MS in the baseline year (as indicated in the table), obtained from the modeling in this paper. Based on data from [35–37].

	France (2012)		Germany (2009)	Spain (2011)		Sweden (2010)		United Kingdom (2010)	
	R	NR	R	R	NR	R	NR	R	NR
Final energy consumption [TWh/yr]	459	193	697	190	92	92	39	754	77
CO_2emissions [Mt CO_2/yr]	69	23	216	65	56	4.2	2	220	29

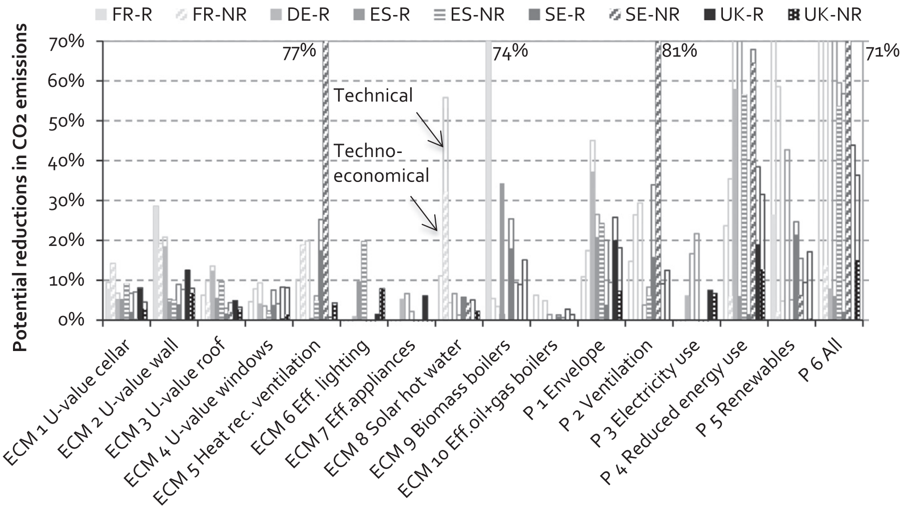

Fig. 3. Technical and techno-economical potential reductions of CO_2 emissions (as % of the emissions for each MS and sector in the reference year) obtained in this work for the different ECMs and packages investigated. The techno-economical potential is shown in the form of pattern-filling of a portion of the technical potential (DE, Germany; ES, Spain; FR, France; SE, Sweden; UK, United Kingdom).

these potential energy savings are profitable, as shown below.

As shown in Fig. 2, the potential reductions obtained by improving the ventilation systems with heat recovery (ECM5 and P2 Ventilation), although generally higher for NR buildings (19% on average) than for R buildings (14% on average) due to the higher ventilation requirements of the former, vary substantially among countries, owing to differences between the outdoor and indoor temperatures (cf. Table 2). Improving the ventilation (Package 2, which includes heat recovery ventilation and air sealing by window replacement) appears to be as energy-efficient as improving the envelope, as described above. This is especially the case for NR buildings (25% reduction in final energy on average, whereas it is 20% on average for R buildings). It can be assumed that control mechanisms to guarantee proper operation of windows and ventilation systems are easier to implement in NR on buildings than in R buildings. Nevertheless, Fig. 3 shows that there the cost-efficient potential available for these measures is small, due to their high investment costs, with the exception of Sweden, where the potential heat to be recovered is higher and where mechanical ventilation systems are already in place.

Doubling the efficiency of lighting and appliances (ECMs 6 and 7) reduces the electricity demand, although the induced increase in demand for space heating (because less heat is released to the indoor air) results in the overall potential being reduced below 6% for each of the ECMs and below 7% for the ECMs in a Package (P3 in Fig. 2). This effect has also been quantified for the R buildings in the UK (cf. Fig. 7 in [12]), for which the estimated savings[6] are in agreement with those in the present paper. DECC [10] has identified as particularly relevant the switch from halogen bulbs to LEDs, as currently 50% of lighting energy consumption in the UK is by halogen bulbs, which account for 37% of light fittings, whereas LEDs use only 1% of the lighting energy from 1% of fittings. As their baseline demand is exceptionally high (cf. Table 1), NR buildings in Spain appear to offer a remarkably large potential from installing efficient lighting. These findings are most relevant in light of the fact increasingly stringent EU minimum energy performance standards will lead to more-efficient appliances entering the marketplace. Furthermore, Fig. 3 shows that these measures are barely cost-efficient in all the MS and sectors.

The potential savings associated with installing solar panels for hot water production (ECM 8) are obviously related to the current hot water demand (cf. Table 2), and are, therefore, higher for R buildings (6% on average) than for NR buildings (2% on average), with the exception of hotels and sport centers (not shown in the figures). Similarly, the potential savings linked to replacing existing oil and gas boilers are proportional to the number of such boilers in the building stock (cf. Table 2), and represent on average 2% and 3% for R buildings and NR buildings, respectively. For the UK, for instance, it is estimated that the decade of the 2020's will witness the replacement of most of the remaining 13 million non-condensing gas boilers with high-efficiency condensing boilers [63]. Overall, the potential savings accrued by deploying on-site renewable energy sources (Package 5) are much higher for R buildings (8% on average) than for NR buildings (4% on average). Fig. 2 shows the limited cost-effective potential of these measures, which is due to their high investment costs in relation to the energy savings projected.

3.2. Effects on CO_2 emissions

The potential effects of ECMs and packages on CO_2 emissions are presented in Fig. 3, where the percentage reductions in CO_2 emissions are summarized per MS and sector. As the reductions for each MS are shown in Fig. 3, in this section we will comment on the average values across the MS investigated, which are not specifically illustrated in the figure. Retrofitting the building envelope would (for ECMs 1–4) lead to CO_2 emission reductions that are proportional to the final energy savings presented above; reductions of up to 26% and 17% on average across the MS investigated, for R and NR buildings, respectively, to insulate all parts of the envelope (P1, which includes ECMs 1–4).

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[6] The summed savings from fossil fuels and electricity pictured in Figure 11 of the previous paper [12] are around 1% and 3%, respectively, for lighting and appliances, whereas in the present work we obtain savings of around 1% for both measures, as shown in Fig. 3.

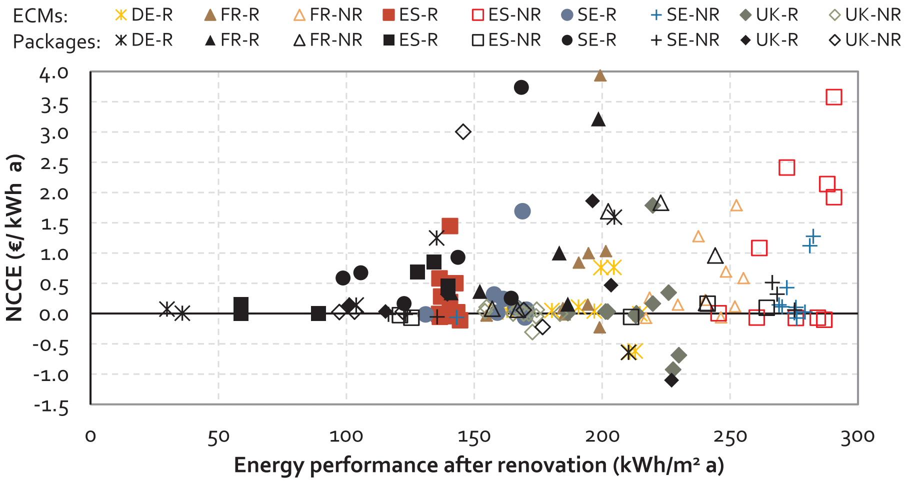

Fig. 4. Annual net cost of conserved energy (NCCE, in €/kWh saved per year) as a function of energy performance after renovation (in kWh/m^2 per year), obtained in this study for the different ECMs and packages (P). DE, Germany; ES, Spain; FR, France; SE, Sweden; UK, United Kingdom. Three values, falling in the range of 5.1–12.7 €/kWh, have not been plotted; these are commented upon in the text and highlighted in Table A1.

Significant cost-effective improvements are available for these ECMs, i.e., reductions of up to 16% and 10% for R and NR buildings, respectively, for P1. It should be noted that the cost-effective potentials referred to in this section are measured in terms of the Net Cost for CO_2 Avoided (NCCA), i.e., per unit of CO_2 avoided, as defined elsewhere [34]. Thus, they differ from the cost-effective potentials provided in Section 3.1.

For the measures related to the use of electricity, such as the installation of more effective ventilation systems (ECM 5) and lighting and appliances (ECMs 6 and 7), the potential for reducing CO_2 emissions depends on the fuel mix used for electricity production (cf. the values assumed in this study listed in Table 5). The technical potential for ECM 5 would allow CO_2 emissions to be reduced by 11% and 27% for R and NR buildings, respectively. These values are higher than the corresponding percentage for energy savings for NR buildings, which generally involve heavier electrical use than R buildings. Significant techno-economical potentials are also available for this ECM, i.e., reductions of up to 4% and 9% for R and NR buildings, respectively.

Emission factors lower than those of the mix used for space heating result in increased CO_2 emissions (with the increase shown in Fig. 4). This is a consequence of the above-referenced increase in space heating demand that results from the reduced use of lighting and appliances (cf. ECMs 6 and 7, as well as Package 3 in Fig. 3). This effect is particularly evident for France and Sweden, given their low emissions factors for electricity. The results for these MS include an increase of CO_2 emissions up to 12% and no cost-effective potential for these ECMs, whereas the average for the other countries (Germany, Spain and UK) in Package 3 (which includes ECMs 6 and 7) could reduce CO_2 emissions by up to 17% and cost-effectiveness by 3% and 2% in the R and NR buildings, respectively. Thus, the potential for CO_2 mitigation through the implementation of ECMs will vary with the MS, depending on the assumptions pertaining to the design of the deregulated electricity market and cross-border trading of electricity, as well as whether an average or a marginal approach is considered.

The effect of RES deployment is, of course, more significant in terms of CO_2 emission reductions than in terms of the final energy. For instance, the installation of solar panels (ECM 8) yields reductions of 7% on average for R buildings and 16% on average for NR buildings. Switching to biomass boilers (ECM 9) gives reductions of 3% on average for R buildings and 1% on average for NR buildings. The latter is lower because gas and oil boilers are used less frequently in NR buildings than in R buildings. Overall, installing RES in Package 5 (which includes ECMs 8 and 9) could reduce CO_2emissions by 32% and 24% in R and NR buildings, respectively, and cost-effectiveness by 10% and 1% in the R and NR buildings, respectively.

Our results show that comprehensive packages, such as P4 or P6, could decrease the CO_2 emissions by 48–67% and cost-effectiveness by 3–28%. For R buildings in the UK, potential reductions of around 30% (60 $MtCO_2$/yr) have been reported [12]; taking in-use factors into account, the revised potential for CO_2 emission reductions is 18%.[7]

3.3. Costs of energy savings potentials

Fig. 4 presents the obtained NCCE (in €/kWh saved per year) as a function of energy performance after renovation (in kWh/m^2 per year). It is clear from the figure that there are many cost-efficient (i.e., negative values on the y-axis), as well as low-cost ECMs (e.g., 25% of the values are lower than 0.5 €/kWh). It is also noteworthy that the packages of ECMs are generally associated with lower NCCEs or vice versa; the values in the top-right area of Fig. 4 correspond to individual ECMs. Finally, the most efficient package (P6) investigated gave very different levels of energy performance in the countries and sectors investigated: 140 kWh/m^2 and 155 kWh/m^2 for R and NR buildings, respectively, in France; 30 kWh/m^2 for R buildings in Germany; 60 kWh/m^2 and 120 kWh/m^2 for R and NR buildings, respectively, in Spain; 100 kWh/m^2 and 115 kWh/m^2 for R and NR buildings, respectively, in Sweden; and finally, 100 kWh/m^2 and 95 kWh/m^2 for R and NR buildings, respectively, in the UK.

In particular for France, many of the measures and packages show an NCCE of less than 1 €/kWh saved per year, with the exception of ECM 7 and Packages 2 and 3 for R buildings, and ECM 3 and Packages 1 and 2 for NR buildings. For Germany, the NCCE is less than 1.3 €/kWh saved per year for all the measures. For Spain, most of the measures and packages show an NCCE of less than 1 €/kWh saved per year. Only the installation of on-site RES features slightly higher costs (maximum of 1.4 €/kWh/yr for R buildings, and 12.7 €/kWh/yr for NR buildings; the latter is not shown in Fig. 4 but appears in Table A1). Nevertheless, their costs are off-set by the profitability of the other ECMs, resulting in the implementation of all ECMs (P 6) being profitable on average for all Spanish buildings. The resulting NCCE values for the different subsectors of R and NR buildings, as well as the aggregated results for the entire building sector are given in a previous report [38].[8] In Sweden, the NCCE values for the individual ECMs lie below 0.4 €/kWh/yr for R buildings, except for efficient lighting and appliances; the different packages allow greater reductions in energy use (down to 100 kWh/m^2), albeit at an increase in NCCE of around 5 €/kWh/yr.

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[7] Taken as the "*cumulative technical potential for emission savings by measures across the stock*" as illustrated in Fig. 1 from [12]. These savings disregard the uptake of low-carbon heating technologies (e.g., combined heat and power systems and heat pumps); if these were taken into account, the revised potential for CO_2 emission reduction would be 49 $MtCO_2$/yr.

[8] Note that the ECMs and Packages investigated in [38] are listed/ numbered in a different order.

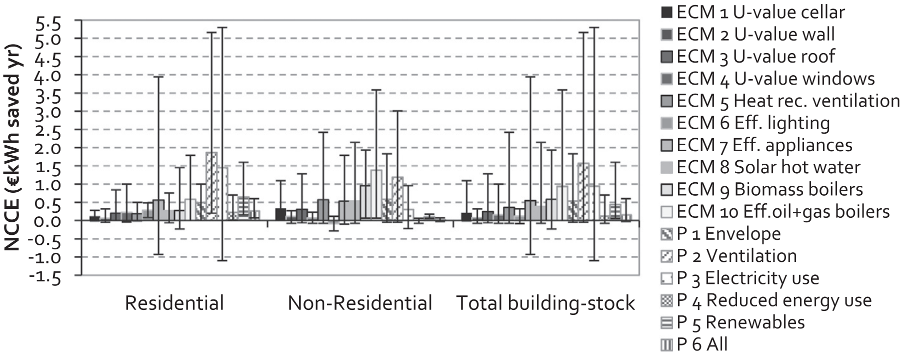

Fig. 5. Variations in the NCCE values obtained for the various ECMs and packages (P) for Residential (R) and Non-Residential (NR) buildings, as compared to the corresponding values for the total building sector (including both R and NR buildings). The values shown are averages for the five MS investigated. Based on the data shown in Table A1 in the Appendix.

Effective lighting and appliances (ECMs 6 and 7) appear as profitable measures for Germany and the UK, as well as for Swedish NR buildings. Although the cost of these ECMs for the MS is assumed to be zero (cf. Table 5), excessive costs may arise if the consumer voluntarily decides to replace still-functioning equipment with more-efficient equipment. The latter has been assumed for France and for the Swedish R buildings; in such cases, the cost of the unused energy – including the above-referenced increase in space heating demand – does not cover the costs of the efficient equipment installed.

In other words, a wide range of costs is found irrespective of performance features. The above-referenced variations in costs observed across the different building types in the MS investigated are presented in Fig. 5, which depicts the variations – of the averages for the five MS investigated – in NCCE values for the R and NR buildings obtained in this study for the different ECMs and packages, as compared to the corresponding values for the entire building sector (including both R and NR buildings). Fig. 6 shows the variations in the NCCE values obtained in this study for the five MS investigated for the various ECMs and packages, as compared to the average values for the five MS. Both figures highlight the remarkable variation among NCCEs within MS, sector, and type of ECM, and underline the subsequent high risk of inaccuracy when using aggregated values for potential improvements and costs for ECMs within the EU.

Fig. 7 illustrates the NCCA values (in €/tCO$_2$-avoided/yr) for the different ECMs and packages as a function of the energy performance following renovation (in kWh/m^2 per year); the values on which Fig. 7 is based are also shown in Table A2 of the Appendix. It is clear that the NCCA varies widely across the ECMs as well as the MS due to the differences in the national energy systems mentioned in Section 3.2. It is also clear that the range of the *y*-axis in Fig. 7 is much broader than that in Fig. 4, as some ECMs result in very few CO$_2$ emissions avoided, with the threshold in the model being 1 tCO$_2$-avoided/yr.[9] The overall appearance of Fig. 7 contradicts the often-claimed low-cost potential for CO$_2$ mitigation in the short to medium term for the building sector. For example, a review of estimations of the reduction potential in CO$_2$ emissions in buildings expressed in USD/tCO$_2$ for the world regions for 2020, present values generally lower than 100 USD/tCO$_2$ [64]. On the other hand, investigations on national building stocks give a large span in abatement costs. For example, abatement costs in Thai residential and building sectors range from −500 to 7,000 USD/tCO$_2$ [65], for Armenia and Georgia range from −275 to 75 USD/tCO$_2$ [66], and for UK range from −300 to 1,000 GBP/tCO$_2$ [67].

A closer look at Fig. 7 shows that there are cost-efficient ECMs and packages (negative values) and that these correspond to those in terms of NCCE values, with the exception of envelope insulation in Spain (ECMs 2–4, cf. Table A2) and in the UK (ECM 3). It is also noticeable that there are many low-cost ECMs: 35% of the values are < 100 €/tCO$_2$/yr. In particular, all measures to reduce energy need (Package 4) could be applied to R buildings in Germany to reduce emissions by 58% (163 MtCO$_2$/yr) at a cost of 21€/tCO$_2$/yr. Thus, Package 4 appears to have a cost of around 100 €/tCO$_2$ in the UK for R and NR buildings, and could reduce CO$_2$ emissions by 38% (85 MtCO$_2$/yr) and 13% (9 MtCO$_2$/yr), respectively.

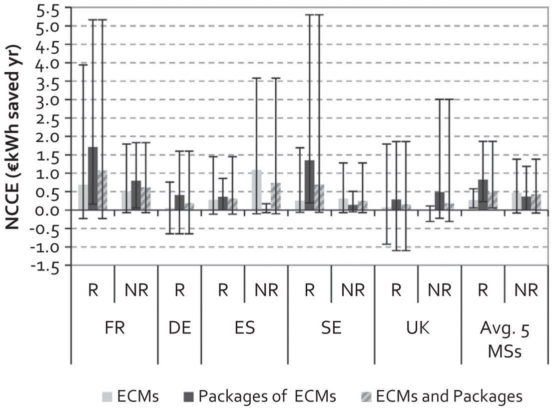

Fig. 6. Variations in the NCCE values across the five MS investigated for the different ECMs and packages (P), as compared to the average values of the five MS (DE, Germany; ES, Spain; FR, France; SE, Sweden; UK, United Kingdom). Based on the data shown in Table A1 in the Appendix.

In particular for Spain, the NCCAs for installing a recovery system (ECM5 and P2) are relatively high, as such a system is expensive in relation to the potential reduction in CO$_2$ emissions projected.[10] The resulting NCCA values for the different subsectors of R and NR buildings, as well as the aggregated results for the entire building sector are provided by [38].

For Sweden, the resulting NCCAs for R buildings are exceedingly high (note that seven values for the R buildings are not shown in the figure, and that the range is 14,000–105,000 €/tCO$_2$ (Table A2), since the CO$_2$ emissions presented in Fig. 4 are quite low. Consequently, the NCAA values could also be quite low, as oil and gas boilers could be replaced by more-efficient biomass boilers at a gain of 3,700 €/tCO$_2$ owing to economic gains driven by savings in unused oil and gas (biomass is assumed to be much cheaper) for moderate absolute levels of CO$_2$ emissions saved (0.8 MtCO$_2$/yr, which is 18% of the total emissions by Swedish R buildings). Therefore, CO$_2$ abatement is not the driving force for ECMs in the Swedish context. Instead, the profits gained from ECMs and indirect effects, such as reduced dependency on electricity (which may give indirect reductions in terms of CO$_2$ emissions), are potent motivations for implementing ECMs. For NR buildings, the NCCA is substantially lower (all < 8,000 €/tCO$_2$) and include

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[9] This means that if a measure results in less than 1 tCO$_2$-avoided/yr, the saving is assumed to be zero. This assumption aims to limit extremely profitable or unprofitable results for measures with very minor potentials for savings.

[10] See Table 6 in [30] for a comparison of the savings and costs, including net annual costs and costs of the unused energy saved.

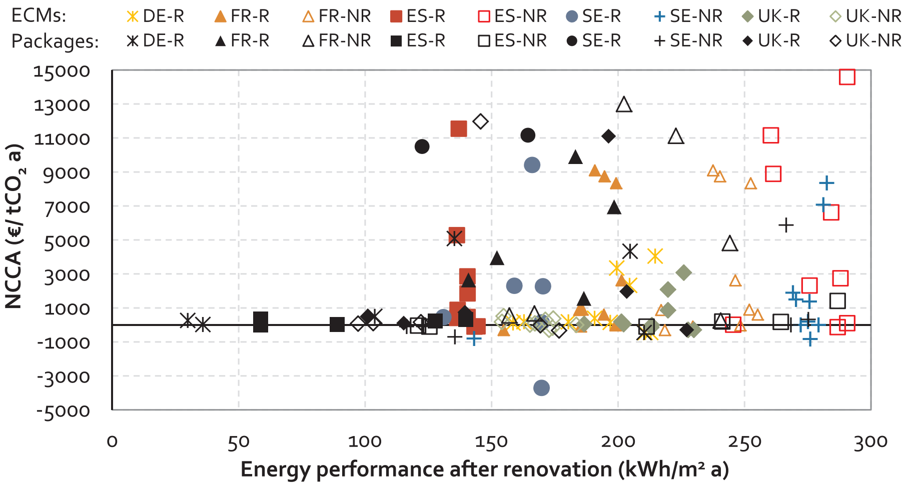

Fig. 7. NCCA (in €/tCO$_2$ avoided per year) as a function of energy performance after renovation (in kWh/m^2 per year), obtained in this study for the different ECMs and packages (P) (DE, Germany; ES, Spain; FR, France; SE, Sweden; UK, United Kingdom). Nine values, falling in the range of 20,000–105,000 €/tCO2, have not been plotted; these are commented upon in the text and highlighted in Table A2.

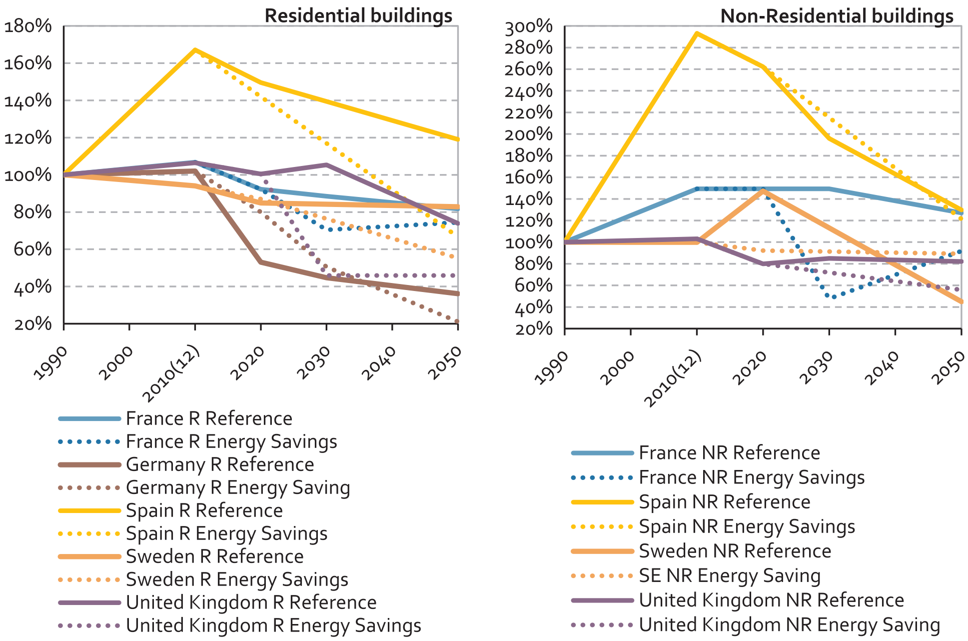

Fig. 8. Evolution of the final energy consumptions of existing Residential (R) and Non-Residential (NR) buildings (in Year 2012) in the selected MS, given as a percentage of the consumption for each country in Year 1990 (from the Eurostat database) for the so-called Reference and Energy Savings projections considered in this study.

cost-effective opportunities as identified above in terms of NCCEs (i.e., upgrade of ventilation ECMs 5, and hot water from solar 8 and packages with different forms of improved insulation P 2, 4 and 6).

For R buildings in the UK, our results for the retrofitting of the different parts of the envelope (ECMs 1–4: 40, 52, 20, and 188 €/tCO$_2$, respectively, cf. Table A2) show an order of magnitude and ranking similar to those published previously [12] (ECMs 1–4: 80, 145, 73, and 1,300 €/tCO$_2$, respectively[11]). For lighting and appliances, there is also agreement on the high cost-efficiency of these ECMs with respect to the CO$_2$ emissions avoided: 295 €/tCO$_2$ and 290 €/tCO$_2$ (our study) versus 320 €/tCO$_2$and 235 €/tCO$_2$ in [12],[12] respectively, for lighting and appliances. For the UK, an Energy Efficiency Marginal Abatement Cost Curve for cost-effective, non-domestic measures [10,69] has estimated that the implementation of all measures shown would result in annual energy savings of 27 TWh by Year 2020. The majority of the potential savings relate to heating energy, whereas the most cost-effective measures involve replacing light fittings and controls, as well as provisions for smart metering.

In summary, the CO$_2$ mitigation cost varies substantially across MS and ECMs, and many ECMs yield abatement costs far higher than 100 €/tCO$_2$, and in some cases, several thousands of €/tCO$_2$. The large span in mitigation cost is due to differences in local conditions such as climate, building characteristics and the carbon intensity of the energy system. Thus, emissions reductions may in many cases not be the main driver for applying ECMs. Instead, other motivating factors, such as reducing energy bills and enhanced security of supply, are in play. In addition, the costs given result from assumptions made as to the different costs for the ECMs and these, also in the future, are subject to variability with the following factors likely to have impacts on real costs: currently prevailing market conditions, economies of scale, the workload of individual contractors (some may increase their prices if they are busy), the negotiations with individual contractors, and discounts secured from material suppliers (varies from contractor to

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[11] These are weighted values of the different solutions assessed in the reference, namely, for floor: Solid and suspended timber floor; for walls: different types of Solid and Cavity Wall; for roof: Loft with different insulation thicknesses and treatability; and for windows: existing windows (Post/ Pre 2002 or Single glazing) to double glazing. The reference also shows how these costs increase when in-use factors are included that reduce energy savings.

[12] These are weighted values of the different solutions assessed in the reference, namely, for lighting: Incandescent light bulb to compact fluorescent light and Halogen to LED. For appliances: A rated tumble dryer; A+ electric ovens and dishwasher; A++ rated Refrigerator, Chest freezer, Fridge freezer and upright freezer; and A+++ washing machine.

contractor, commercial views of profitability levels charged by individual contractors, individual product selection, and specification). In addition, the literature reports that the more ambitious the targets, the slightly higher the costs. Therefore, it is difficult to formulate robust statements from a cost perspective. Furthermore, the sensitivities of these NCCEs and NCCAs to variations in energy prices and interest rates have been studied for France [45], Germany [50], and Sweden [38,68].

4. Discussion of and comparison to projections and targets

Fig. 8 illustrates the potential for energy savings obtained in the present study and compares them to the corresponding national targets. The *reference* evolution of the final energy demand for buildings is plotted for Year 2020 and Year 2030, which are the projections reported by the MS (where available),[13] whereas for Year 2050, all of the cost-effective opportunities obtained in the present study for each MS are plotted. It is assumed that the total cost-effective potential obtained in this study is implemented at a continuous rate until Year 2050. The so-called *energy savings* evolution of the final energy demand of buildings includes targets for Year 2020 that refer to existing buildings alone and that is taken from EED/NEEAPs, when provided.[14] The national targets specified in the NEEAPs have been calculated as totals based on annual data, per R and NR sector separately in the case of final energy, final energy consumption, and CO_2 emissions provided in the Eurostat [59] and Odyssee [70] databases, respectively. As the reductions are compared to projections and, therefore, include new buildings, it is assumed that all new buildings have near-zero energy demand. For Year 2050, the energy savings evolution plots the total technical potential obtained in this study for each MS, again assuming a continuous annual rate of implementation until Year 2050.

Although the actual evolution shortly after Year 2010 is not evident in Fig. 8, the final energy consumption in the French, German and British R buildings sectors increased in Year 2013 compared to Year 2012. In their Annual Reports, this increase was attributed to the colder climate in Germany in Year 2013, whereas France identified an increase in electricity use for both heating appliances and home electronic equipment [13].

For France, the projected evolution of the final energy demand corresponds to what has been reported for the so-called AME scenario (*Avec Mesures Existants*; in English: *With Existing Measures*) [5], which is available for the period 2010–2035. For NR buildings, the AME scenario shows no reductions in energy demand by Year 2035[15] (including new buildings). After Year 2035 and until Year 2050, we have assumed that only the cost-effective measures listed in our study will be implemented. For R buildings, it is apparent from Fig. 8 that the AME projection for Year 2035 is in line with the attainment of the cost-effective potential by Year 2050, whereas the so-called AMS2 scenario (*Avec Mesures Supplémentaires*; in English: *With Supplementary Measures*) has already attained all the technical improvement potential calculated for Year 2035 for both R and NR buildings. For NR buildings in particular, this target appears to be ambitious and decoupled from trends and cost-efficiency levels, whereas for R buildings, 400,000 full renovations (per year) are planned after Year 2013 and until Year 2020 [4]. After Year 2020, the AMS2 scenario for R and NR buildings assumes the implementation of effective financial and informative measures that will boost the installation of insulation and efficient heating systems, in addition to legislative measures that will force extensive energy retrofitting of social dwellings, as well as buildings in need of general repair. Furthermore, the case study assessment [5] shows that the initial investments required for a profitable renovation are generally higher that the budget of residential or non-residential owners (€30,000 for an SFD, €821 to €11,712 per dwelling in a MFD, and €200,000 to €5,889,000 for an NR building).

Thanks to a broad policy approach to incentivize extensive energy renovations, the German energy demand is projected to decrease by 50% [6] by Year 2020. Although the projection for Year 2020 is consistent with attaining the cost-effective potential identified in this paper for Year 2050, the projected savings for Year 2020 extend beyond a 20% reduction, and are far beyond the progress attained to date. The observed rate of decoupling floor areas and energy consumption[16] is, to date, lower than the rate illustrated in Fig. 8. As for the Year 2050 projection, the figure illustrates the goal of the German Federal Government to reach a “nearly climate-neutral” building stock with a non-renewable primary energy demand to condition a building that is 80% lower than that in Year 2008. In particular, depending on the scenario the final energy demand will be 40–70% or 25–45% lower; we have assumed average values for the R and NR buildings, supplied by more than 50% RES. None of these scenarios studied previously [7] would be preferable from the perspective of cost.

For Spanish R and NR buildings, the energy demand in Year 2020 is projected to meet the targets set out in EDD Article 7, i.e., savings on the cumulative final energy consumption for the 2014–2020 period equal to 20% of the total average energy consumption for the period 2010–2012. This target is in line with implementation of the technical improvements obtained in this study by Year 2050, although significant efforts would be required to change the trend in energy demand. It should be noted that for NR buildings, most of the potential for energy savings obtained in the present work is cost-effective and, therefore, the two projections in Fig. 8 appear to be rather similar. As concluded in the national study [8] for NR buildings, the problem does not involve funding the interventions to improve energy efficiency,[17] but rather setting forth the policies that will break down the barriers to action in order for ESCOs to ensure that the most efficient investments are made in these buildings.

For Sweden, Fig. 8 shows the Year 2020 “*Prognosis for the consumption of energy*” in the NEEAP[18] [9] as a reference, which for R buildings is similar to the cost-effective potential calculated in this study. For NR buildings, an increase in the demand for energy by Year 2020 is expected,[19] although it is not explained in the plan. Even for Year 2016 (with respect to Year 2007), small increases are reported for all indicators.[20] The prognosis only includes the savings required by EED Article 5: two authorities[21] own approximately 95% of Swedish public buildings and are assumed to have implemented, by the end of

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[13] Including the energy efficiency obligation schemes (EEOS), which 16 MS plan to embrace, implying that the 1.5% annual end-use energy savings required by Article 7 of the EED will be mainly achieved by the R buildings sector. Most of the MS have chosen to apply the exemptions allowed to achieve the maximum permitted reduction of 25% (with the exceptions of Denmark, Portugal and Sweden), which will reduce the energy savings goals by Year 2020 [13].

[14] The savings may not be provided in terms of final energy consumption, as EDD allows the MS the flexibility for the 20% targets to be also based on primary energy consumption, primary or final energy savings, or energy intensity.

[15] For comparison purposes, Fig. 8 shows for Year 2030 what [5] reports for Year 2035.

[16] The publication [6] reports great progress in reducing the (climate-corrected) space heating consumption per heated floor area in buildings: for private households the demand for Year 2012 was 147 kWh/m^2 a, which is almost 30% lower than the corresponding 205 kWh/m^2 a in the late-1990's. The trend in energy consumption in NR buildings is similar; particularly in the commercial sector, for which renovation rates higher than those for R buildings have been observed.

[17] Since today, at the current price of energy, interventions can be carried out that – in the sector as a whole – can generate totaling savings of between 35% and 50% of the energy consumed [8].

[18] 83 TWh.

[19] Prognosis for Services in Year 2020 is 59 TWh, which is substantially higher than the Year 2010 consumption level of 30.6 TWh (i.e., 17.7 TWh for space and water heating plus 12.9 TWh for electrical purposes) reported in the statistics [71].

[20] Indicator P6: The change in energy consumption (not electricity) in relevant subsidiary sectors, i.e., Public services (public administration and government services), Office premises (Offices), Healthcare (Hospitals), Trade (Wholesale and retail trade services), Hotels and restaurants, and Other, per square meter is − 0.26 TWh. Indicator P7: The change in electricity consumption in relevant subsidiary sectors per square meter is − 0.42 TWh.

[21] The National Property Board of Sweden and the Swedish Fortifications Agency, with a total floor area of 1.59 million square meters and a total energy consumption of 270 GWh.

Year 2020, measures that reduce by at least 21 GWh the energy consumption of buildings. The energy savings illustrated in Fig. 8 are based on the *expected trend for the reference option*[22] in the NEEAP, which assumes that existing instruments continue until Year 2050 and are distributed to R and NR buildings in proportion to their consumption levels in Year 2010. For R buildings, the trend for Year 2050 suggests weaker efficiency improvements than those projected to attain all the technical improvements calculated in this study, whereas for NR buildings, the trend would require more extensive efficiency improvements than those corresponding to the technical projections calculated in the present study. Furthermore, the target is formulated in such a way that energy use per square meter would fall by 20% by Year 2020 and by 50% by Year 2050, in relation to the Year 1995 consumption level.[23] The energy savings in the NEEAP do not meet targets that would imply, for R and NR buildings, respectively, reductions of 12% and 46% in Year 2020 and of 27% and 46% in Year 2050. Consequently, in agreement with the prognosis in the NEEAP and our calculations, it appears that savings might be met by primarily improving the efficiency of R buildings, as only a minor cost-efficient potential was identified for NR buildings.

For the UK, the reference energy demand projection in Year 2020 corresponds to the “estimates of key national energy production and consumption figures in Year 2020 [24] in the NEEAP [10] and in Year 2030, it is assumed to be proportional to the ”energy demand by the final user” projected in [69] for Year 2030.[25] For R buildings, these projections are in line with attaining the cost-effective potential calculated in this study for Year 2050, whereas for NR buildings, these projections are more ambitious and require savings similar to the range of the cost-effective savings projected in this study already by Year 2020. This uneven contribution by sectors is consistent with the estimates for Year 2012 in reference [69]; the need for increased empirical knowledge in the NR sector, in particular where a substantial cost-effective energy saving potential remains to be attained, has also been identified in reference [10]. DECC has also estimated that to meet the Year 2050 goals, a majority of all R buildings in the UK would be required to comply with new building standards. To guide renovation decisions, the rapidly increasing number of EPC assessments is seen as an effective way to increase awareness of the cost-effective packages of ECMs that can be used to achieve the equivalent of this required new building standard.

5. Conclusion

The results of our modeling show that retrofitting different parts of the envelope can reduce the building energy demand by at least 5–10% for all MS and sectors, and by up to 50% if the entire envelope is insulated. Due to the long lifetimes of these ECMs, the window of opportunity and lock-in risk are identified as key issues. The modeling also indicates that the reduction in electricity demand linked to more-efficient lighting and appliances can be offset by the increased demand for space heating, as less heat is released to the indoor air. Although there is significant variability across the MS and sectors, improving ventilation systems could result in average reductions of 14% and 19% for R and NR buildings, respectively, for the MS studied. The different ECMs that can be used for deploying on-site RES each result, on average, in reductions of 2–8% and 2–4%, respectively, for R and NR buildings in the MS studied, albeit with great variability.

Although the associated reductions in CO_2 emissions are generally proportional to the energy saving potentials for the ECMs related to the use of electricity, the potential for reducing CO_2 emissions depends on whether the intensity of the fuel mix used for electricity production is lower than that of the space heating mix. The additional reductions in CO_2 emissions that could be achieved by increasing the deployment of on-site RES have been quantified. The potential for such reductions is substantially higher in the R sector (32%) than in the NR sector (24%) thanks to the higher share in the former of fossil fuel boilers – which could be replaced by biomass – and higher hot water demand – which could be met by solar panels. The total technical energy saving potential for a package of all ECMs investigated in this paper amounts to 30–60% for the various MS.

There are many cost-efficient, and even low-cost ECMs, and the packages generally appear to be the most profitable. Nevertheless, both our results and the data in the literature demonstrate high variability with respect to the cost-efficiencies of the ECMs for the various representative buildings. Finally, the packages investigated lead to highly variable levels of energy performance in the MS and sectors investigated. Significant variability of cost-efficiency levels was also found among the different buildings analyzed, as the renovation should adapt to the existing building materials, technical systems, use and occupancy.

Clearly, there are challenges that need to be overcome before the potentials identified can be realized. The energy savings for Year 2020 projected in the NEEAPs appears to be optimistic when one considers the efficiency trends, current regulatory framework, and techno-economical potential reported in this paper. For Year 2030, the demand for NR buildings is projected to grow in several MS; substantial efforts will therefore be required, beyond the EED requirements for public buildings, in order for the NR sector to be transformed by Year 2050. The scenarios found in the NEEAPs or related national documents seem ambitious: all assume that new buildings will be Near Zero Energy Buildings and will have a high share of RES in the energy system and on-site. Although no clear national commitments have been made for Year 2050, the national reports rely on the belief that many existing policy actions will be effective for unleashing the potentials revealed as profitable.

The NEEAPs still do not fully accomplish the requirements set by the EDD. Many data gaps have been identified on a national level for all the MS (i.e., use of heat recovery, profiles for electricity use, fuel use, cost data for investments), including large differences in how the energy savings are reported and have been calculated in the NEEAPs. The variability of the results shown in this paper with respect to the cost-efficiency of the energy saving and retrofitting measures suggests a need for an individual analysis of each specific building to be renovated. It is also in agreement with the observation made in the NEEAPs that it is vital to understand the EU building stock and its potential, in particular the NR stock, for which the information is admittedly limited. To facilitate the implementation and monitoring of energy savings in existing buildings, the EDD requirements in Article 4 must be more specific in addressing identified information gaps, as well as in linking the various EED elements.

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[22] Table 35 reports total energy consumption: 121–123 TWh in year 2020 and 111–124 TWh in year 2050.

[23] 222 kWh/m^2 and 397 kWh/m^2 for R and NR buildings, respectively, according to Year 1995 data for final energy demand from Eurostat and for the floor areas from Odyssee.

[24] Final energy consumption provided for Households and Services is, respectively, 38.2 Mtoe and 14.3 Mtoe.

[25] The Year 2030 estimates for Domestic and Services and agriculture are 46 Mtoe and 17 Mtoe, respectively [72]. We have assumed that the Year 2020 estimates of final energy consumption reported in the NEEAP [10] refer to existing buildings only, as they are 2.8 Mtoe and 1.7 Mtoe (for R and NR buildings, respectively) lower than the projections given previously [72].

Declaration of interest

I declare no conflict of interest.

Present/permanent address

If an author has moved since the work described in the article was done, or was visiting at the time, a 'Present address' (or 'Permanent address') may be indicated as a footnote to that author's name. The address at which the author actually did the work must be retained as the main, affiliation address. Superscript Arabic numerals are used for such footnotes.

Appendix

See Table A1 and A2

Table A1

NCCE (€/kWh saved per year) values obtained in this study for the ECMs and Packages (P) for R and NR buildings in the five MS studied. The values shown are the weighted averages of the results obtained for the different representative buildings modeled for each MS and sector. Values > 4 €/kWh – marked with an asterisk– have not been included in Fig. 4.

	France		Germany	Spain		Sweden		United Kingdom	
ECM no.	R	NR	R	R	NR	R	NR	R	NR
ECM 1	− 0.01	0.15	0.04	0.28	1.09	0.25	0.11	0.03	0.00
ECM 2	− 0.03	0.27	0.05	− 0.05	− 0.07	0.32	0.14	0.01	0.11
ECM 3	0.84	1.28	0.05	0.00	− 0.06	0.10	0.02	0.01	0.00
ECM 4	1.00	0.23	0.11	− 0.04	− 0.07	0.02	0.10	0.04	0.04
ECM 5	0.09	− 0.07	0.03	0.50	2.42	− 0.01	− 0.06	0.35	0.00
ECM 6	1.03	− 0.06	− 0.62	0.02	0.01	1.69	0.03	− 0.69	− 0.31
ECM 7	3.94	1.79	− 0.64	− 0.11	− 0.10	6.73*	0.43	− 0.93	0.00
ECM 8	0.12	0.12	0.76	0.58	2.14	− 0.06	− 0.07	− 0.03	− 0.05
ECM 9	− 0.23	0.70	0.00	1.45	1.93	− 0.01	1.12	0.17	0.07
ECM 10	0.15	0.59	0.76	0.19	3.58	0.001	1.28	1.79	0.07
P 1	1.00	1.83	0.14	0.00	− 0.05	1.00	0.51	0.32	0.03
P 2	5.16 *	1.69	1.25	0.86	0.10	0.20	− 0.05	1.86	3.01
P 3	3.22	0.96	− 0.64	0.46	0.17	5.30	0.32	− 1.10	− 0.22
P 4	0.37	0.06	0.01	0.01	− 0.07	0.70	− 0.01	0.04	0.03
P 5	0.16	0.18	1.60	0.69	12.67*	0.30	0.06	0.47	0.06
P 6	0.35	0.08	0.08	0.15	− 0.02	0.60	− 0.01	0.14	0.03

Table A2

NCCA (€/tCO$_2$-avoided/yr) obtained in this study for the ECMs and Packages (P) for R and NR buildings in the five MS studied. The values shown are the weighted averages of the results obtained for the different representative buildings modeled for each MS and sector. Values > 20,000 €/tCO$_2$ – marked with an asterisk – have not been included in Fig. 7. n.a., Not applicable due to the ECM or package not reducing the CO$_2$ emissions.

	France		Germany	Spain		Sweden		United Kingdom	
ECM no	R	NR	R	R	NR	R	NR	R	NR
ECM 1	− 100	1000	145	11000	8000	20000*	1250	40	10
ECM 2	− 305	1750	185	885	2250	25000*	1750	50	515
ECM 3	9000	8000	175	5000	11000	9000	190	− 20	− 5
ECM 4	8000	1500	385	2800	6000	2300	1250	185	180
ECM 5	875	− 550	105	92000*	40000*	455	− 800	3000	295
ECM 6	2500	− 1000	− 450	− 95	10	2250	n.a.	− 290	− 285
ECM 7	8000	18000	− 450	− 80	− 125	20000*	n.a.	− 294	n.a.
ECM 8	895	850	2250	405	2750	105000*	− 830	− 152	− 165
ECM 9	− 30	165	4000	465	100	− 3700	7000	857	85
ECM 10	600	2500	3300	1855	14000	145	8000	2000	375
P 1	9000	11000	495	15	− 100	35000	5000	735	155
P 2	50000*	12000	5000	17000	175	10000	− 700	11000	11000
P 3	6000	4750	− 450	320	195	105000*	n.a.	− 290	− 330
P 4	3900	670	20	− 15	− 100	40000*	− 90	105	100
P 5	1500	250	4300	245	1410	11000	320	1750	− 20
P 6	2600	550	255	330	− 40	35000*	− 95	495	70

References

[1] Saheb Y, Bódis K, Szabó S, Ossenbrink H, Panev S. Energy renovation: the Trump card for the new start for Europe [editor]. JRC European Commission, Institute for Energy and Transport; 2015.

[2] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union, 18(06); 2010.

[3] Directive/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32. Official Journal, L, 315, 1-56; 2012.

[4] Transposition de l'article 4 de la directive 2012/27/UE Stratégie à long terme pour mobiliser les investissements dans la rénovation du parc national de bâtiments à

usage résidentiel et commercial, public et privé. Ministère de l'écologie, du développement durable et de l'énergie (MEDDE), Ministère du Logement et de l'Égalité des Territoires (MLET); 2014.
[5] Scenarios prospectifs Energie – Climat – Air pour la France à l'horizon 2035, Ministère de l'écologie, du développement durable et de l'énergie (MEDDE); 2015.
[6] Report on the long-term strategy for mobilising investment in the renovation of the national building stock pursuant to Article 4 of the Energy Efficiency Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012. Government of the Federal Republic of Germany to the Commission of the European Union of 16 April 2014; 2014.
[7] Bürger V, Hesse T, Quack D, Palzer A, Köhler B, Herkel S, et al. Climate change 06/2016 Klimaneutraler Gebäudebestand 2050. Freiburg, Germany: Öko-Institut and Fraunhofer Institut, for the German Environment Agency (UBA); 2016.
[8] Long-term strategy for energy renovation in the building sector in Spain pursuant to article 4 of Directive 2012/27/UE. Ministerio de Fomento; 2014.
[9] Annex 3 in: Sweden's Third National Energy Efficiency Action Plan, Annex to Government Decision 24 April 2014; 2014.
[10] Annex B and D in: UK National Energy Efficiency Action Plan, April 2014. Department of Energy and Climate Change (DECC); 2014.
[11] Cuchí A, Sweatman P, Informe GTR. Estrategia para la rehabilitación: claves para transformar el sector de la edificación en España. Rehabilitation Working Group GTR; 2014. [, editor; 2014].
[12] Review of potential for carbon savings from residential energy efficiency, Final report for The Committee on Climate Change, Element Energy & Energy Saving Trust (EE-EST); 2013.
[13] EC, Assessment of the progress made by Member States towards the national energy efficiency targets for 2020 and towards the implementation of the Energy Efficiency Directive 2012/27/EU as required by Article 24 (3) of Energy Efficiency Directive 2012/27/EU, COM(2015) 574 final, Brussels, Belgium; 2015a.
[14] IWU. Typology Approach for Building Stock Energy Assessment: Main Results of the TABULA project – Final Project Report (Deriverable D2). TABULA Project Team October 2012, Institut Wohnen und Umwelt GmbH (IWU), Darmstadt, Germany; 2012.
[15] IWU. Scenario Analyses Concerning Energy Efficiency and Climate Protection in Local Residential Building Stocks Examples from Eight European Countries - EPISCOPE Synthesis Report No. 2 - (Deliverable D3.4). Institut Wohnen und Umwelt (IWU), Darmstadt, Germany; 2016.
[16] IWU. Scenario Analyses Concerning Energy Efficiency and Climate Protection in Regional and National Residential Building Stocks Examples from Nine European Countries - EPISCOPE Synthesis Report No. 3 - (Deliverable D3.5). Institut Wohnen und Umwelt (IWU), Darmstadt, Germany; 2016.
[17] IEA. Transition to Sustainable Buildings – Strategies and Opportunities to 2050, International Energy Agency (IEA); 2013.
[18] Lucon O, Ürge-Vorsatz D, Zain Ahmed A, Akbari H, Bertoldi P, Cabeza LF, et al. Buildings. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, editors. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge (United Kingdom) and New York (USA): Cambridge University Press; 2014. p. 671–738.
[19] Petersdorff C, Boermans T, Harnisch J. Mitigation of CO_2 emissions from the EU-15 building stock – beyond the EU directive on the energy performance of buildings. Environ Sci Pollut Res 2006;13:350–8.
[20] Nemry F, Uihlein A, Makishi Colodel C, Wetzel C, Braune A, Wittstock B, et al. Options to reduce the environmental impacts of residential buildings in the European Union—potential and costs. Energy Build 2010;42:976–84.
[21] ECOFYS, Estudio sobre el ahorro energético en edificios en España; 2005. ⟨http://www.rehabilita.es/fotos/100104092508_hwWE.pdf⟩ [accessed 16 November 2009].
[22] Balaras CA, Gaglia AG, Georgopoulou E, Mirasgedis S, Sarafidis Y, Lalas DP. European residential buildings and empirical assessment of the Hellenic building stock, energy consumption, emissions and potential energy savings. Build Environ 2007;42:1298–314.
[23] Sweatman P, Cuchí A. GTR'S 2012 report: a national perspective on Spain's building sector: action plan for a new housing sector. Rehabilitation Working Group GTR; 2012.
[24] Tommerup H, Svendsen S. Energy savings in Danish residential building stock. Energy Build 2006;38:618–26.
[25] Clinch JP, Healy JD, King C. Modelling improvements in domestic energy efficiency. Environ Model Softw 2001;16(1):87–106.
[26] Ardente F, Beccali M, Cellura M, Mistretta M. Energy and environmental benefits in public buildings as a result of retrofit actions. Renew Sustain Energy Rev 2011;15:460–70.
[27] Clarke J, Johnstone CM, Kondratenko I, Lever M, McElroy LB, Prazeres L, et al. Using simulation to formulate domestic sector upgrading strategies for Scotland. Energy Build 2004;36:759–70.
[28] Ortiz O, Bonnet C, Bruno JC, Castells F. Sustainability based on LCM of residential dwellings: a case study in Catalonia, Spain. Build Environ 2009;44:584–94.
[29] Propuesta de revisión del código técnico de la edificación: sección HE 1 Limitación de demanda energética; 2009. ⟨http://www.andimat.es/wp-content/uploads/propuesta-de-revision-del-cte-seccion-he1-limitacion-de-la-demanda-energetica.pdf⟩ [accessed 16 November 2009].
[30] Potencial de ahorro energético y de reducción de emisiones de CO2 del parque residencial existente en España en 2020. Madrid, España: WWF/Adena; 2010.
[31] Papadopoulos AM, Theodosiou TG, Karatzas KD. Feasibility of energy saving renovation measures in urban buildings: the impact of energy prices and the acceptable pay back time criterion. Energy Build 2002;34:455–66.
[32] Tsikaloudaki K, Laskos K, Bikas D. On the establishment of climatic zones in Europe with regard to the energy performance of buildings. Energies 2012;5:32–44.
[33] Ciscar JC, Iglesias A, Feyen L, Goodess CM, Szabo L, Christensen OB, et al. Climate change impacts in Europe. Final report of the PESETA research project. Seville, Spain: JRC; 2009.
[34] Mata É, Sasic Kalagasidis A, Johnsson F. A modelling strategy for energy, carbon, and cost assessments of building stocks. Energy Build 2013;56:100–8.
[35] Mata É, Sasic Kalagasidis A, Johnsson F. Building-stock aggregation through archetype buildings: France, Germany, Spain and the UK. Build Environ 2014;81:270–82.
[36] Mata É, Sasic Kalagasidis A, Johnsson F. Energy usage and technical potential for energy saving measures in the Swedish residential building stock. Energy Policy 2013;55:404–14.
[37] Grundsell J. Bottom-up characterization of the Swedish non-residential building stock – archetype buildings and energy demand (M.Sc. Thesis). Gothenburg, Sweden: Chalmers University of Technology; 2013.
[38] Mata É, Sasic Kalagasidis A, Johnsson F. Cost-effective retrofitting of Swedish residential buildings: effects of energy price developments and discount rates. Energy Effic 2015;8:223–37.
[39] Décret n°2006-592 du 24 mai relatif aux caractéristiques thermiques et à la performance énergétique des constructions; 2006.
[40] Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden (Energieeinsparverordnung – EnEV); 2009.
[41] Real Decreto 314/ de 17 de marzo, por el que se aprueba el Código Técnico de la Edificación (CTE); 2006.
[42] Conservation of fuel and power, Approved Document L. Department for Communities and Local Government; 2010.
[43] Boverket. Så mår Våra Hus. Redovisning av Regeringsuppdrag Beträffande Byggnaders Tekniska Utformning m.m.(in Swedish). Karlskrona, Sweden; 2009.
[44] Arrêté du 20 juillet 2011 portant approbation de la méthode de calcul Th-B-C-E; 2011.
[45] Dinh TC, Lundevall H. Energy efficiency potential of the european building stock (M.Sc. thesis). Gothenburg, Sweden: Chalmers University of Technology; 2012.
[46] Asociación Nacional de Industriales de Materiales Aislantes (ANDIMA), IDAE. Guía Práctica de la energía para la rehabilitación de edificios. Spain: Instituto para la Diversificación y Ahorro de la Energía (IDAE); 2008.
[47] EN 15459 Energy performance of buildings—economic evaluation procedure for energy systems in buildings; 2007.
[48] Guide prix indicatifs et critères de choix - EQTOR II – 2011. ANAH; 2011.
[49] Liste de prix, ventilateur récupérateurs de chaleur. Powrmatic; 2012.
[50] Tillman G. Energy efficiency potential of the European building stock: case study for Germany (M.Sc. Thesis). Gothenburg, Sweden: Chalmers University of Technology; 2013.
[51] Mata É, Sasic Kalagasidis A, Johnsson F. Modelling opportunities and costs associated with energy conservation in the Spanish building stock. Energy Build 2015;88:347–60.
[52] CLG. Implementation Stage Impact Assessment of Revisions to Parts F and L of the Building Regulations from 2010. London: Communities and Local Government (CLG).⟨http://webarchive.nationalarchives.gov.uk/20120919132719/http://www.communities.gov.uk/documents/planningandbuilding/pdf/1531558.pdf⟩ [accessed 16 November 2009].
[53] Statistics and prospects for the European electricity sector (1980–2000, 2004, 2005, 2010–2030). Brussels: Eurelectric; 2007. ⟨http://www.eurelectric.org/⟩ [accessed 16 November 2009].
[54] Arrêté du 15 septembre 2006 relatif au diagnostic de performance énergétique pour les bâtiments existants proposés à la vente en France métropolitaine; 2006.
[55] GEMIS (Globales Emissions-Modell integrierter Systeme) Database. International Institute for Sustainabily Analyisis and Strategy (IINAS); 2012.
[56] Coeficientes de paso desde energía final a emisiones de CO2. Capítulo VI anexos Condiciones de aceptación de Procedimientos alternativos a LIDER y CALENER. Madrid: Ministerio de Industria, Turismo y Comercio; 2009.
[57] BNXS01: Carbon Dioxide Emission Factors for UK Energy Use. Defra's Market Transformation Programme (MTP); 2010.
[58] Guidelines to Defra/DECC's GHG Conversion Factors for Company Reporting. London: Department for Environment, Food and Rural Affairs and Department for Energy and Climate Change (DECC); 2011.
[59] Eurostat Database. Brussels, Belgium: European Commission; 2015.
[60] Informe de precios energéticos regulados: carburantes y combustibles Año 2011. Ministerio de Industria, Energía y Turismo, Instituto para la Diversificación y el Ahorro de la Energía; 2012.
[61] Energy price statistics. Department of Energy and Climate Change (DECC); 2012.
[62] The Government's Standard Assessment Procedure for Energy Rating of Dwellings. Garston, Watford: Published on behalf of DECC by BRE; 2013.
[63] ILES P. J Standard Dwellings For Energy Modelling, Centre for Technology Statistics and Assessment, Department of the Environment Transport and the Regions; 1999.
[64] Ürge-Vorsatz D, Novikova A, Köppel S, et al. Bottom–up assessment of potentials and costs of CO 2 emission mitigation in the buildings sector: insights into the missing elements. Energy Effic 2009;2(4):293–316.
[65] Promjiraprawat K, Winyuchakrit P, Limmeechokchai B, Masui T, Hanaoka T, Matsuoka Y. CO_2 mitigation potential and marginal abatement costs in Thai residential and building sectors. Energy Build 2014;80:631–9.
[66] Timilsina GR, Sikharulidze A, Karapoghosyan E, Shatvoryan S. Development of marginal abatement cost curves for the building sector in Armenia and Georgia. Energy Policy 2017;108:29–43.
[67] Rysanek and and Choudhary R. Using building simulation to create marginal Abatemetn Cost Curves for individual buildings; Proceedings of the 13th

Conference of International Building Performance Simulation Association, Chambéry, France, August 26–28; 2013.

[68] Mata É, Johnsson F. Cost-effectiveness of retrofitting Swedish buildings. In: Pacheco Torgal F, Granqvist C, Jelle B, Vanoli G, Bianco N, Kurnitski J, editors. Cost-effective Energy Efficient Building Retrofitting, 12. Elsevier; 2017. p. 343–62.

[69] The Energy Efficiency Strategy: The Energy Efficiency Opportunity in the UK, Department of Energy and Climate Change (DECC); 2012.

[70] ODYSSEE Database European Energy Efficiency Indicators. Grenoble, France: Enerdata; 2015.

[71] Energy statistics for non-residential premises 2010 Eskilstuna, Sweden: Energimyndigheten; 2011.

[72] Updated energy and emissions projections 2013. Department of Energy and Climate Change (DECC); 2013.