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A comprehensive indicator set for measuring multiple benefits of energy efficiency

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ABSTRACT

In this paper, we develop a quantitative indicator approach including 20 indicators to measure the multiple benefits of energy efficiency (MB-EE). The MB-EEs are classified into three groups: environmental (e.g. energy savings, emissions), economic (e.g. GDP, employment), and social (health, energy poverty) aspects. We explain the methodological approach, the underlying data sources and limitations. The indicator set has been applied to 29 countries (EU28 plus Norway) for the period 2000 to 2015, proving that it allows to conduct in-depth comparisons of developments and differences across Europe. The indicator set also supports the design of well-suited energy policies by allowing to take into account, on an informed basis, more of the multiple impacts of energy efficiency.

For example, our analysis of the effect of energy savings for the period 2000 to 2015 in Germany shows GHG savings of about 158 MtCO2eq., about 30,000 avoided deaths due to less air pollution, a reduction of Germany's import dependency by 5.8 percentage points and a growth of GDP by around 0.3% per year for the period 2010 to 2015) as a consequence of improved energy efficiency. To conclude, the presented approach allows to comprehensively and regularly assess policies in terms of their MB-EEs.

1. Introduction

Energy efficiency (EE) is considered as essential for the achievement of all major objectives of climate and energy policies and was coined as the "first fuel" in the EU 2030 climate and energy policy framework (Saheb and Ossenbrink, 2015) and by the International Energy Agency (IEA, 2013). EE is one of the five core dimensions of the Energy Union, next to energy security, solidarity and trust; the internal energy market; decarbonisation of the economy; and research, innovation and competitiveness (European Commission, 2014b). Today, a significant share of the EE options are not (or not enough) cost-effective from an investor perspective when only energy savings are accounted as benefits, while policy makers frequently justify energy efficiency measures by pointing to co-benefits. Co-benefits of energy efficiency like the reduction of emissions, enhanced competitiveness, health and economic benefits can be significantly higher than the cost of energy measures (Zhang et al., 2016). Counteracting effects such as additional material consumption for energy-efficient equipment are not considered, for example, because the approach presented does not include such upstream chains. However, other effects such as reduced tax revenues or job losses are (partly) considered in our approach.

The environmental and health benefits of efficiently using primary and final energy have repeatedly been studied (Maidment et al., 2014; Howden-Chapman, 2015; Mudarri and Fisk, 2007; Ringel et al., 2016; Willand et al., 2015). Also, the economic impacts have been well studied over the last years. More recently, a rapidly increasing number of studies has been dealing with social impacts of EE, e.g. effects on living conditions (Ugarte et al., 2016; Schleich, 2019). To unify these different aspects and ensure a more holistic view on the benefits of EE in a single framework, Ryan and Campbell (Ryan and Campbell, 2012) presented the Multiple Benefits (MB) approach, which was further refined by the IEA (IEA, 2014). Ürge-Vorsatz et al. (2016) proposed several methods

Abbreviations: MB-EE, Multiple benefits of energy efficiency; EE, Energy Efficiency; RES, Renewable Energy Sources; BU, bottom-up; TD, Top-down.

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Table 1
Set of indicators for the quantification of multiple benefits of energy efficiency.

Category	Nb	Sub-category	Indicator	Q*
Environmental		***Energy/Resource Management***		
	1	Energy savings	Annual energy savings (top-down/bottom-up)	A
	2	Savings of fossil fuels	Annual fossil fuels saved due to EE	A
	3	Impacts on RES targets	Lowering of RES targets due to EE	A
		Global and Local Pollutants		
	4	GHG savings	Annual CO_2 savings linked to energy savings	A
	5	Local air pollution	Avoided local pollutants from PM2.5, PM10, NOx (incl. from electricity/heat generation)	B
Social		***Energy Poverty***		
	6	Alleviation of energy poverty	Reduction of energy cost shares in disposable incomes as a consequence of energy savings	C
		Quality of life		
	7	Health and well-being	Externalities linked to health impacts	C
	8	Disposable household income	Changes in energy cost share in disposable HH income due to EE	B
Economic		***Innovation/Competitiveness***		
	9	Innovation impacts	Revealed Patent Advantage (RPA)	A
	10	Competitiveness	Revealed Comparative Advantage (RCA)	B
	11	Turnover of EE goods	Investments linked to energy savings	C
		Macro-economic		
	12	Impact on GDP	Impacts of Energy savings on GDP growth	B
	13	Employment effects	Additional FTE linked to energy savings	B
	14	Potential impact on energy prices	Lower energy prices based on price elasticities	B
	15	Impact on public budgets	Additional income tax revenue from employment based on energy savings	B
		Micro-economic		
	16	(Industrial) productivity	Change of productivity due to lowered cost	C
	17	Asset value	Change in asset value of commercial buildings due to EE benefits	C
		Energy Security /Energy Delivery		
	18	Energy security 1	Lower import dependency	A
	19	Energy security 2	Larger supplier diversity (Herfindahl-Hirschmann-Index)	A
	20	Impact on integration of RES	Demand response potential by country	C

Abbreviations: Q* = Indicator quality (see Chapter 5); EE = Energy Efficiency; RES = Renewable Energy Sources; GHG: Greenhouse Gases; PM = Particulate Matter; FTE = full-time equivalents; HH = Households.

for the quantification of multiple benefits or 'multiple impacts' of EE in a green economy context developed as part of the COMBI project (Thema et al., 2019; COMBI, 2018). Some of these methods incorporate more qualitative indicators, which can be more prone to subjective views than quantitative indicators.

While the studies referred to have generated conceptually valid approaches, the availability of data strongly determines their applicability and hence their usefulness for practical use. This calls for broadly accepted definitions for concrete quantitative indicators, allowing to assess the total (co-)benefits and their components, to monitor trends over time as well as to make comparisons across countries or regions, with the ultimate objective of contributing to the design of future effective energy policies. An example for the latter is the monitoring system set up to track the progress of energy system transformation in Germany on the basis of a (small) subset of such indicators (BMWi, 2019). In general, knowledge about the benefits in quantitative terms is scattered and not easily accessible for actors in the policy field.

Against this background, it is the objective of our paper to develop a set of indicators that present different aspects of energy savings in a comparable and comprehensive way. The methods should be simple to apply and, if possible, based on data that is easy to obtain, to build a comprehensive toolbox on MB-EE (Reuter et al., 2017a). We henceforth refer to MB as both the direct benefits of EE such as energy savings as well as co-benefits such as economic or social impacts.

The present paper builds on EE indicator analysis of the European countries based on decomposition analysis, as developed within the EU Horizon 2020 project ODYSSEE-MURE (ODYSSEE-MURE, 2019), where partners from more than 30 European countries gather information on EE trends and policy impacts.

In section 2 and 3 we set out the general methodology for the indicator approach to MB-EE, discuss the different indicators, including limitations and data availability (the indicator set was defined with the objective of applying it to all European countries). Section 4 presents, given space limitations, results for the indicator set, focussing on Germany, having a good coverage for the indicators. In section 5 we discuss the indicator approach in a cross-cutting manner, comparing it with alternative methods to determine MB-EE and we draw conclusions.

2. Methodology

For our approach, we designed a set consisting of 20 indicators, which allows examining the most important MB-EE. The selection of the indicators is based on a trade-off between comprehensiveness and practicality in view of data availability and the complexity of modelling. Thus, we have chosen the indicators in such a way that they can shed adequate light on as many of the aspects as possible without, however, requiring great efforts in terms of data collection and very elaborate methods and/or modelling. Some aspects, e.g. the effects of noise on health, would require a spatially and temporally differentiated analysis of the noise sources and the affected humans, which is beyond the scope of the present paper not only in terms of data collection but also with regard to modelling of the ultimate health impacts. Furthermore, the link with energy efficiency is rather indirect (since traffic is the most likely to play a role here and primarily activity reduction would lead to lower noise pollution, which cannot be easily matched with energy efficiency improvement).

In order to preserve the character of the simple applicability of our indicator set, we do not include such and similar indicators. The goal of our approach is a set of easy-to-use indicators that allow the user to estimate the multiple benefits of energy savings without having to resort to time and data-intensive models. We also consider ready availability of the required data. Thus, the indicator set may evolve to cover further aspects as data availability improves in future.

As displayed in Table 1, these indicators are grouped into three main

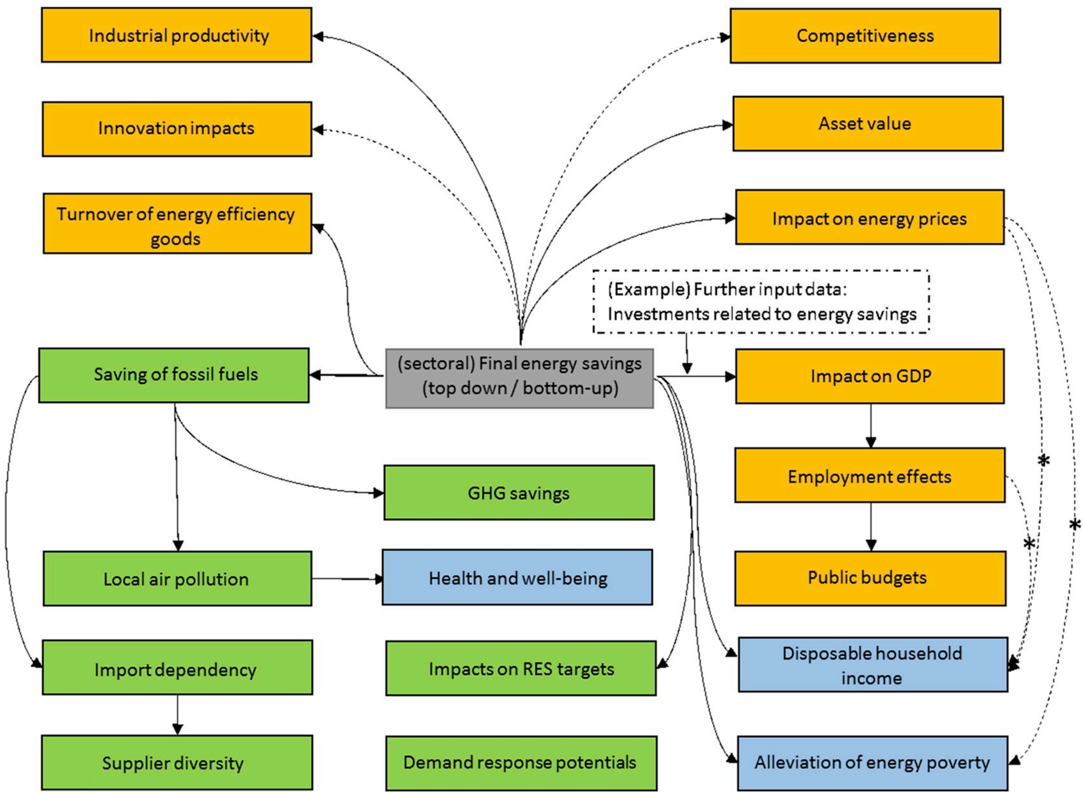

Fig. 1. Overview of multiple benefits of energy efficiency and their interconnections (environmental: green, economic: orange, social: blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

categories: environmental, social and economic and eight sub-categories[1]:

- *Environmental impacts* include the direct effects of EE on primary/final energy consumption, the mitigation of Greenhouse Gases (GHG) and other (local) emissions. Primary energy consumption and the related emissions are also directly related to the penetration of electricity and heat generation from renewable energy sources (Reuter et al., 2017b).
- *Social impacts* are defined as direct effects of EE on energy poverty alleviation, health and well-being (including improved living comfort) and disposable household income.
- *Economic impacts* comprise EE impacts on economic growth, employment, competitiveness and energy security.

We consider the time period from 2000 to 2015 as these years are strongly impacted by the Energy Efficiency Directive (EED) and the national policy measures including those which the EED has triggered in the EU Member states since 2007.

2.1. The basis indicator of energy savings

Important starting points to establish MB-EE indicators on an annual basis are the annual energy savings calculated from the ODYSSEE database,[2] which is a compilation of statistical EE indicators (top-down savings), and the MURE database,[3] which consists of around 2400 EE measures in Europe and their impacts derived from individual evaluations (bottom-up savings). Fig. 1 shows the relationships of indicators starting from final energy savings.

Dashed arrows indicate that there is no direct relationship with the central indicator of final energy savings. This is the case for the indicators on innovation and competitiveness, or for demand response potentials. For some other indicators linked with dashed arrows and marked with an asterisk, such as energy prices and employment, there are second order impacts on other indicators, which are not within the scope of our analysis. Such interconnections of second or higher order, i.e. connected through feedback loops, could be found for many other indicators, but would require extensive modelling, which would not be compatible with the character of our indicator approach.

To determine the values of the selected indicators we use we use both top-down and bottom-up energy savings as they provide different but equally interesting perspectives:

- The top-down savings from the ODYSSEE database are derived from statistics and calculated based on the unit consumption (energy consumption divided by physical or monetary activity level, for up to 30 sub-sectors or 9 end-uses). Top-down savings include also so-called autonomous energy savings, i.e. energy savings, which are not related to changes in the price of energy or energy efficiency policies, and savings from EE policies undertaken before the period

[1] This categorisation - especially economic and social - is not fully distinct due to interlinkages between aspects. Some indicators like disposable household income could also be labelled as economic while being directly related to well-being and are therefore categorised as social aspects. As we are only considering effects individually and do not aggregate indicators or categories, our categorisation should not raise concern about double counting.

[2] https://www.indicators.odyssee-mure.eu/.

[3] https://www.measures.odyssee-mure.eu/.

Table 2
Overview of environmental MB-EE indicators.

Purpose and Definition of the Indicator	Calculation Approach/Formula
(1) Final energy savings (either top-down or bottom-up) [a]	Derived from the ODEX developed in the ODYSSEE-MURE project (top-down) and/or detailed policy evaluations (bottom-up; both types of savings are included when available for a country). These energy savings are calculated for all final demand sectors (households, industry, services and transport).
(2) Saving of fossil fuels: measures the impact of final energy savings on the reduction of the consumption of fossil fuels. For each sector, the total final savings are allocated to the various types of fuel (oil, coal and gas) according to the breakdown of fuel consumption in each sector (data based on the ODYSSEE database).	Fossil fuel savings are expressed as savings compared to 2000 and are calculated according to the following formula: $ES_{fossil,j} = \sum_i ES_{final,i} * \frac{FEC_{ij}}{FEC}$ *ES* represents energy savings from fossil energy carrier j and FEC_{ij}/FEC is the final energy consumption share of energy carrier *j* in sector *i* (households, industry, services, transport) relative to total final energy consumption *FEC*.
(3) Impact of EE on RES target achievement: energy savings allow to reach RES targets more easily, i.e. the share of RES in (gross) final energy consumption, as set in Directive 2009/28 for 2020. The RES share is calculated as ratio between final RES consumption and total gross final energy consumption. The actual values are published by Eurostat Datatables (2019).	The share of RES without energy savings (as a total of all final demand sectors) is calculated by dividing the final consumption of RES (from Eurostat) by the total final consumption without energy savings (final consumption plus energy savings). The difference between the "actual RES share" (given by Eurostat) and the "RES share without energy savings" represents the effect of energy efficiency on the RES target.
(4) Avoided CO_2 emissions from energy savings: measures the impact of energy savings on the reduction of CO_2 emissions. CO_2 savings are calculated by multiplying the total energy savings by sector by the average emission factor *emf* of the sector (tCO_2/toe). *emf* is calculated by dividing the total CO_2 emissions of the sector (including the indirect CO_2 emissions from the power sector and heat production) by its final energy consumption, both data originate from the ODYSSEE database.	CO_2 savings are expressed in relation to the year 2000. They are calculated using the following formula: $EM_i = \sum_j ES_{final,i} * \frac{FEC_{ij}}{FEC} * emf_j$ where the *EMi* represents the CO_2-emissions of sector *i*, which are calculated from the energy savings ES for sector *i* multiplied with the share of energy carrier *j* in sector *i* (households, industry, services, transport) multiplied by the average emission factor *emf* for the energy carrier *j*. The emissions are given in Megatonnes of CO_2 [$MtCO_2$].
(5) Local air pollution: measures local emissions avoided due to energy savings. Based on a typical break-down of energy savings by energy source, we calculate avoided local pollutants (NO_x, SO_x, particulates PM2.5 and PM10, as well as CO), which come mostly from local sources, such as transport or industry, using end-use and fuel specific emission factors. The values are determined by combining data from the ODYSSEE-MURE project with national emission factors as for example published by the European Environment Agency (EEA) (EEA, 2016). Avoided emissions of air pollutants are calculated by multiplying energy savings expressed in primary terms (using country specific factors to calculate the primary energy from final energy savings) by the average emission factor *emf* of the country, for each type of pollutant, per unit of final energy consumed.	The emission factor *emf* is calculated by dividing the total emissions of each local pollutant of the country ("national total emissions for the entire territory based on fuels sold", data from EEA's data viewer on air pollutants emissions (EEA, 2016) by the primary energy consumption from the ODYSSEE database. The emissions E_k per capita of pollutant *k* are calculated using the following formula: $E_k = \frac{\sum_j ES_j * emf_{jk}}{pop}$ ES_j represents energy saving per energy carrier *j*; $emfj_k$ the emission factor for energy carrier *j* (gas, oil, coal and electricity) and pollutant *k*; pop refers to the population. Local emissions are given in kilotons [kt] and as a relative value in kilogram per capita [kg/cap] and they are calculated for the sum of all sector and on a national level (i.e. no spatial analysis is performed). In order to put these values into perspective, the calculated emissions are related to the population of the respective country.

Notes.
[a] Energy savings can be expressed as top-down or bottom-up savings (see 2.1).

under consideration. These savings also bring about Multiple Benefits and should therefore be considered. They are derived from the ODEX,[4] an indicator that measures progress in physical energy efficiency by sector (ODYSSEE-MURE). For each sector, this index is calculated as a weighted average of sub-sectoral indices on energy efficiency. Such sub-sectors are branches of the sectors industry (e.g. chemicals and petro-chemicals, primary metals etc.) or services (e.g. wholesale and retail trade or hospitality), end-uses in households (e. g. space heating) or modes of transport (e.g. road transport).

- The bottom-up savings provided by the MURE database originate from policy evaluation studies on a national level and National Energy Efficiency Plans (NEEAP) as well as so-called Article 7 notifications published by each EU Member State related to EE obligations, as specified by the EED (European Commission). To calculate annual energy savings from the measures available in MURE, the available data by reference year are interpolated linearly per country and sector from the year 2000 onwards. The savings from cross-cutting measures are divided between sectors in proportion to the share of each sector in the country's total final energy consumption.

In the following, we describe for each main group the indicators derived from energy savings as well as the ones not directly linked to energy savings.

2.2. Environmental benefits of energy efficiency

The environmental effects of EE are mostly evident and well researched. For example, reduction of the impact of climate change is one of key drivers for the implementation of EE measures. In addition, we consider in this category the contribution to the attainability of RES targets and the benefits of avoided air pollution (see definitions, data sources and calculation formulae in Table 2).

2.3. Social benefits of energy efficiency

EE can have a range of social benefits to households, e.g. effects on disposable household income and, derived from this, the alleviation of energy poverty, as well as the positive effects on the health of residents (see Table 3).

2.4. Economic multiple benefits of energy efficiency

The economic effects linked to investments play a major role in the evaluation of energy efficiency policies, because these are usually designed and developed with cost-effectiveness in mind to keep their

[4] ODEX is the index used in the ODYSSEE-MURE project to measure the energy efficiency progress by main sector and for the whole economy. Further information is available online: https://www.odyssee-mure.eu/publications/other/odex-indicators-database-definition.html.

Table 3
Overview of social MB-EE indicators.

Purpose and Definition of the Indicator	Calculation Approach/Formula
(6) Alleviation of energy poverty: Tackling energy poverty is explicitly stated as a policy objective in the European Commission's Communication on the Energy Union Package (European Commission, 2015) [d]. We represent this benefit with an indicator measuring the impact of energy savings on the share of energy costs in disposable household income, as this is a commonly used definition.	In order to determine the effect of energy efficiency on the financial situation of low-income households, we consider the impact of energy costs saved through EE on the disposable income of households in the first income decile (e.g. below an average of 8,000€ p.a. of household income for the EU28 as a whole in 2015 (Eurostat, 2018)). $\Delta INC_{E,D1} = [INC^{0}_{E,D1}] - [INC^{1}_{E,D1}] = INC^{0}_{E,D1} - [INC^{0}_{E,D1} + (ec * \overline{ES_{HH}})]$ Where $INC_{E,D1}$ represents the share of energy cost in the disposable income of a household of the first income decile (lowest 10%) in the country considered, ec the is cost per energy unit and $\overline{ES_{HH}}$ the average energy savings per household. $\Delta INC_{E,\ D1}\ /INC_{E,\ D1}$ provides the change of the share of energy costs in the disposable household income in percentage points [%p]. As we assume an equal distribution of energy savings over all income deciles this approach might lead to an overestimation of the benefits of EE on low-income households, which are more prone to energy poverty, because, in reality, the do not benefit as much from EE policies as higher income groups (Ugarte et al., 2016).
(7) Health and well-being: Health benefits represent a more indirect effect of EE. Impacts on health are strongly related to (local) emissions, e.g. from power plants, district heating and local residential heating systems as well as from transport and industry [e]. By reducing the energy consumption, a part of this air pollution can be avoided. Health and well-being benefits can be estimated by combining avoided local air pollution with premature mortality rates from studies such as (Lelieveld et al., 2015) [f]. Of course, human health is also impacted by many other impacts, such as indoor air quality and room temperatures and resulting cold-weather deaths and also can have impact on other aspects, e.g. on disposable income etc. However, estimating these second-order effects would require analyses with higher spatial resolutions, which explicitly would be beyond the proposed indicator.	We estimate health benefits in the form of avoided premature deaths related to NOx and PM2.5 based on the average relationship between concentration and deaths per 1000 inhabitants derived from EEA data (EEA, 2017). The health benefits in relation to final energy savings for each country are calculated based on the following formula: $AD_i = EM_i * cf * \Delta conc_i * pop$ Where the avoided deaths AD related to the pollutant i are calculated from the emission EM of the pollutant multiplied with the concentration factor cf and the corresponding change in pollutant concentration and population of the country (derived from EEA data (EEA, 2019)).
(8) Disposable household income: can be increased by EE in space heating, hot water generation or energy-using products like fridges or televisions, given that the overwhelming share of all implemented measures are cost-effective (Yushchenko and Patel, 2017; Dodoo et al., 2017). Initial investments in EE for renovation of buildings usually pay off in terms of heating cost reduction, which enables consumers to spend their money elsewhere in the long run. However, as the evaluation of the German KfW Energy-efficient Refurbishment Programme emphasizes, it must be noted that these investments are profitable after a period of several decades (KfW Group, 2016) [a]. Disregarding investment costs is hence a simplification and likewise the neglect of rebound and spill-over effects [b].	To calculate the effect of energy saving on the disposable incomes of households we use the following formula: $\Delta INC_E = [INC^{0}_{E}] - [INC^{1}_{E}] = INC^{0}_{E} - [INC^{0}_{E} + (ec * \overline{ES_{HH}})]$ where INC_E represents the share of energy costs in the disposable income of an average households with (1) and without energy savings (0), ec the cost per energy unit and $\overline{ES_{HH}}$ the energy savings of an average household. $\Delta INC_E/INC_E$ provides the change of the share of energy costs in the disposable household income in percentage points [%p] for an average household of the respective country (see Fig. 7 for Germany).

Notes:
a) These profits result in an increase of disposable income. In addition, energy savings might be realized by behavioral change, better consumer access to less energy-consuming appliances and to and to higher levels of comfort (e.g. due to higher indoor temperatures). Taking energy-using products as an example, the net financial savings of fully implementing the Ecodesign Directive, which establishes minimum efficiency requirements for those products, are estimated at 332 EUR per household per year in Europe (European Commission).
b) Estimates on the reduction of energy savings through rebound effects range from 1% to 30% (Sorrell, 2007). The scale varies by sector, location and time, but it should still be taken into account by policy makers (Sorrell and Dimitropoulos, 2008).
c) The definition of energy poverty differs from country to country and over time (Robić et al., 2015). For example, in the United Kingdom, a household is described as 'fuel poor' when more than 10 percent of its total income is spent for heating (Bird et al, 2010). France has recently formulated a similar definition of 'energy precariousness' based on a household spending more than 10 percent of its income to meet its energy needs (Bouzarovski, 2014).
d) In the European Union the problem of energy or fuel poverty is not limited to colder climates or particularly poor Member states as one might expect. It exists also in the South of the EU, e.g. in Spain, Portugal, Italy, Greece and Cyprus, as well as in relatively well-situated Member states like the UK and Ireland. BPIE (BPIE, 2015) estimates that between 50 and 125 million people in the EU are currently suffering from energy poverty and are unable to afford proper indoor thermal comfort. The importance of targeting low-income and energy poor households in energy efficiency policy is confirmed by the fact that about 8 percent of the population in the European Union were in arrears with payment of their utility bills, and thus, can be considered to be energy poor this emphasizes the (Ugarte et al., 2016; Eurostat, 2018). At the same time energy efficient renovation of buildings in the EU holds a large potential for energy savings. Fraunhofer ISI et al. (Fraunhofer et al., 2009) identified an overall energy efficiency potential in residential heating of 16 Mtoe to 45 Mtoe in the European Union (1.5–4.1% of total final energy demand). To unlock these potentials, it is necessary to address all types of households in the residential sector.
e) Zhang et al. (2016) discusses an example regarding the effects of EE measures on the emissions of China's cement industry and the related premature deaths. For the European Union, the EEA estimated 403,000 deaths related to PM2.5 and 72,000 deaths related to NO_x in 2012 (EEA, 2015).
f) The IEA (IEA, 2014) gives some examples of possible indicators used in measuring health and well-being impacts of EE. However, those are mainly based on (in situ) measurements (e.g. average indoor temperature or humidity levels), which should be performed before and after certain EE measures were carried out. Thus the database for those indicators is every limited.

Table 4
Overview of economic MB-EE indicators - Part 1: Innovation and Competitiveness.

Purpose and Definition of the Indicator	Calculation Approach/Formula
9) Innovation impacts: Innovation is a driver for economic growth and an enabler for the transition towards a competitive, secure and sustainable energy system. A country with strong energy efficiency policy and thus high energy savings may have high R&D activity in this field (Braungardt et al., 2014). To study the impacts on innovation related to the diffusion of EE technologies in a country, patent indicators have been used in the past (Eurostat, 2018). Suitable indicators are in particular patent shares for a given EE technology as well as the Revealed Patent Advantage (RPA), normalised to the size of a country and calculated by dividing the patent share of the country for energy efficiency technology by the sum of the patent shares of the country in all fields (Eichhammer and Walz, 2009). Due to its methodological foundation this indicator is not directly linked to energy savings in our indicator approach, since the RPA only reflects the innovative activity of a country in a specific area.	The formula for the indicator is as follows [41]: $RPA_{ij} = 100^{*}\tanh\ln\left[\frac{(p_{ij}/\sum_i p_{ij})}{(\sum_j p_{ij}/\sum_{ij} p_{ij})}\right]$ where p_{ij} represents the number of patents for a certain technology j from a country i. The value of RPA is positive if the patent share of a given technology is over-proportionally large: compared to other technologies there is more national innovation activity. When interpreting the results it should, however, be taken into account that it is more difficult for a technology to achieve a positive RPA value if a country is generally strong in patents.
10) Competitiveness impacts: Developing innovative EE technologies can contribute to the competitiveness of a country. Indicators such as world market shares, or specialisation indicators such as the Revealed Comparative Advantage (RCA), which is normalised to the size of a country, are commonly used in economics for calculating the relative competitive advantage or disadvantage of a certain country in a certain class of goods or services as evidenced by trade flows. The RCA is defined in a similar manner as RPA. As is the case for the innovation impacts indicator, this indicator is not directly linked to energy savings in our indicator approach. Nonetheless, we include this indicator to provide comparable data on this important aspect.	The formula for the indicator is as follows (Eichhammer and Walz, 2009): $RCA = 100^{*}\tanh\ln\left(\frac{X_i/IM_i}{X/IM}\right)$ Where X_i and IM_i describe the exports and imports of a branch i, while X and IM describe the total exports and imports of a country. The formula gives normalised results for the RCA between −100 and + 100. If the RCA is greater than zero a comparative advantage is "revealed", otherwise it is considered to have a comparative disadvantage for the branch studied.
11) Turnover of energy efficiency goods: This indicator represents the turnover of EE goods. We focus here on the residential sector due to availability of suitable data, while this indicator is actually relevant for all sectors. A high turnover with EE goods may contribute to the economic benefits of a country and might trigger innovation in this field. To estimate the total turnover related to EE goods, the total energy saved is multiplied by the weighted average of these investments per unit of energy savings. For the latter, we used a dataset based on a case study[a] from the Netherlands (Ministerie van Economische Zaken en Klimaat, 2015), assuming a similar split of cost in all European countries. Lack of comparable data for other countries could constrain the meaningfulness of the indicator.	The formula for the indicator is as follows: $TO = ES^{*}SH_i^{*}f_{in}^{*}IN_{tech}$ Where the turnover TO is calculated based on the residential energy savings ES and the share of space heating SH in final energy consumption of country i as well as the share of savings f_{in} due to insulation and efficient heating systems in the residential sector and the typical investments IN per unit of energy saved. The turnover of energy efficiency goods is given in billion Euro [G€].

[a] The study „Monitor Energiebesparing Gebouwde Omgeving" (Fraunhofer et al., 2009) published yearly by the Ministry of Interior of the Netherlands collects these data for the Netherlands.

impact on public budgets low and likewise the burden for businesses as well as private households. Considering economic effects other than costs can make investments in energy efficiency more attractive. For example, including these effects in the calculations of profitability can reduce payback times significantly. We consider four parts in this section:

- Part 1: Innovation and Competitiveness (Table 4)
- Part 2: Macro-economic (Table 5)
- Part 3: Micro-economic (Table 6)
- Part 4: Energy Security /Energy Delivery (Table 7)

3. Results

In this chapter, we present the MB-EE indicator set for Germany due to the good data availability for this country. We show examples of impacts derived from top-down and bottom-up energy savings.

3.1. Environmental benefits of energy efficiency

Fig. 2 depicts the final energy savings linked to energy efficiency showing both top-down and bottom-up savings compared to the year 2000. These final energy savings amount to 48 Mtoe[6] (TD) and about 37 Mtoe (BU) in 2015. Possible reasons why BU-savings are smaller than TD-savings are incomplete accounting of EE measures in the BU approach and the consideration of spill-over effects in the TD approach.

The calculated avoided consumption of coal, oil and gas calculated according to the top-down approach (based on ODEX) amounted to about 1.6 Mtoe, 18.6 Mtoe and 13.3 Mtoe respectively for the year 2015 (Fig. 3). According to the bottom-up approach, we calculated the avoided consumption of fossil fuels to amount to 1.5 Mtoe (coal), 13.1 Mtoe (oil) and 10.1 Mtoe (gas).

By reducing final energy consumption, EE can contribute to the attainability of renewable energy targets. For Germany, in 2015 a difference of 2.7 (TD)/1.6 (BU) percentage points of the renewable energy target of 18% of gross final energy consumption was achieved through final energy savings (Fig. 6). This can be roughly translated to a installed capacity of 13 GW (TD) or 8 GW (BU) of renewable energy plants saved due to energy efficiency.

Based on the savings of fossil fuels as well as the electricity saved, we calculated the avoided GHG emissions by sector. As shown in Fig. 4 the main share of emission reduction in 2015 was realized in the household sector (71 $MtCO_2$eq.) followed by industry and transport (36 $MtCO_2$eq and 30 $MtCO_2$eq., respectively). In total, EE allowed to avoid a total of 137 MtCO2eq., which represents 12% of the total GHG emissions in 2000 (1064 MtCO2eq. according to (EEA, 2019).

Besides the GHG emissions, we also estimated the local emissions of pollutants linked to energy consumption, such as CO, NOx, SOx and particular matter (PM). In 2014, Germany's improvements in energy efficiency compared to the year 2000 resulted in the avoidance of 635 kt of CO (or 7.7 kg/cap) as well as 280 kt of NOx (3.4 kg/cap), 82 kt of SOx (1.0 kg/cap) and 51 (0.52 kg/cap) and 23 kt (0.24 kg/cap) of particulate

[5] In contrast, *net* effects would be calculated by deducting from the *gross* effects the impact of the standard spending pattern without considering the existence of EE policies.

[6] One Mtoe equals 41.868 PJ.

Table 5
Overview of economic MB-EE indicators - Part 2: Macro-economic.

Purpose and Definition of the Indicator	Calculation Approach/Formula
12) Impact on GDP: The impacts of EE measures on GDP are determined by using I/O analysis (Miller and Blair, 2009).	To calculate the GDP from I/O tables, the total gross value added (GVA) plus taxes on products minus subsidies on products in final and intermediate consumption are summed up (income approach) and given as a percentage of total GDP [%].The input data are the same as for the analysis of employment effects.
13) Employment effects have used as major arguments in the past to justify EE programmes. Direct effects of EE on employment are based on two main drivers: investments in EE measures and related energy savings. The former triggers demand impulses in industries producing relevant technology, the latter reduces demand related to energy supply in the long run. In both cases, these impacts indirectly affect other sectors, e.g. energy producers and distributors. As various studies have shown, net employment gains are likely to occur when shifting from spending on energy consumption to investing in EE measures (Bacon and Kojima, 2011; Wei et al., 2010; Scott et al., 2008). Provided that EE measures are cost-effective they also increase disposable incomes, which further stimulates job creation in the long-run.	To comprehensively trace economic impacts of demand changes to all sectors affected, Input-Output (I/O) analysis is applied [a]. It calculates how demand changes affect gross value added (GVA) in selected sectors (Tanaka, 2011), from which employment effects (in fulltime equivalents FTE) can be calculated by using sector specific productivity coefficients. Data on energy savings from the ODYSSEE database are represented as demand changes in economic sectors, currently using fossil fuels. The nature of the EE measure implemented determines which sectors invest and for how long they remain in operation. Investment data are provided by either policy evaluations from the MURE database or other specific studies. Results for this indicator are given as FTE.
14) Potential impacts on energy prices: EE measures reduce energy purchase or production. As most markets for energy products are characterized by an increasing supply curve, energy prices should decline with falling demand[b]. However, besides the reduction of energy demand, energy prices are also impacted by factors such as energy mix, domestic energy supply capacity, substitutability and trading conditions. EE measures may impact the consumption of one type of energy carrier more than the others, depending on the sector affected or on price differences across fuels. Nevertheless, in general, energy savings are likely to induce downward pressure on energy prices. At present, the impact of energy savings on energy prices in the current market constellations is not clearly measureable for either oil or gas within our indicator approach. Nevertheless, it is to be expected in the future that the merger of the world markets away from various trading centres into a single global market will result in these markets responding more quickly to changes in demand and thus effects from the saving of energy can become apparent. We therefore keep this indicator in our set.	Fuels like oil and gas, are globally and regionally traded commodities, hence, global energy prices will hardly change due to decreasing energy consumption of a single country (IEA, 2014; Chernick and Plunkett, 2014). Thus, to represent potential changes in energy prices due to changes in consumption we use price elasticities η_i for the European Union as a whole for the world market prices for different energy carriers *i* (natural gas and crude oil) according to the following formula. $\frac{(P_2 - P_1)}{P_1} = \eta_i * \frac{(Q_2 - Q_1)}{Q_1}$ Q_1 and Q_2 represent the quantities of energy consumed in the starting/end year considered while P_1 and P_2 represent the price of energy in both years and thus showing the change in price.
15) Impact on Public Budgets: Public budgets are affected by EE in multiple ways. For this indicator we consider changes in public budgets triggered by new jobs generated by EE (e.g. in the building sector). As an example for the impact on public budgets we calculate additional income tax revenue (in million Euro) for a typical average job in the related sectors/subsectors using country specific income tax rates. Thus, this indicator directly builds on data from the indicator "employment effects". Losses of income tax in the energy sector are also considered here. The approach can be extended to other impacts related to the public budget, such as VAT and energy taxes to calculate positive or negative effects on public budgets.	The calculation formula is as follows: $\Delta IT_i = \Delta FTE * \overline{In} * Ir_i$ where additional income tax *IT* of the country *i* is calculated by multiplying additional jobs in FTE with the average income *In* of the branch considered and the income tax rate *Ir* of the country. We assume a uniform distribution of employment effects over all occupational groups of the branches considered.

Notes:
[a] This approach focusses on *gross* effects, excluding other factors such as displacement effects (replaced system)[5] and indirect second order effects through additional tax revenues, export/imports of EE related goods, etc.
[b] There is widespread evidence both from empirical data and from modelling studies for a direct relationship between demand and price.

Table 6
Overview of economic MB-EE indicators - Part 3: Micro-economic.

Purpose and Definition of the Indicator	Calculation Approach/Formula
16) Industrial productivity: Since energy is an important production factor for industry, energy efficiency enhances productivity. Saving energy reduces the energy costs. In companies, this will have an effect on energy productivity expressed as added value per unit of energy used. Based on the savings calculated and a typical mix of energy carrier of the sectors the energy cost saved can be estimated and related to additional industrial value added. The approach described here can easily be transferred from the example of industry to the tertiary sector.	The change in productivity is calculated as follows: $\Delta P = P^0 - P^1 = \frac{GVA^0}{FEC^0} - \frac{GVA^0 - \sum_i (ES_i * p_i)}{FEC^1}$ Where *P* represents the productivity with (P^0) and without (P^1) energy savings. The product of the energy savings *ES* for energy carrier *i* and the price for the energy carrier *i* and the corresponding price (*i* standing for coal, gas, oil, electricity) gives the energy cost saved. These are subtracted from the GVA without energy savings (GVA^0) to calculate the difference between the productivities. The change in productivity is given in million euro per Peta joule [M€/PJ].
17) Asset value: EE in buildings has an impact on the evaluated market values. According to a study published by the US department of Energy (DOE), commercial buildings waste 30% of the energy paid for on average (EnergyStar, 2019). This wasted energy was estimated at around 61 billion dollars for 2007. Based on a capitalization rate of 8%, a typical value used for building values, the lost asset value amounts to approximately $750 billion. Buildings with a certification of high EE generate a rent which is about 7% higher than otherwise identical buildings and their selling prices is 16% higher. For this indicator we consider commercial buildings as the market value of residential buildings is less dependent on EE than on location and other factors, though this may change in future.	To estimate the changes in asset value through increased EE we calculate the average savings in services related to the building itself, i.e. heating and cooling. Using average costs per energy for heating and cooling, we assess the additional average net income due to avoided energy costs. Assuming a capitalization rate of 8% the change in asset value can be calculated for the service sector as a whole using the following formula: $\Delta AV = \frac{\sum_i ES_i * p_i}{cr}$ Where ES_i represents the annual energy savings regarding energy carrier *i* (electricity and gas) with the price *p* for each energy carrier and the capitalisation rate *cr* (in our case 0.08).

Table 7
Overview of economic MB-EE indicators - Part 4: Energy Security /Energy Delivery.

Purpose and Definition of the Indicator	Calculation Approach/Formula
18) Import dependency: Many EU countries are highly depend on a few suppliers of fossil fuels, making them vulnerable to supply disruptions, whether caused by political or commercial disputes, or infrastructure failure. To address this issue, the European Commission released its Energy Security Strategy in 2014 (European Commission, 2014a), putting forward the 2030 energy and climate goals (in particular EE) as long-term measures to mitigate the energy import dependency of the EU. This indicator shows the contribution of energy savings to the reduction of energy import dependency. Dependency is measured through the energy dependency rate (ratio of primary consumption minus primary production over primary consumption). This ratio is first calculated with the observed primary energy production and consumption ("actual dependency rate") and secondly in a fictive situation without energy savings ("dependency rate without savings"). This second ratio is calculated by removing final energy savings in primary terms from the primary energy consumption.	The difference between the actual dependency rate and the dependency rate without savings represents the effect of energy savings on import dependency. Final energy savings in primary terms are calculated by multiplying the final energy savings (see energy savings indicator) by the ratio of primary to final consumption (annual and country-dependent factor). $\Delta ID = ID^0 - ID^1 = \left(\frac{net\ imports}{GIEC + bunkers}\right) - \left(\frac{net\ imports}{GIEC + bunkers + primary\ savings}\right)$ The indicator is calculated as net imports divided by the sum of gross inland energy consumption (GIEC) plus bunkers, which represents the import dependency without energy savings (ID^0). The import dependency with energy savings (ID^1) is deducted from the import dependency without energy savings (ID^0).
19) Supplier diversity: Supplier diversity is considered a corner-stone of a secure energy supply system and is therefore frequently used as a key indicator to assess energy security. It is beneficial for an energy system both through extending choice and increasing competition. The rationale behind the enhancement of supplier diversity through energy efficiency measures is that energy savings allow for reduction of the share of the dominant supplier. To measure the degree of supplier diversity of a country we use the Herfindahl-Hirschman-Index (HHI) (Rhoades, 1993). HHI accounts for the share of each supplying country by weighting the respective imports by the square of their shares. If there is only one supplier, the index is unity, i.e. representing a monopoly. If there are N suppliers with equal shares, the index is 1/N.	We assume that the energy savings (expressed in primary terms) reduce the primary energy imports from the main supplier (i.e. minimizing the share of the dominant supplier). The impact of EE in supplier diversity is measured with the difference between the observed HHI ("actual HHI") and a fictive HHI "without energy savings". The calculation of the total HHI for each cases is done with following formula: $HHI = \sum_{i}^{4} \frac{\left(\sum_j (MS_{ij})^2\right) * I_i}{I_{tot}}$ Where MS_{ij} represents the share of the supplying country j in the imports I of energy carrier i (solid fuels, oil, gas, electricity) of the country considered, multiplied by the imports of the respective energy carrier.
20) Integration of renewables (RES): RES such as wind/solar depend on weather influences and supply fluctuating power to the grid. In order to keep the grid stable, demand response may be used (shift of energy services to counteract increased feed-in or bottlenecks in production). This contributes to increased efficiency in electricity generation through better integration of RES, as it increases their share in electricity consumption.	This indicator shows the demand response potential per country in gigawatt [GW] and is not directly derived from energy savings; instead, it is determined by decomposing total sectoral demand into the main processes and establishing the demand response potential for each of them (Sia Partners, 2014).

matter (PM10 and PM2.5, respectively) (see Fig. 5). Compared to the total amounts of the respective types of emissions reported by (EEA, 2019), EE consequently allowed to avoid 12% of NOx, 13% of SOx, 18% of PM10 and 14% of PM2.5 relatively to the emissions in 2000.

3.2. Social benefits of energy efficiency

With regard to the social effects of energy efficiency, we studied the impact of energy savings on disposable household incomes in average and low-income households. We also estimated premature deaths from energy-related local emissions, which have been avoided by increasing energy efficiency.

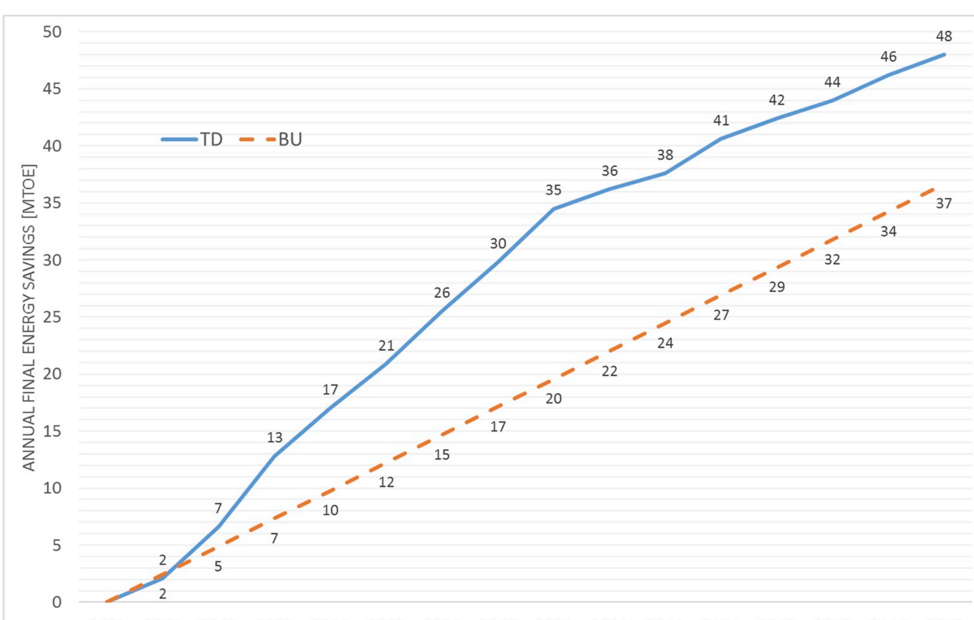

Fig. 2. MB-EE1 - Final energy savings in Germany relative to the year 2000 according to the top-down (TD) and bottom-up (BU) approach.

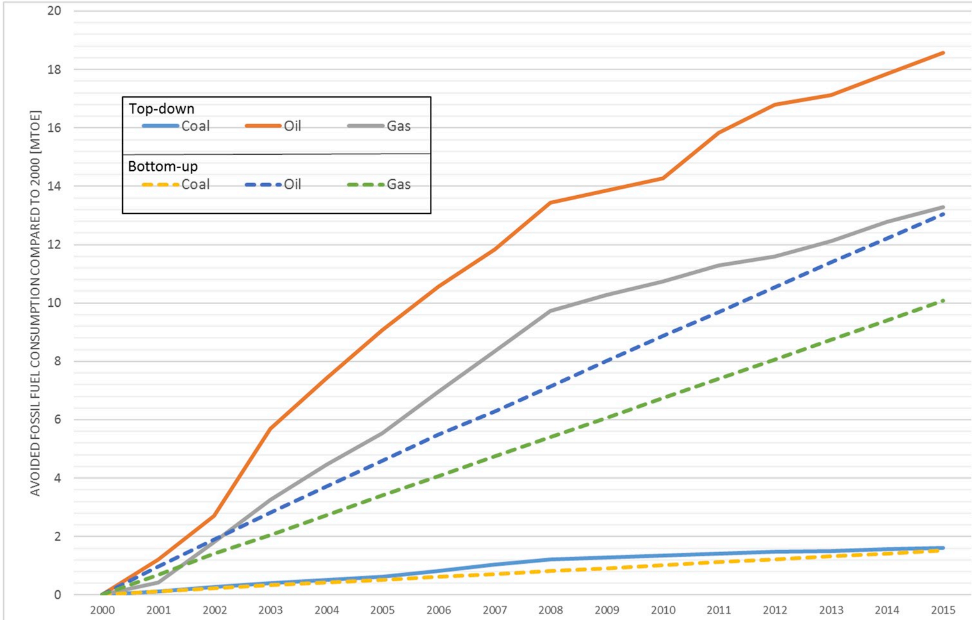

Fig. 3. MB-EE2 - Fossil fuel consumption avoided by EE compared to 2000 for Germany.

For the average German household, energy efficiency resulted in about 2.2 (TD) and 1.1 (BU) percent lower expenditure on energy from disposable household income in 2015. Low-income households benefit more from energy efficiency, namely, 3.6 (TD) or 1.8 (BU) percent of the disposable household income in 2015 (see Fig. 7).

Energy savings also help to improve health and well-being by avoiding local emissions caused by power or heat generation, as well as direct fossil fuel uses. Based on top-down energy savings around 31,000 premature deaths were prevented: 18,000 from avoided emissions of particulate matter (PM2.5) and 13,000 from avoided NOx (Fig. 8). Based on bottom-up savings, these were 12,800 (PM2.5) and 9,500 (NOx), respectively.

3.3. *Economic multiple benefits of energy efficiency*

For measuring the influences on innovation, we use the revealed patent advantage (RPA) for relevant technology groups as internationally comparable indicator (this indicator ranges between values of −100 and 100). Fig. 9 shows a stable positive value for Germany which, compared to other countries, indicates a high level of innovation for EE technologies (as a value over zero represents a higher level of innovation than the average of all countries).

The revealed comparative advantage (RCA), which indicates how strong the trade of a country is for a certain product group in comparison to other countries and total trade, is an indicator for the competitiveness of a country.

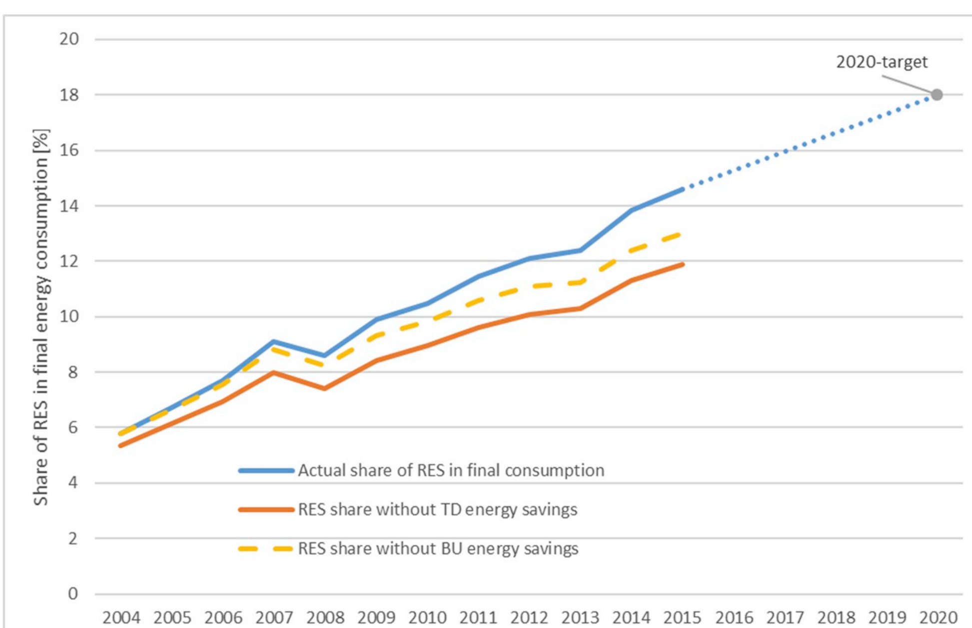

Fig. 4. MB-EE3 – Contribution of EE to change in RES share in gross final energy due to EE in Germany compared to 2000.

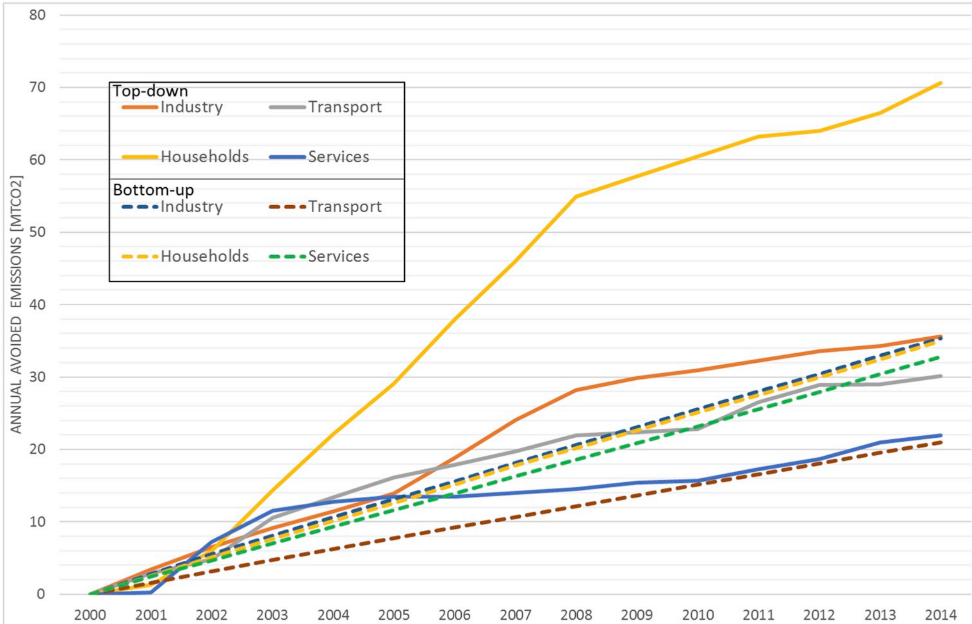

Fig. 5. MB-EE4 - GHG emissions avoided by EE compared to 2000 for Germany.

Fig. 10 shows the RCA for energy efficiency products for Germany between 2003 to 2013. Germany shows a consistently strong position in the European context, taking the second place after Italy on a par with Finland.

The annual turnover with energy efficiency goods for building retrofits (insulation, heating systems) for Germany is shown in Fig. 11. While bottom-up savings in the period 2011 to 2015 were almost constant around 2.5 to 3 billion Euro the turnover based on top-down savings fluctuated more strongly (between 1 to 4.5 billion Euro).

Other economic effects linked to EE in our analysis are those on employment, GDP and income tax revenue. Fig. 12 shows the job effects we have calculated for EE in buildings for Germany. We focus on buildings because the related EE measures have strong effects on employment in this sector. Based on top-down savings, this translates to between 40,000 to 180,000 full-time equivalents in the period 2010 to 2015 (or around 570,000 full-time equivalents for the entire period). Based on bottom-up savings the respective value amounts to about 107,000 full-time equivalents (535,000 FTE in total for 2010 to 2015).

Fig. 12 also shows the effects of energy savings (top-down and bottom-up) on economic growth in Germany in the period 2010 to 2015.

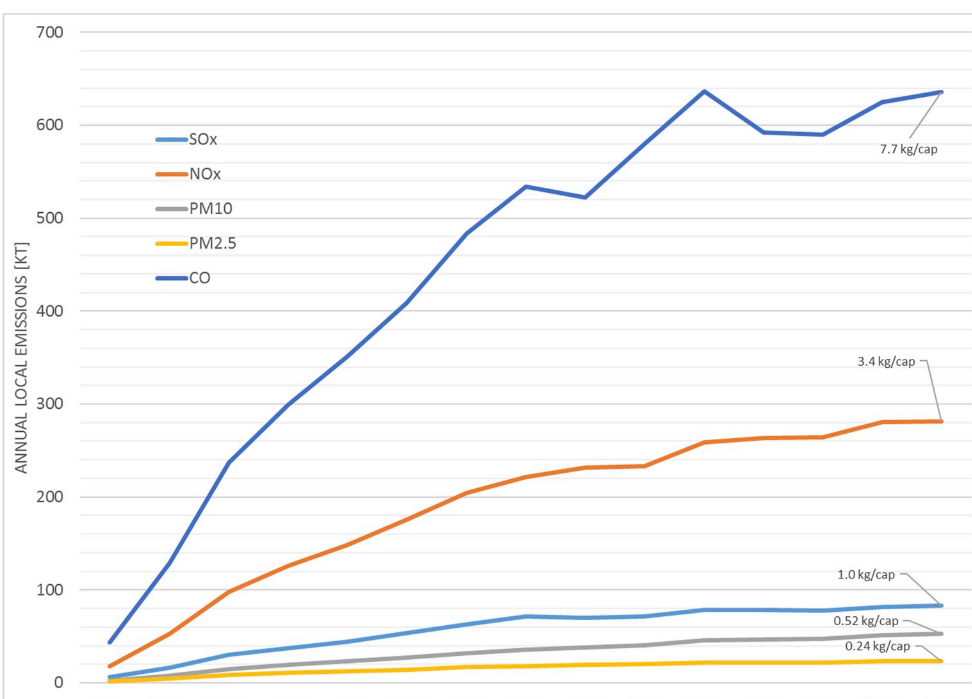

Fig. 6. MB-EE5 - Local emissions avoided by EE since 2000 for Germany (TD-savings).

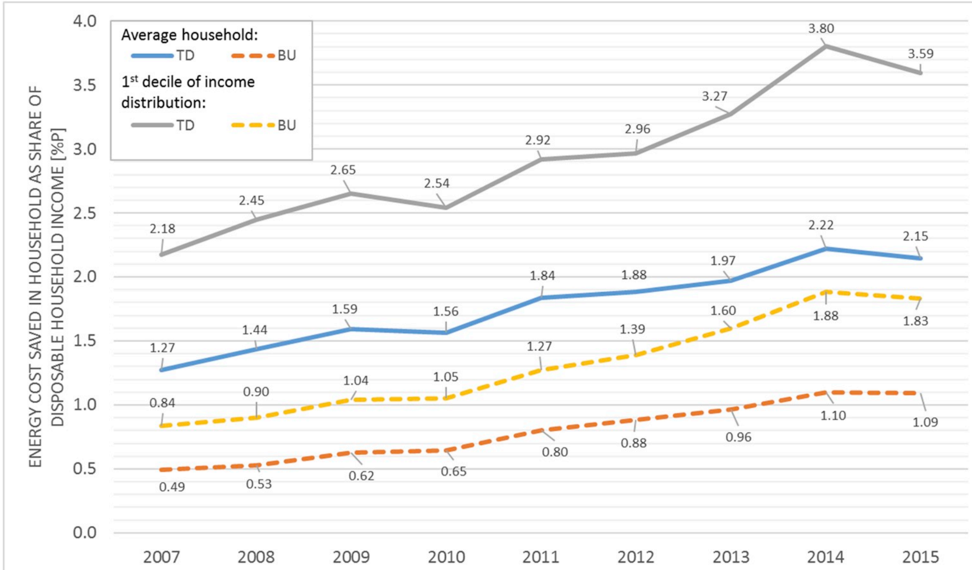

Fig. 7. MB-EE6/MB-EE8 - Change in share of energy cost in disposable household income related to energy efficiency /Change of disposable income for low-income households (1st quintile of income distribution) compared to 2000 (Germany, TD and BU savings).

We calculate a GDP growth of GDP by 3.0–13.9 bln € (TD) or an annual average of 8.3 bln € (BU) due to energy efficiency in the building sector (i.e. an average of 0.3%/a of a 3.4%/a total GDP growth in this period). The main share of these additional GVA was realized in the sectors "Constructions and construction works" and "Machinery and equipment".

The additional income tax revenue in Germany based on the changes in employment due to energy efficiency measures in residential buildings (see Fig. 13) is estimated at 4.4 billion Euro (TD savings) and 4.1 billion Euro (BU savings) in the period 2010 to 2015.

As shown in Fig. 14 the impact of energy efficiency on the productivity of industry in the form of reduced energy cost as part of GVA amounts to 6% (2007) to 9% (2015) for TD savings and 5% (2007) to 10% (2015) for BU savings.

The additional asset value of commercial buildings in the German service sector due to top-down and bottom-up savings increased steadily over time peaking in 2013 (Fig. 15). After 2013, a slight decrease occurred due to decrease of energy prices for commercial customers in Germany.

Fig. 16 shows the impact of energy savings on Germany's import dependency for fossil fuels. Without those energy savings, the import dependency would have been 64.9% (TD savings) or 63.7% (BU savings) in 2015 instead of the actual value of 59.1%.

Another indicator for a country's energy dependency is the level of concentration of energy suppliers, which can be measured by the HHI. As displayed in Fig. 17 Germany's energy supply became more

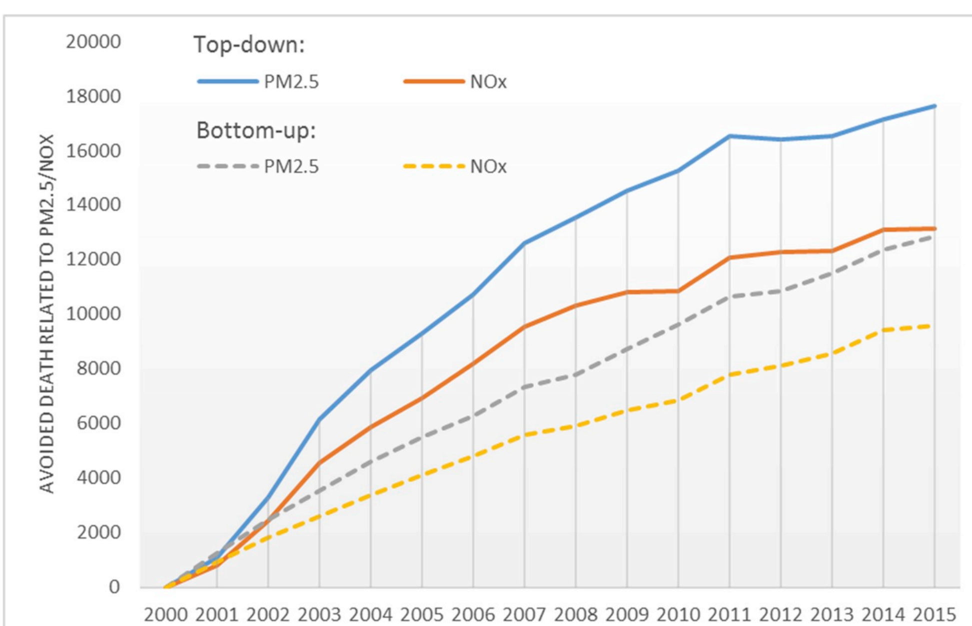

Fig. 8. MB-EE7 - Avoided premature deaths related to NOx and PM2.5 (TD and BU) for Germany compared to 2000.

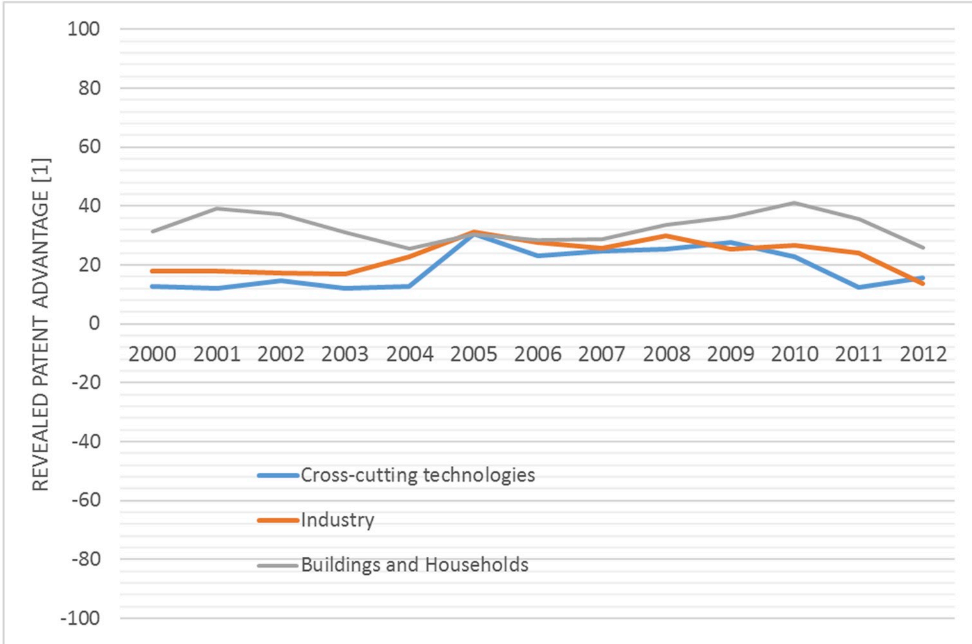

Fig. 9. MB-EE9 - Development of the revealed patent advantage for EE technologies for Germany (2000–2012).

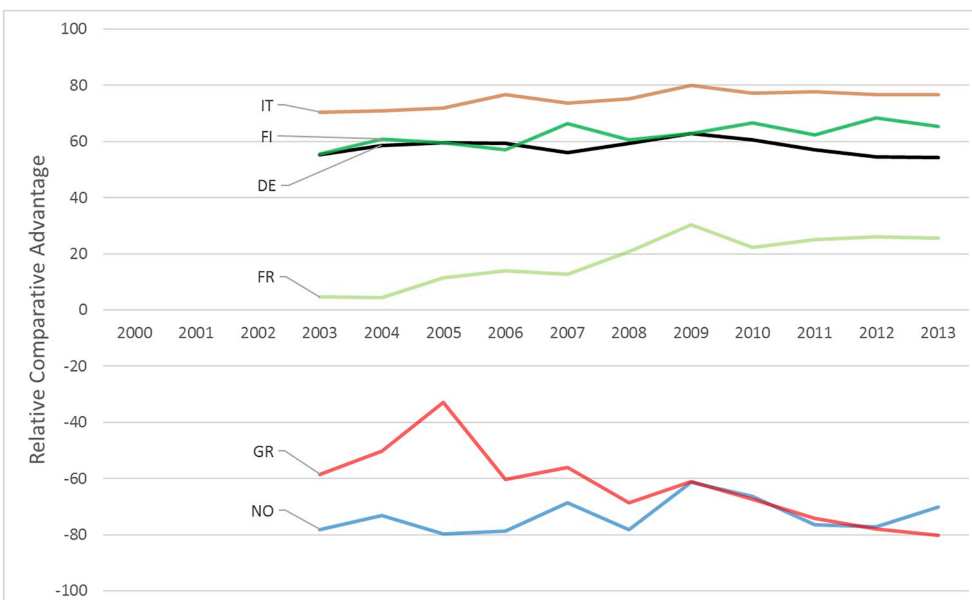

Fig. 10. MB-EE10 - relative comparative advantage for Germany compared to other countries.

concentrated between 2000 and 2015. However, the concentration process would have been faster if there had been no energy savings.

Demand response (DR) potentials contribute to the integration of renewable energy sources by providing flexibility to the power grid. Fig. 18 shows the demand response potential of several European Member States in 2012. DR potentials cannot be directly linked to energy savings but depend on the end-use technologies. Further, a country's demand response potential is impacted by EE as it may lower the demand of energy services. This may result in a lower demand response potential. However, in relative terms, also less DR potentials are required when less electric energy is consumed.

4. Discussion

Table 8 summarizes the results we presented in section 3. The indicators have been compiled from several sources, which differ in their temporal and spatial scope. The resulting indicator quality levels (A, B, C) distinguished in Table 1 (repeated below in Table 8) can, however, be regarded as acceptable in view of the framework of our indicator approach. We deliberately designed the indicator set without complex modelling and additional data collection compared to the statistical data collected in the ODYSSEE-MURE project (e.g. surveys), with the purpose of covering a broad set of aspects and allowing rapid updating on an annual basis.

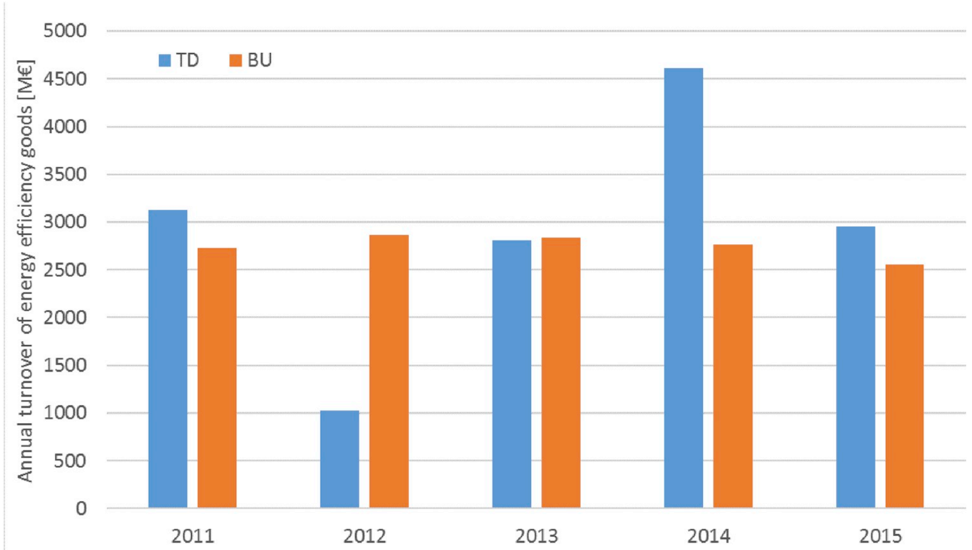

Fig. 11. MB-EE11 - Annual turnover of energy efficiency goods related to energy savings in households (space heating) (Germany, TU and BU savings).

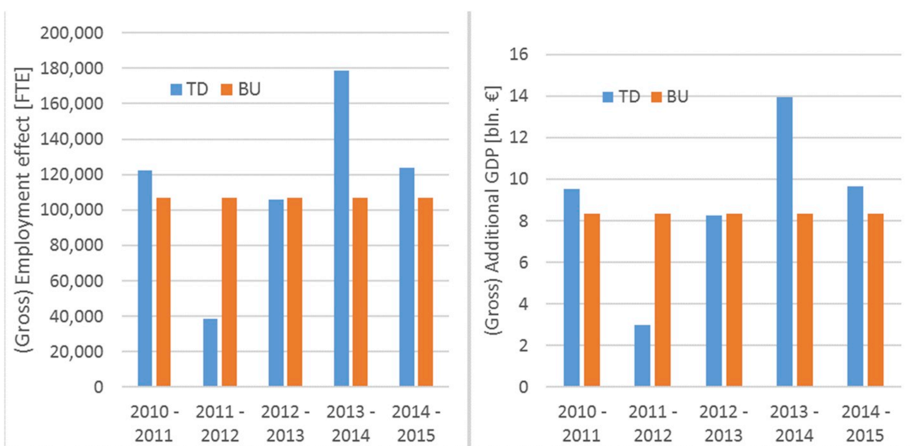

Fig. 12. MB-EE12 /MB-EE13 - Employment effects and MB-EE13 - Change in GDP linked to EE for German for TD and BU savings (2010–2015).

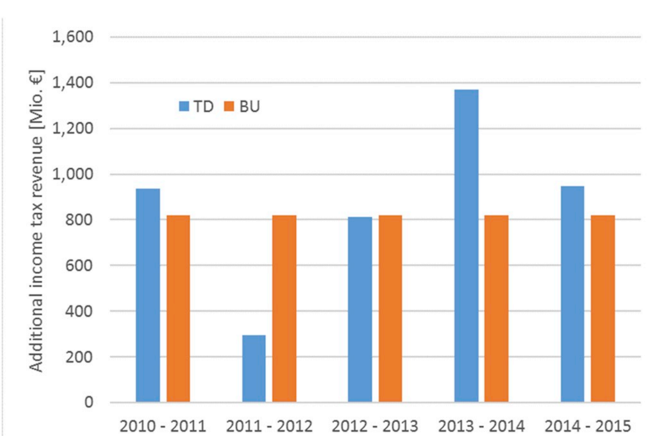

Fig. 13. MB-EE15 – Additional income tax revenue due to energy efficiency in residential Buildings in Germany for top-down and bottom-up savings (2010–2015).

Nevertheless, individual indicators and their input data have limitations which we present and discuss here. One general limitation would be the overlap between some indicators (e.g. among indicator 1 and 2 and in particular among economic indicators such as GDP, public budgets and employment as well as some socio-economic indicators such as poverty alleviation and disposable income). On the other hand, all chosen indicators are present in the scientific and public debate and we refrain from creating an overall, weighted score which would call for a mutually exclusive set of indicators. Furthermore, focussing on the co-benefits of energy efficiency, we do not necessarily pay equal attention to potential drawbacks (e.g. foregone growth opportunities due to investments in EE).

In the following, we briefly discuss the indicators which are potentially subject to large uncertainties while allowing for comparison with other studies. This is in particular the case for the employment effects we calculated. The validity of our approach can be tested using an evaluation by KfW (KfW Group, 2016; IWU, 2015) that is based on other studies on the impacts of energy efficiency policies. The underlying studies calculate effects in a similar order of magnitude. This suggests that the validity and quality of our methodology are reasonable for the relevant indicators. For other important effects, such as avoided deaths, direct comparison is more difficult. Most studies suggest similarly strong

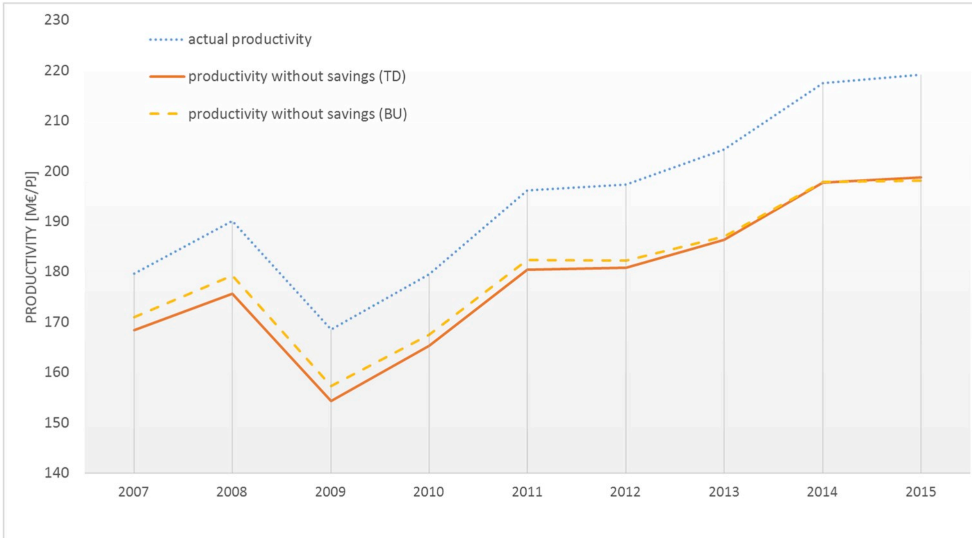

Fig. 14. MB-EE16 - Changes in productivity due to EE (TD savings) for Germany.

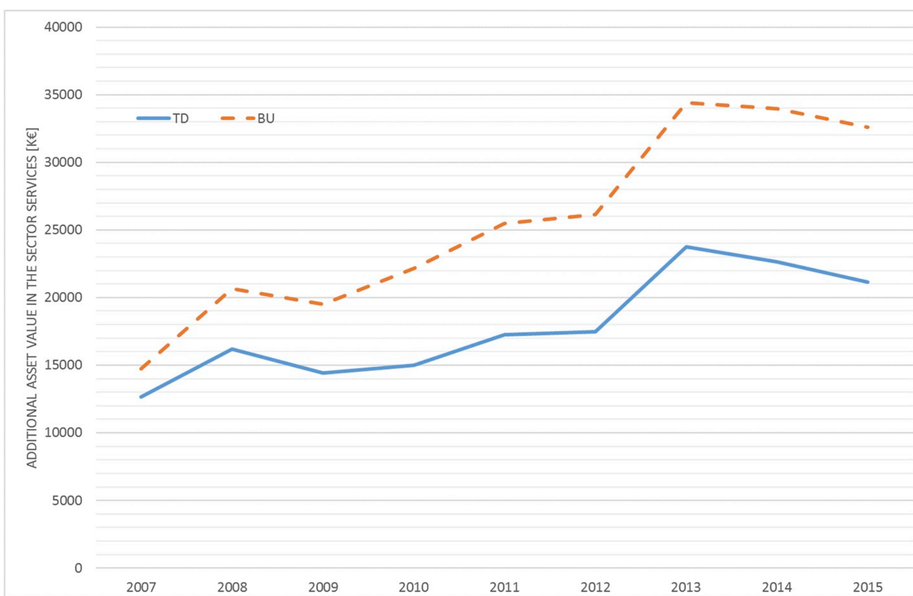

Fig. 15. MB-EE17 - Additional asset value in the service sector due to EE compared to 2000 for Germany.

effects of energy efficiency in preventing premature deaths (e.g. Maizlish et al., 2013; Woodcock et al., 2009; Grabow et al., 2012). However, our analysis may tend to overestimate the deaths as we typically assume linear relationships as opposed to more complex approaches such as the GAINS model (IIASA, 2019). To assess the different quality levels we divided the indicators into several groups (category A to C):

- The first group (A) has a good temporal and spatial coverage within the EU as well as a solid methodological basis. This group includes *final energy savings*, *fossil fuels savings*, *impact on renewable targets* and *supplier diversity* and *import dependency*. These cover almost all Member States of the European Union as well as the complete period from 2000 to 2015. Moreover, the methods on which they are based are straightforward with an excellent database originating directly from ODYSSEE or Eurostat. This should guarantee robust results with a high validity and low uncertainty. Innovation and competitiveness impacts are part of this group as well as they have a good database, coverage and method, even if they are not directly linked to energy savings.
- The second group (B) of indicators consists of those with a limited spatial and temporal coverage, while still being based on a good methodological foundation. This group includes the indicators based on I/O-analysis, such as *GDP effects*, *employment effects* and the *effect on public budgets*, as these only cover a few countries. Nonetheless,

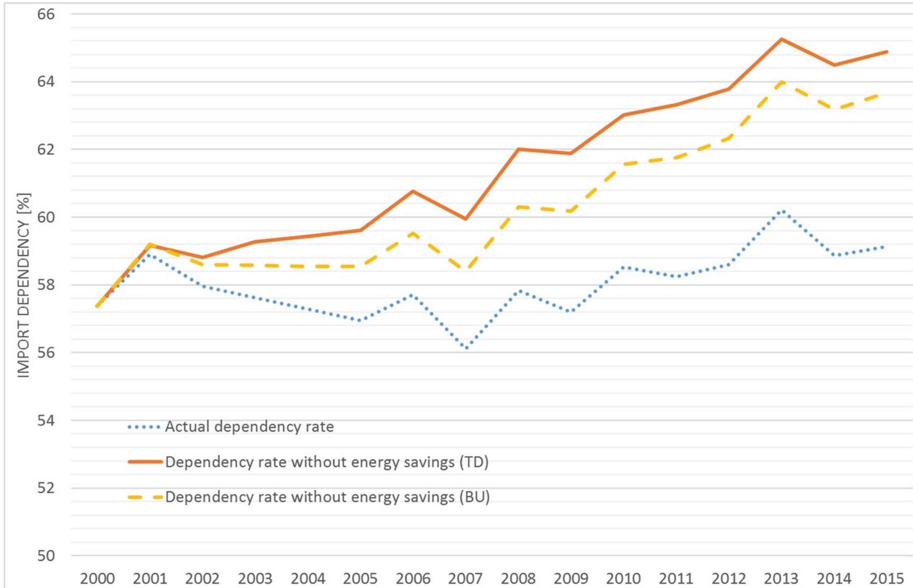

Fig. 16. MB-EE18 – Effect of EE (TD and BU savings) on the dependency on fossil fuels for Germany.

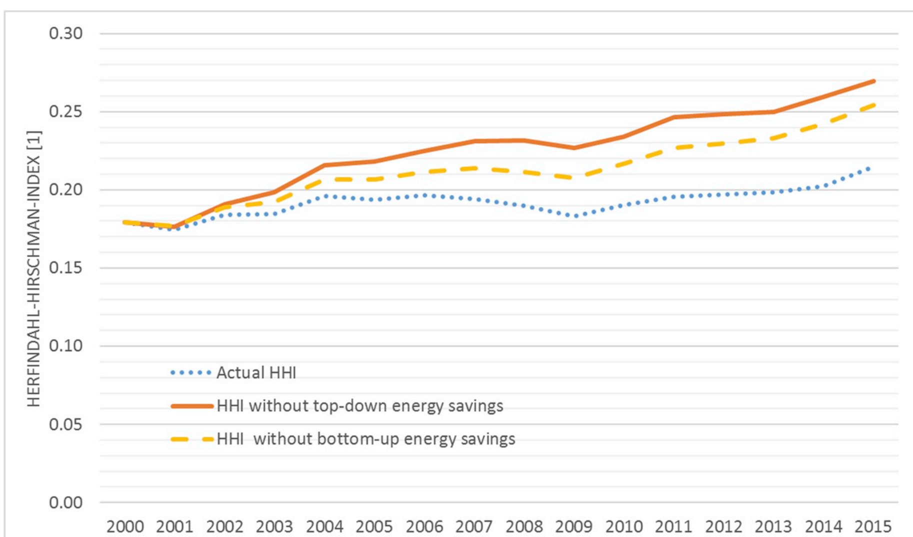

Fig. 17. MB-EE19 - Difference in supplier diversity (measured with the Hirsch Herfindahl Index - HHI) due to EE (TD and BU savings) for Germany.

the methods used for these indicators are solid even if we only calculate (near) gross effects in the limited scope of our indicator approach. The approach of using I/O-analysis is sometimes criticized for assuming investments to be additional (while they may actually be crowding out others) or for assuming economies to be able to absorb the positive demand shock (while this may not be possible). Accounting for these disadvantages, I/O-analysis nevertheless provides useful results and is at the same time much less complex than extensive economic modelling.

We include under quality category B also the indicators measuring the impact of EE on disposable household income and industrial productivity, as data on income structure and energy prices is only available from 2007 onwards. As potential improvements, various adjustments can be considered for these indicators, in particular by further developing them into indicators showing net impacts for employment.

- The last group (C) includes the indicators calculating the *local emissions* as well as *health and well-being*. These are based on only average emission factors for linking final energy savings to *GHG* or other *pollutants* (and further to *avoided premature deaths*). Also, the indicator *turnover of EE goods*, which is based on the data of a single study supplying data for a single European Country, has been assigned to this group. Potential future improvements for these indicators include methodological refinements that take into account temporal and spatial changes in the systems under consideration and thus provide even more substantiated values. However, most of these improvements call for detailed data sets which are typically not available. As a consequence of the resulting relatively simple

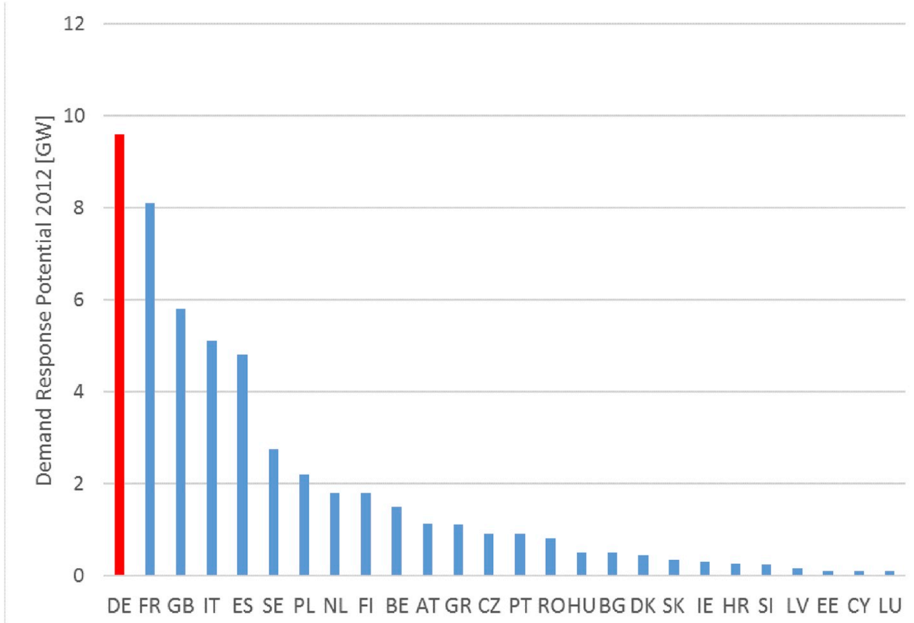

Fig. 18. MB-EE20 - Demand response potentials in 2012 (Sia Partners, 2014).

Table 8
Overview of the results by MB:EE indicator for Germany.

Nb	Indicator (Category)	Quality Category	Results Germany (TD/BU, compared to 2000 if not specified otherwise)	
			TD	BU
1	Energy savings	A	Total annual savings 2015: 48 Mtoe	37 Mtoe
2	Saving of fossil fuels	A	Total fossil fuel savings 2015: 33.5 Mtoe	24.7 Mtoe
3	Impacts on RES target achievement	A	Difference to actual RES share: +2.69%p	+1.59%p
4	GHG savings	A	Total GHG savings 2015: 158 MtCO2eq.	124 MtCO2eq.
5	Local air pollution	B	Avoided emission 2015: 83.4 kt SOx; 281.5 kt NOx; 52.5 kt PM10; 23.6 kt PM2.5; 636.1 kt CO	60.8 kt SOx; 205.4 kt NOx; 38.3 kt PM10; 17.2 kt PM2.5; 464 kt CO
6	Alleviation of energy poverty	C	Energy cost reduction relative to disposable income in low income household in 2015: 3.5%p	1.8%p
7	Health and well-being	C	Avoided deaths in 2015 related to: NOx 13082 PM2.5 17157	NOx 9416 PM 2.5 12349
8	Disposable household income	B	Energy cost reduction relative to disposable income in an average household in 2015: 2.2%	1.1 %
9	Innovation impacts	A	RPA, average 2000–2012: 18.9 (Cross-cutting technologies), 22.8 (Industry), 32.6 (Buildings and Households)	
10	Competitiveness	B	RCA, average 2003–2013: 57.94	
11	Turnover of energy efficiency goods	C	Turnover in 2015 for insulation and heating systems: 91.2 M€	46.5 M€
12	Impact on GDP	B	Change in GDP due to energy efficiency in residential buildings (2010–2015): 0.36% p.a.	0.3% p.a.
13	Employment effects	B	Additional employment due to energy efficiency in residential buildings (2010–2015): 114k FTE per year	107k FTE per year
14	Potential impact on energy prices	B	-	
15	Public budgets	B	Additional income tax revenue due to energy efficiency in residential buildings (2010–2015) 4362 M€	4099 M€
16	Industrial productivity	C	Change in industrial productivity due to energy efficiency in 2015: 20.4 Meuro/PJ	21 Meuro/PJ
17	Asset value	C	Additional asset value in service sector in 2015 (compared to 2000): 12029 k€	17780 k€
18	Energy security 1	A	Change in import dependency in 2015: 5.8 %p	4.6 %p
19	Energy security 2	B	Supplier diversity measured by the HHI changed by 0.06 (i.e. more diverse supply)	0.04
20	Impact on integration renewables	C	-	

Table 9
Shortcoming and improvement potentials of indicators.

Indicator	Shortcomings of indicator	Potential improvement of indicator
Energy savings	• BU savings depend on a limited number of policy evaluations	• Continuous updating of BU savings from current studies
Savings of fossil fuels	• Calculation based on yearly split of energy carriers	• Refinement of method considering the order (sequence) in which the energy carrier contributes to energy savings
Impacts on RES target achievement	• No relevant shortcomings	-
GHG savings	• Calculation based on yearly split of energy carriers and their respective emission factors	• Refinement of method considering the order (sequence) in which the energy carrier contributes to energy savings
Local air pollution	• Calculation based on yearly split of energy carriers and their respective emission factors • Only on a national level	• Refinement of method considering the order (sequence) in which the energy carrier contributes to energy savings • Integrating a higher spatial resolution
Alleviation of energy poverty	• 1st income decile might not cover only energy poor households in all countries • Assumption of even distribution of energy savings over all income groups • See disposable household income	• Inclusion of country specific energy poverty characteristics regarding energy poor households • Inclusion of more detailed data regarding distribution of energy savings when available
Health and well-being	• Method based on average pollutant concentration changes • Limitation to outdoor air quality	• Refinement of methodology based on more detailed modelling • Extension of the indicator to indoor air quality
Disposable household income	• Method based on average energy prices in households and average savings per households	• Inclusion of more detailed statistics on energy prices and typical split of savings per income group
Innovation impacts	• Not directly linked to energy savings	• Development of methods to quantify the impacts of energy savings on innovation
Competitiveness	• Not directly linked to energy savings	• Development of methods to quantify the impacts of energy savings on competitiveness
Turnover of energy efficiency goods	• Values for specific investments derived from national study	• Extension of data basis to at least country groups with certain climatic and economic similarities
Impact on GDP	• Limited adjustment of the gross effects	• Inclusion of other main effects in order to estimate the net effect on GDP
Employment effects	• Limited adjustment of the gross effects	• Inclusion of other main effects in order to estimate the net effect on employment
Potential impact on energy prices	• Impacts on prices not reliably measureable with current method	• Refinement using more elaborate methods (e.g. regression models)
Public budgets	• Limitation to income tax revenue	• Extension to other types of taxes
Industrial productivity	• Limitation to industrial productivity • Limitation to effect of reduced energy costs	• Extension to the sector tertiary/services • Extension to other more indirect effects (e.g. performance of employees, etc.)
Asset value	• Limitation to commercial buildings	• Extension of the indicator to private buildings where possible
Import dependency	• See savings of fossil fuels	• See savings of fossil fuels
Supplier diversity	• See savings of fossil fuels	• See savings of fossil fuels
Impact on integration of renewables	• Not directly linked to energy savings	• Development of methods to quantify the impacts of energy efficiency on demand response potentials

As part of future research, the indicator approach developed may be gauged with studies that apply more detailed methods, e.g. based on macro-economic models. Our approach has the advantage that it is easily extended from year to year, making it attractive for policy makers to include the multiple benefits of energy efficiency in their reporting.

approach these indicators may be over- or underestimating the effects.

Indicators, which have no direct linkage to energy savings, such as innovations impacts, competitiveness and the impact on the integration of renewables through demand response, help to provide a more holistic evaluation. The specific shortcomings of the indicators of our framework are listed in Table 9.

On basis of currently available data an online tool was implemented, which can be found on the project's website.[7] It contains data for all 29 countries, although not all of them have a full coverage for every indicator as explained above. Table 10 shows the coverage per indicator and country.

5. Conclusions and policy implications

Our approach sheds light on the impacts of energy efficiency from various angles (multiple benefits of EE) and allows to quantify the effects by means of 20 MB-EE indicators. This approach aims to provide a broad overview on MB rather than an in-depth analysis of a single aspect. By application to Germany for a time period of at least five to ten years the operationality of the approach has been demonstrated.

In the past, a methodologically limited approach using a subset of indicators was implemented by German authorities to monitor the progress of the energy system transformation. However, so far, such a broad indicator set as presented in the present paper has not yet been implemented given the lack of a suitable approach to analyse MB-EEs.

Our methods can be applied by policy makers in the design process of energy efficiency policies, thereby allowing to consider the various aspects at an early stage and potentially facilitating the promotion of EE policies. Also monitoring processes related to energy efficiency policies could benefit from an implementation of our indicator set (or a subset), e.g. by tracking the effects over time.

The indicator set can be applied by researchers to assess several or single aspects of energy savings from energy efficiency policies or related to top-down energy savings.

While we characterised the quality of the various indicators, future improvements in the methodology, e.g. through a systematic gauging of results with in-depth studies on single MB-EE indicators, can further improve the quality of the indicator approach. Further work may also analyse how such MB-EE indicators could be combined to composite indicators, aggregating categories into single indicators. Such aggregate indicators have been developed for renewables (Boie et al., 2016) and for some aspects of energy efficiency (Bosseboeuf et al., 2005).

We exemplified in this paper the MB-EE approach for Germany. For example, our analysis regarding the employment effects of energy

[7] http://www.odyssee-mure.eu/data-tools/multiple-benefits-energy-efficiency.html.

Table 10
Overview of country coverage per indicator (Indicator available for top-down (TD) or bottom-up (BU) data on energy savings; X: Indicator available, but not based on top-down or bottom-up data).

Indicator	AT	BE	BG	HR	CZ	CY	DE	DK	EE	ES	FI	FR	UK	GR	HU	IE	IT	LV	LT	LU	MT	NL	NO	PL	PT	RO	SE	SI	SK
Energy savings	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU
Savings of fossil fuels	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU
Impacts on RES target achievement	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU
GHG savings	TD BU	TD BU	TD BU	TD BU	TD BU	TD	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD	TD BU	TD	TD	TD	TD	TD BU	TD BU	TD BU	TD BU	TD	TD BU
Local air pollution	TD BU	TD BU	TD BU	TD BU	TD BU	TD	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD	TD	TD	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU
Alleviation of energy poverty		TD BU	TD BU	TD BU		TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU		TD	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU
Health and well-being	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU		TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU		TD BU	TD BU	TD BU	TD BU	TD BU	TD BU
Disposable household income		TD BU	TD BU	TD BU		TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU		TD BU	TD BU	TD BU			TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU
Innovation impacts	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Competitiveness	X	X			X		X	X		X	X	X	X	X	X	X	X					X	X	X	X		X		
Turnover of energy efficiency goods	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	BU	TD BU		TD BU	TD BU		TD BU	TD BU	TD BU
Impact on GDP	TD BU	TD BU	TD				TD BU		TD			TD BU			TD BU		TD BU					TD				TD	TD BU	TD	
Employment effects	TD BU	TD					TD BU		TD BU			TD BU	TD BU				TD					TD					TD		
Potential impact on energy prices	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Public budgets	TD BU	TD					TD BU		TD BU			TD BU	TD BU				TD					TD					TD BU		
Industrial productivity	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU		TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU
Asset value	TD BU	TD BU	TD BU	TD BU	TD BU		TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU		TD BU	TD BU	TD BU	TD BU	BU	TD BU		TD BU		BU	TD BU	BU	TD	TD BU	TD BU
Import dependency	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU		TD BU	TD BU	TD BU	TD BU	TD BU	TD BU
Supplier diversity	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU	TD BU
Impact on integration of renewables	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X		X		X	X	X	X	X	X

efficiency showed that from 2010 to 2015 around 570,000 FTE of new jobs were created solely related to energy efficiency of buildings. By way of comparison, the automotive industry, which is one of the most important economic sectors in Germany, employs around 790,000 people equalling to around 610,000 FTE. Extension of the scope of the methodology to a larger number of countries in Europe and beyond appears as feasible, e.g. in the frame of reporting to the United Nation Framework Convention on Climate Change UNFCCC.

Declaration of competing interest

The authors declare that they have no conflict of interest.

CRediT authorship contribution statement

Matthias Reuter: Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing, Investigation, Software, Formal analysis, Visualization. **Martin K. Patel:** Writing - review & editing, Investigation, Methodology. **Wolfgang Eichhammer:** Conceptualization, Methodology, Writing - review & editing. **Bruno Lapillonne:** Methodology, Data curation. **Karine Pollier:** Methodology, Data curation.

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