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Linking energy efficiency indicators with policy evaluation – A combined top-down and bottom-up analysis of space heating consumption in residential buildings

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A B S T R A C T

This paper studies the factors underlying the evolution of the energy consumption for space heating in residential buildings by linking top-down analysis, based on *meso*-indicators, and bottom-up analysis, based on policy evaluations. The top-down analysis (i.e. the perspective from energy statistics) allows one to separate the change in total energy use into activity level, societal factors and energy efficiency gains. The explanatory power of the resulting meso-(statistical) indicators is often limited, if the underlying factors are not examined (e.g. changes in heating levels and patterns, weather effects, cost of energy and policies regarding insulation and heating system standards). We overcome most of these drawbacks by conducting a bottom-up analysis (i.e the perspective from single policy measures), which enables us to discern the contribution of energy efficiency policies to the changes observed with the *meso*-analysis. We focus on space heating consumption in the residential sectors for Germany and Switzerland. A major aim of this analysis is to show the contribution of energy efficiency policies (such as thermal building regulation, subsidy programmes, fiscal measures etc.) towards the changes in this indicator. The results show that the progress in energy efficiency (both autonomous and policy induced) in both countries had the greatest effect (-776 PJ for Germany, −42 PJ for Switzerland) regarding the change in energy consumption for space heating in the period from 2000 to 2016. However, the impacts of "technical and comfort" rebounds (+436 PJ for Germany, N/A for Switzerland) and other developments such as societal changes (+316 PJ for Germany, +35.5 PJ for Switzerland) were found to compensate for a significant part of the energy efficiency gains. In both countries, it was possible to link physical energy efficiency indicators to policy evaluation, but limitations were also identified which are primarily related to data gaps.

1. Introduction

Different aspects of energy efficiency developments in the household, transport and industry sectors have been studied in literature. The energy demand in these sectors has been analysed, both from a top-down perspective (statistical analysis) and from a bottom-up perspective by aggregating individual energy efficiency measures. Thomas et al. [1] developed and discussed several bottom-up and top-down methods for evaluating energy savings in general. An evaluation of methods used to determine realised energy savings was conducted by Boonekamp [2]. Abeelen compared several top-down and bottom-up methods for monitoring the Dutch Long-Term Agreement [3].

Top-down indicators were analysed to monitor the energy transition in Germany [4] and to determine energy efficiency trends and policies in Slovenia [5]. Top-down ex-post evaluation of energy savings is applied in several of Germany's National Energy Efficiency Plans for different sectors [6–9]. Tiangket et al. [10] analyse the energy savings in Thailand's residential sector using top-down methods.

The bottom-up evaluation of energy efficiency policies is the topic of many publications. Grealis et al. [11] review energy policies and civil society efforts to achieve the targets set for Germany's energy transition, with a specific focus on their impact on household energy use. Thollander et al. [12] evaluate several Swedish energy policies targeted at industrial energy efficiency. Ó Broin

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et al. [13] evaluate different types of energy efficiency policies targeting energy consumption for space heating in several European countries.

Overall, this article aims to link top-down indicators to bottom-up policy evaluation to unravel the underlying effects that drive the development of total energy consumption for space heating in households. Most previous analysis focused separately on top-down or bottom-up analysis. To the best knowledge of the authors, earlier efforts have not yet combined top-down and bottom-up approaches to close the research gap concerning the analysis of space heating consumption in a comprehensive way.

The overarching research questions studied in this paper are: what are the main factors influencing the change in energy demand for space heating in households. What is the impact of energy efficiency policies on space heating?

We strictly focus on space heating, thereby excluding domestic hot water supply.

The building sector is most appropriate for a combined analysis of energy efficiency improvement and policy evaluation, as it is characterised by the large and relatively homogeneous energy use for space heating (with regard to the energy carriers and heating technologies) as well as by rather uniform energy efficiency policies, such as building regulations and large subsidies.

In Section 2 of this article, we present the methods used in our analysis, combining both a top-down and a bottom-up approach. After that, we show the policy impacts and other factors, which affect the final energy demand in households. In Section 3, we present the results and in Section 4 discuss these and our method. We provide conclusions from our analysis and the judge the feasibility of further research in Section 5.

2. Methodology

Fig. 1 schematically illustrates the link between the change in final energy consumption (top-down approach) and individual policy measures (bottom-up approach). Changes in energy consumption are only partly related to energy savings or increasing energy efficiency as changes in activity (such as growth in population, number and size of dwellings), or structural changes (economic activity in different sectors etc.) typically also affect energy consumption. Energy savings can be broken down into autonomous savings, i.e. savings that would have occurred even without the influence of policies, and energy savings generated by policies. The latter can be allocated to individual energy efficiency measures.

Both top-down and bottom-up approaches are applied to determine energy savings, in particular those related to energy efficiency policies. However, in both cases, additional factors influence the impacts observed, making it impossible to compare the results directly (Fig. 2).

Energy savings calculated with top-down approaches based on statistical analysis include - apart from the effect of the energy efficiency policy measures (PM) - effects of autonomous savings and policy measures before the time period (including market transformation) under consideration, economic rebound effects, exogenous factors (such as energy prices on the market, annual climate) and structural changes in the economy (e.g. shifting towards less energy-intensive industries) [15]. Bottom-up approaches, based on detailed measure analysis, include - aside from the effect of energy efficiency policy measures - free-rider effects, multiplier effects, direct rebound effects and the effect of a number of exogenous factors similar to the top-down approaches [1].

The "gross savings" established by application of the two approaches (i.e. bottom-up or top-down, see Fig. 2) are not necessarily the same as the results depend on the disaggregation of data and the approach chosen for the bottom-up analysis.

Our analysis is composed of four parts.

1. We begin with a top-down approach using an index decomposition analysis (IDA), which serves to break down the total change in energy consumption for space heating into four main effects: population (pop), dwellings per person (dw/pop), area per dwelling (A/dw) and energy consumption per unit of area (E/A). The fourth component represents the energy efficiency effect from a top-down perspective. In Subsection 2.2, more details are provided on this part of the analysis.
2. We then analyse the energy efficiency effect further from a bottom-up perspective. We identify the impacts of different energy efficiency policies on the energy efficiency effect (see Subsection 2.3).
3. Following that, we analyse factors which counteract policy impacts such as rebound effects (e.g. increased indoor temperature level, longer heating period or larger share of heated living space ("treated area")) and non-compliance (i.e. imperfect policy implementation (see Subsection 2.4).
4. Finally, we discuss the results considering that there may also be autonomous technical progress not necessarily triggered directly by policies. Autonomous progress may also include the impact of earlier policies in force before the period under consideration.

In the following text, after a brief overview of the evolution in energy demand in Germany and Switzerland, we describe the methodology used for the four parts of the analysis.

2.1. Evolution of energy demand

Households (or the residential sector) represent a high percentage of many countries' final energy consumption (27% or 285 Mtoe in the EU; 28% in Germany; and 32% in Switzerland in 2016) [16]. Therefore, this sector has become a focus for policy makers.

According to the 2010 "Energy Concept" of the German Federal Government, the final energy consumption associated with heating in buildings should be decreased by 20% by 2020, as compared to 2008 [17]. However, between 2008 and 2017, a reduction of only 6.9% was achieved [18], leaving a gap of around 13% which is unlikely to be met in the remaining three years. For 2030, Germany has the ambitious target of reducing the GHG emissions of the whole building sector by two thirds compared to 1990 [19].

The Swiss energy strategy 2050, which came into force on 1st January 2018, has a target of reducing the average overall energy consumption per capita by 16% and 43% (relative to the base year 2000) by 2020 and 2035, respectively [20].

The final energy consumption of German households declined by 11% (0.74% per year) from 66.9 Mtoe to 59.5 Mtoe in the period from 2000 to 2016 (see Fig. 3). The dominating end-use in Germany is space-heating, consuming approximately 70% of total final energy [16]. Domestic water heating represents about 10 to 17% while appliances and lighting account for about 10% of final energy in households. The rest, about 3%, is used for cooking. In Switzerland, the final energy consumption of households was about a tenth of the value in Germany but declined similarly by 12% (0.77% per year) from 6.4 Mtoe to 5.65 Mtoe in the period considered. As in Germany, space-heating accounts for approximately 70% of total final energy consumption [16]. The share of domestic hot water is about 12 to 14% while appliances and lighting account for about 11–15% of final energy in households. As in Germany about 3% is used for cooking.

In Germany, the share of space heating decreased by 8 percentage points in the period under review, while the share of hot water production rose by around 7 percentage points. The shares of other end uses remained more or less constant. As a consequence of

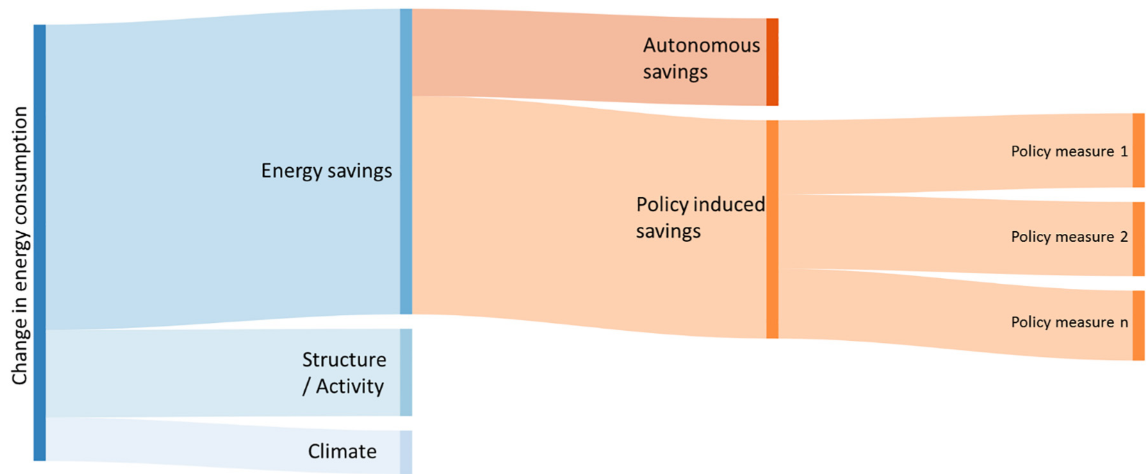

Fig. 1. Link between change in final energy consumption and policy measures [14].

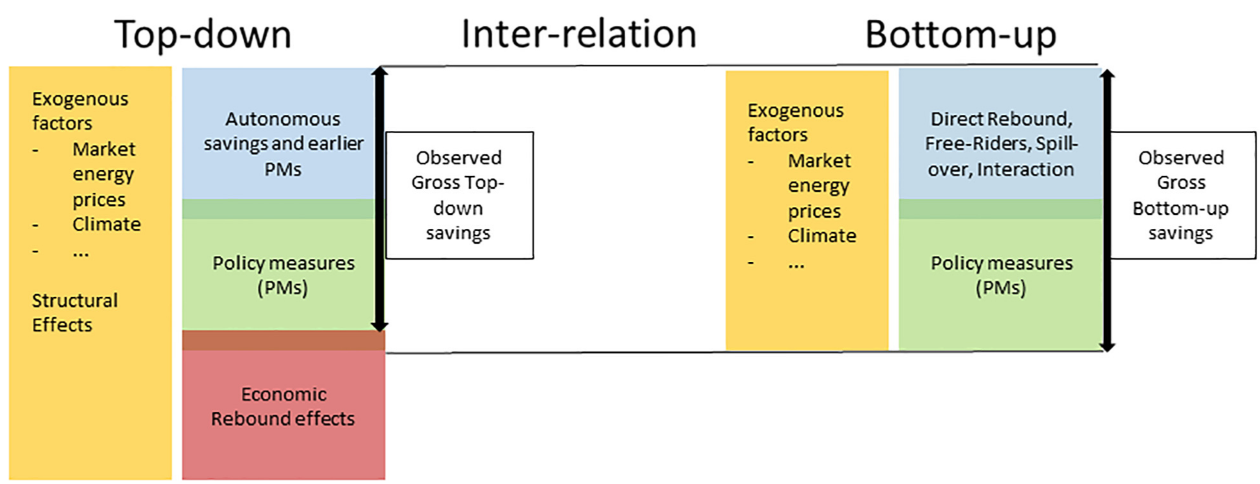

Fig. 2. Factors affecting top-down and bottom-up analysis of energy savings.

reduced specific heat consumption in residential buildings, final energy demand for space heating dropped by 21% (or 1.5%/a between 2000 and 2016). For comparison, in Switzerland, the corresponding reduction was 20% (or 1.3%/a).

Fig. 4 shows the development of weather adjusted[1] specific energy consumption for space heating for Germany and Switzerland during the period from 2000 to 2016. It decreased to a similar degree in both countries (by 33 and 35%, respectively). On the other hand, as a consequence of the counteracting rise in activity (increasing number of dwellings and dwelling size[2]), total energy consumption for space heating decreased less rapidly over the same period.

2.2. Decomposition of energy demand for space heating

For the task of analysing the factors affecting the change of final energy demand for space heating in the building sector, we use an index decomposition analysis (IDA) based on the (additive) Logarithmic Mean Divisia Index (LMDI) method for the top-down approach. We describe the methodology in more detail in Annex A1.

2.3. Energy efficiency policy impacts

We consider Swiss and German energy efficiency policies, which have an impact on space heating consumption in households in the period from 2000 to 2016. As a main source for impact evaluation of energy policies, we use the MURE database [21], which is compiled by national energy policy experts from 30 countries ensuring a high quality of data. The data are enhanced using recent national reporting and policy evaluations from a number of other sources (see Table 1). We here only present a brief overview of measure impacts (see Table 2). More details on measures in Switzerland and Germany can be found in Annex A2.

For Germany, we compiled the measures addressing energy use for space heating in households in the period from 2000 to 2016 (see Table 2). Based on the selected evaluations, which stem from official evaluations that allow us to assume a high degree of comparability, we estimated the share of these impacts affecting only space heating consumption. For our analysis, we also consider policy measures which were in place before 2000 (replaced by more recent ones) but are relevant for the period under review. In order to calculate the overall impact of relevant energy efficiency policies in 2016 we linearly interpolate the impacts indicated in the evaluations, i.e. interpolating between impacts for years given in the policy evaluations (e.g. 2015 and 2020). The aggregate impact (as cumulative annual savings) is corrected for interactions among the package of measures (see Section 4).

[1] Climatic corrections are done in a linear way on the space heating (H) or cooling (AC) consumption on the basis of the ratio between normal degree days and actual degree days: $H = H_n * (1-K) + H_n * K * \frac{HDD}{HDD_n}$ with the share of space heating consumption independent of climate fluctuations K (e.g. 10%) and the consumption at normal climate $H_n = H * \left(\frac{HDD}{HDD_n}\right)^{-1}$

[2] For further information on the developments see the ODYSSEE decomposition facility: http://www.indicators.odyssee-mure.eu/decomposition.html

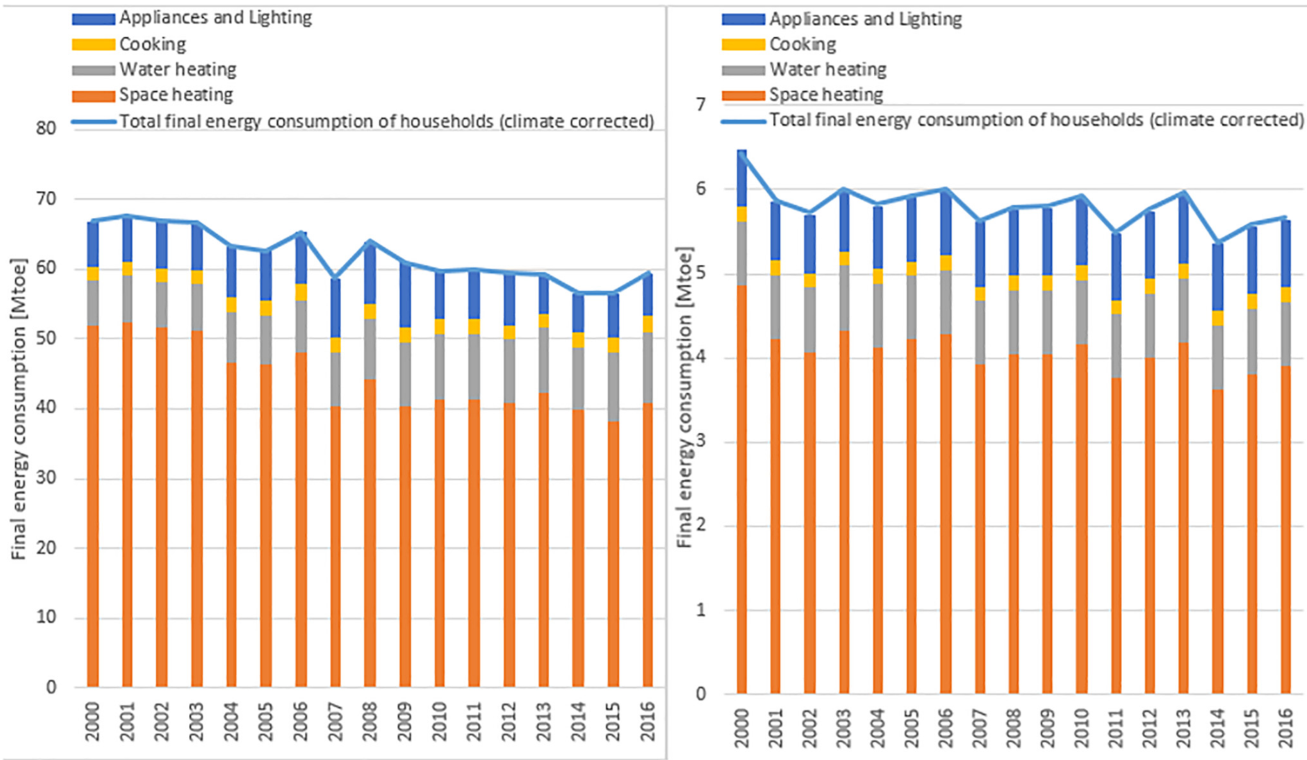

Fig. 3. Development of final energy consumption for households by end-use in Germany (left) and Switzerland (right) for the period 2000 to 2016 [16].

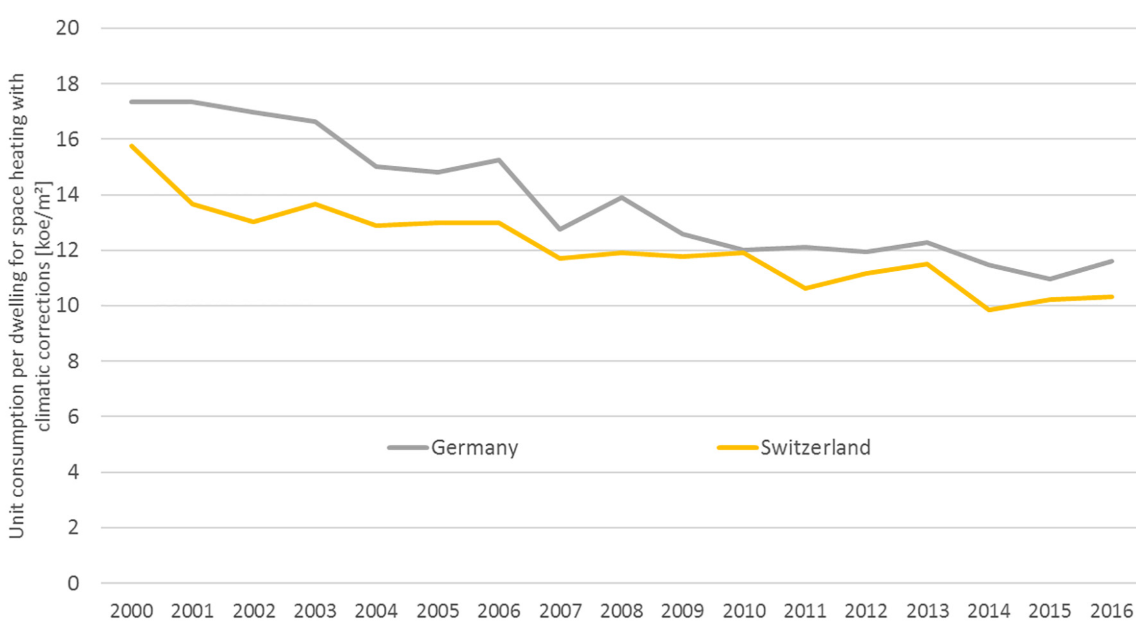

Fig. 4. Development of weather adjusted specific energy consumption for space heating in Germany and Switzerland [16].

In order to account for interactions between policies, we applied a simple discount factor of 0.95 on the gross impact. This value is usually applied for building-related measures to achieve net values including interaction [27]. This factor is applied to measures implemented before 2000 as well, in order to account for possible double counting.

Fig. 5 shows the chronological sequence of implementation of these policies and that of the energy saving ordinances (EnEV) that followed the thermal insulation ordinances.

In Switzerland, there are limited energy policies at the federal level. For this study, three different energy policies are chosen, the aggregate impact of which is shown in Table 3 for the period

Table 1
Data sources for the evaluation of energy efficiency policy measures for Germany and Switzerland.

Main sources for Germany	Main sources for Switzerland[1]
Germany's National Energy Efficiency Action Plan (NEEAP) 2017 [9]	
National Action Plan for Energy Efficiency (NAPE) 2017 [22]	
Annual notifications as required by Article 7 EED [23]	
Evaluations of KfW programmes [24]	Global contributions to the cantons according to Art. 15 EnG. Impact analysis
Cantonal funding programmes – Results of the survey (various years) [25]	
Buildings Programme 2018 Annual Report [25]	
Impact assessment on CO_2 Levy Update until 2015 [26]	

Unlike Germany, for Switzerland, the MURE database only reports the impact of energy policies in terms of CO_2 savings with respect to the starting year and does not report the energy savings. Therefore, we use different background studies to estimate the energy savings attributable to energy policies (see below, Table 3). As we do not have access to the complete model used in the background studies, we are limited by having to rely on the reported results.

Table 2
Impact of energy efficiency policy measures implemented in Germany [21].

Main policy measures (2000–2016)	Starting year	Ending year	Impact on space heating in 2016 [PJ]
Energy Savings Ordinance (EnEV) (new and existing buildings), implementing the European Energy Performance Directive of Buildings EPBD	2002	–	601
KfW programmes for energy-efficient construction and renovation (incl. KfW CO_2 Building Redevelopment Programme)	2005	–	80
Renewable Energy Heat Act (EEWärmeG)	2009	–	36
Market Incentive Programme for Renewable Energies (MAP)	1999	–	53
KfW CO_2 reduction	1999	2004	13.9
KfW Housing Modernisation Programme II	2000	2002	4.2
KfW Housing Modernisation Programme 2003	2003	2004	1.2
KfW Ecological Construction	2005	2009	1.4
On-site advice (carried out by the Federal Office for Economic Affairs and Export Control BAFA)	1998	–	2.1
Relevant policy measures before 2000			
Wärmeschutzverordnung of 1977 (WSVO'77; Thermal Insulation Ordinance of 1977)	1977	1982	-/- (estimated by
Wärmeschutzverordnung of 1982 (WSVO'82)	1982	1994	simulation)
Wärmeschutzverordnung of 1994 (WSVO'94)	1994	2002	2.0

from 2000 to 2016. The three most important policy measures are cantonal energy policies, the Buildings Programme and the CO_2 Levy.

Table 3 shows the estimated policy impacts for Switzerland:

- We estimate that cantonal energy policies contributed to 14 PJ of energy savings in the period from 2001 to 2016 (2001 was the pilot implementation year).
- The CO_2 Levy was not allocated any energy savings; we argue in Annex A2 that most of the impact is on fuel change. However, this may lead to some degree of underestimation of impacts from this measure.
- We estimate the cumulative energy saved due to the measures implemented under the Buildings Programme from 2010 to 2016 at 6.0 PJ

2.4. Identification and quantification of measure overlap, rebound effects, non-compliance and over-achievement

When evaluating energy saving from energy efficiency policies under the National Energy Efficiency Action Plan (NEEAP) or National Energy and Climate Plan (NECP), applying a bottom-up approach, the aim is to minimise the effects of distorting factors by introducing different correction factors. In this section, we deal with the overlap of different measures, rebound effects, non-compliance and over-achievement.

So-called instrument factors have been developed to correct for double counting [9]. Double counting can occur because a specific energy end-use is addressed by a larger bundle of instruments and programmes. For example, building owners often simultaneously take advantage of information measures, such as an energy consulting programme, and a subsidy programme for the renovation of the building. If one were to evaluate the two instruments separately, the full energy savings achieved could be attributed to either of them. The instrument factors used in the German NEEAP ensure that double counting is corrected and that the calculated energy savings are included in the total savings only once. Regional and municipal policy measures can play an important role, however, there are no reliable individual quantitative evaluations, and hence their impacts cannot be included in the total.

A second distorting factor is the rebound effect. Rebound effects that influence the use of space heating can play a significant role because of the high proportion of space heating in the total energy consumption of households. These rebound effects mainly result from the increasing demand on thermal comfort. This increase depends on attitudes toward thermal comfort, individual activity levels, air temperature or humidity. In addition, the income level of occupants as well as building ownership affect the magnitude of rebound effects [28]. The rebound effect for space heating in households is estimated at 10–50% [29–33]. Rebound effects can have a shorter and a longer-term component. Short-term rebound effects are directly linked to the insulation of a house, for example, and occur not long after the house has been insulated (e.g. due to changes in thermal comfort). Longer-term effects occur because the share of expenses for heating is shrinking, which allows residents to reach higher comfort levels. Examples for such longer-term rebound effects are at least in part larger dwelling sizes per

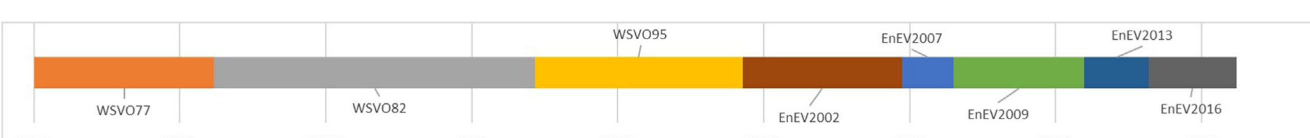

Fig. 5. Timeline of the energy savings ordinance (EnEV) and its predecessor Wärmeschutzverordung (WSVO) in Germany.

Table 3
Impact of energy efficiency policy measures implemented in Switzerland.

Main policy measures (2000–2016)	Starting year	Ending year	Impact on space heating in 2016 [PJ]
Cantonal Energy Policies (Energiepolitik in den Kantonen / Politique énergétique dans les cantons / Politica energetica dei cantoni)	2001	–	14.0
CO_2 Levy (CO_2-Abgabe / Taxe sur le CO_2 / Tassa sul CO_2)	2008	–	0.0
Buildings Programme (Gebäudeprogramm / Programme Bâtiments / Programma Edifici)	2010	–	6.0

capita, which was already included in the top-down analysis of Section 2.1. The lower specific costs for heating as a result of improved thermal performance of buildings contribute to the behaviour of heating larger floor areas to comfortable temperatures.

In this section we consider the following rebound effects, which are not easily separated statistically: increase in the room temperature level after the implementation of efficiency measures and the extension of the heating period.

The rebound effect due to heating to a higher room temperature after the implementation of efficiency measures such as the replacement of heating systems or building retrofit can be estimated by comparing the "standard" temperature levels assumed in the Energy Savings Ordinance (EnEV) and in-situ measurements by energy service providers for the real estate industry and private apartment owners. These determined an average room temperature of 19.6 °C within the heating period of 2014 (October to March, see Table 4). In the EnEV of 2014, the standard room temperature was set at only 19 °C instead of the 20 °C that had been the standard before[3], thus setting a lower average room temperature.

The comfort driven rebound effect typically diminishes over time as the need for additional energy services saturates over time. In the case of space heating, these energy services would be the increasing spread of central heating and increasing average indoor temperature, temperature, the demands for which would then be more saturated.

While there was an undeniable increase in average room temperatures in residential buildings in the time period from 1970 to 2000 according to Fig. 6, temperature levels have levelled off in Germany in the last 5–10 years, arguably following a similar trend as in the UK (albeit at a higher temperature level, i.e. 19.6 °C; see Table 4).

The overall rebound effect regarding space heating consumption after retrofitting of buildings is estimated to still be around 36% of the energy savings achieved for Germany Table 5 [33]. Not only rising room temperatures contribute to this overall rebound effect, but also inappropriate operation of the heating system by the resident, overdesign of the heating system (i.e. heating loads too low), changes in heating from radiators to underfloor heating ("thermal inertia"). Further reasons can be over-ventilating by the residents or technological failures (regarding installation of heating systems or insulation or usage) [33,36].

The effect of non-compliance with building standards for new constructions or retrofitting of residential buildings in Germany might only be limited. A study by ICF [37] found that the compliance with MEPS (minimum energy performance standards) regarding buildings is one of the highest in the European Union and

Table 4
Average room temperatures in multi-family homes in the heating period 2013/2014 (n = 38,500) [34].

Room type	Average room temperature [°C]
All heated rooms	19.6
Living room	20.3
Kid's room	18.9
Bathroom	20.2
Kitchen	19.4
Bed room	18.5

achieves a value of at least 87% for new buildings (existing buildings in Germany not covered), while also having an overall strong MEPS regime. While the results of the study suggest that the compliance rate for renovation of existing building is usually lower compared to the one for new building, the strong MEPS regime in Germany should lead to a relative small deviation between both. This suggests that the effects of non-compliance for new construction and retrofitting can be interpreted as being relatively small in Germany.

At the same time, a certain degree of over-achievement can be observed in German renovation practice. The study by IWU [38] shows that the requirements for renovation of the EnEV 2002/2007 were clearly exceeded in the modernisation practice of the years up to 2009. In this time the insulation material thicknesses on average were already close (up to approx. 1 cm) to the level required by the EnEV2009. This indicates that the impact of regulating policies might not be properly represented in evaluations regarding their direct effect on the standards actually implemented in construction and renovation.

Even in those renovation cases in which no subsidies were claimed, such over-fulfilment can be observed as the average thickness of the insulation in modernisation measures from 2005 to 2009, at 10.6 cm, is only 1.5 cm below the requirements of EnEV2009, thereby exceeding the requirements of both EnEV2002 and EnEV2007.

The thermal transmittance value (U-value) strongly exceeded the minimum requirements set by EnEV2007. If standard insulation materials for exterior walls are assumed, the additional insulation thickness achieved in previous modernisation practice already almost reaches the minimum U-value of 0.24 W/(m^2*K) stipulated by EnEV2009, while EnEV2007 and EnEV2004 only required a U-value of 0.35 W/(m^2*K) for the insulation of exterior walls for the retrofitting of existing buildings. This example of course only covers exterior walls. However, since heat losses are highest in exterior walls (~30%) followed by roofs (~20%), this example shows how exceeding the standards can generates high unexpected savings.

We estimate the additional effect of over-fulfilment for new buildings to be about 10% of the estimated saving for buildings standards for new construction based on the data regarding the achieved building standard beyond EnEV standards and the respective funding rates (to avoid overlap with KfW financial support measures) found by the study of IWU ([38]). For the renovation of existing buildings we estimate the additional effect of over-fulfilment at around 27% of the savings estimated for the buildings standards for existing buildings (taking into account only measures implemented without financial support, for which the share is very high for retrofitting measures in Germany). Table 5 lists a summary of the assumptions applied for estimating the different effects.

In the case of Switzerland, cantonal energy policies are cross-cutting across sectors and different measures evaluated as a part of these policies are shown in the Table A.1 (Appendix). Although the Buildings Programme is managed at the federal level, it is implemented by cantons (see Annex A.2 for details) and runs in parallel with cantonal energy policies. Further, there is no double

[3] Standard DIN V 4108–6 defines a room temperature of 19°C and a ventilation rate of 0.7 volumes per hour as the energy service to be achieved. [35]

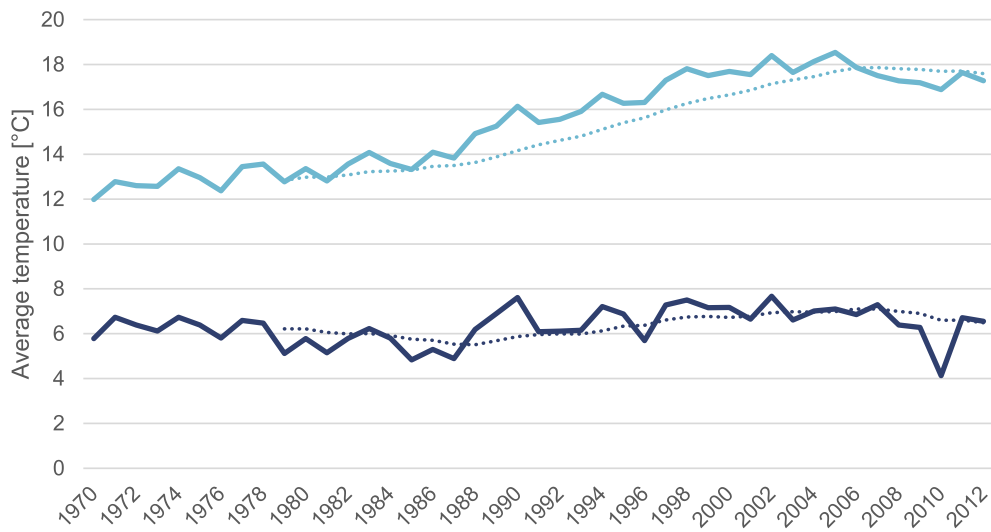

Fig. 6. Average (and trend) indoor temperatures (light blue) vs. outdoor temperatures (dark blue) in the UK [35] (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Table 5
Assumptions applied for the calculations of factors.

Effect	Factor
Rebound effect (societal)	Calculated using decomposition
Rebound effect (technical/comfort)	36% of energy efficiency gains
Over-fulfilment of standards	10% for new construction 27% for existing buildings

counting of the impact of both programmes as financial resources for both programmes are separate and models used for estimating energy saving impacts of these programmes evaluate the impact of funded measures only. However, an overestimation of energy savings from the building programmes has been reported [39].

Rebound and prebound effect, non-compliance and overachievement also play a role in Switzerland. A prebound effect, which is the difference between the theoretical and actual final energy consumption before building renovation, has been reported as being at 30% (assessed for 3,400 households) in Germany [40] (also reported in [41]) and is estimated at 23% (assessed for 1,172 buildings) in Switzerland [42]. In both countries, rebound effects have been reported especially in low energy consumption dwellings.

A thermal energy performance gap (actual energy consumption lower than theoretical) of 11% (median value) was reported for Switzerland, which is attributable in part to the rebound effect [43]. However, it varied with the energy label and the period of construction of the building. In general, buildings with low energy ratings were found to consume less energy than expected while those with higher energy ratings consumed more than expected, leading to a mixed effect of overperformance and underperformance of buildings [43]. Khoury et al. [44] and Mojic et al. [45] also observe the rebound effect in Switzerland and report user behaviour as an important reason for the thermal performance gap in buildings. In a qualitative study (based on interviews of energy experts), non-compliance was identified as one of the reasons of thermal energy performance gap in Switzerland among others [46,47].

2.5. Other effects

Besides the rebound effects, which are mainly linked to residents' demand for comfort, there are different other effects which have an impact on the energy demand in buildings. These are not only effects counteracting energy efficiency but also positive ones (e.g. autonomous technological progress) and can have a substantial impact on the overall energy efficiency progress in the buildings sector. This autonomous progress is driven by the increasing availability of new energy efficient technologies over time as well as increasing or higher expected energy prices [15]. In the context of this study, autonomous progress is identified as the overall progress in energy efficiency in residential buildings minus the impact of policies adjusted for other important effects such as rebound, over-fulfilment and non-compliance.

Due to the long lifetime of building stock, policy targeting this sector has a long-lasting effect, meaning that policies implemented prior to the period analysed continue to have an effect on the energy efficiency of the overall building stock even though these policies have already ended. Thus, we include the impact of discontinued policies in our analysis to distinguish autonomous progress properly from policy impacts.

We estimate the improvement of the building stock's thermal performance based on the observed tightening of German building regulations (every 5–7 years) by about 20% compared to previous regulation. Assuming a destruction rate of 0.5%/a of the overall building stock, a new construction rate of 0.6%/a of the total building stock, and a retrofitting rate of 0.5%/a, we estimate the effect of "old policies" implemented prior to the year 2000 (such as WSVO'77 and its successors WSVO'82 and '95), for the period 2000–2016.

The results of this simulation as depicted in Fig. 7 illustrate the strong effect of "old policies" on the building stock in 2016 and beyond. About two thirds of the overall changes in energy consumption per square meter in residential buildings can be attributed to the impact of measures implemented prior to the year 2000.

As the German building stock grew more rapidly in the latest period i.e. by 0.4%/a in the period from 2000 to 2016 as compared to 0.2%/a from 1976 to 2000, the absolute effect of "old policies" is smaller than shown in Fig. 7. The absolute effect of policies active prior to 2000 can be linked to about half of the total reduction in final energy consumption related to space heating in residential buildings.

Energy prices are seen as another driver of autonomous progress. However, for Germany, expenditure elasticity for residential heating energy demand is below zero, which suggests that German households see it as a necessity and thus residential energy demand does not react significantly to price changes. For high-income households, the reaction on energy prices is slightly greater compared to low-income households [48], which suggests that energy can be characterised as a luxury good with increasing

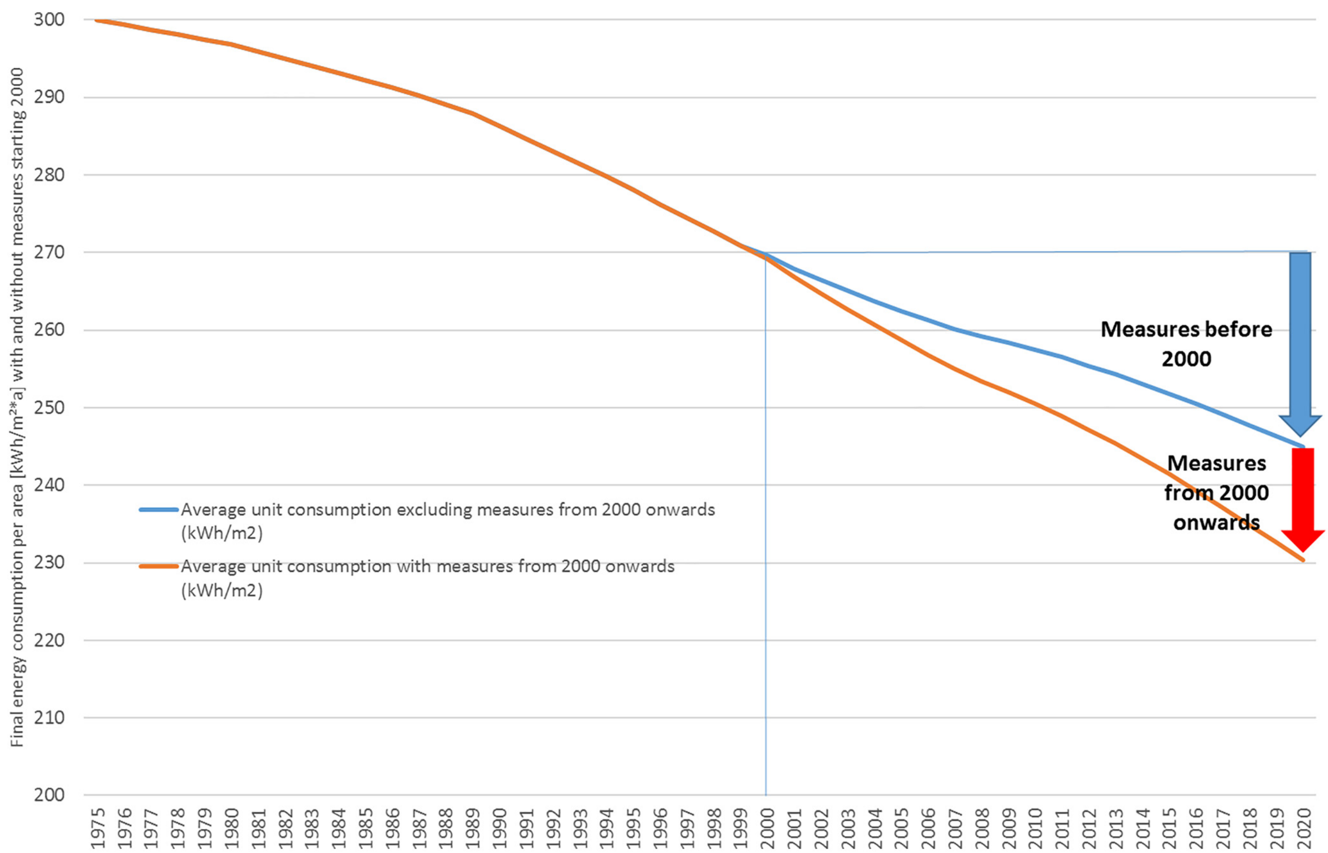

Fig. 7. Estimated effect of energy saving measures prior to 2000 on the average specific energy consumption in residential buildings (compared to the effects of more recent measures).

household income. This may lead to a rebound effect in the case of higher income households [49]. A meta-analysis by Labandeira et al. [50] suggests that agents somewhat react to price changes in energy products; this reaction is greater in the long term than it is in the short term and it is quite similar among different energy carriers. Thus, in the long term, price changes and the reaction of households could contribute to autonomous progress. As shown in Fig. 8, energy prices related to space heating were quite stable over the last 12 years (though with more cyclic changes for heating oil), suggesting the limited impacts of those prices.

Another factor that affects the energy consumption for space heating in households is the choice of heating technology. We discuss this factor in Annex A4.

Unlike the case of Germany, where policy measures have been in place since 1982, policies in Switzerland have been implemented more recently with cantonal energy policies commencing in 2001. Thus, heat demand savings in buildings cannot be attributed to policies before 2000. However, as in Germany, there are autonomous improvements due to higher technical efficiency of heating systems, better building insulation, and an increased awareness concerning energy efficiency in Switzerland. Furthermore, as in Germany, there is a limited impact of fuel prices, as the heating demand is inelastic to changes in prices.

It is important to note that in the case of Switzerland cantonal energy policies have not been comprehensively assessed, instead only the impact of those measures which involve the use of public money (listed in Table A.1) have been evaluated. Apart from these, there are other policies at the federal and cantonal levels such as model regulations of the cantons in the energy sector or MuKEn (Mustervorschriften der Kantone im Energiebereich), tax laws and incentives, spatial planning instruments etc. to encourage energy efficiency in buildings, which also lead to energy savings. The impacts of these measures have not been evaluated separately and are not reported in this paper. Hence, 'other effects' in the case of Switzerland include over-fulfilment, under-fulfilment, prebound, rebound, non-compliance, and autonomous improvements effects, yet their independent impact is indiscernible.

3. Results

In the following section, we present the results of our analysis for Germany and Switzerland.

3.1. Germany

Final energy consumption for space heating in Germany's households decreased from 2,170 PJ in 2000 to 1,710 PJ in 2016 (see Fig. 9). The effect due to changes in population numbers were rather small (-2 PJ) as these were quite stable in the period considered. At the same time, the number of persons per dwelling decreased from 2.14 to 1.95, leading to in an increasing effect on final energy demand of 162 PJ. The size of the dwellings in Germany also grew in the period studied (from 84.5 m^2 to 91.75 m^2 or by 9%), resulting in a final energy increase of 156 PJ (practically identical in size with the reduced occupancy rate). Due to the increase in energy efficiency, the energy consumption for space heating in relation to living space has fallen sharply. This resulted in a reduction of 776 PJ, representing the dominating effect according to the top-down decomposition.

Of this effect of increasing energy efficiency in residential buildings, about 840 PJ can be directly attributed to the impact of energy

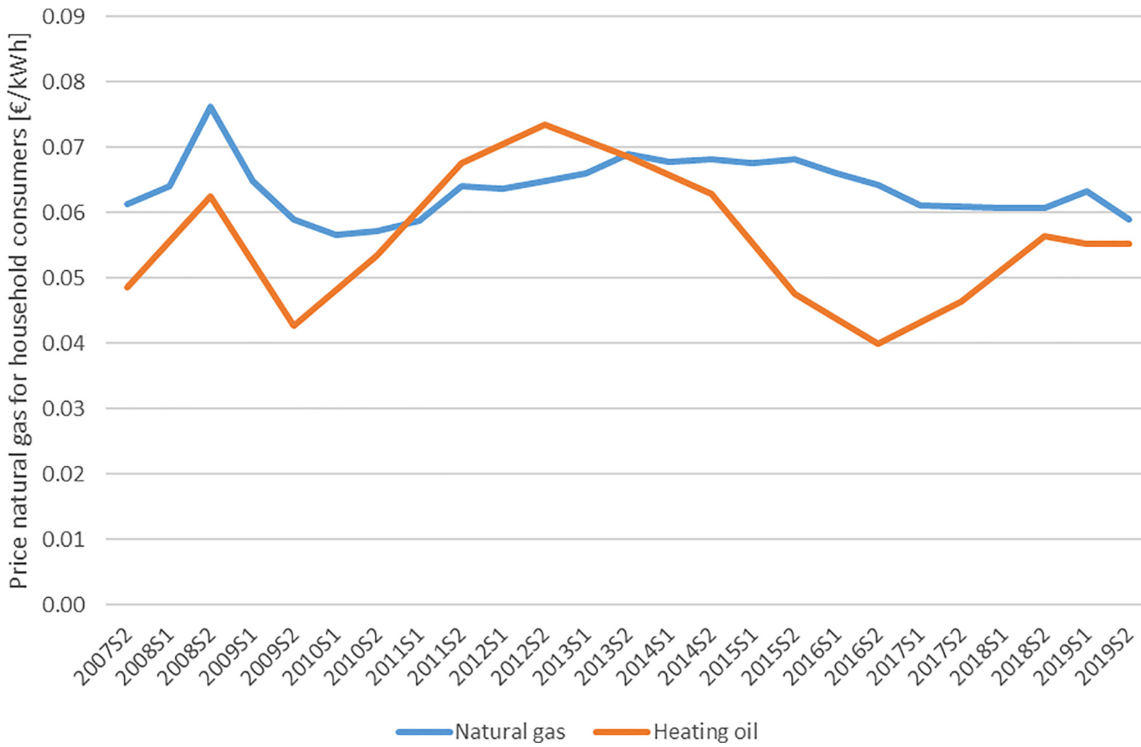

Fig. 8. Cost of natural gas for household consumers (Band D2: 20 GJ < Consumption < 200 GJ) [51] and heating oil (delivery of 30–50 hectolitres) [52] in Germany.

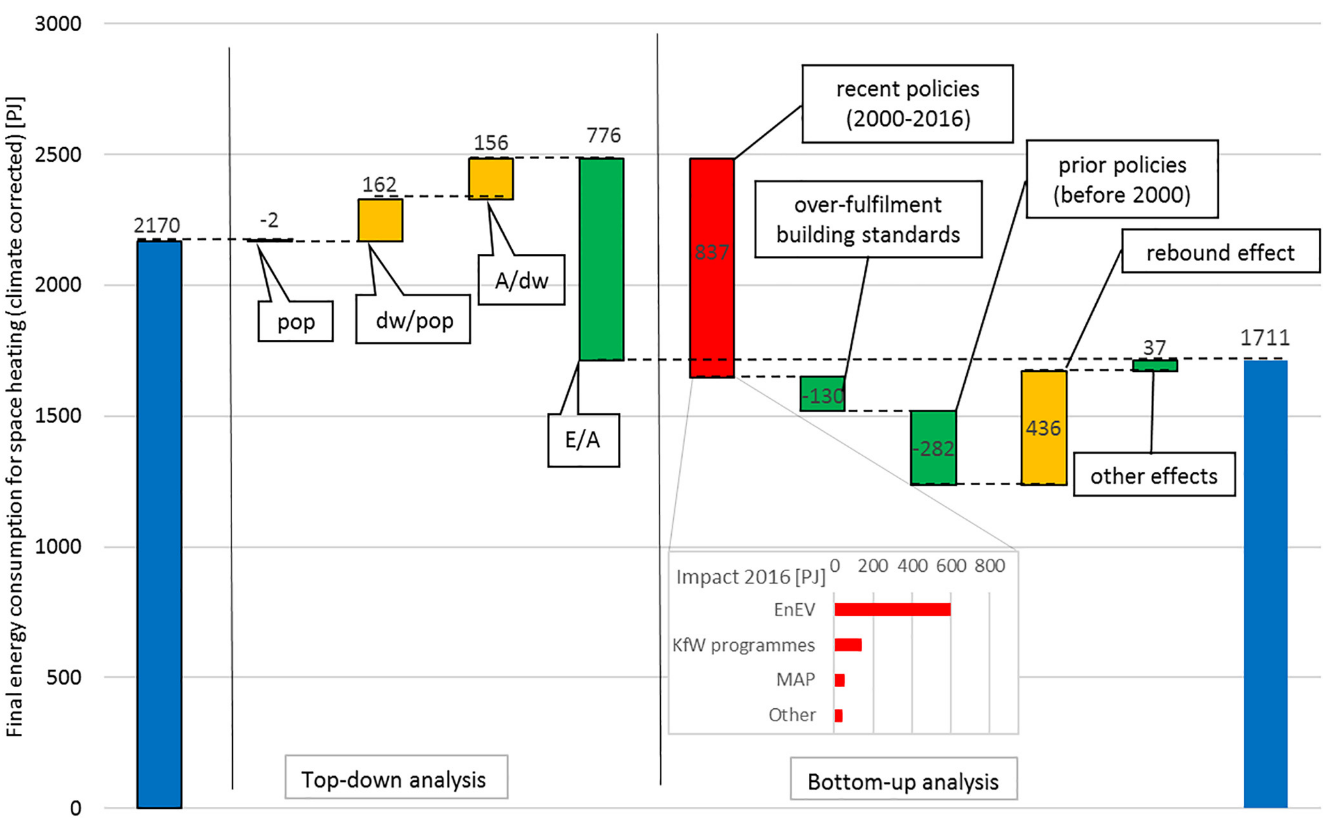

Fig. 9. Linking bottom-up and top-down analysis of space heating consumption for Germany.

efficiency policies on a national level, which have been subject to an evaluation. As we are comparing the energy savings for a specific end-use in a single sector bottom-up savings are of a higher magnitude as the top-down savings, as in the latter effects such rebound etc. are already included, which decreases their size substantially.

In addition, a significant share of energy retrofits were implemented without any subsidies. According to the evaluations of Diefenbach et al. [53] buildings meeting much higher standards than the applicable EnEV (i.e. KfW standards) were built without subsidies in well over a third of cases between 2005 and 2009. This over-fulfilment of building standards in new construction and renovation of existing buildings amounts to about 130 PJ of energy savings.

The energy savings from pre-2000 policies (energy efficiency standards for buildings WSVO'77 and WSVO'82), in the current building stock were estimated at 282 PJ between 2000 and 2016.

Regional programmes for renovation and new buildings exist in several federal states in Germany. These programmes are not systematically evaluated resulting in a lack of information. This might be due to the minor effects induced by these programmes on a larger scale. Thus, the impacts from these programmes are attributed to the residual "other effects".

The rebound effect (short-term after retrofits) is estimated to be around 436 PJ (36% of total energy savings achieved). Together with the "societal" rebound (due to the increase in floor area; quantified in top-down analysis, 156 PJ) the short-term rebound effect after retrofitting accounts for almost 600 PJ, meaning that the change due to energy efficiency improvements (factor E/A) would have been more than 1,350 PJ had no rebound effect occurred.

"Other effects" covers developments such as further autonomous progress and account for the rest of total change (37 PJ) and cannot be split up further.

In combination the societal and technical rebound effects have strongly influenced the energy savings in space heating in Germany's residential sector and eroded a large share of the impact potentially achieved by policy induced and autonomous energy efficiency improvements.

3.2. Switzerland

Energy consumption for space heating in Swiss households decreased from 174 PJ in 2000 to 167 PJ in 2016 (Fig. 10). The effect of population growth was large and contributed to an increase of about 27 PJ during the period considered. At the same time, the number of persons per dwelling remained almost constant at 2.2, leading to negligible changes in energy consumption. The size of the dwellings grew marginally from 95 m^2 to 98 m^2 (by 4%). This contributed to an increase in final energy use of about 8 PJ. Due to the higher energy efficiency, the energy consumption for space heating per unit area deceased by about 42 PJ. About 20 PJ can be attributed to the impact of energy policies at the federal level, which have been subject to an evaluation.

About 22 PJ of energy savings is the remaining impact which can be attributed to other cantonal energy policies and programmes, which have not been considered in this study. These include economic instruments such as tax exemptions and tax incentives, regulatory instruments such as energy efficiency obligations and utility demand side management programmes; and energy efficiency awareness programmes, which led to wider adoption of energy efficiency measures. These measures are implemented as a part of cantonal energy policies which are funded by the cantons themselves but their cost effectiveness and impact have not been evaluated [25]. Autonomous improvements could also explain some part of energy savings, while some energy retrofitting would have been implemented without subsidies. Unlike in Germany, the considered energy policies commenced in 2000 in Switzerland and hence there is no impact of policies prior to 2000. Over-fulfilment of building standards and rebound effects have not been reported in any of the studies and are therefore not included in the assessment for Switzerland.

4. Discussion of results

In the first part of this section, we discuss the main results, while in the second part we focus on methodological choices.

Our analysis is divided into two separate parts. First, we applied index decomposition to identify the underlying effects of the total change in energy consumption for space heating in residential buildings. This analysis shows that the change in final energy consumption for space heating in residential buildings is related to increasing energy efficiency. For Germany, this is counteracted by a decrease in occupancy rate and an increase in dwelling size. These factors are much lower in Switzerland (esp. a much less pronounced trend to lower occupancy rate) however, they are also present. These findings are in line with our analysis in Reuter et al. [54] or with an analysis performed for a comparable country such as Austria in Holzmann et al. [55].The top-down analysis shows different results for Germany and Switzerland, notably in a number of societal trends and rebound effects: while in Germany, the effect of changes in population size is almost zero, in Switzerland this contributes to the strongest increasing effect due to the growth of the population, in particular through immigration. In addition, the "societal rebound" due to the decrease of persons per dwelling differs between both countries. In Switzerland, this effect is very limited, while it represents the most important upward driver in Germany. This difference could be due to the natural limitation of built area in Switzerland, which prevents or slows down development of single-family homes (SFH) more than in Germany. This effect could increase in Germany in the future as the housing shortage in metropolitan areas increases.

An increasing effect due to larger homes can be observed in both countries. While in Germany an increase in living area per dwelling of almost 10% can be observed, in Switzerland it is limited to 4%.

The change due to energy efficiency is further decomposed using a bottom-up approach. The analysis shows that this change can be only partially explained by the effect of policies implemented in the time period considered (2000–2016), but that preexisting policies (in force before 2000) allow us to close the explanation gap. In Germany, the building standards (EnEV) and KfW subsidy programmes have the largest impact with contributions of 601 PJ and 143 PJ respectively by 2016 (including interaction among policies) covering most of the total policy impact of 838 PJ.

Further, we estimated the effects of over-fulfilment of building standards in the renovation practice and the new construction of residential buildings as well as other effects including rebound.

While the method (i.e. LMDI) used in the first part of our analysis for the top-down decomposition of energy demand is well established, the methods we used for estimating the effects of the second part might have some caveats and uncertainties due to assumptions included in the calculations.

The simulation we conducted to estimate the effect of policies prior to 2000, is partly based on assumed average effects of the implementation of improved buildings standards and changes in surface area and number of dwellings. Where no data were available (i.e. up to 1987 for the number of dwellings and 1994 for surface areas), data for earlier years (back to 1975) were calculated based on average changes, which should not deviate too much from actual developments earlier than 1987 or 1994.

The policies that are considered in our analysis are often not purely aiming at space heating demand but may also have impacts

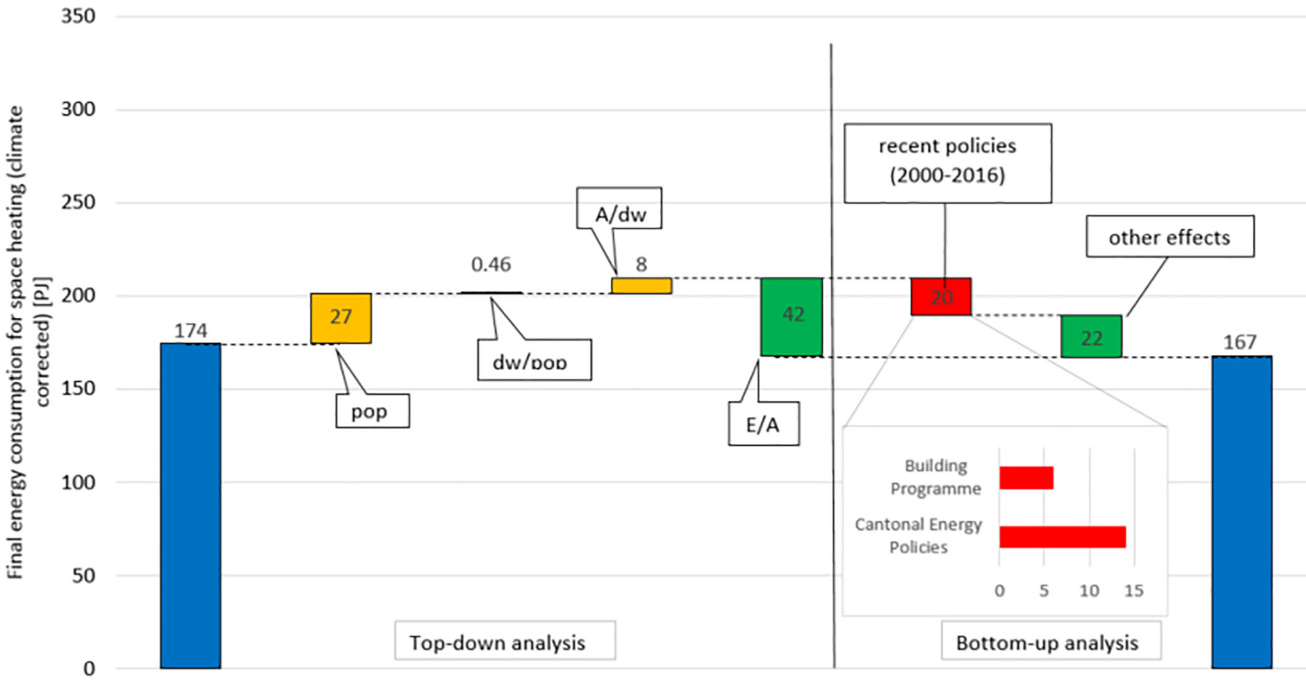

Fig. 10. Linking bottom-up and top-down analysis of space heating consumption for Switzerland (2000–2016).

on energy consumption for domestic water heating through the replacement of heating systems, most of which are also used to produce hot water. This share of the total savings can be expected to be quite small, though, as the accompanied increase of overall efficiency regarding water heating due to fuel switching can be considered marginal and has more of an effect on related GHG emissions rather than on energy savings. Thus, the impact of energy policies in our analysis tends to be slightly overestimated due to the possible inclusion of energy savings, which cannot be completely linked to space heating.

The effect of over-fulfilment is estimated based on the in-depth study on the buildings standards in Germany, which provides an excellent detailed basis but covers the status quo before 2009. Of course, rapid changes in construction and renovation practices from 2009 up to 2016 are not impossible, however, we assume them to be unlikely. The experience reported regarding compliance with standards is more mixed for Switzerland.

While the rebound effect plays an important role for energy efficiency in residential buildings, the numerous studies devoted to this topic come to very different conclusions regarding the possible magnitude of such an effect for residential heating (estimates range from 20% to 50% for Western European countries). For Germany, this effect is estimated to be around 36% of the energy savings achieved after retrofitting of a building. We argue that a certain level of saturation regarding rise in room temperatures and heating duration over time, as one important rebound effect, should have occurred in German households already. Other possible contributions to rebounds are also likely to occur (e.g. misuse and overdesign of heating systems, technical failures). Based on available data it is impossible to separate the contributions underlying this rebound effect and would require further large-scale measurement campaigns. Thus, we show only an aggregated rebound effect in our analysis.

While we include as many effects as possible, we cannot completely account for the residual savings, which arise from the comparison of top-down with bottom-up approaches and which is explained by "other effects". For Germany, this residual term is small, but further analysis could provide further insights regarding potentially important effects.

For Switzerland, the bottom-up analysis is more limited than for Germany due to the lack of suitable data regarding the over-fulfilment of energy performance standards or (non–) compliance in general, as well as rebound effects that are not associated with societal trends and developments. Policies prior to the period 2000 to 2016 are not relevant in Switzerland as no relevant policies were implemented prior to 2000. The "other effects" for Switzerland are almost as big as the overall policy impact. This is due to the fact that only half of the total energy savings associated with energy efficiency progress, as derived from top-down analysis, can be explained with energy efficiency policy impacts as other cantonal programmes and energy policies had not been evaluated and hence could not be included in this analysis.

While our analysis shows some caveats and could be improved upon in the future, as more data are available, it establishes new knowledge regarding the effects that influence the development of space heating consumption in residential buildings and provides insights regarding their size and how they are connected.

5. Outlook and conclusion

This paper examines space heating in the residential sector and the factors underlying the evolution of key energy efficiency indicators by linking top-down analysis, based on meso- (statistical) indicators, and bottom-up analysis (contribution of energy efficiency policies to the top-down indicators).

Our top-down analysis shows how different developments in the time period from 2000 to 2016 affect the energy consumption for space heating in residential buildings and it quantifies the effects of changes in population, in dwellings per capita and area per dwelling. Changes due to energy efficiency improvements have the biggest impact from the top-down perspective, besides "societal" rebounds for both Germany and Switzerland.

The effect of energy efficiency improvements, established from a top-down perspective, is linked to the bottom-up perspective and the results imply that besides direct policy impacts, effects such as over-fulfilment of building standards and rebound after retrofit ("technical" rebound), strongly influence space heating demand in residential buildings in Germany. For Switzerland, such effects cannot be included in the analysis at this point. These could be further investigated when data regarding the compliance with minimum energy performance standards and rebound after retrofits become available for Switzerland.

For Germany, our analysis shows that subsidy programmes have strong spill-over and multiplying effects. Further, an anticipatory effect can be derived from the observation of over-fulfilment regarding minimum performance standards in buildings. This observation could also lead to the conclusion that raising the minimum requirements is not fast enough to follow real developments and could therefore be accelerated.

Future research could be devoted to further decomposing and particularly quantifying the components of the residual effects ("other effects") in our analysis. Although these residual effects are quite small for Germany, quantification of these could be of particular interest to identify other important effects that might be hidden in the aggregated residual effect. For Switzerland, these "other effects" have a substantial part in explaining the overall change due to energy efficiency and should be further assessed. This is on the one hand due to the lack of evaluations of other cantonal programmes and energy policies and on the other hand due the lack of data regarding the already identified effects.

The methodological basis for the determination of these "other effects" requires further refinement and - more importantly - additional data. This is especially the case for Switzerland as such data would help to decompose the "other effects" regarding important influences such as (non–) compliance with building standards, rebound (after retrofitting of buildings) or over-fulfilment.

The individual components of the overall rebound effect (societal and technical) represent another interesting future research topic, as these effects strongly influence the savings achieved in residential buildings as shown in our analysis. Learning more about these components which contribute to rebound effects plays an important role in the design and adaptation of existing policies, also in view of their importance for the achievement of more ambitious targets on an EU and national level.

An improved data basis, relevant for future research, should, for example, cover the development of indoor temperatures in dwellings over time and monitor changes within the building stock more precisely. Improved and openly available databases on energy performance certificates (EPCs) for buildings, for example, could help to provide at least parts of such data needed and allow more sophisticated analyses through a better mapping of the properties in the building stock (e.g. at the level of single buildings).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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Appendix A

A1 – Methodology: Index decomposition analysis

The methodological foundation index decomposition analysis and its application has been described in several studies [54,56].

In this study, we decompose the changes in climate corrected final energy consumption for space heating FEC_{sh} between 2000 (0) and 2016 (T) as follows:

$$\begin{aligned} \mathrm{FEC}_{\mathrm{sh}}^{\mathrm{T}} - \mathrm{FEC}_{\mathrm{sh}}^{0} &= \Delta FEC_{sh} \\ &= \Delta FEC_{ACT} + \Delta FEC_{SOC} + \Delta FEC_{COM} + \Delta FEC_{EFF} \end{aligned} \tag{1}$$

The four factors are defined as follows:

- Population (activity)

$$ACT = \mathrm{w_i} * \ln\left(\frac{pop^T}{pop^0}\right) \tag{2}$$

- Dwellings per population (societal)

$$SOC = \mathrm{w_i} * \ln\left(\frac{\left(\frac{dw}{pop}\right)^T}{\left(\frac{dw}{pop}\right)^0}\right) \tag{3}$$

- Area per dwelling (comfort)

$$COM = \mathrm{w_i} * \ln\left(\frac{\left(\frac{A}{dw}\right)^T}{\left(\frac{A}{dw}\right)^0}\right) \tag{4}$$

- Energy efficiency (efficiency) (related to the area A of residential buildings)

$$EFF = \mathrm{w_i} * \ln\left(\frac{\left(\frac{FEC_H}{A}\right)^T}{\left(\frac{FEC_H}{A}\right)^0}\right) \tag{5}$$

With $\mathrm{w_i}$ being the weight function, $w_i = \frac{FEC_H^T - FEC_H^0}{\ln\left(FEC_H^T\right) - \ln\left(FEC_H^0\right)}$

As the statistical foundation for this analysis, we used publicly accessible data for Germany and Switzerland provided by the ODYSSEE-MURE project [16]. For Germany, these data are based mostly on national sources such as AGEB [57] (energy related data) and the national statistical office Destatis (data on buildings, construction activity, etc.).

A2 – Details on the energy efficiency measures of Germany and Switzerland used in the analyses

Energy efficiency measures in Germany

The Energy Savings Ordinance (EnEV) sets minimum standards for buildings (residential and non-residential), while the KfW programmes offer grants for the construction and renovation of residential buildings, which are built or retrofitted to a certain standard (so called KfW-Effizienzhausstandard). These are funded by the federal CO_2 Building Modernisation Programme. For estimating the savings from the EnEV, which applies to both residential and non-residential buildings, we segregate the impact based on previous bottom-up modelling for the third NEEAP in Germany as well as more recent evaluations [58]. The majority share of about 75% of the energy savings is accounted for by residential buildings.

The MAP subsidised renewable energy installations for heating and cooling, as well as certain heat storage facilities and local heating networks, both in residential and non-residential buildings. The programme is nearly exclusively limited to heating systems in existing buildings, whereas systems in new buildings are supported only in exceptional cases.

Within the framework of on-site energy consulting (carried out by the Federal Office for Economic Affairs and Export Control BAFA), refurbishment concepts are developed by qualified and independent experts for residential buildings. These consulting activities are financially supported.

Since 2009 the EEWärmeG has stipulated an obligation to use renewable energies for heating and cooling for new buildings. The regulation covers both residential and non-residential buildings.

The following policies target a reduction in energy demand for space heating, but were implemented very recently and are therefore not considered in this analysis:

- Förderprogramm Heizungsoptimierung (Heating Optimisation Funding Programme; started in late 2016)
- Anreizprogramm Energieeffizienz APEE (Energy Efficiency Incentive Programme; started in August 2016)
- Nationales Effizienzlabel für Heizungen (National Energy Efficiency Label for Old Heating Installations; started in 2017)

Policy measures which target a reduction in electricity consumption in households are neglected as the share of electricity in Germany's final energy consumption for space heating is below 2% [59]. For the ecological tax reform, the impact on fuel consumption in general is expected to be very low to non-existent (e.g. Projection Report 2017 for Germany [60], German National Action Plan on Energy Efficiency (NAPE) [61]).

The "Wärmeschutzverordnung" of 1995 (WSchV'95) was evaluated by Ziesing et al. [62]. Also, in later years, a very good implementation practice was certified for the heat insulation ordinance [63].

Energy efficiency measures in Switzerland

Table A1 shows different measures implemented as a part of cantonal energy policies.

The cumulative impact of cantonal energy policies is estimated over the lifetime of measures [26]. Different lifetimes are considered for different measures, e.g. 40 years for the deep energy retrofitting of the building envelope, 30 years for grid connected solar PV, 25 years for solar collectors, 20 years for heating networks using waste heat, 15 years for wood boilers, heat pumps etc. [25]. Assuming an average lifetime of 30 years for the measures, we estimate that cantonal energy policies contributed to 14 PJ of energy savings in the period from 2001 to 2016.

The CO_2 Levy is a key instrument of the Swiss energy policy (defined in the Federal Act on the Reduction of CO_2 Emissions (Swiss CO_2 Act, [64]) and can be expected to have an impact on energy efficiency improvement. The levy is imposed on the production, extraction and import of fossil fuels (oil, natural gas) in Switzerland and applies, inter alia, to the residential sector. The CO_2 Levy was introduced in 2008 at 12 CHF/tonne CO_2 and was gradually increased to the current rate of 96 CHF/tonne CO_2 on 1st January 2018. This policy was estimated to save 4.1–6.9 million tonnes of CO_2 emissions from 2005 to 2015 [65]. The impact commenced prior to 2008 as consumers shifted to low carbon sources in anticipation of the implementation of the levy [26]. The emission abatement due to the CO_2 levy in buildings in the residential sector was approximately 1 million tonnes for the year 2015. This quantity was established based on the substitution of fuel oil primarily by natural gas and renewable energy sources (such as wood, solar, ambient heat used in heat pumps), i.e. no CO_2 savings were assigned to energy efficiency improvement. Although the energy efficiency of gas boilers is typically slightly higher than for oil boilers, the study assumed the same final energy demand for heating in the residential sector (possibly to compensate for the lower efficiency of biomass-fired boilers). It further argued that due to the low CO_2 Levy (60 CHF/tonne CO_2 until 2014), the levy did not lead to retrofitting of buildings (as energy demand is inelastic in the short term to relatively low change in prices), but only resulted in fuel substitution in the short to medium term. In light of the presented arguments and methodology adopted by the study, we do not allocate any energy savings to the implementation of the CO_2 Levy in Switzerland, arguably resulting in an underestimation of energy savings. Further, with the forthcoming revision of the CO_2 Act, there is a possibility of increasing the levy to up to a maximum of 210 CHF/tonne CO_2. This could be expected to lead to at least some proactive investment behaviour related to energy efficiency (by analogy to the pre-2008 effect described above) [26].

The Buildings Programme commenced in 2010 and was jointly developed by the 26 cantons and the Swiss confederation. The Swiss Federal Office of Energy (SFOE) is responsible for the strategic management of the programme while the cantons are responsible for its implementation [66]. The Buildings Programme promotes retrofitting of buildings and is targeted at building owners. Direct financial support is provided in the form of subsidies for various measures under the Buildings Programme. Although the building owners contribute a major share of the costs of energy retrofitting, they benefit from the increased market value of the property, while the impact on the tenant is the reduced annual heating costs (maybe sometimes partly compensated for by an increase in rent). The major part of the Buildings Programme is funded by the federal government using income from the CO_2 Levy, which is primarily utilised for the deep energy retrofitting of existing building envelopes. Cantonal funding was also provided for the programme, which was used for promoting renewable energy sources, waste heat recovery and the improvement of heating systems in the buildings.

Fig. A.1 shows the estimated annual energy savings from cantonal energy policies and the Buildings Programme for the assessed time period. The yearly impacts of cantonal energy policies are derived from annual assessment reports for various years [67–77]. The average annual impact of the Buildings Programme has been estimated at about 0.86 PJ/year while that of the cantonal energy policies programme was 1.16 PJ/year over the respective time periods.

A3 - Discussion of the impact of heating types and changes in heating periods on energy consumption. Fig. A.2 shows the shares of heating types over the period 2002 to 2018 in Germany. During this time, the share of central heating systems slightly declined from 90 to 72% of all newly completed dwellings. This loss in share was mainly taken up by district heating systems (7% in 2002 to 22% in 2018) and to a smaller degree by CHP systems (1% in 2002 to 4% in 2018). This development can be assumed to have only a minor effect on final energy consumption for space heating as centralised heating systems had already reached a very high penetration in the period we consider in our analysis, with the main changes happening prior to the year 2000. Also, the increase of district heating and CHP does not change the heating behaviour, since these new heating systems simply replace the building's central heating system while typically not changing the thermal comfort preference.

Fig. A.3 does not indicate any trend towards higher heating degree days outside the typical heating period in Germany in the period from 2000 to 2017 (dotted line). We hence conclude that the comfort-induced extension of the heating period in Germany came to an end before the year 2000, representing the starting year of our analysis.

Strictly speaking, however, this can only be assumed for multifamily houses with central heating, since the heating period is

Table A1
Measures implemented as a part of cantonal energy policies.

Building envelope efficiency (building standards, MuKEn)	Energy retrofitting of buildings (building energy performance certificate)	MINERGIE (-P) buildings (building labels)	Renewable energies	Other	Indirect measures
New building system	GEAK renovation to level "B"	MINERGIE renovation	Log fires	Use of waste heat	Information activities
Type of energy retrofitting	GEAK renovation to level "A"	MINERGIE new building	Aut. wood firing systems < 70 kW	Special measures outside the scope of energy retrofitting of buildings (electricity efficiency, mobility, industry etc.)	Events
Envelope (roof/wall insulation), home ventilation		MINERGIE-P renovation	Aut. wood firing greater than 70 kW (with/without additional measures flue gas cleaning)		Initial and continuing education
Special measures for deep energy retrofitting		MINERGIE-P new building	District heating network wood		Consultation
			Solar panels (collectors)		
			Photovoltaic		
			Heat pumps		

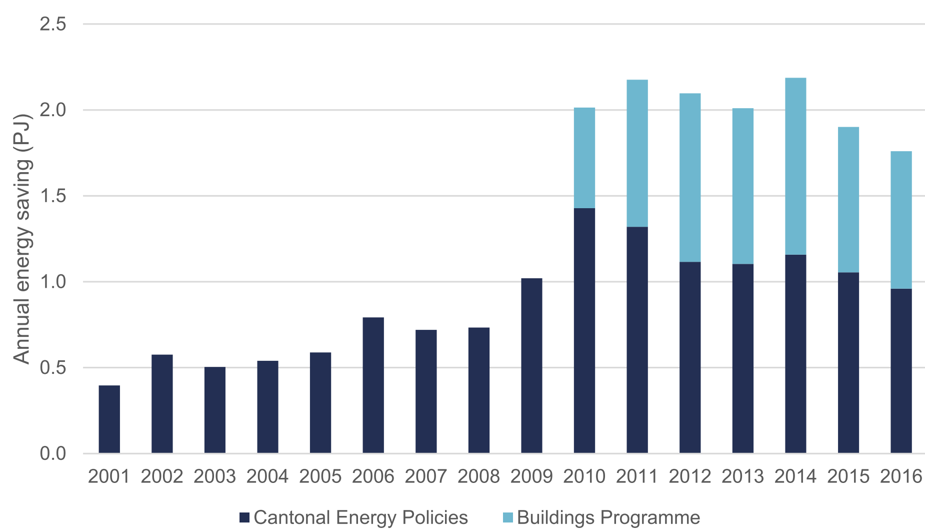

Fig. A1. Estimated annual energy savings from federal energy policies in Switzerland (2000–2016) [68,68–79].

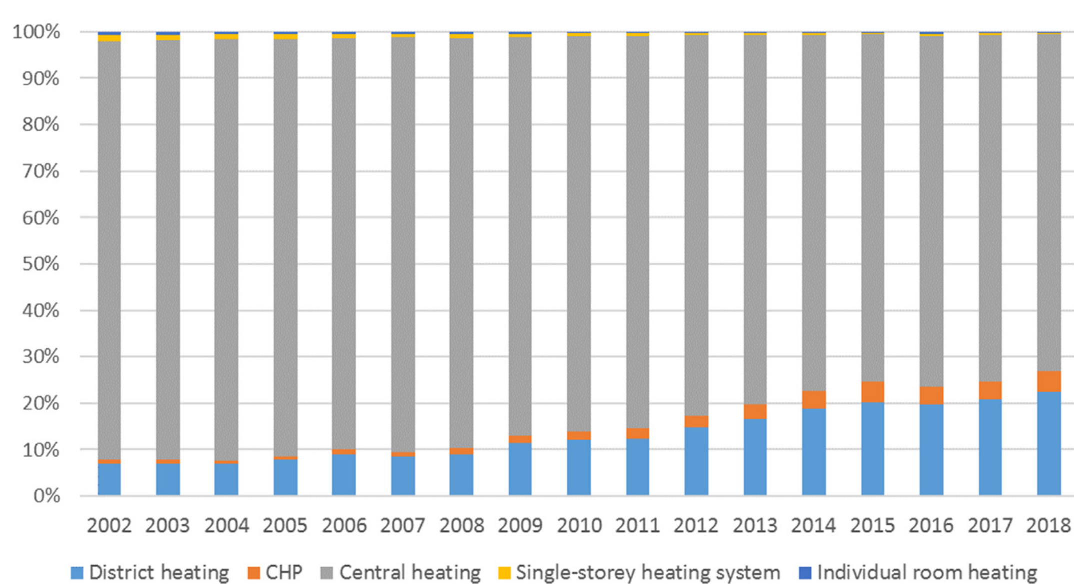

Fig. A2. Newly built dwellings by type of heating in Germany [78].

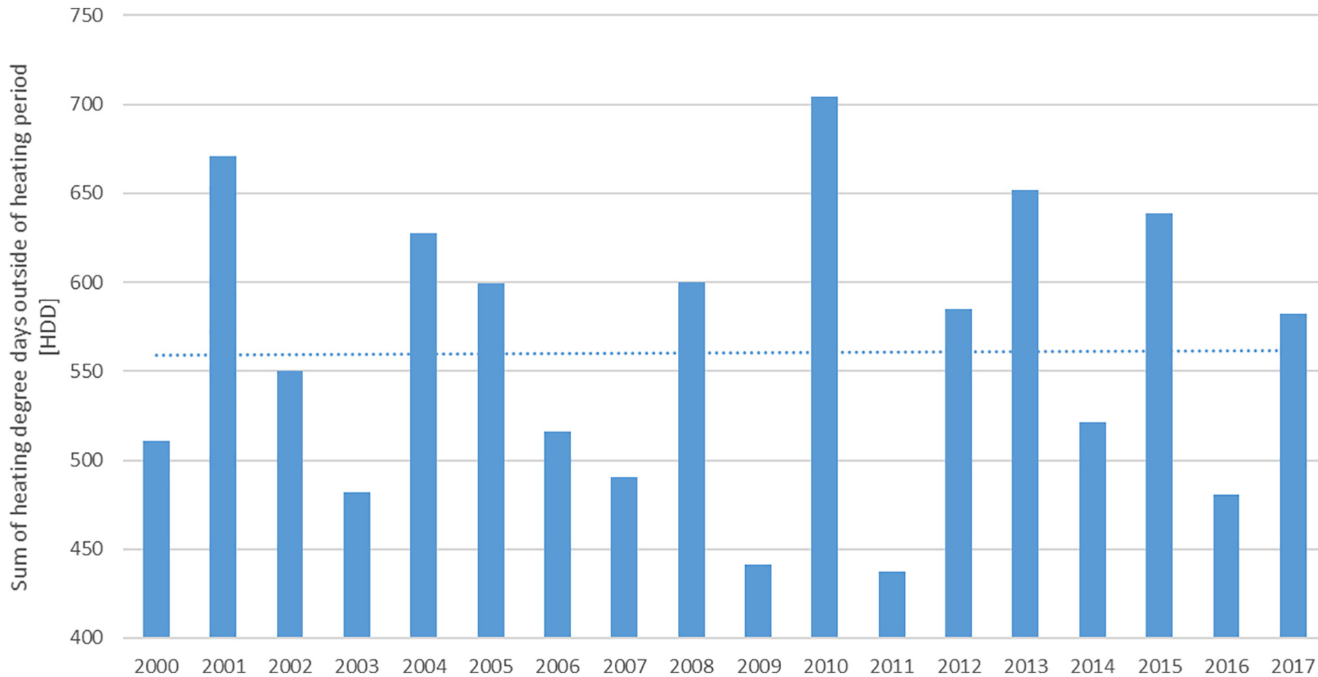

Fig. A3. Sum of heating degree days (HDD) outside the heating period in Germany (average shown as dotted line) [79].

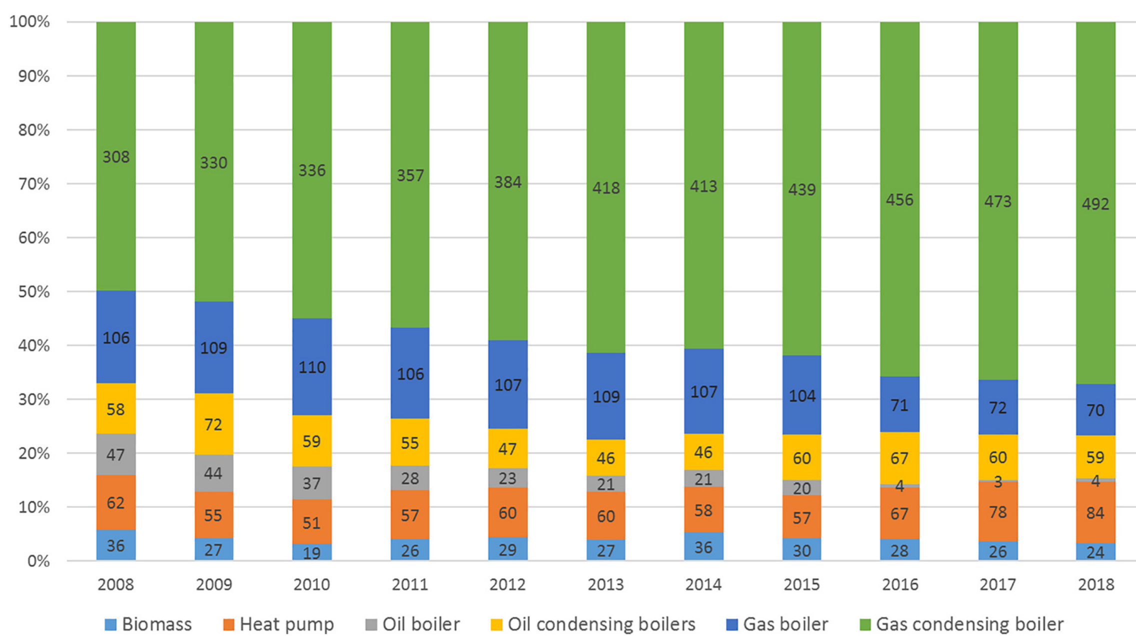

Fig. A4. Share in sale of heating technologies in Germany from 2008 to 2018 (Source: BDH).

rather centrally determined here. For single-family houses, the heating period is mostly decided upon by the occupants themselves. However, it can be assumed that these effects are only marginal overall, as general changes in heating periods would not be expected in view of the development of heating degree days over the years (see Fig. 8).

A4 – Impact of the choice of heating technologies and energy carriers on energy consumption. In Germany, a trend towards efficient gas condensing boilers can be observed in sales of heating technologies between 2008 and 2018 (increased from around 50% to 67%). During the same period, the share of biomass boilers decreased slightly while the share of heat pumps remained about the same (see Fig. A.4).

A trend towards gas heating as well as biomass and heat pumps can also be observed in newly constructed residential buildings (see Fig. A.5). This change of fuel as well as the switch to more efficient heating technologies is to a certain degree driven by policy (e.g. investment subsidies "KfW 430" as part of the KfW programme for energy efficient refurbishment).

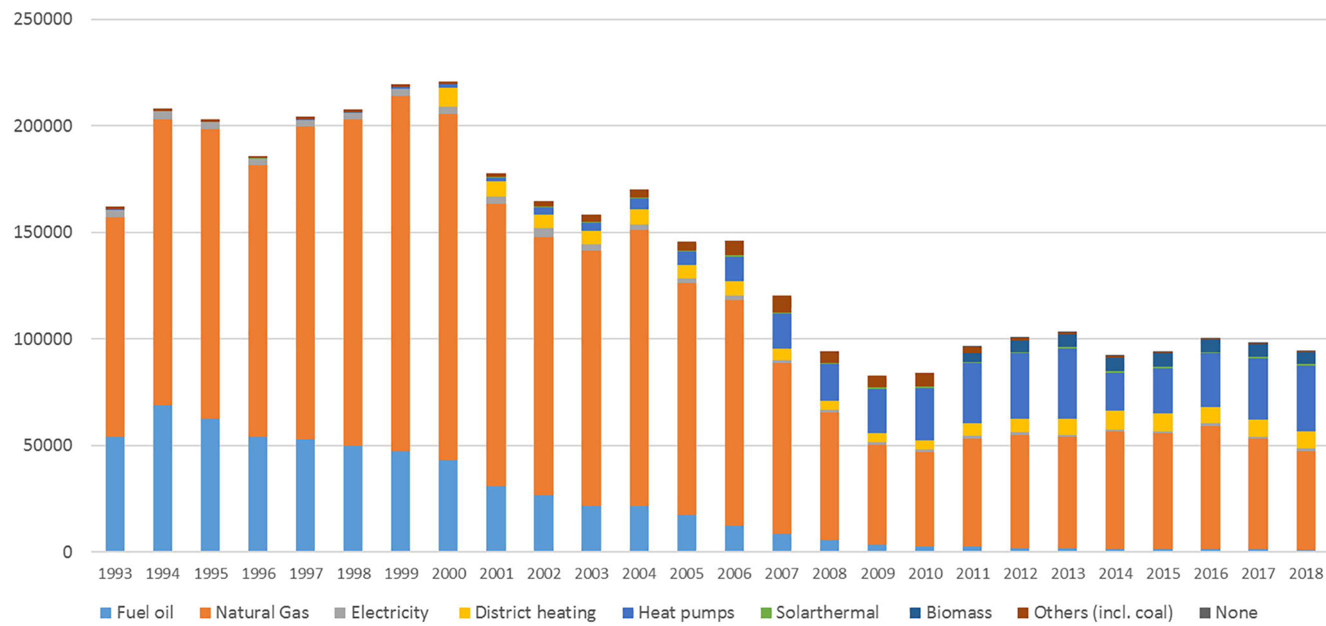

Fig. A5. Heating systems by energy carrier in newly constructed residential buildings in Germany 1993–2018 [78].

Also, an increasing share of multi-family homes (MFH) at the expense of single-family homes (SFH) can contribute to decreasing energy consumption for space heating in residential buildings as MFH typically consume less energy per unit area. This is mainly due to the thermal advantages compared to detached residential buildings. SFH have on average almost twice as much exterior surface area per cubic metre of heated building volume and thus almost twice as much heat loss via the building envelope compared to large multi-family houses [80], which consume only about 36% of the energy for space heating per m^2. However, in Germany, a significant trend towards MFH cannot be observed.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2021.110987.

References

[1] S. Thomas, P. Boonekamp, H. Vreuls, J.-S. Broc, D. Bosseboeuf, B. Lapillonne, N. Labanca, How to measure the overall energy savings linked to policies and energy services at the national level?, Energ. Effi. 5 (1) (2012) 19–35, https://doi.org/10.1007/s12053-011-9122-x.
[2] P.G.M. Boonekamp, Evaluation of methods used to determine realized energy savings, Energy Policy 34 (18) (2006) 3977–3992, https://doi.org/10.1016/j.enpol.2005.09.020.
[3] C. Abeelen, From Top-down to Bottom-up; Two Ways to Monitor Energy-Efficiency in Dutch Voluntary Agreements, Eceee 2013 Summer Study on Energy Efficiency: Rethink, (2013).
[4] Schlomann, B., Reuter, M., Lapillonne, B., Pollier, K., & Rosenow, J., Monitoring of the "Energiewende" –energy efficiency indicators for Germany, 2014.
[5] F. Al-Mansour, Energy efficiency trends and policy in Slovenia, Energy 36 (4) (2011) 1868–1877, https://doi.org/10.1016/j.energy.2010.05.018.
[6] BMWi, Nationaler Energieeffizienz-Aktionsplan (NEEAP) der Bundesrepublik Deutschland, 2007.
[7] BMWi, 2. Nationaler Energieeffizienz-Aktionsplan (NEEAP) der Bundesrepublik Deutschland, 2011.
[8] BMWi, 3. Nationaler Energieeffizienz-Aktionsplan (NEEAP) 2014 der Bundesrepublik Deutschland, 2014.
[9] BMWi, Nationaler Energieeffizienz-Aktionsplan (NEEAP) 2017 der Bundesrepublik Deutschland, 2017.
[10] A. Tiangket, B. Chullabodhi, K. Eam-O-Pas, S. Watechagit, The Energy Saving Calculation for a Residential Sector in Thailand with Top-Down Methodology, Energy Procedia 79 (2015) 415–422, https://doi.org/10.1016/j.egypro.2015.11.512.
[11] E. Grealis, A.K. Musch, H. Rau, The Impact of German Energy Policy on Household Energy Use, Palgrave Pivot, Cham, 2019.
[12] P. Thollander, M. Danestig, P. Rohdin, Energy policies for increased industrial energy efficiency: Evaluation of a local energy programme for manufacturing SMEs, Energy Policy 35 (2007) 5774–5783, https://doi.org/10.1016/j.enpol.2007.06.013.
[13] E.Ó. Broin, J. Nässén, F. Johnsson, Energy efficiency policies for space heating in EU countries: A panel data analysis for the period 1990–2010, Appl. Energy 150 (2015) 211–223, https://doi.org/10.1016/j.apenergy.2015.03.063.
[14] P.G.M. Boonekamp, Improved methods to evaluate realised energy savings, Utrecht University, 2005.
[15] P.G.M. Boonekamp, How much will the energy service directive contribute to the 20% EU energy savings goal?, Energ Effi. 4 (2) (2011) 285–301, https://doi.org/10.1007/s12053-010-9088-0.
[16] ODYSSEE-MURE, Database on energy efficiency indicators and energy consumption by end-use and their underlying drivers in industry, transport and buildings.
[17] Bundesregierung, Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung (2010).
[18] BMWi, Zweiter Fortschrittsbericht zur Energiewende: Die Energie der Zukunft, 2019.
[19] BMU, Climate Action in Figures: Facts, Trends and Incentives for German Climate Policy 2018 edition, Berlin, 2018.
[20] Bundesamt für Energie, Energiestrategie 2050 nach dem Inkrafttreten des neuen Energiegesetzes, 2018.
[21] ODYSSEE-MURE, MURE (Mesures d'Utilisation Rationnelle de l'Energie) database on energy efficiency policies in the EU plus Norway, Switzerland and Serbia.
[22] BMWi, Making more out of energy: National Action Plan on Energy Efficiency, 2014.
[23] M. Weyland, S.D. Steuwer, Germany's Struggle for Energy Efficiency: Policy Instruments after the National Action Plan for Energy Efficiency (NAPE), GAIA - Ecological Perspectives for Science and Society 27 (2018) 216–221. 10.14512/gaia.27.2.8.
[24] IWU, Fraunhofer IFAM, Monitoring der KfW-Programme Monitoring der KfW-Programme "Energieeffizient Sanieren", und "Energieeffizient Bauen", 2018.
[25] Donald Sigrist, Stefan Kessler, Globalbeiträge an Die Kantone Nach Art. 15 EnG. Wirkungsanalyse Kantonaler Förderprogramme. Ergebnisse der Erhebung 2016., 2017. https://www.newsd.admin.ch/newsd/message/attachments/49610.pdf.
[26] Bundesamt für Umwelt BAFU, Faktenblatt 1 : CO2-Abgabe auf Brennstoffe, 2019.
[27] Prognos, Fraunhofer ISI, Methodisches Begleitdokument zum 2. Nationalen Energieeffizienz-Aktionsplan (NEEAP) der Bundesrepublik Deutschland gemäß EU-Richtlinie über Endenergieeffizienz und Energiedienstleistungen (2006/32/EG)., 2011.
[28] R. Madlener, M. Hauertmann, Rebound Effects in German Residential Heating: Do Ownership and Income Matter?, SSRN Journal (2011), https://doi.org/10.2139/ssrn.1887030.

[29] Lorna A. Greening, David L. Greene, Carmen Difiglio, Energy efficiency and consumption — the rebound effect — a survey, Energy Policy 28 (6-7) (2000) 389–401, https://doi.org/10.1016/S0301-4215(00)00021-5.
[30] Reinhard Haas, Peter Biermayr, The rebound effect for space heating Empirical evidence from Austria, Energy Policy 28 (6-7) (2000) 403–410, https://doi.org/10.1016/S0301-4215(00)00023-9.
[31] Reinhard Haas, Hans Auer, Peter Biermayr, The impact of consumer behavior on residential energy demand for space heating, Energy Build. 27 (2) (1998) 195–205, https://doi.org/10.1016/S0378-7788(97)00034-0.
[32] B. Volland, Efficiency in Domestic Space Heating: An Estimation of the Direct Rebound Effect for Domestic Heating in the U.S, IRENE Working Papers (2016).
[33] R. Galvin, The rebound effect in home heating: A guide for policymakers & practitioners, Routledge Taylor & Francis Group, London, New York, NY, 2016.
[34] techem Energieservice GmbH, Techem Energiekennwerte 2018: Transparenz zum Energieverbrauch für Heizung und Warmwasser in deutschen Mehrfamilienhäusern, Eschborn, 2018.
[35] Department for Business, Energy & Industrial Strategy, Energy consumption in the UK (ECUK), 2018. https://www.gov.uk/government/statistics/energy-consumption-in-the-uk (accessed 26 February 2020).
[36] S. Cozza, J. Chambers, A. Brambilla, M. Patel, In search of optimal consumption: A review on the Energy Performance Gap in residential buildings, Submitted manuscript.
[37] ICF International, Energy Performance of Buildings Directive (EPBD), Compliance Study, Brussels (2015).
[38] IWU, Evaluierung und Fortentwicklung der EnEV 2009: Untersuchung zu ökonomischen Rahmenbedingungen im Wohnungsbau, 2012.
[39] Swiss Confederation, Wirksamkeit der Finanzhilfen zur Verminderung der CO 2 -Emissionen bei Gebauden gemäss Artikel 34 CO2-Gesetz. Bericht des Bundesrates an die Bundesversammlung, 2016.
[40] M. Sunikka-Blank, R. Galvin, Introducing the prebound effect: the gap between performance and actual energy consumption, Build. Res. Inform. 40 (2012) 260–273, https://doi.org/10.1080/09613218.2012.690952.
[41] Martin Jakob, Marginal costs and co-benefits of energy efficiency investments, Energy Policy 34 (2) (2006) 172–187, https://doi.org/10.1016/j.enpol.2004.08.039.
[42] S. Cozza, J. Chambers, C. Deb, J.-L. Scartezzini, A. Schlüter, M.K. Patel, Do energy performance certificates allow reliable predictions of actual energy consumption and savings? Learning from the Swiss national database, Energy Build. 224 (2020), https://doi.org/10.1016/j.enbuild.2020.110235 110235.
[43] S. Cozza, J. Chambers, M.K. Patel, Measuring the thermal energy performance gap of labelled residential buildings in Switzerland, Energy Policy 137 (2020), https://doi.org/10.1016/j.enpol.2019.111085 111085.
[44] J. Khoury, Z. Alameddine, P. Hollmuller, Understanding and bridging the energy performance gap in building retrofit, Energy Proc. 122 (2017) 217–222, https://doi.org/10.1016/j.egypro.2017.07.348.
[45] I. Mojic, M. Lehmann, S. van Velsen, M. Haller, ImmoGap – Analysis of the performance gap of apartment buildings, E3S Web Conf. 111 (2019) 4016, https://doi.org/10.1051/e3sconf/201911104016.
[46] S. Cozza, J. Chambers, A. Brambilla, M.K. Patel, Energy Performance Certificate for buildings as a strategy for the energy transition: Stakeholder insights on shortcomings, IOP Conf. Ser.: Earth Environ. Sci. 588 (2020) 22003, https://doi.org/10.1088/1755-1315/588/2/022003.
[47] B. Frei, C. Sagerschnig, D. Gyalistras, ParkGap – Performance Gap Gebäude Bestandsaufnahme und Handlungsempfehlungen für den Gebäudepark der Schweiz, Unpublished, 2018.
[48] I. Schulte, P. Heindl, Price and income elasticities of residential energy demand in Germany, Energy Policy 102 (2017) 512–528, https://doi.org/10.1016/j.enpol.2016.12.055.
[49] Reinhard Haas, Lee Schipper, Residential energy demand in OECD-countries and the role of irreversible efficiency improvements, Energy Econ. 20 (4) (1998) 421–442, https://doi.org/10.1016/S0140-9883(98)00003-6.
[50] X. Labandeira, J.M. Labeaga, X. López-Otero, A meta-analysis on the price elasticity of energy demand, Energy Policy 102 (2017) 549–568, https://doi.org/10.1016/j.enpol.2017.01.002.
[51] Eurostat, Gas prices for household consumers - bi-annual data (from 2007 onwards)[nrg_pc_202], 2020. https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_203&lang=en.
[52] destatis, Lange Preisreihen für leichtes Heizöl, Motorenbenzin und Dieselkraftstoff, 2020.
[53] N. Diefenbach, H. Cischinsky, M. Rodenfelds, K.-D. Clausnitzer, Datenbasis Gebäudebestand, Datenerhebung zur energetischen Qualität und zu den Modernisierungstrends im deutschen, Wohngebäudebestand (2010).
[54] M. Reuter, M.K. Patel, W. Eichhammer, Applying ex post index decomposition analysis to final energy consumption for evaluating European energy efficiency policies and targets, Energ. Effi. 52 (2019) 64, https://doi.org/10.1007/s12053-018-09772-w.
[55] A. Holzmann, H. Adensam, K. Kratena, E. Schmid, Decomposing final energy use for heating in the residential sector in Austria, Energy Policy 62 (2013) 607–616, https://doi.org/10.1016/j.enpol.2013.07.027.
[56] Matthias Reuter, Martin K. Patel, Wolfgang Eichhammer, Applying ex-post index decomposition analysis to primary energy consumption for evaluating progress towards European energy efficiency targets, Energ. Effi. 10 (6) (2017) 1381–1400, https://doi.org/10.1007/s12053-017-9527-2.
[57] AGEB, Energiebalances for Germany: AG Energiebilanzen e.V.
[58] Fraunhofer ISI, Prognos, Studie zur Vorbereitung des Nationalen Energieeffizienz-Aktionsplans 2014 der Bundesregierung für die Berichtspflichten im Bereich "Maßnahmen und Energieeinsparungen" (gemäß Artikel 24 i.V.m. Anh. XIV Teil 2 Nr. 2 EU-Energieeffizienzrichtlinie), 2014.
[59] RWI, Erstellung der Anwendungsbilanzen 2016 und 2017 für den Sektor der Privaten Haushalte und den Verkehrssektor in Deutschland: Endbericht - Oktober 2018, 2018.
[60] Bundesregierung, Projektionsbericht 2017 für Deutschland gemäß Verordnung 525/2013/EU, Berlin, 2017.
[61] BMWi, Mehr aus Energie machen.: Nationaler Aktionsplan Energieeffizienz., Berlin, 2014.
[62] H.-J. Ziesing, J. Diekmann, G. Stein, B. Strobel (Eds.), Politikszenarien für den Klimaschutz: Untersuchungen im Auftrag des Umweltbundesamtes, Jülich, 1997.
[63] Uwe Römmling, Ingrid Vogler, Anton Maas, Gabriele Lorenz, Evaluierung der Wärmeschutzverordnung '95, Fraunhofer IRB Verlag, Stuttgart, 1998.
[64] Bundesrat, Federal Act on the Reduction of CO2 Emissions: 641.71, 2011.
[65] André Müller and Tobias Schoch, Wirkungsabschätzung Zur CO2 -Abgabe. Aktualisierung Bis 2015., Bern, 2017.
[66] Federal Office for the Environment FOEN, The federal and contonal buildings programme, 2018.
[67] Christian Schneider, Stefan Kessler, Rolf Iten, Contributions Globales Aux Cantons Selon L'Art. 15 LEne Analyse de l ' Efficacité Des Programmes Cantonaux d ' Encouragement Résultats de l ', Enquête 2006 (2007).
[68] Donald Sigrist, Stefan Kessler, Contributions Globales Aux Cantons Selon L'Art. 15 LEne Analyse de l ' Efficacité Des Programmes Cantonaux d ' Encouragement Résultats de l ', Enquête 2010 (2011).
[69] Donald Sigrist, Stefan Kessler, Contributions Globales Aux Cantons Selon L'Art 15 LEne. Analyse de l ' Efficacité Des Programmes Cantonaux d ' Encouragement Résultats de l ', Enquête 2011 (2012).
[70] Donald Sigrist, Stefan Kessler, Contributions Globales Aux Cantons Selon L'Art. 15 LEne Analyse de l ' Efficacité Des Programmes Cantonaux d ' Encouragement Résultats de l ', Enquête 2012 (2013).
[71] Donald Sigrist, Stefan Kessler, Contributions Globales Aux Cantons Selon L'Art. 15 LEne Analyse de l ' Efficacité Des Programmes Cantonaux d ' Encouragement Résultats de l ', Enquête 2013 (2014).
[72] Donald Sigrist, Stefan Kessler, Contributions Globales Aux Cantons Selon L'Art. 15 LEne Analyse de l ' Efficacité Des Programmes Cantonaux d ' Encouragement Résultats de l ', Enquête 2014 (2015).
[73] Donald Sigrist, Stefan Kessler, Contributions Globales Aux Cantons Selon L'Art. 15 LEne Analyse de l ' Efficacité Des Programmes Cantonaux d ' Encouragement Résultats de l ', Enquête 2015 (2016).
[74] Donald Sigrist, Stefan Kessler, Contributions Globales Aux Cantons Selon L'Art. 15 LEne Analyse de l ' Efficacité Des Programmes Cantonaux d ' Encouragement Résultats de l ', Enquête 2016 (2017).
[75] Christian Schneider, Stefan Kessler, Rolf Iten, Contributions Globales Aux Cantons Selon L'Art. 15 LEne Analyse de l ' Efficacité Des Programmes Cantonaux d ' Encouragement Résultats de l ', Enquête 2005 (2006).
[76] Fabia Moret, Stefan Kessler, Florian Kasser, Rolf Iten, Contributions Glo-bales Aux Cantons Selon L'Art 15 LEne. Analyse de l ' Efficacité Des Pro-grammes Cantonaux d ' Encouragement Résultats de l ', Enquête 2008 (2009).
[77] Florian Kasser, Stefan Kessler, Contributions Globales Aux Cantons Selon L'Art. 15 LEne Analyse de l ' Efficacité Des Programmes Cantonaux d ' Encouragement Résultats de l ', Enquête 2009 (2010).
[78] destatis, Fachserie 5 Reihe 1: Bautätigkeit und Wohnungen, 2019.
[79] Eurostat, Cooling and heating degree days by country: annual data, 2019. https://ec.europa.eu/eurostat/web/products-datasets/product?code=nrg_chdd_a (accessed 26 February 2020).
[80] dena, dena-GEBÄUDEREPORT: Statistiken und Analysen zur Energieeffizienz im Gebäudebestand, Berlin, 2016.