PREMOŠČAVANJE JAZA (RAZLIKE) IZMEĐU STVARNOG I PRORAČUNATOG KORIŠĆENJA TOPLOTNE ENERGIJE U MODELOVANJU STAMBENIH ZGRADA ODOZDO NAVIŠE

BRIDGING THE GAP OF ACTUAL AND CALCULATED HEATING ENERGY CONSUMPTION IN BOTTOM-UP RESIDENTIAL BUILDING STOCK MODELING

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Stambene zgrade su u središtu evropskih i nacionalnih napora koji se ulažu u postizanje ciljeva u pogledu energije i emisije nametanjem strožih propisa za nove zgrade i podsticanjem transformacije postojećih zgrada kako bi zadovoljile više standarde energetskih karakteristika. Modeli građevinskog fonda se obično koriste za procenu različitih mera energetske efikasnosti, za kvantifikovanje njihovog uticaja na smanjenje upotrebe energije u cilju postizanja nacionalnih ciljeva i za određivanja prioritetnih politika. Međutim, razne studije su pokazale da postoji jaz odnosno razlika između proračunatog i stvarnog korišćenja energije u zgradama. U radu je detaljno izložen metod za prilagođavanje predviđanja modela kako bi se dobile realnije proce ne o korišćenju energije. U ovom pristupu se koriste podaci iz sertifikata o energetskoj efikasnosti da bi se dobili jednostavni empirijski faktori prilagođavanja (definisani kao odnos stvarnog i proračunatog korišćenja energije), dopunjeni dokazima iz kratke ankete sa terena za kvantifikovanje uticaja promene u ponašanju stanara i uloge ljudskog faktora u korišćenju grejanja prostora koje odstupa od normativnih proračunskih pretpostavki. Rezultati iz sertifikata ukazuju da je prosečna razlika granične vrednosti korišćenja energije za porodične kuće 48% manja od proračunate (an average bound difference of 48% lower energy use than calculated), i 44% za kuće u kojima živi više porodica. Rezultati iz anketa sa terena koje su sprovedene da bi se kvantifikovala odstupanja od standardnih radnih uslova korišćenih u normativnim proračunima (npr. manji broj sati rada i niže podešene temperature u prostoriijama, grejanje manjih površina stambenog prostora) daju nižu granicu od 68% kao konzervativnu procenu stvarnog korišćenja energije.

Ključne reči: modeliranje građevinskog fonda, gap analiza, stvarno korišćenje energije naspram predviđenog, faktori prilagođavanja
Residential buildings have been at the center stage of European and national efforts to meet the energy and emissions targets by imposing more stringent codes for new buildings and encouraging the transformation of existing buildings to higher energy performance standards. Building stock models are commonly used to assess different energy efficiency measures, quantify their impact on reducing the energy use towards meeting the national targets and to prioritize policies. However, various studies have demonstrated the gap of calculated and actual energy use in buildings. The work elaborates a method to adapt model predictions in order to obtain more realistic estimates of energy use. The approach exploits data from energy performance certificates to derive simple empirical adaptation factors (defined as a ratio of actual to calculated energy use), complemented by evidence from short field surveys to quantify the impact of behavioral changes of occupants and the role of the human factor on the use of space heating that deviate from normative calculation assumptions. The results from the certificates indicate an average bound difference of 48% lower energy use than calculated for single-family houses and 44% for multi-family houses. The results from the field surveys that were carried out in order to quantify the deviations from standard operating conditions used in the normative calculations (e.g. lower hours of operation and indoor temperature settings, heating smaller floor areas of dwellings) provided a lower bound of 68% as a conservative estimate of actual energy use.

**Key words:** building stock modeling, gap analysis, actual vs predicted energy use, adaptation factors

### 1. Introduction

Various European and national policies focus on improving the energy performance of buildings. Residential buildings are at the center stage since they dominate the building sector and play a significant role in the energy and environmental footprint of buildings. Energy use in residential buildings represents about 20%-36% of total final energy consumption in several countries (Fig. 1). The energy use is allocated for satisfying the buildings' operational needs and indoor environmental quality for heating, air-conditioning, lighting and plug loads.

#### 1.1 European Residential Buildings

In the European Union Member States (EU-28) final energy consumption in residential buildings reached 263.22 million tonnes of oil equivalent (Mtoe) in 2014 (EU 2016), decreasing in absolute terms since its historic peak at 311 Mtoe in 2010. Compared to 1990, final energy use is 0.33% lower than the 264.09 Mtoe in the corresponding EU-28 at that time. Residential buildings account for 75% of the of the 25 billion m² existing building stock in EU-28 (Gynther et al. 2015). Space heating is the most important end-use in the residential buildings (67%), but its share has been slightly declining since 2000. Domestic hot water (DHW) ranks second with a stable share at 13% of the total, electrical appliances have climbed to 11%, followed by cooking at 6%, lighting at 2% and cooling at only 0.5%.
Figure 1. Final energy use breakdown by sector in several countries (% contribution of buildings in the parenthesis).

More stringent European Directives, national codes and regulations make new buildings more energy efficient. It is estimated that on average, new dwellings (theoretically) consume 40% less than dwellings built before 1990 (Gynther et al. 2015). However, new buildings average less than 1.1% per year (average over 2000-2012) and new construction has been dropping since 2009 as a result of the economic crisis throughout Europe. In several countries new construction rates are even below 0.5% (Sandberg et al. 2016). Annual demolition rates in most European countries have ranged at 0.3-0.7% and are expected to remain at the same level or slightly increase to about 1.0% by 2050, while annual renovation rates have ranged at 1-1.5%. Consequently, in order to meet the aggressive EU targets on reducing the energy use in the building sector, the focus of European policies and national efforts has been on the existing building stock. The main European legislation instruments for reducing the energy consumption of buildings include the energy performance of buildings Directive (EPBD recast 2010/31/EC), the Energy Efficiency Directive (EED 2012/27/EU), the Renewable Energy Directive (RED 2009/28/EC), while there is an ongoing effort to transform the market of energy related products (ERPs)
and energy-using products (EUPs) through the Ecodesign Directive (ECODESIGN recast 2009/125/EC).

1.2 Hellenic Residential Buildings

In Greece, the residential sector accounts for 3.79 million tonnes of oil equivalent (Mtoe) or 24.3% of the total final energy consumption in 2014, according to the latest officially available data (EU 2016). As illustrated in Fig. 2 the observed variations are partly due to the prevailing winter conditions, expressed by the heating degree days (HDD), the severe economic recession of recent years and the tax increase on heating oil first imposed in 2012. According to the national Buildings Census, there are ~3.2 million residential buildings (i.e. 2.990 million exclusive use and 0.256 mixed use buildings that their main type of use is residential) that represent about ~79% of the building stock (ELSTAT 2015).

Figure 2. Total final energy consumption in Greece and contribution of the residential sector (main y-axis). The line corresponds to the average heating degree days (secondary y-axis).

About half of the Hellenic buildings have no kind of thermal protection, since the majority of them were built prior to 1980, the year that the first national Hellenic building thermal insulation regulation (HBTIR) was introduced. According to 1990 data for Hellenic dwellings (ELSTAT 1993), 95% of the external walls, 99% of floors, 87% of pilotis, 70% of the roofs were not thermally insulated, and 98% had single glazing. Moving in the EPBD era as of 2010, several new national laws, codes and regulations have been introduced in Greece for new buildings in the framework of the national regulation on the energy performance of buildings – KENAK (Dascalaki et al. 2012). As a result, the U-values for the building’s thermal envelope became more stringent and minimum specifications were also introduced for HVAC installations. For example, the U-value for external vertical walls in contact with outdoor air was 0.7 W/m².K with HBTIR and is reduced with KENAK by 14% to 43%, depending on the climate zone. Minimum specifications for the building’s HVAC installations include, for example, the use of outdoor temperature com-
pensation systems, zone thermostatic controls, along with heat recovery for central air-handling-units, energy efficient lighting for non-residential buildings, etc. For DHW production, all new (post-2011) buildings should cover 60% of the load from renewables or substantiate the technical difficulties for non-compliance. However, due to the deep economic recession in Greece, the new building construction activity has plunged, reaching a rate of 0.15% in 2014.

On a positive note, over the past decades, there has been some progress as a result of routine maintenance, building and system refurbishment efforts. However, the fact remains that the vast majority of existing buildings have no proper thermal envelope protection, based on the most recent national household survey in 2010 (ELSTAT 2013). Specifically, only 16% have double glazing and thermally insulated external walls. Double glazing is a common practice in new construction and the most frequent refurbishment activity in existing buildings, encountered in about 43% of the dwelling stock.

1.3 Building Stock Models

The majority of European buildings will need some kind of refurbishment to the thermal envelope and technical installations to meet the new energy efficiency standards for buildings. EPBD mandates that all buildings subject to major refurbishment should meet minimum energy performance requirements and for new construction as of January 2021 to be nearly zero energy buildings (NZEB). These efforts can play an important role in meeting the European and national targets to become a highly energy-efficient, low carbon economy, reduce energy import dependency and increase Europe's security of supply in accordance to the European 2020 Strategy and the new plan towards 2030 and beyond. Furthermore, EED mandates national measures to expedite improved energy efficiency at all stages of the full energy chain, including a long-term national strategy for building renovations. This is to be reached by way of energy services and other cost-effective, practicable and reasonable energy efficiency measures (EEMs). As a result, most EU national energy efficiency action plans focus on public buildings and residential buildings. Over the years, several studies have been performed to assess the potential of EEMs in residential buildings that constitute the majority of the building stock. They all reach the same conclusion, i.e. there are significant energy savings in the buildings sector that remain untapped.

Assessing the effectiveness of EEMs for single buildings is a straight-forward process. However, calculations and even simulation tools may provide different results even for the same building. This may be due to a multitude of reasons including occupants’ behaviour and deviations from the assumptions of normative calculations. As a result, several studies have documented that there may be significant deviations amongst calculated versus actual energy use or estimated savings as a result of implementing EEMs resulting to significant over- or under-consumption (Sorrell et al. 2009, Sunikka-Blank and Galvin 2012, De Wilde 2014). One may argue that for a specific building analysis of different scenarios the accuracy of the results in terms of actual energy use is not detrimental, since the goal is to look at
the relevant differences and quantify savings in terms of a base case scenario. Furthermore, there are well prescribed methods on how to validate the accuracy or calibrate software predictions for detailed analysis at building level. For example, building monitoring can also provide quality data that may be used to adjust the predictions from energy simulation tools and improve their accuracy. However, the challenge remains on how to adapt the estimations from official calculation tools and facilitate the process of handling the diversities of large building portfolios or building stocks on a regional and national basis. In building stock modelling, it is critical to realistically predict energy use and emissions in order to properly assess measures and set policies for meeting specific targets that would realistically capture the actual trends.

Various approaches are available to handle energy use performance and environmental impact for building stock models, which are mainly identified as top-down and bottom-up (Kavgic et al. 2010). The top-down approach aims at fitting a historical time series of national energy use or CO₂ emissions to investigate the inter-relationships between the energy sector and the economy at large. The bottom-up approach builds up from data on a hierarchy of disaggregated components (e.g. period of construction, geographical areas as they relate to typical envelope construction and installations), which are then combined according to their estimated individual impact on energy use, weighted by their breakdown in the building stock. These models initiate the analysis at a disaggregated level by exploiting extensive databases of empirical data. They are based on typical buildings that are representative of the building stock, which are then used to calculate their energy use, assess different EEM and the resulting energy savings and abatement of CO₂ emissions. The results are estimated per unit floor area and then extrapolated using the total floor area of the corresponding total floor area in the building stock. Findings can then be used for medium- to long-term energy supply strategy. Amongst the main weaknesses of such an approach are the accuracy of the calculations compared to actual energy use and other assumptions regarding the impact of behavioral factors on actual energy use, for example, the hours of occupancy and use of heating systems, the heated areas, indoor temperature settings, etc.

2. Method

A notable effort to handle the complexities of building stock modeling is based on the TABULA building typologies that have been created in 20 European countries (Loga et al. 2016). Each national typology consists of a classification scheme grouping buildings according to their size, location (climate zone) and construction age that relates to energy-relevant building characteristics (e.g. construction, technical installations) and a set of exemplary buildings representing these building types. The national building typologies serve as an instrument for modelling the energy performance of building portfolios in order to support regional or national energy saving policies. The concept was further enhanced during a multinational effort within the European project EPISCOPE (http://episcope.eu) to include new buildings meeting
the national requirements or more ambitious standards towards the national NZEB definitions. The project motivated a number of national pilot actions targeting regional or national residential building stocks, considering different approaches. The approach presented in this work refers to the findings from the Hellenic pilot project.

One of the key issues addressed during this work was the need to close the gap of actual versus calculated energy use when assessing the effectiveness of EEMs for millions of cases in national building stock analysis. This challenge mandated the development of an easy to implement generic two-fold approach. The first exploits information from the energy performance certificates for deriving simple empirical adaptation factors that relate the normative calculated heating energy consumption with the actual energy use included in the certificates. The second approach exploits complementary data collected from field surveys that document recent behavioral changes of occupants and the role of the human factor in the operation of residential space heating systems in order to adapt normative calculations. Finally, the overall approach is used with a building stock model to demonstrate a preliminary assessment of different energy efficiency measures, towards meeting the national targets for 2020 and 2030.

2.1 Hellenic Residential Building Typology

The national typology that describes the Hellenic residential building stock followed the TABULA classification scheme (Dascalaki et al. 2016). The Hellenic building matrix was defined for 24 classes depending on: Building Size (i.e. SFH for single-family houses that are low-rise buildings with one or two floors and MFH for multi-family houses); Building Age (using three vintage bands based on the year of building construction, i.e. pre-1980 to represent buildings that are not thermally insulated, 1981-2010 to represent partially or fully insulated buildings as a result of compliance with HBTIR that is the first thermal insulation code, and post-2011 to represent buildings that are thermally insulated in compliance with the new national regulation - KENAK); Building Location (using the four climate zones defined by the national regulation (KENAK) on the basis of the heating degree days, i.e. Zone A (averaging 859 HDD) for the south, Zone B (averaging 1163 HDD) that includes Athens that is the largest metropolitan region of Greece with 33% of the total number of dwellings in the country, Zone C (averaging 1825 HDD) and Zone D (averaging 2260 HDD) for the northern parts of the country and some high elevation regions in the mainland with the coldest conditions.

A “typical” building was assigned to each of the above 24 building classes, which is a real (existing) building considered to be representative of all buildings in the particular class (Dascalaki et al. 2016). Supplementary sub-typologies regarding building elements and systems were prepared in accordance to the construction and system installation trends in Hellenic residential buildings, throughout the three age bands. Data on the “typical” buildings were assigned to the building types, including general features (i.e. number of storeys, living area), geometrical data (i.e. building volume, envelope areas), thermal properties of the envelope, as well as technical characteristics and performance of the heating systems.
2.2 Insight from EPCs

Energy performance certificates (EPC) of buildings are being issued throughout Europe in accordance to the national EPBD provisions. Over the years, this has initiated a mapping process of European buildings. The EPCs progressively reflect the national building stock and offer a unique opportunity to reveal key data for accessing and improving the existing buildings. The Hellenic EPC is a two-page document (Dascalaki et al. 2012) and is being issued in Greece as of January 2011 for all buildings that are being sold and for entire buildings that are being rented out for the first time to a new tenant. The EPC for a building unit (e.g. an apartment) that is being rented out for the first time to a new tenant was initiated in January 2012. The EPC includes general building information, the building’s energy class label, annual calculated and actual (if available) final and primary energy consumption, CO₂ emissions, breakdown of energy carriers and different end-uses, and up to three cost effective recommendations for improving the building’s energy performance with calculated energy savings and payback period. The normative calculations are performed using the official national software (TEE-KENAK) in accordance to the European standards EN 13790, with the main calculation procedure of the building energy demand estimated using the quasi-steady state monthly method, the relevant national technical libraries, weather data and other technical specifications outlined in four supporting technical guidelines (Dascalaki et al. 2012). Inherent to the calculations are several assumptions according to the national methodology and technical guidelines, in order to minimize judgment errors by the software user, e.g. assuming for residential buildings an 18-hour daily operation for the entire heating season (e.g. from November to mid-April in the south and from mid-October to April in the north of the country) for achieving indoor thermal comfort conditions set at 20°C (accounting for thermostatic controls) for the entire conditioned floor area of the dwelling, DHW consumption (e.g. 27.38 m³/bedroom at 45°C), fixed values for infiltration and natural ventilation rates (e.g. 0.75 m³/h/m² heated floor area), occupancy and internal heat gains (e.g. from lights at 0.1 W/m², people at 4 W/m² and equipment at 2 W/m² heated floor area).

Simple empirical adaptation factors are defined as a ratio of actual to calculated energy use, extracted from the EPCs that include both types of data. The analysis is performed by classifying the available data according to the Hellenic residential typology. These factors are then used as multipliers for correcting the calculated values to obtain a more realistic actual energy use for representative building types used in the building stock model. The detailed methodology and data analysis for deriving the adaptation factors is elaborated in (Balaras et al. 2016).

2.3 Insight from Field Surveys

Complementary data were also collected from field surveys that document recent behavioral changes of occupants and the role of the human factor in the operation of residential space heating systems. These short surveys record the average actual operating conditions, for example, hours of the heating system (i.e. how many hours do the occupants usually heat their dwelling?), the indoor set-point temperatu-
re (i.e. at what temperature do you set your indoor thermostat?) and the percentage area of the dwelling that is usually heated (i.e. what area of your dwelling do you heat?). This was an effort to capture common practices either as a result of occupant preferences or other socio-economic factors (e.g. fuel poverty) that deviate from normative calculation assumptions according to national regulations (i.e. 18-hour daily operation for the entire heating season, at 20°C indoor temperature, heating the entire dwelling). The data are then used to derive similar correction factors for adapting calculations to more conservative estimates of the actual energy use for the representative building types used in the building stock model.

2.4 Building Stock Model

Each one of the 24 building types is used in the building stock model for numerous different combinations of space heating & DHW generation systems and energy carriers (Fig. 3). The calculations are performed using the official national software (TEE-KENAK) to estimate the annual space heating and DHW energy demand, primary energy consumption and CO₂ emissions per unit floor area. The results from the normative calculations are then adapted using the derived sets of empirical adaptation factors (f) as multipliers for correcting the calculated values to obtain more realistic estimates of the actual energy use.

Figure 3. Overall process of the building stock model and main calculation steps.

The inputs to the building stock model are derived from an analysis of Census or statistical data (e.g. number of buildings and floor areas for occupied dwellings) that correspond to the different building types, with the specific construction and system characteristics. The adapted estimates for the various building types are finally projected to the entire building stock. New construction, demolition and refurbishment rates are also taken into account in order to estimate on an annual basis the number of
buildings and floor areas that correspond to the building matrix and estimate the annual final or primary energy use or savings, fuel mix and CO2 emissions. Currently, the evolution of the building stock over the years considers only constant annual demolition, construction and refurbishment rates, over the entire period of interest. Different scenarios can then be evaluated by implementing various EEMs on the building envelopes or the systems or both, coupled with different modernization rates for assessing the results towards the national CO2 emission targets for 2020 and 2030. For each annual calculation, over 960 input files are generated by combining all 24 building types with the different space heating systems, DHW systems and energy carriers that are fed in the calculation engine. The technical characteristics of the typical buildings change each year, by redefining the U-values, system efficiency and energy carriers, depending on the different modernization scenarios and EEMs. The details of the building stock model are elaborated in (Dascalaki et al. 2016).

3. Results

The available valid EPCs that included data on actual thermal and/or electrical energy consumption were about 16,000 cases (or 3.5% of the total), since this information is provided on a voluntary basis. The first stage analysis used all the available “raw data” of unique EPCs from dwellings that use only one energy carrier for space and DHW heating that amounted to ~11,800 cases, of which about 85% are for MFH. At a second stage, the data was processed with some basic quality controls, e.g. splitting the data in bins and censoring top outliers (erroneous or questionable values) of thermal or electrical energy use. The resulting “screened data” included ~8,500 cases, of which 83% are for MFH. Apparently, the available data is currently biased towards multi-family dwellings.

The primary energy is estimated using national conversion factors for different energy carriers, i.e. 2.9 for electricity, 1.1 for heating oil and 1.05 for natural gas. The available raw and screened data was clustered and analyzed for the 24 building types. Representative results of the primary energy use intensity (EUIp) values are illustrated in fig. 4 for the pre-1980, SFH and MFH building types, at the four climate zones (e.g. zone A in the south and zone D in the north of the country). The cloud data is the actual primary energy use retrieved from the corresponding EPCs. The available data exhibit large variations as a result of the unique building characteristics or prevailing weather conditions (since the normative calculations are performed using standard weather files) and occupant behavior.

The complete list of the derived average ratios (i.e. actual to calculated EUIp) are summarized in Table 1 along with the best-fit linear regressions to the corresponding actual EUIp data from the EPCs. Each time, the adapted estimates are the product of the calculated data with the corresponding adaptation factors for the specific building type, for example, as illustrated with the triangles in Fig. 4. The ratios should be comparable to the slope obtained from a linear regression on the same set of data, with zero intercept.
Figure 4. Representative results for the pre-1980 construction period with correlations of actual (bullets) and calculated (triangles) primary energy use intensity for SFH and MFH types at the four climate zones, using the screened data. Dashed lines represent the best-fit linear regression to the corresponding actual EUI_p data (bullets) from the EPCs. Solid regression lines are fitted to the calculated EUI_p data (triangles) using the corresponding adaptation factors.
As shown in table 1, for some building types that correspond to recent building construction periods, there is limited available data at this stage, so one would expect that for these specific building types there is low confidence in the derived factors. Another bias of the currently available data is that the database is dominated with EPCs from MFH (i.e. 85% in the raw data or 83% in the filtered data) that are the most commonly issued certificates for renting out apartment units. For the time being, this ratio does not meticulously reflect the national average of MFH in the residential building stock. However, as the database is progressively enriched with EPCs that include actual energy use data from more building types (e.g. SFH and new construction periods), it will be possible to periodically repeat the process and update the corresponding empirical adaptation factors.

The average calculated and actual EUIₚ for space heating and DHW in the different building types are illustrated in fig. 5. The lowest average values for the calculated vs actual EUIₚ are observed for the post-2011 types of buildings (i.e. new buildings that correspond to the EPBD - KENAK era) and the highest to the older buildings (i.e. pre-1980).

![Figure 5. Bubble plots of raw (left) and screened (right) data for the average calculated and actual primary energy use intensity for space heating and DHW in the different building types. The size of the bubble represents the corresponding data population. The least-square regression lines correspond to the entire SFH and MFH data. The 45-degree line (i.e. y=x) identifies the case when the calculated and actual energy consumption values are in perfect agreement.](image)

The higher calculated EUIₚ correspond to lower actual energy use, which is more evident for dwellings with a poor energy performance (i.e. high calculated EUIs). This is known in the literature as the “prebound effect” ranging in European households from 30% to 40% less than the calculated values (Sunikka-Blank and Galvin 2012, Magalhaes and Leal 2014, Dall’O et al. 2015, Dineen et al. 2015). The opposite behavior is most notable for dwellings with a good energy performance for which the lower calculated EUIₚ correspond to higher actual energy use. This is
Table 1. Average empirical adaptation factors derived using the raw and screened data for the different building types and the corresponding best-fit linear regressions to the corresponding actual $EUI_p$ data from the EPCs (actual ($y$) as a function of the calculated ($x$) energy use data sets). The $f_1$ factors are derived from the EPCs and the $f_2$ from the field studies. The corresponding data population ($N$) is included in parentheses.

<table>
<thead>
<tr>
<th>Construction period</th>
<th>Climate zone</th>
<th>Single-family houses (SFH)</th>
<th>Multi-family houses (MFH)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f_1* y=bx  (N)</td>
<td>f_1** y=bx  (N)</td>
<td>f_2 (N)</td>
</tr>
<tr>
<td>pre-1980</td>
<td>0.5919 y=0.4379x (1075)</td>
<td>0.4933 y=0.4158x (909)</td>
<td>0.2829 All pre-1980 (24)</td>
</tr>
<tr>
<td>A</td>
<td>0.5726 y=0.4294x (66)</td>
<td>0.5290 y=0.4329x (54)</td>
<td>0.8658 y=0.6151x (213)</td>
</tr>
<tr>
<td>B</td>
<td>0.6894 y=0.5055x (500)</td>
<td>0.5153 y=0.4595x (422)</td>
<td>1.0565 y=0.5833x (3276)</td>
</tr>
<tr>
<td>C</td>
<td>0.5931 y=0.4435x (382)</td>
<td>0.5051 y=0.4210x (315)</td>
<td>0.7472 y=0.5134x (1386)</td>
</tr>
<tr>
<td>D</td>
<td>0.4807 y=0.3509x (127)</td>
<td>0.4414 y=0.3529x (118)</td>
<td>0.7884 y=0.5566x (321)</td>
</tr>
<tr>
<td>1981-2010</td>
<td>1.0905 y=0.6238x (700)</td>
<td>0.6267 y=0.5422x (500)</td>
<td>0.3414 All post-1981 (30)</td>
</tr>
<tr>
<td>A</td>
<td>1.0001 y=0.5822x (101)</td>
<td>0.5746 y=0.4483x (68)</td>
<td>1.7222 y=0.7533x (360)</td>
</tr>
<tr>
<td>B</td>
<td>1.9876 y=0.6581x (295)</td>
<td>0.6083 y=0.5564x (196)</td>
<td>2.4935 y=0.7201x (2660)</td>
</tr>
<tr>
<td>C</td>
<td>0.8384 y=0.6316x (227)</td>
<td>0.6331 y=0.551x (166)</td>
<td>1.1373 y=0.7367x (1451)</td>
</tr>
<tr>
<td>D</td>
<td>0.7483 y=0.5694x (77)</td>
<td>0.6421 y=0.5334x (70)</td>
<td>1.0943 y=0.7861x (339)</td>
</tr>
<tr>
<td>post-2011</td>
<td>0.8609</td>
<td>0.7254</td>
<td>2.5647</td>
</tr>
</tbody>
</table>
commonly referred to in the literature as the “rebound effect” that is most notable for dwellings with a good energy performance. Several European studies report a rebound effect of 20% up to 68% (Burman et al. 2014). The results confirm that both prebound and rebound effects should be taken into account in order to make more realistic estimates in building stock modeling, by adapting the calculated estimates of energy performance for new buildings or the anticipated energy savings for existing buildings as a result of implementing EEMs (Sunikka-Blank and Galvin 2012).

The average ratios ($f_1$) based on the analysis using the raw data (considered as an upper bound of the actual energy use) range from 0.70 for SFH (i.e. 30% lower energy use than calculated) to 1.08 for MFH (i.e. 8% higher energy consumption than calculated). The values for the different groups of data (e.g. all pre-1980 or all data) are calculated as the best-fit to the averages using the corresponding adaptation factors for the different building types. Analyzing the screened data (considered as an average bound of the actual energy use) the ratios ($f_1$) range from 0.52 for SFH to 0.56 for MFH (i.e. 48% or 44% lower actual energy consumption than calculated).

Overall, higher calculated EUIs correspond to lower actual energy use (i.e. buildings that are characterized by poor energy performance according to normative calculations will have a lower actual energy use). This is an anticipated result since old and low energy performance dwellings are usually occupied by low-income households who are struggling with heating energy costs and keeping their homes adequately warm. Occupants with low household incomes are usually at higher risk of fuel poverty and occupant behavior will practically determine the actual energy use.
The short field surveys provided a lower bound of energy use that captures recent occupant reactions by limiting the operating hours for space heating, lowering the indoor temperature settings, and reducing the heated floor area of their dwellings (e.g. by isolating rooms). These deviations from normative calculation assumptions may even come at the expense of indoor thermal comfort conditions in an effort to reduce operational costs for space heating. The collected information revealed that only 17% of SFH and 10% of MFH have operating hours close to the assumed continuous heating hours of the normative calculations. On average, the heating systems are actually operated 5-6 hours vs the assumed 18 h/day in the calculations. Only 28% of the occupants in SFH and 27% in MFH reported that their average indoor temperature is set at 20°C that resembles the specified indoor set-point in the calculations. The weighted average temperature reported by the occupants is 19.6°C during the day, with a temperature night set-back at 16.9°C. Finally, only 33% of SFH and 43% of MFH actually heat the entire floor area of their dwelling that corresponds to the calculation approach. Individually or collectively, one can derive a series of similar empirical adaptation factors for adjusting the calculated values and account for deviations from the standard operating conditions used in the normative calculations. The representative results were 0.39 for the heating operating hours, 0.88 for the heated floor area and 0.91 for indoor temperature deviations. The impact of these behavioral changes is a lower actual energy use but at the expense of proper indoor thermal conditions. Only 56% of the occupants in SFH and 45% in MFH manage to feel comfortable in their homes. Overall, the results are in agreement with the national averages (ELSTAT 2013) giving some level of confidence that the available field survey data capture the recent trends of occupant reactions to lower the operational energy consumption for heating their dwellings.

The available field survey data was clustered to derive similar adaptation factors (f2) for adjusting the calculated values to account for the deviations from the standard conditions used in the normative calculations, e.g. lower hours of operation and indoor temperature settings, heating smaller floor areas of dwellings (Balaras et al. 2016). The representative results (table 1) are presented for only two major construction periods (pre- and post-1980) of SFH and MFH, since the available data during this pilot action originate from only 211 dwellings. The lower bound adaptation factor (f2) averages about 0.32 and is considered a conservative estimate of actual energy use.

The building stock model illustrated in fig. 3 was set-up and implemented, taking into account the annual construction rates of new buildings, demolition of older buildings, as well as different refurbishment rates of the existing building stock. The results from different refurbishment scenarios are elaborated in (Dascalaki et al. 2016). The 2030 targets for CO2 emissions and final energy consumption are reached by applying an aggressive annual refurbishment rate of 3.6% for thermal improvement of the envelope and 1.15% for improvement of the systems’ efficiency to minimize heat demand and promote the use of solar energy systems for DHW and solar heating together with a gradual fuel change from oil to natural gas.
To validate the overall approach, the current state of the building stock model was used to generate results for the 2012 base year (fig. 6). The results were compared against the officially reported data (EU 2014), which was the most recent base year with available data at the time of the study. Since then, the official Eurostat data (EU 2016) for 2013 and 2014 were published and are also included in Fig. 6 as snap-shots of the short-term current trends, under the adverse impacts of the prevailing economic crisis.

The officially reported values for 2012-14 are bracketed by the building stock model results for occupied dwellings that have been corrected with the adaptation factors (f1**) that serve as an average of the general trend of actual energy use and the results using the (f2) factors that serve as a conservative estimate. Apparently, the use of the more conservative lower bound adaptation factors appear to capture the current dropping trend of actual final heating energy use in Hellenic dwellings as a result of the economic crisis.

4. Conclusions

A pilot study exploited recent data on actual energy performance of Hellenic dwellings as a first attempt to close the gap between calculated (predicted) and actual energy use. This work was not an attempt to test the accuracy of the calculation tool, but rather to set an easy to implement conceptual approach for making more realistic estimates of actual energy use for different building typologies and energy savings for common EEMs. The two-step approach exploits available information from EPCs and collects new data through manageable short field surveys. The work was based on data from Greece but the streamline approach can also be implemented in other European countries using data from energy performance certificates and the building typologies that are already available for 20 EU Member States (Loga et al. 2016).

Actual energy consumption exhibits large variations for the same calculated EUIp. Although it was not possible to implement a comprehensive quality control on
the available data and for some building types there is not yet sufficient number of
data, the results reveal some interesting trends and insight. An upper bound average
ratio of actual to calculated primary energy use ranges from 0.70 for SFH to 1.1 for
MFH, while the average bound results indicate that dwellings may use about 48%
(SFH) to 44% (MFH) less energy than calculated. The homeowner field surveys
revealed a lower bound that reflects a conservative estimate of actual energy use
driven by recent behavioral changes and trends in the use and operation of heating
systems. Representative results for two major construction periods (pre- and post-
1980) of SFH and MFH indicate an average of 69% less energy use than calculated.
Policy makers should take these findings into consideration when assessing different
scenarios and prioritizing EEMs in building stock model projections.

To support future work and further analysis, more good quality data would be
valuable. The adaptation factors should be periodically updated. As the number of
EPCs increases it will be possible to cover all building types with sufficient number
of data. Energy inspectors should also be encouraged to include and report the actual
energy use. Short field surveys could be used in order to capture the trends of occu-
pant behaviors in terms of actual hours of operation, indoor temperature settings and
heating floor areas of dwellings, which have the most direct impact on the deviations
of actual energy use from the normative calculations. Another angle of attack is to
collect data and develop a knowledge base for the effectiveness of more EEMs
under actual operating conditions in order to quantify the actual energy savings
before vs after the implementation of the measures, especially during nationally
funded refurbishment projects. The building stock model itself could also be improved
by considering variable annual demolition, construction and refurbishment rates
in order to more realistically reflect the evolution of the building stock over the
years.

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