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ScienceDirect

Energy Procedia 62 (2014) 32 – 41

Energy Procedia

6th International Conference on Sustainability in Energy and Buildings, SEB-14

Are internal heat gains underestimated in thermal performance evaluation of buildings?

Rainer Elsland[a,*], Ilhan Peksen[a], Martin Wietschel[a]

[a] *Fraunhofer Institute for Systems and Innovation Research ISI, Breslauerstr. 48, 76139 Karlsruhe, Germany*

Abstract

Improving the energy performance of buildings can contribute substantially to reducing energy demand. To evaluate the useful energy demand for space heating purposes from an energy economics perspective norm-based bottom-up models are applied that capture the energy-related characteristics of buildings. As electricity demand per household attributed to appliances and lighting has increased substantially in the EU27 during the last two decades (+50 %), the question arises whether the static norm-based approach is underestimating the contribution of internal heat gains to covering useful energy demand. To analyze the impact of dynamic internal heat gains in the residential sector, a bottom-up vintage model is applied that covers the EU27 building stock with a country-specific typology. This means the internal heat gains are time-dependent and heat dissipation is distinguished by appliances, lighting and residents. The analysis consists of two explorative scenarios for the residential building stock of EU27 until 2050. A reference scenario represents the static norm-based modelling of internal heat gains while the second scenario considers their dynamic development. The study reveals that the norm-based approach underestimates the contribution of internal heat gains to covering thermal heat demand. Comparing the countries throughout the EU27 climate zones indicates that on average the static and the dynamic share of internal heat gains differ in a range from 20-70 % by 2050. Especially in the case of nearly Zero-Energy Buildings (nZEB), e.g. with 30 kWh/m²*a useful energy demand, the internal heat gains are about 10-15 % higher using the dynamic approach compared to the norm-based approach.

Selection and peer-review under responsibility of KES International

Keywords: bottom-up approach, residential sector, buildings, internal heat gains, scenario analysis

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* Rainer Elsland. Tel.: +49-721-6809-438 ; fax: +49-721-6809-272.
E-mail address: Rainer.Elsland@isi.fraunhofer.de.

Selection and peer-review under responsibility of KES International
doi:10.1016/j.egypro.2014.12.364

1. Background and objectives

Lowering energy demand is known to be the most significant driver in the attempt to mitigate climate change and meet the energy and climate policy targets of the European Union [1,2]. In this context it is of great interest that space heating demand in the residential sector is set to significantly decline over the coming decades. In 2010, 8,595 PJ were attributed to residential space heating in the EU 27, which is equivalent to 17.8 % of the total final energy demand (48,291 PJ) [3]. Against this background, improving the energy performance of buildings can contribute substantially to reducing energy demand. European and national norms are applied to evaluate the useful energy demand for space heating purposes of a single building, e.g. DIN V 4108-6, DIN V 4701-10 and DIN EN ISO 13790, that describe the energy-related characteristics of a building based on physical and behavioural parameters [4-6]. When analysing buildings' energy demand from an energy economics perspective bottom-up vintage models are applied [7-10]. These bottom-up models capture the building typology of entire countries by construction period, building type and building standard, where each segment is represented by a reference building.

However, although norm-based modelling is a well established approach in bottom-up analysis, this methodology displays a crucial limitation in terms of its negligence of the dynamic characteristics of internal heat gains. An analysis of the development of residential appliances and lighting over the last two decades reveals that their electricity demand per household has increased substantially in each EU member state by +50 % [3]. In spite of the fact that energy policy instruments like the Ecodesign Directive have been implemented during the last decade in an attempt to reduce energy use by setting minimum efficiency standards at the design phase, increased ownership of appliances has still led to rising electricity demand. [11]. Against this background, applying a static approach to internal heat gains could lead to a systematic underestimation of their contribution to covering useful energy demand. This methodological limitation becomes even more significant in nearly Zero-Energy Buildings (nZEB), where the relative share of internal heat gains is even larger.

To analyse the impact of the dynamic development of internal heat gains on the useful energy demand in the residential sector of the EU27, the bottom-up vintage model FORECAST-Residential is applied, which covers the European building stock by country. In the framework of this study, internal heat gains are analysed in detail distinguished by the heat given off by different types of appliances, lighting and residents. To the knowledge of the authors, no prior study has focused on this research question on such a broad regional scope. We begin by discussing the methodological concept of the bottom-up approach (section 2). In section 3 a case study is conducted for the residential building stock of the EU27 on a country basis until 2050. The case study consists of two explorative scenarios; the reference scenario represents the norm-based modelling of internal heat gains and the second scenario considers the dynamic development of appliances, lighting as well as residents. The results are then discussed and conclusions drawn (section 4).

2. Methodological approach

2.1. Structural framework

For the analysis the simulation based bottom-up model FORECAST-Residential is applied, which models the useful energy demand for space heating purposes of the EU27[†] by country up to 2050. FORECAST-Residential is designed as a vintage stock model, which enables a detailed modelling of the stock turnover taking into account regulatory requirements. In this study the country-specific useful energy demand is calculated differentiated by construction period (<1960, 1961-1990, 1991-2008, 2009-2020, 2021-2050), which are in turn divided into building types (single-family-houses (SFH), multi-family-houses (MFH)) and energy efficiency standards (5 varying standards). Distinguishing the new building stock into buildings constructed before and after 2020 is related to the fact that major policy regulations regarding the energy performance of buildings are defined for the year 2020 (e.g.

[†] *FORECAST is a modelling platform that captures the final energy demand of the sectors industry, households, tertiary, transport and agriculture for the EU 27+3 (3: Norway, Switzerland, Turkey) by country up to 2050 [1,12,13].*

EPBD recast) [14]. In total, considering the building typology in this way results in 50 reference building segments (see section 2.2) per country and thus 1350 building segments for the EU27.

An additional module is integrated into the building stock model (see section 2.3) to evaluate the dynamic impact of internal heat gains. The internal heat gains module covers large appliances (including: refrigerators, freezers, washing machines, dryers, dishwashers, stoves), ICT (including: desktop-computers, PC-screens, laptops, televisions, set-top-boxes, modems/routers), lighting (including: incandescent lamps, halogen lamps, energy saving lamps, fluorescent lamps, LEDs) as well as 'Others' (this category captures all end-uses that are not explicitly modelled). The internal heat gains module has three hierarchical levels: appliances (e.g. television), technologies (e.g. LCD, plasma) and efficiency classes (e.g. A++, A+). The energy demand of the end-uses is captured by techno-economic (e.g. operating power, investments) and user behavioural parameters (e.g. operating hours). The high level of disaggregation makes it possible to also consider rebound effects, policy regulations, saturation effects and investment barriers.

The structural design of the norm-based building module and the dynamic internal heat gains module is illustrated in Fig. 1. The socio-economic parameters database provides the framework data for the modelling process. In both modules, the investment decision is based on the Total Cost of Ownership (TCO) and the energy policy framework as well as technological preferences which are considered in terms of diffusion restrictions (e.g. demolishment of buildings at earliest 20 years after construction, replacement of appliances at earliest after 40 % of their lifetime). In the norm-based building module, the number of demolished buildings is based on their age distribution and a predetermined demolition rate [15]. The number of new builds and the refurbishment of existing buildings are calculated based on a multinomial Logit-approach [16]. In general, the dynamic internal heat gains module has a similar structure to the building module apart from the fact that a different set of methodologies is applied: the replacement cycles are captured by a normal distribution function [16], the technological choice is determined using a multinomial Logit-approach [16] and the development of the ownership rate is plotted using a Bass-model [17]. Depending on the scope of the analysis, the internal heat gains are evaluated in a static (norm-based building module) or in a dynamic (dynamic internal heat gains module) manner.

2.2. Norm-based modelling of useful energy demand for space heating purposes

The useful energy demand per building segment is calculated based on the heating period method taken from the German norms DIN V 4108-6 and DIN V 4701-10 (German Institute for Standardization) [4,5] which is comparable to the heating and cooling period method of DIN EN ISO 13790 and consequently conform to EU regulations [6]. The annual useful energy demand is the amount of energy supplied to a building during the heating period in order to obtain the target indoor temperature. According to DIN V 4108-6 and DIN V 4701-10, the useful energy demand is calculated by equation (1):

$$\mathrm{Q_h = (H_T + H_V) \cdot F_{DDF} - \eta_n \cdot (Q_I + Q_S)\ [kWh/a]} \tag{1}$$

where Q_h is the annual useful energy demand of a single building, H_T is the transmission heat loss, H_V is the heat ventilation loss, F_{DDF} is the degree day factor, η_n is the utilization factor including internal and solar heat gains assumed to be 0.95 [4], Q_I is the internal heat gain and Q_S is the solar heat gain. The utilization factor reduces the total gains to the share that covers the thermal heat demand of a building. In terms of internal heat gains the utilization factor considers that end-use power is only partially transferred into convection and radiation and that the location of an end-use is not necessarily located in the heated part of a building (e.g. washing machines are often located in unheated basements).

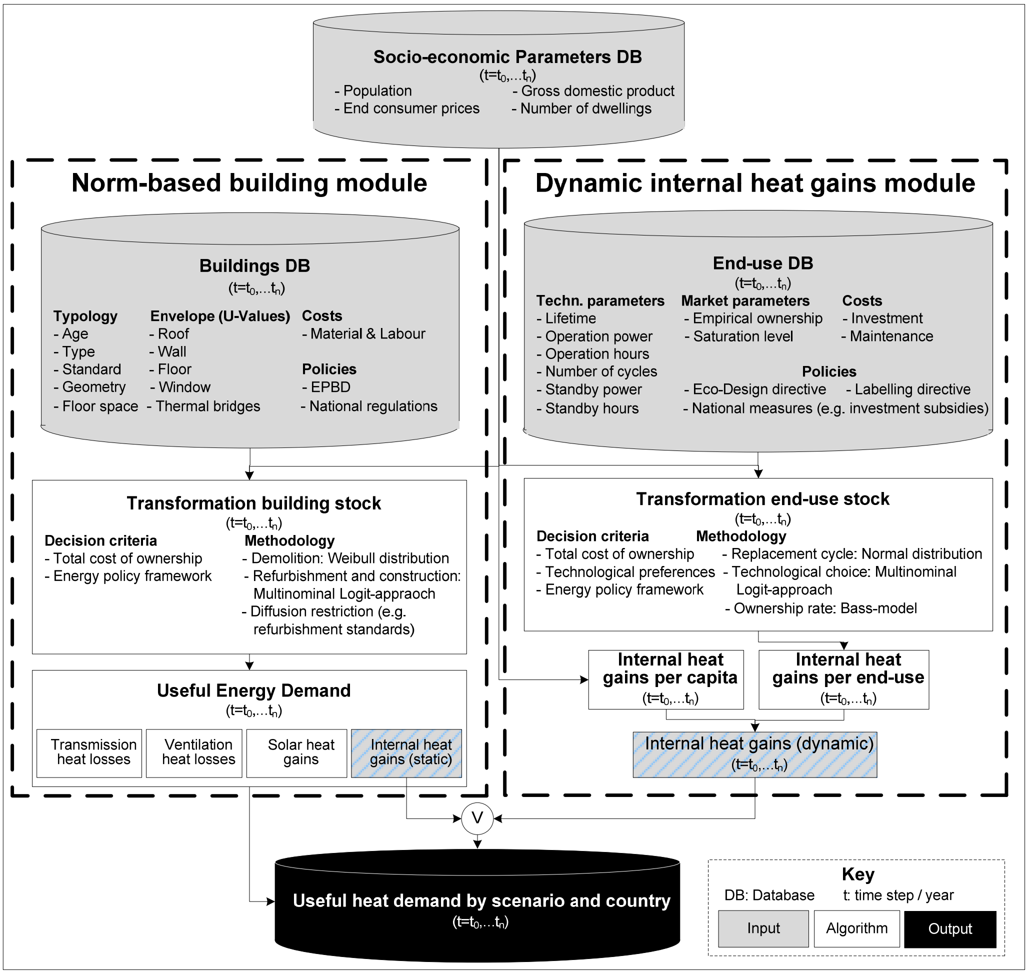

Fig. 1. Structural framework of the norm-based building module and the dynamic internal heat gains module of FORECAST-Residential

The transmission heat loss is derived from the heat transfer to the outer surface of the building elements and is therefore a measure of the thermal quality of a building envelope. The thermal quality of an element is defined by its U-value which indicates the level of insulation (W/m²K). Transmission heat losses are calculated based on equation (2):

$$H_T = \sum_{i=1}^{n} \left(F_{x,i} \cdot U_i \cdot A_i\right) + \Delta U_{TB} \cdot A_{tl}\ [W/K] \tag{2}$$

where H_T is the transmission heat loss, $F_{x,i}$ is the temperature correction factor for each building element, U_i is the mean U-value of a building element, A_i is the surface area of each building element and the additional loss caused by thermal bridging is defined by ΔU_{TB} as the thermal bridge correction factor (0.05 W/m²·K) [4] and A_{tl} as the heat transmitting surrounding area. The second part of the heat losses is caused by ventilation losses calculated by

$$H_V = c_{air} \cdot n_{air} \cdot V\ [W/K] \tag{3}$$

where H_V is the ventilation heat loss, c_{air} is the volume-specific heat capacity of the air, n_{air} is the airflow rate and V is the air volume. For SFH and MFH with up to three storeys V is equal to 0.76 and for all other buildings 0.80 [4]. Internal heat gains are caused by the waste heat of electrical end-uses and the heat dissipation of residents, respectively. The calculation of internal heat gains is described in equation (4):

$$Q_I = 0{,}024\ [\mathrm{kh/d}] \cdot q_i \cdot l_{HP} \cdot A_{ref}\ [\mathrm{kWh/a}] \tag{4}$$

where Q_I is the internal heat gain, q_i is the average thermal output of internal heat sources, l_{HP} is the length of the heating period and A_{ref} is the energy reference area of the building [4]. The average thermal output of internal heat sources is considered to be constant with 2.5 W/m² for SFH and 3.2 W/m² for MFH which varies from the norm according to the analysis from IWU [18]. These average values are derived from a field test where a similar ownership of end-uses and resident occupancy is assumed in a SFH and a MFH and thus the difference is the result of the energy reference area ratio per dwelling. Solar heat gains assume complete exposure to sunlight as calculated by

$$Q_S = \sum_{i=1}^{n} (F_i \cdot g_i \cdot A_W \cdot I_{sol})\ [\mathrm{kWh/a}] \tag{5}$$

where Q_S is the solar heat gain, F_i is the solar radiation reduction factor, g_i is the total energy transmittance of glazing type in case of vertical insolation, A_W is the area of windows corresponding to the effective collector area and I_{sol} is the average global irradiation during the heating period depending on orientation. According to DIN V 4108-6 [4] the degree day factor is calculated based on the amount of degree days and a factor of 0.95 for the night setback (time-limited heating) calculated by

$$F_{DDF} = 0{,}024\ [\mathrm{kh/d}] \cdot (\theta_{i,eff} - \theta_{e,HP}) \cdot l_{HP}\ [\mathrm{kKh/a}] \tag{6}$$

where F_{DDF} is the degree day factor, $\theta_{i,eff}$ is the effective room temperature during the heating period, $\theta_{e,HP}$ is the average outdoor temperature during the heating period and l_{HP} is the length of the heating period.

2.3. Modelling dynamic internal heat gain development

Analysing the literature shows that in most cases, an average value is taken for internal heat gains either dependent or independent on the type of building [4,18-22]. A more detailed approach is taken by [23,24], who analysed the drivers of internal heat gains by distinguishing between the heat dissipation of residents and end-uses. Depending on the subject of research, the data basis for internal heat gains results from modelling [21,23], measurements [20,25] or surveys [26] and varies widely in a range from 1 to 5 W/m². According to [23,24], the dynamic development of internal heat gains comprises the heat given off by residents, appliances and lighting (equation 7).

$$Q_{I,t} = Q_{I,e,t} + Q_{I,r,t}\ [\mathrm{kWh/a}] \tag{7}$$

where $Q_{I,t}$ is the total internal heat gain, $Q_{I,e,t}$ is the internal heat gain from appliances as well as lighting and $Q_{I,r,t}$ is the internal heat gain from the presence of residents. Thus, equation 7 replaces equation 4 when analysing the impact of a dynamic development of internal heat gains. The internal heat gain from appliances as well as lighting is related to the energy reference area of a building and calculated by

$$Q_{I,e,t} = l_{HP} \cdot \left(\sum_{j=1}^{m} p_{j,t} \cdot d_j \cdot o_{j,t} \cdot \frac{\eta_{m,j}}{\eta_n}\right) [\mathrm{kWh/a}] \tag{8}$$

where $Q_{I,e,t}$ is the internal heat gain from appliances as well as lighting, l_{HP} is the length of the heating period, $p_{j,t}$ is the power of an end-use distinguished by operation and standby, d_j is the running time of an end-use distinguished by operation and standby per day, $o_{j,t}$ is the ownership rate of a dwelling by end-use and $\eta_{m,j}$ is the modified utilization factor for the inclusion of internal heat gains in relation to η_n the norm-based utilization factor (see equation (1)). As a result, the utilization factor ratio adjusts the general norm-based default value of 95 % to the value of 80 % based on the findings of [27-30]. In addition, an end-use specific adjustment to the level of 25 % is applied for washing machines and dishwashers, as most of the heat they generate is discharged with the drain water (Fig. 2) [25]. The amount of thermal heat provided by residents is captured as follows:

$$Q_{I,r,t} = l_{HP} \cdot r_t \cdot d \cdot h \; [\mathrm{kWh/a}] \tag{9}$$

where $Q_{I,r,t}$ is the internal heat gain from the presence of residents, l_{HP} is the length of the heating period, r_t is the number of residents per dwelling, d is the average heat dissipation of 70 W per capita of a resident [22,29,31] and h is the average daily period spent by a resident in a dwelling, which is assumed to be 12 hours here (Fig. 2) [29].

3. Scenario analysis

3.1. Scenario definition and framework

The explorative scenario analysis examines the useful energy demand of the EU27 residential sector in the period 2008-2050. The reference scenario (REF-S) evaluates internal heat gains based on the static approach and the second scenario (DYN-S) analyses the impact of dynamic internal heat gains. To provide a high level of comparability, the scenarios only differ in terms of the alternative approach used to evaluate the internal heat gains. The socio-economic framework parameters are taken from a study conducted by the ESA[2] for the EU27 by country [1,32]. Regarding the ownership rate and the number of lighting points the following saturation levels per dwelling are assumed: large appliances (0.5-1.1 %), ICT (0.7-2.1 %) and lighting (15-30 lighting points). The exact value of the saturation level depends on the type of end-use and the country. The model is calibrated using recently published studies on building typology [8,33] and ownership rates as well as the specific demand by end-use [3,34] of each country. The base year for the scenario analysis is 2008.

3.2. Results

Comparing the internal heat gains related to end-use in 2008 indicates a broad range of 818-3,929 kWh/dwelling (Fig. 2), which is equivalent to 3.8-6.6 W/m². In 2008, by far the highest internal heat gains related to end-use are found in Sweden (3,929 kWh/dwelling) and Finland (3,561 kWh/dwelling), whereas most Eastern European countries are on a level below 1,500 kWh/dwelling. Analysing the results by end-use in 2008 reveals that the largest share is attributed to large appliances, lighting and the category ‘Others’. In terms of growth until 2050, the largest variation is seen in Germany, Austria and Belgium countries with +22-36 %. This is mainly attributed to a strong increase in ICT ownership rates and an ongoing rising trend of the category ‘Others’ as witnessed over the last two decades. Cushioning effects are provided by the phase-out of incandescent lamps and by efficiency improvements to large appliances due to the Eco-Design and Labelling Directive. In contrast, 14 countries witness a decrease of internal heat gains in the long-run either due to strong efficiency improvements or due to a large number of end-use already close to their saturation level in 2008 whereas moderate efficiency improvements are sufficient to overcompensate demand increasing effects.

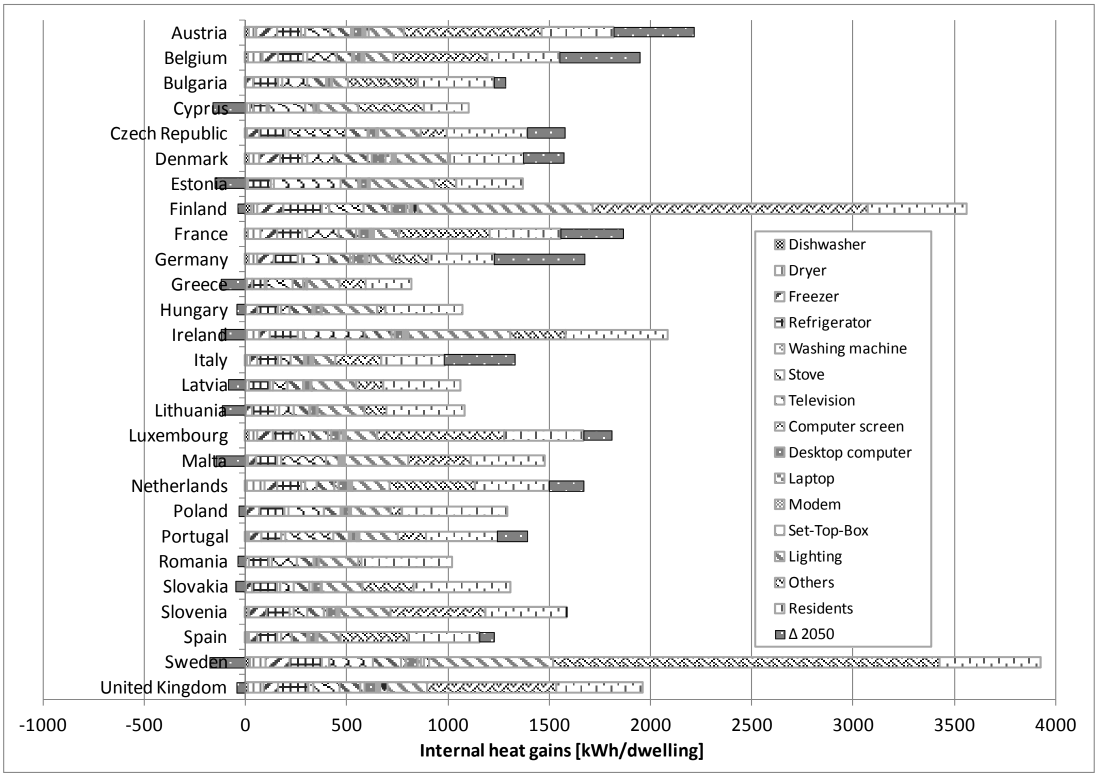

Fig. 2. End-use related annual internal heat gains per capita by country in 2008 and 2050 (dark grey area)

In a first step the share of internal heat gains is analyzed from an aggregated point of view. The results of the cohort modelling by reference building are cumulated on a country level to obtain an average SFH and MFH for 2008 and 2050 (Fig. 3). In addition to the country-specific results an average (AVG) per climate zone is given in Fig. 3, as a benchmark. The climate zones are distinguished by heating degree days (HDD) into a cold climate zone (>4,200 HDD), a moderate climate zone (2,200-4,200 HDD) and a warm climate zone (<2,200 HDD). On average, the specific useful energy demand of buildings declines by 47 % until 2050 in case of a static approach, with cold climate zones witnessing the largest percentage decrease by about 54 %, starting from a very high level in 2008 of 159 kWh/m²*a. Due to the improved thermal performance of buildings, the relative share of internal heat gains compared to the overall heat losses (transmission heat losses plus ventilation heat losses) also increases in the static norm-based approach (REF-S), partially by a level of more than 50 %. In terms of the DYN-S, the results indicate that the increasing share of internal heat gains is relatively larger for MFH than for SFH compared to the static approach. Especially in the warm climate zone the average share of internal heat gains (AVG) reaches a level of above 35 % in 2050.

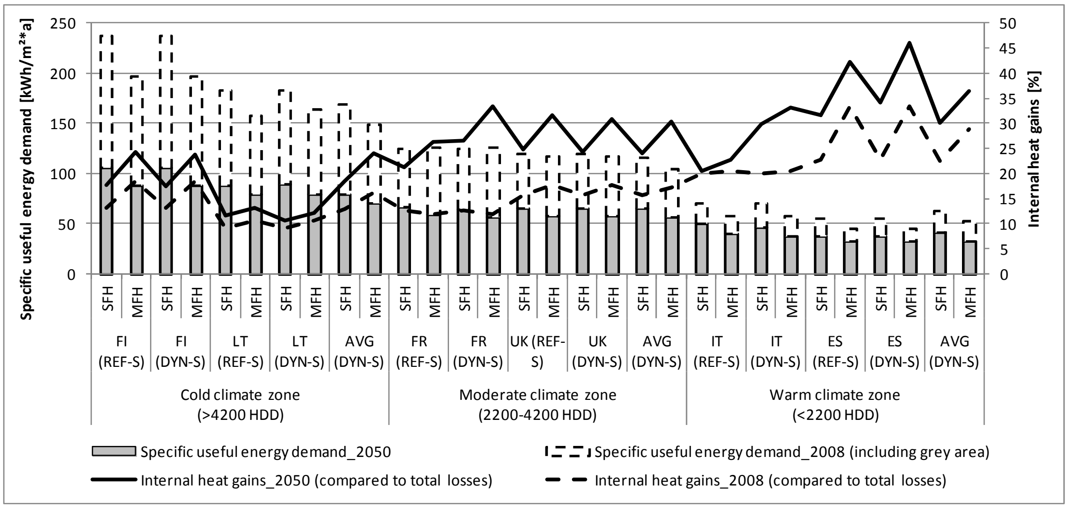

Fig. 3. Average useful energy demand and share of internal heat gains in selected EU27 countries in 2008 and 2050

In a second step, a decomposition analysis is conducted for the dynamic approach to obtain deeper insights with regard to nZEB, for instance with a thermal performance of 30 kWh/m²*a. Fig. 4 indicates that the increasing ownership rate of end-uses leads to increased internal heat gains which are cushioned by the decreasing number of persons per dwelling as well as the energy efficiency improvements of end-uses. The degree of compensation depends strongly on demographic change, the trend towards more single-person households and the ambitiousness of energy policies as well as their enforcement on a country basis. Comparing the countries in Fig. 4 with each other shows that climate-related heterogeneity as well as differences between SFH and MFH in terms of building physics lead to varying levels of internal heat gains. In Fig. 4, the values without brackets quantify the percentage impact of each effect on the overall change between 2008 and 2050 by selected country. The values in the brackets beneath represent the mean of each climate zone as a benchmark. Analysing the results shows that in Finland the demand decreasing effect of end-use ownership is almost compensated entirely by efficiency improvements. In contrast, the specific useful energy demand for France and Italy decreases by about 2 kWh/m²*a respectively 3 kWh/m²*a by 2050.

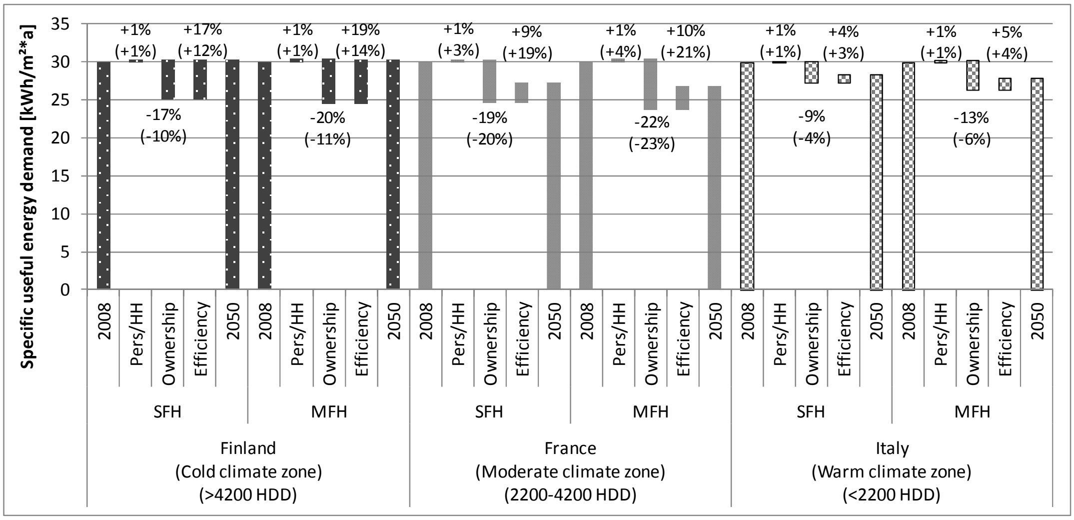

Fig. 4. Decomposition of useful energy demand for a nZEB (30 kWh/m²*a) of selected EU27 countries in 2008 and 2050

4. Conclusions

The analysis reveals that the values obtained by applying a static norm-based approach underestimate the contribution of internal heat gains to thermal heat demand. Comparing the benchmark evaluations for each climate zone indicates that on average the static and the dynamic share differ in a range from 20-70 % by 2050. Increased ownership of appliances is the key driver for increased internal heat gains. Cushioning effects come from the decreasing number of persons per dwelling and an increasing level of end-use efficiency. As the share of the heat load covered by internal heat gains correlates with a decrease in the specific useful energy demand, the magnitude of underestimation is amplified for a nZEB. In buildings with a specific useful energy demand of 30 kWh/m²*a, for instance in France and Italy, the dynamic approach leads to decreasing specific useful energy demand by 10-15 %. Overall, it can be concluded that it is essential to take dynamic heat dissipation into account for a differentiated evaluation of useful energy demand.

The analysis also contains elements of uncertainty. There is only limited empirical evidence for the utilization factor of end-uses and the average period residents spend in the heated building area. In particular, the contribution of the end-use category ‘Others’ is difficult to predict due to an increasing number of mobile devices. As 30-40 % of the share of end-use-related internal heat gains can already be attributed to the category ‘Others’ in some countries, there is substantial uncertainty surrounding its future development when estimating internal heat gains.

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