Draft

# Energy Efficiency of Buildings: A New Challenge for Urban Models

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***Abstract***

*Despite some recent conceptual studies and a modicum of empirical evidence, urban models do not currently take into account the energy efficiency of buildings. This paper presents a framework for incorporating energy efficiency and energy use of buildings into urban models based on microeconomic theory and pricing mechanisms in real estate markets. Using the example of the IRPUD urban land use, transport and environment model, it is demonstrated how a simplified model of building energy-efficient new buildings and retrofitting existing buildings can be integrated into the model to forecast the overall greenhouse gas emissions of households.*

## Introduction

The transport and building sectors are estimated to constitute more than two thirds of greenhouse gas emissions of cities. In an effort to better understand the linkages between these two largest contributors to climate change, researchers have used urban models to identify the multiple feedback loops that link transport costs and behaviour to spatial urban structures, real estate prices and vice versa. A hitherto separate strand of economic research has explored the economics of energy efficiency at the building level and the contribution of policies that promote energy efficiency in residential and commercial buildings. Despite some recent pioneering studies and a modicum of empirical evidence, this strand of research is still in its infancy and urban models do not currently take into account the energy efficiency of buildings.

Preliminary empirical evidence suggests that the environmental cost of sprawl may be even higher when energy efficiency is taken into account as houses in these areas tend to be spacious and detached which may adversely affect the energy efficiency of these structures. However, there are a number of factors, notably the average age of building structures, that work towards mitigating these purported adverse effects. For example, new buildings built to the latest standards generally tend to be more energy efficient. As these buildings are more likely to be located at the urban fringe or in other previously not built-up areas with poorer public transport links than their older, less energy-efficient inner city counterparts, this presents an interesting problem of countervailing effects for urban modelling. Overall, it is vital for urban models and ultimately for policy interventions promoting energy efficiency to understand and empirically estimate the magnitude of these effects. If, for example, policies were designed to favour high-density urban-core neighbourhoods and if these are typically older and less energy-efficient, it would be important to weigh potential gains in reduced transport emissions against potential increases in building-related energy use.

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This paper reviews the literature on the interactions between urban form and energy-efficiency of buildings and domestic energy efficiency investments. It then presents a framework for incorporating energy efficiency and energy use of buildings into urban models based on microeconomic theory and pricing mechanisms in real estate markets and illustrates this by a simplified pilot application. It concludes that urban models should include energy costs associated with a given property and location composed of both energy and transport cost.

**Does location determine domestic energy consumption?**

The impact of urban form on energy consumption and greenhouse gas emissions in the transport sector is the subject of many scientific studies and is an important component of most contemporary urban models. It is now well established that a significant positive association exists between the degree of dispersion in regions and countries and their average total household energy use (Kenworthy 2003). A more recent study by Glaeser and Kahn (2010) finds a strong negative association between greenhouse gas emissions and land use regulations and reports that urban density is associated with lower emissions both when comparing central cities to their suburbs and comparing different metropolitan areas. However, the potential implications of urban form on energy efficiency and energy consumption of buildings have received far less attention than the study of the land use transport nexus, possibly because any such relationship is fraught with a number of mediating and confounding factors. Chief among these are the vintage of the local building stock, the level of household incomes, lifestyle choices and the prevalence of detached housing.

A first attempt to estimate the overall energy footprint of an urban area, including residential energy consumption, is presented by Larson, Liu and Yezer (2012). In their general equilibrium framework, the authors include household energy consumption as a function of dwelling area, household income, energy prices, structure type of the dwelling and a vector of other controls and find that physical characteristics of the dwelling (particularly size and structure type) are among the strongest predictors of total household energy demand.

One of the few studies that explicitly focus on the relationship between urban form and residential energy use was conducted by Ewing and Rong (2008) who conducted an empirical analysis both at the household and US county level and conclude that low-density, detached housing is generally associated with higher energy use. Of the three causal pathways discussed by the authors, electricity transmission losses, urban heat islands and energy requirements of different housing stocks, only the latter will be considered in the present paper.

Using US census data, Ewing and Rong demonstrate that residents of ‘sprawling’ counties are more likely to live in large and detached houses. While this finding may not be surprising, they also report that households living in detached houses consume 54% more energy for space heating and 26% more for space cooling compared to households living in multifamily units. Similarly, a household living in a 2,000 square-foot house consumes 16% more for space heating and 13% more for space cooling. The authors’ general conclusion is that compact urban development carries a double benefit in that it not only reduces transportation energy and Greenhouse gas emissions by 20-40% compared to sprawl but also reduces domestic energy use and emissions to a similar extent. Ewing’s and Rong’s conclusions have been challenged, among others by Randolph (2008) and Staley (2008) mainly on methodological grounds. Their critical evaluation mainly targets the fact that Ewing and Rong combine three unrelated datasets to conduct their analysis and do not take into account spatial differences in energy efficiency of houses and appliances. They also criticise the failure to consider the market dynamics underlying domestic energy consumption which encompasses complex trade-offs and choices of households, technological progress and energy pricing reforms, all of which are likely to have a significant impact on the energy profiles of detached suburban homes.

Further empirical evidence on the energy consumption patterns of residential buildings is presented by Myors, O'Leary and Helstroom (2005) for Australian buildings. Perhaps surprisingly, the authors find in their study that high rise apartments have considerably higher $CO_2$ emissions per dwelling (10.4 tonnes) than low-rises (6.5), mid-rises (7.3) town houses & villas (5.1) and detached houses (9.0). When adjusting for the number of occupants, the carbon profile of detached houses becomes even more favourable with per capita $CO_2$ emissions of 2.9 tonnes versus 5.4 tonnes for high-rises, 3.8 tonnes for mid rises and 3.4 for low rises. However, the authors caveat these findings with several important data limitations. Randolph and Troy (2007) argue based on the available empirical evidence from Australia that the large variability within a certain type of density suggests that other, possibly more important factors are at play that explain the differential energy use and greenhouse gas emissions.

By contrast, a Canadian study conducted by Norman, MacLean and Kennedy (2006) shows that building operations for low-density development are twice as energy and carbon-intensive as high-density development per capita. However, when measured on a square foot basis, the authors find almost no difference between the two types underlining the importance of the denominator when comparing consumption metrics. These findings also point back to the basic fact that dwelling size matters in explaining energy consumption. More to the point, both neighbourhood density and house type appear to be linked to differences in the average size of a typical dwelling across locations, e.g. larger detached houses in suburban locations versus smaller apartments in central locations. In an effort to disentangle these effects, Kaza (2010) applies a quantile regression framework and finds that the effect of reducing housing size by $100m^2$ only has the same effect as a relatively moderate price increase of electricity by 9-25 USD per MWh. The author concludes from these findings that a focus on energy price instruments is preferable over policies that target consumption of living space. This appears plausible as policy measures to limit or reverse average space consumption per capita are likely to be very slow, difficult to implement and might be considered by most households an infringement on their quality of life.

Apart from building type and size, building vintage appears to be a crucial determinant of energy and carbon intensity. A recent study by the NHBC Foundation (2012) using the SAP assessment tool demonstrates that households living in houses built under current UK regulations consume about 50% less energy than in a comparable Victorian-age building, even if modern improvements to the latter are taken into account.. Energy consumption is expected to drop by another 50% between 2012 and 2016 if government aspirations for future building standards are implemented as planned.

**Domestic Energy Efficiency Investments: A History of Paradoxes?**

Much of the scholarly debate on energy efficiency investments in the domestic sector revolves around the existence of an 'efficiency paradox' or 'energy paradox' (not to be confused with the 'green paradox' relating to Hotelling's rule on resource extraction). At the heart of this paradox is the observation that the diffusion rate of energy-efficient technologies and appliances is considerably slower than what would be expected from a pure profit-maximising return-on-investment perspective. Early studies on this phenomenon such as Hausman (1979), Train (1985), Jaffe and Stavins (1994) and Howarth and Sanstad (1995) commonly argue that the paradox arises because investors apply exceedingly high implicit discount rates to these investments. In a similar vein, van Soest and Bulte (2001) argue that the observed slow adoption rate may not be a paradox after all when including the option value of waiting under conditions of rapid technological progress that is marked by 'jumps' in both affordability and efficiency. Investments in energy efficiency, even as they concern the proverbial 'low-hanging fruit', are to a certain extent irreversible and hence need to be weighed against the costs and benefits of investing at a future point in time. Going beyond this widespread discount rate argument, however, more recent studies such as Allcott and Mullainathan (2010) and Jaffe et al. (2005) identify additional barriers to large-scale investments into energy-efficient technology ranging from behavioural economic explanations to negative externalities in the diffusion process. More recently, Keirstead and Calderon (2012) have highlighted the importance of adequate modelling frameworks in the decision-making process. They argue that the current bottom-up assessment by local authorities to develop energy strategies is likely to miss the dynamic interactions between technologies, spatial neighbourhood factors and the differential impact of policies.

In essence, the efficiency paradox may be the result of a triple market failure. The first market failure occurs because of negative externalities of greenhouse gas emissions, i.e. the social cost of the emissions is not reflected in prices paid by consumers, which is effectively a disincentive for firms to increase research and development expenditure on energy-efficient technologies. The second market failure is brought about by positive externalities in the development of green technology. Firms investing in research to develop innovative energy efficient solutions incur high costs but are unable to reap all the benefits of their investments due to inevitable knowledge spillovers to other firms. The third market failure is due to adoption externalities, i.e. the adoption process is characterised by dynamic increasing returns which accrue from widespread production and use of a technology. Compounding these three types of market failure is the fact that energy markets are by no means perfectly competitive in that there exist high barriers to entry and complex price and tariff regulations in most countries.

Apart from these barriers relating to investment and adoption processes, further paradoxes arise on the consumer's side. The most prominent of these is termed 'Jevons paradox' (also called the 'rebound' or 'backfire' effect) which posits that improvements in energy efficiency result in an increase rather than a reduction in energy consumption. Jevons (1865) derived this paradox from his observations of vastly increased resource use of coal following efficiency improvements to the steam engine in the 19th century. More recently, Khazzoom (1980) has specified the economic principles underlying the rebound effect. At present, the existence and relevance of this phenomenon is the subject of a broad academic and political debate. Critics of the concept point to the fact that the increasing use of 'smart' technologies (e.g. motion sensors for lighting) is likely to dampen or even neutralise any direct rebound effects. While empirical evidence is still relatively piecemeal, the debate is of immediate relevance to environmental and climate change policy. If Jevons' paradox applies even in the current and future environment, then energy efficiency improvements would be insufficient or even counter-productive for mitigating climate change and resource scarcity. As Alcott (2005) points out, in the fundamental I=PAT equation (Environmental Impact is a function of Population, Affluence and Technology), all right-hand side factors influence each other, resulting in increased environmental stress and resource use.

Greening et al. (2000) distinguish three types of rebound effects. Firstly, the direct rebound effect implies that any efficiency gains will be offset by increased demand for a product or resource. Secondly, indirect effects alter the demand functions for a number of other consumer products via increased disposable incomes. Thirdly, economy-wide equilibrium effects arise from a series of changes to final and intermediate demand functions and the expansion of firms' production capacities, resulting in complex adjustments to equilibrium prices and quantities which can only be captured by a general equilibrium analysis. Ultimately, the supply response to changes in energy efficiency depends on the type of production function. In a Cobb-Douglas framework, technological progress is bound to result in increased consumption due to its fixed rate of substitution. By contrast, in a CES production function the outcome will depend on the parameter value of the elasticity of substitution between primary resources and other factor inputs. If this parameter is less than unity, aggregate energy consumption will decline and vice versa. Overall, empirical identification and estimation of these effects and parameter values have proven to be difficult. Empirical studies estimate a direct rebound effect in the order of magnitude of 10-20 per cent. Considering the policy implications of these findings, several critics of the 'gospel of efficiency', such as Herring (2006) propose a primacy of energy sufficiency over energy efficiency in the formulation of effective market-based policy interventions.

## Modelling Investments in Domestic Energy Efficiency

The financial characteristics of energy efficiency investments are often expressed in payback periods, i.e. the time period required to repay the investment via savings in energy costs. While this popular metric has a number of drawbacks and limitations, for example regarding risk adjustment and the time value of money, it is an apt tool for investors seeking to gauge and compare expected amortisation periods. Typically, investments with shorter payback periods are favoured over longer periods. This is equivalent to a higher marginal return or internal rate of return (DeCanio 1998).

A key practical problem in calculating payback periods is the uncertainty surrounding the true future cost savings as well as any investment inefficiencies at the market or individual level which may in turn lower investors' willingness to invest or willingness to pay. Allcott and Greenstone (2012) present a comprehensive model that takes into account investment inefficiencies such as imperfect information, lack of attention or interest, excessive risk aversion and credit constraints. The decision to invest in domestic energy efficiency is also modelled as a function of the social cost or uninternalised externality of energy use. A large uninternalised externality in energy prices implies longer payback periods and, consequently, lower aggregate levels of investment. Conversely, when a Pigovian tax, carbon trading scheme or similar measure that aims to internalise externalities is implemented, payback periods become shorter and investments in energy efficiency become generally more attractive. However, the attractiveness of this investment opportunity must be measured relative to competing asset classes. For example, if risk-adjusted returns on stocks, bonds and other asset classes decrease, a rise in energy efficiency investment can be expected, even if the absolute payback period of the latter has not changed.

However, a complete model of energy efficiency investment decisions also needs to capture the fundamental *split incentives* problem that characterises real estate rental markets in particular. Hence, the investment decision becomes even more intricate for rental properties for which the costs and benefits outlined above typically accrue to different agents. Assuming that the rent paid by the tenant is net of utilities and payable according to their individual energy usage, there is no *a priori* incentive for the landlord to bear the upfront capital investment of energy efficiency measures regardless of the payback period or internal rate of return of the investment. However, a landlord may still be able to recoup her retrofitting expenses through higher rent payments, provided that tenants exhibit a higher willingness to pay for inhabiting a more energy-efficient property and benefitting from lower energy bills (for a discussion of tenants' willingness to pay see for example Fuerst and McAllister 2011). On the cost side of the formula, cost reductions are to be expected when energy retrofits are carried out as part of a general modernisation or refurbishment of a property, for example when contracts are bundled and other cost savings arising from a simultaneous upgrade of the general quality of a dwelling as well as its heating, cooling, ventilation and air conditioning systems, wall and loft insulation, lighting systems etc.

## Data

Empirical data about retrofitting of buildings to improve the energy efficiency of buildings are still very rare. There exists quite some research on the retrofitting costs and energy savings of different types of measures, such as wall insulation, new windows or more efficient heating systems based on samples of retrofitted buildings. But there is very little information about the willingness of home owners, landlords and housing associations to invest in energy retrofitting under different market conditions, energy prices, energy standards, public subsidies and other investment alternatives.

In the United Kingdom, several efforts are underway to specify the conditions under which the Government's legally binding greenhouse gas reduction target of 80% by 2050 may be achieved. Possibly the most prominent of these is the 2050 Pathways project of the Department of Energy and Climate Change (DECC) which is a spreadsheet-based application for defining detailed energy demand and supply scenarios for each sector of the economy. The household sector is broken down into the basic categories (a) domestic space heating and hot water and (b) domestic lighting, appliances and cooking. The Pathways model then calculates the energy flows and greenhouse gas emissions for each scenario using user-supplied assumptions on average room temperatures, penetration rates of insulation retrofits, average thermal leakiness, type of new domestic heating systems and energy demand from domestic lighting and cooking (DECC 2010, 2011). While impressive in its comprehensiveness and long time horizon forecasts, the Pathways 2050 model has been criticised for being relatively inflexible and not recognising the crucial importance of governance, behavioural and technical parameters (Foxon 2012).

A further strand of research on the deployment of energy efficiency in buildings is being undertaken under the auspices of the Energy Efficient Cities Initiative (EECi) at the University of Cambridge. This is a cross-disciplinary effort to enhance the current understanding of urban energy systems and suitable strategies for reducing energy demand and greenhouse gas emissions through building and transport technology, micro-generated power and planning policy. Within the EECi framework, a number of pertinent micro-level studies of building energy performance have been carried out, for example by Booth and Choudhary (2012), Booth et al. (2012) and Choudhary (2012). The main contribution of these studies is that they demonstrate how the considerable uncertainty surrounding energy efficiency retrofits can be quantified using Bayesian and probabilistic methods.

Parallel efforts to build a knowledge base have been made by the Climate Change Risk Mitigation Project also at the University of Cambridge, in particular the Building Retrofit Project in a cooperation of academic institutions, businesses. local residents and local authorities. In the context of this project, valuable information on the cost of individual energy efficiency measures has been collected. For example, interior and exterior insulation as well as enhanced glazing were identified as the costliest measures. By contrast, loft insulation is a relatively cheap measure but its greenhouse gas reduction potential is comparable to that of these more expensive measures (Crawford-Brown 2012).

In the UK commercial property sector a report by the Investment Property Forum (IPF 2012) has identified the cost and improvement retrofitting measures required for achieving higher energy efficiency as reflected in Energy Performance Certificates (EPCs). The authors report that all offices investigated in this study could be upgraded by at least one grade on the A to G scale for EPCs with just 1% or less of the general refurbishment budget. Among these, they find that older air-conditioned offices present the most cost-effective investment opportunity as they can be 'future-proofed' with a moderate additional capital investment of 2.6% above the standard refurbishment budget. Local statistics collected by the Department of Energy and Climate Change showed that retrofitting of buildings almost tripled between 2008 and 2012 (DECC 2012).

In Germany the German Energy Agency collected data on retrofitting costs and energy savings based on a large sample of retrofitted buildings (DENA 2010, 2011). The analysis showed that it is difficult to disentangle energy retrofitting from normal upgrading of residential buildings aimed at improving the quality and comfort of flats or houses. The Fraunhofer Institute of Buildings Physics published the diagram shown in Figure 1 summarising the development of energy efficiency standards for residential buildings and the actual building practice since 1980 with extrapolation into the near future compared with the energy efficiency that can be achieved in theory but has been achieved only in few demonstration projects (Erhof et al. 2010). The stepwise descending horizontal lines at the top of the diagram indicate the already implemented and planned energy standards of the Federal Heat Protection (WSVO) and Energy Conservation (EnEV) directives.

Despite the growing interest of national and local governments in energy efficiency of buildings, data on the quantitative volume of energy efficiency retrofitting are still fragmentary. There are neither spatially high-resolution inventories of the energy efficiency of the existing building stock nor data on the adoption of various policies to promote energy retrofitting in response to various policy incentives. This makes it nearly impossible to statistically estimate sophisticated models of landlord behaviour based on microeconomic theory proposed in the literature reviewed above.

Because of this the following experimental implementation of a retrofitting submodel in an urban model works with elasticities which capture the aggregate behaviour of groups of landlords in residential submarkets, i.e. types of dwellings in zones. The model used for this is the model of urban land use, transport and environment developed the Institute of Spatial Planning of the University of Dortmund, the IRPUD model (Wegener 1982, 2011). A challenge in this exercise was the fact that specifics of structural building characteristics such as current insulation, heating systems and household consumption and preference parameters were not directly observable at the building level in the study region. It was therefore necessary to apply average values to each zone and housing type.

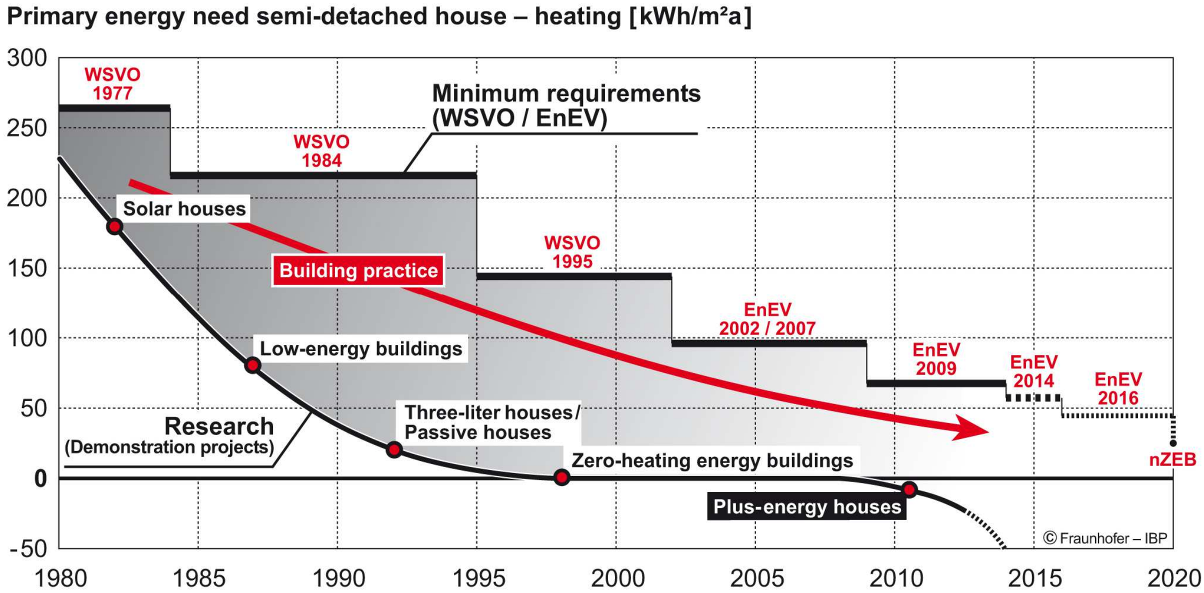


Figure 1. Energy standards and building practice in Germany (Erhorn et al. 2012, 3, reproduced with kind permission by the authors)

## Implementation in the IRPUD model

The IRPUD model is a simulation model of intraregional location and mobility decisions in a metropolitan area. The model predicts for each simulation period intraregional location decisions of industry, residential developers and households, the resulting migration and travel patterns, construction activity and land use development and the impacts of public policies in the fields of industrial development, housing, public facilities and transport.

Figure 2 is a schematic diagram of the major subsystems considered in the model and their interactions and of the most important policy instruments. The four square boxes in the corners of the diagram show the major stock variables of the model: *population*, *employment*, *residential buildings* (housing) and *non-residential buildings* (industrial and commercial workplaces and public facilities). The actors representing these stocks are *individuals or households*, *workers*, *housing investors* and *firms*. These actors interact on five *submarkets* of urban development: the *labour market*, the *market for non-residential buildings*, the *housing market*, the *land and construction market* and the *transport market*. For each submarket, the diagram shows *supply* and *demand* and the resulting *market transactions*.

The large arrows in the diagram indicate exogenous inputs: these are either *forecasts* of regional employment and population subject to long-term economic and demographic trends or *policies* in the fields of industrial development, housing, public facilities and transport.

To date the IRPUD model only calculates energy consumption and $CO_2$ emissions of transport. To consider also energy consumption and $CO_2$ emissions of buildings, the existing submodels for new construction and upgrading of residential and non-residential buildings are currently being extended. Here the new submodel for upgrading of residential buildings and first results are presented.

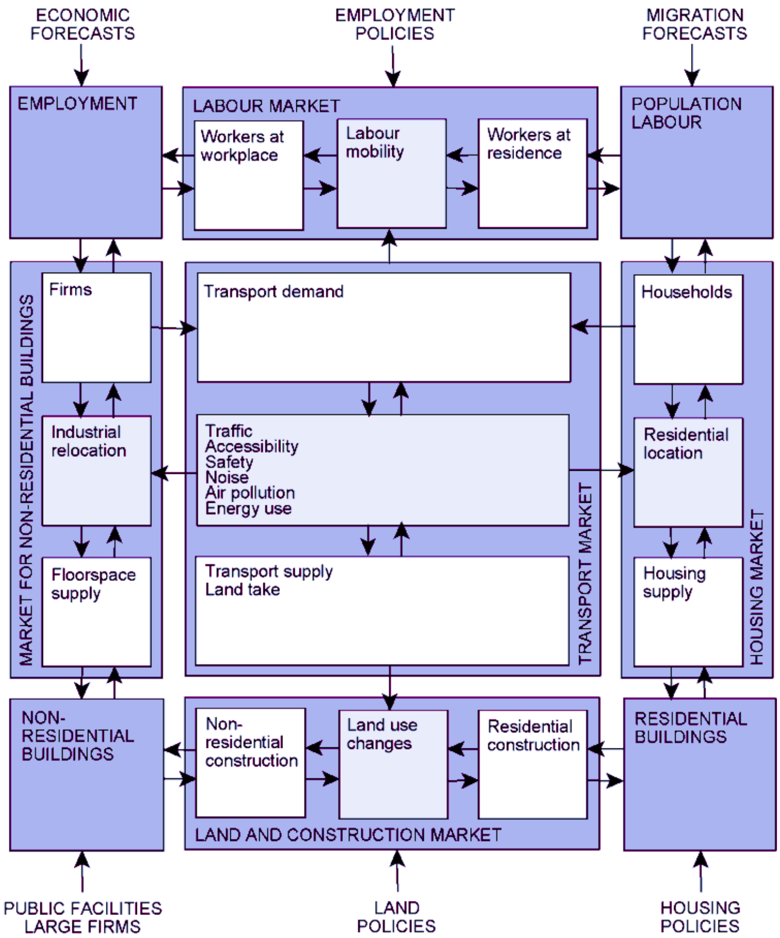


Figure 2. The IRPUD model

There are several motivations for upgrading residential buildings. Owner-occupiers want to improve quality and comfort of their houses. Landlords invest in their housing stock if they can expect to raise their profits when selling or letting their units. With rising energy prices retrofitting of houses for saving energy has become an additional motivation.

Landlord behaviour is assumed to be demand-oriented. The proportion of dwellings upgraded in each period is calculated for each dwelling type in each zone as a function of the expected rent increase in that submarket after improvement. As the eventual rent increase is not known at this point in time, the landlords employ a simple rent expectation model based on vacancy rates at the beginning of the simulation period:

$$U_{ki}(t,t+1) = D_{ki}(t)\ \ \mathrm{f}\left[\frac{V_{ki}(t)}{D_{ki}(t)}\right] \tag{1}$$

where $U_{ki}(t,t+1)$ is the number of dwellings of housing type $k$ in zone $i$ to be upgraded if a sufficient number of dwellings of the same size and building type but lesser quality exists in the zone, $D_{ki}(t)$ is the number of dwellings of this type in the zone and $V_{ki}(t)$ is the number of vacant dwellings of this type. The exogenous elasticity curve f [.] controlling the investment behaviour of landlords reflects the assumption that landlords upgrade their housing stock if the number of vacancies is low.

Figure 3 shows the function that is used in the pilot application presented in this paper:

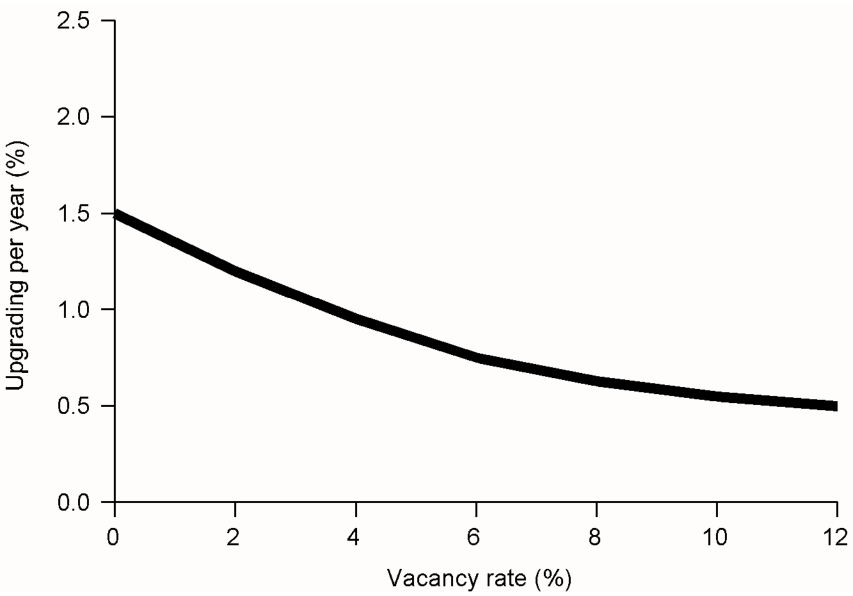


Figure 3. Elasticity of upgrading v. vacancy rate

The willingness of landlords to invest in energy retrofitting depends on the probability of cost savings through measures to improve the energy efficiency of buildings, such as better insulation or more efficient heating systems. It is assumed that if energy prices rise and/or government incentives support energy retrofitting, the number of retrofitted units will grow.

As it was pointed out above, the attractiveness of energy retrofitting investments can be measured by the payback period, i.e. the number of years needed until the accumulated discounted savings in building energy have become greater than the initial investment. The payback period $P_{ki}$(t) ends in year *t* if

$$C_{ki}(0) \leq \sum_{t} S_{ki}(t) / (1+r)^{t} \tag{2}$$

where $C_{ki}(0)$ is the initial cost minus any subsidies, $r$ is the interest rate if the money were invested elsewhere and $S_{ki}(t)$ are the savings in energy made in each year until year $t$ or, in the case of rented dwellings, the proportion of savings that can be recovered from tenants. This formulation makes it possible to assume changes in energy prices over time but requires that the length of the payback period is found by simulation. To illustrate this, in Table 1 the changes in investment costs and energy savings over the years are shown for several alternatives. The grey areas indicate the years after the payback period when the accumulated savings in energy costs are larger than the investment costs plus interests.

Figure 4 shows the four payback scenarios in graphical form. The payback period ends where the curved lines intersect with the null line.

Table 1. Payback scenarios

| After year | Base[1] | | Subsidies[2] | | Higher energy price[3] | | Rental market[4] | |
|---|---|---|---|---|---|---|---|---|
| | Costs | Savings | Costs | Savings | Costs | Savings | Costs | Savings |
| 0 | 20.000 | 0 | 13.332 | 0 | 20.000 | 0 | 20.000 | 0 |
| 1 | 20.000 | 2.330 | 13.332 | 2.330 | 20.000 | 4.660 | 20.000 | 1.165 |
| 2 | 20.000 | 4.592 | 13.332 | 4.592 | 20.000 | 9.185 | 20.000 | 2.296 |
| 3 | 20.000 | 6.789 | 13.332 | 6.789 | 20.000 | 13.577 | 20.000 | 3.394 |
| 4 | 20.000 | 8.921 | 13.332 | 8.921 | 20.000 | 17.842 | 20.000 | 4.461 |
| 5 | 20.000 | 10.991 | 13.332 | 10.991 | 20.000 | 21.983 | 20.000 | 5.496 |
| 6 | 20.000 | 13.001 | 13.332 | 13.001 | 20.000 | 26.003 | 20.000 | 6.501 |
| 7 | 20.000 | 14.953 | 13.332 | 14.953 | 20.000 | 29.905 | 20.000 | 7.476 |
| 8 | 20.000 | 16.847 | 13.332 | 16.847 | 20.000 | 33.695 | 20.000 | 8.424 |
| 9 | 20.000 | 18.687 | 13.332 | 18.687 | 20.000 | 37.373 | 20.000 | 9.343 |
| 10 | 20.000 | 20.472 | 13.332 | 20.472 | 20.000 | 40.945 | 20.000 | 10.236 |
| 11 | 20.000 | 22.206 | 13.332 | 22.206 | 20.000 | 44.413 | 20.000 | 11.103 |
| 12 | 20.000 | 23.890 | 13.332 | 23.890 | 20.000 | 47.779 | 20.000 | 11.945 |
| 13 | 20.000 | 25.524 | 13.332 | 25.524 | 20.000 | 51.048 | 20.000 | 12.762 |
| 14 | 20.000 | 27.111 | 13.332 | 27.111 | 20.000 | 54.221 | 20.000 | 13.555 |
| 15 | 20.000 | 28.651 | 13.332 | 28.651 | 20.000 | 57.302 | 20.000 | 14.326 |
| 16 | 20.000 | 30.147 | 13.332 | 30.147 | 20.000 | 60.293 | 20.000 | 15.073 |
| 17 | 20.000 | 31.599 | 13.332 | 31.599 | 20.000 | 63.197 | 20.000 | 15.799 |
| 18 | 20.000 | 33.008 | 13.332 | 33.008 | 20.000 | 66.017 | 20.000 | 16.504 |
| 19 | 20.000 | 34.377 | 13.332 | 34.377 | 20.000 | 68.754 | 20.000 | 17.189 |
| 20 | 20.000 | 35.706 | 13.332 | 35.706 | 20.000 | 71.412 | 20.000 | 17.853 |

1 Base scenario: floorspace: 100 sqm; retrofitting cost: 200 €/sqm; interest rate: 3%/year; energy consumption before retrofitting: 200 kWh/sqm; energy consumption after retrofitting: 80 kWh/sqm; energy costs: 0.20 €/ kWh.
2 Subsidies scenario: 33% of retrofitting cost.
3 Higher energy cost scenario: energy costs doubled.
4 Rental market scenario: 50% of energy cost savings recouped from tenants.

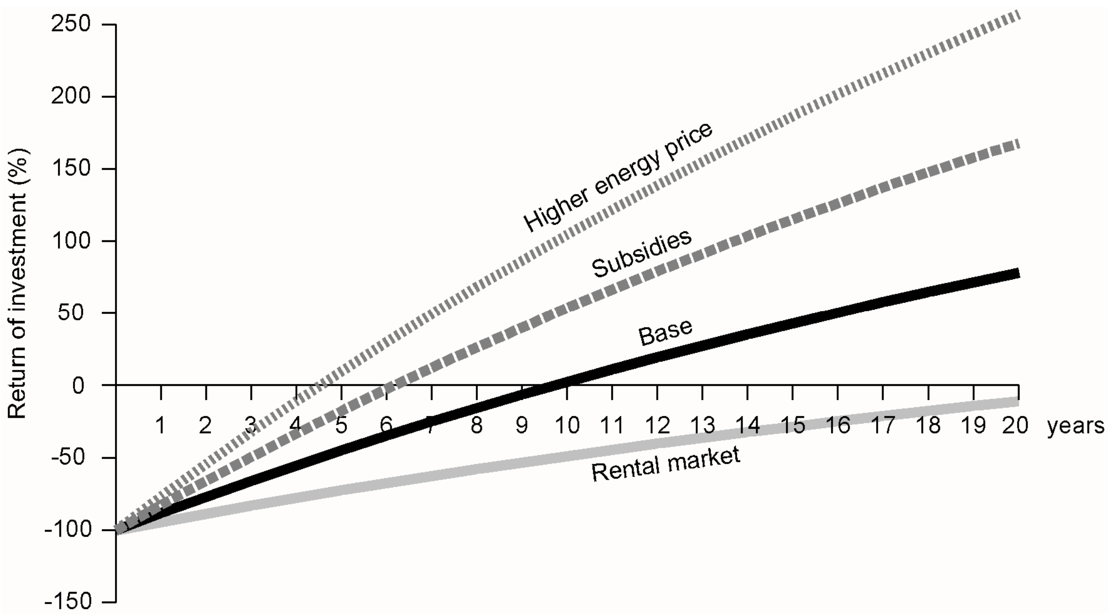


Figure 4. Payback scenarios

Table 1 and Figure 4 show that the length of the payback period becomes shorter through subsidies and a higher energy price, but extends beyond 20 years if the costs of the retrofitting cannot be fully recouped from tenants in the rental market.

It is assumed that investment in energy retrofitting is lower if the payback period is longer and higher if the payback period is shorter:

$$R_{ki}(t,t+1) = \mathrm{f}'[P_{ki}(t)] \quad (3)$$

The form of function f'[.] used is shown in Figure 5.

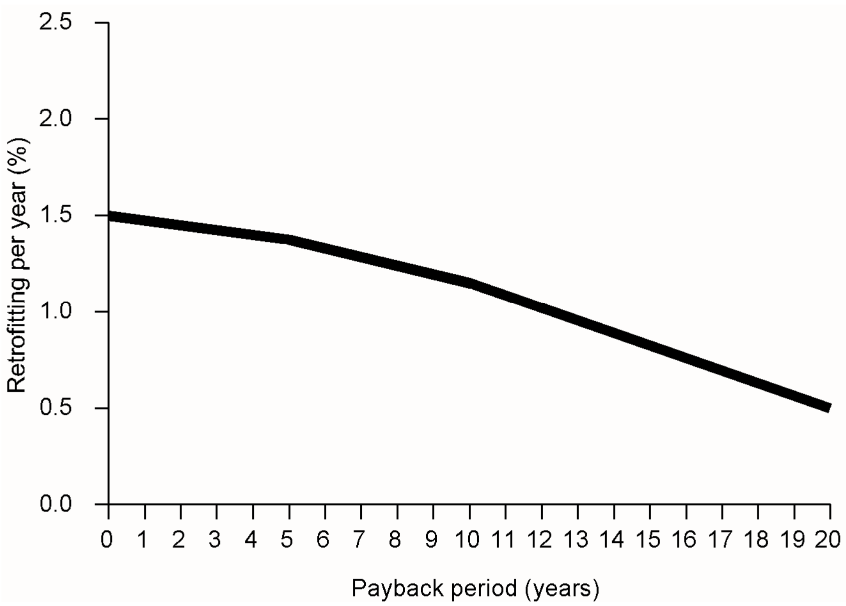


Figure 5. Elasticity of retrofitting v. payback period

The two elasticities shown in Figures 3 and 5 are not exclusive as also upgrading in response to market demand (Figure 3) is likely to include improvements of energy efficiency. It is therefore assumed that the actual number of upgrading including energy retrofitting is either $U_{ki}$ or $R_{ki}$, whichever is larger.

A last choice to be made is the degree of energy efficiency selected for the energy retrofitting. It is again assumed that this depends on the payback period:

$$e_{ki}(t) = \mathrm{f}''[P_{ki}(t)] \quad (4)$$

where $e_{ki}(t)$ is the energy efficiency of the building after the improvement expressed in per cent of the full energy efficiency standard for residential buildings valid in year $t$. If the payback period is short, landlords are more likely to invest in full-scale energy efficiency. Figure 6 shows the form of the elasticity of energy efficiency to payback period used in this pilot application.

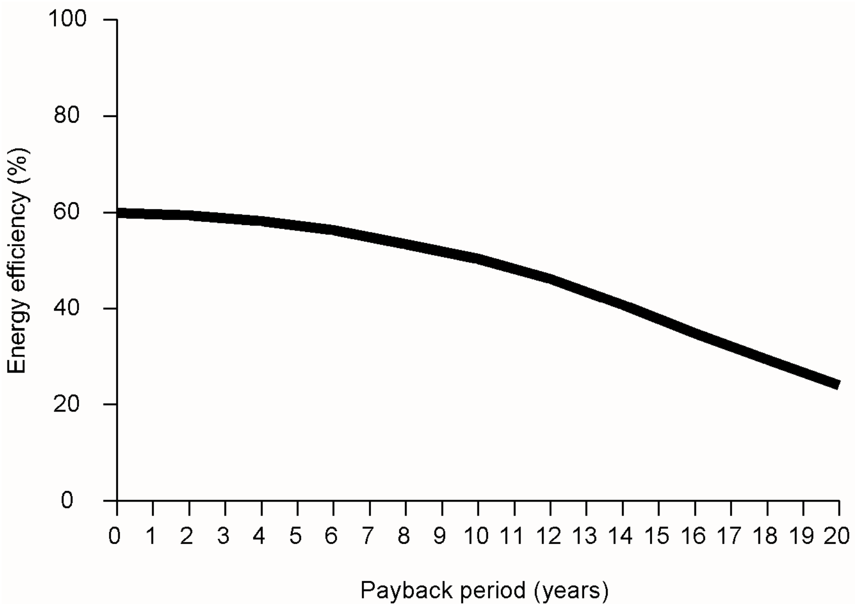


Figure 6. Elasticity of energy efficiency v. payback period

Because the decisions about the volume and energy efficiency level of energy retrofitting measures are interdependent, the two elasticities shown in Equations 3 and 4 and Figures 5 and 6 are evaluated simultaneously. In summary, the payback periods used in Figures 5 and 6 take into account the volume and energy efficiency of the planned retrofitting measures, the expected construction costs and the expected development of energy prices and inflation and interest rates.

At the end of each simulation period housing prices and rents are adjusted to reflect changes in housing demand in the previous housing market simulation. In addition to changes of housing prices and rents due to changes in the composition of the housing stock and inflation, housing prices and rents by housing type and zone are adjusted as a function of the demand for housing in that submarket in the period expressed by the proportion of vacant units.

$$p_{ki}(t+1) = p_{ki}(t)\left[1 + \mathrm{f}'''\left(\frac{V_{ki}(t+1)}{D_{ki}(t+1)}\right)\right] \tag{5}$$

where $p_{ki}(t)$ is monthly rent or imputed rent per square metre of housing floorspace of dwelling type $k$ in zone $i$ at time $t$, $V_{ki}(t+1)$ is the number of vacant dwellings of housing type $k$ in zone $i$ at time $t+1$, and $D_{ki}(t)$ is the total number of dwellings of that type in the zone at time $t+1$.

The function results in a reduction of housing prices and rents if there is a large percentage of vacant dwellings of that kind not bought or rented in the previous housing market simulation, and in a price or rent increase if there are no or only few vacant dwellings left. No attempt is made to determine equilibrium housing prices or rents. The price adjustment model reflects price adjustment behaviour by landlords. If they reduce or increase prices or rents too much, they may experience more vacancies in the subsequent simulation period.

Figure 7 shows the form of function f''' [.] used:

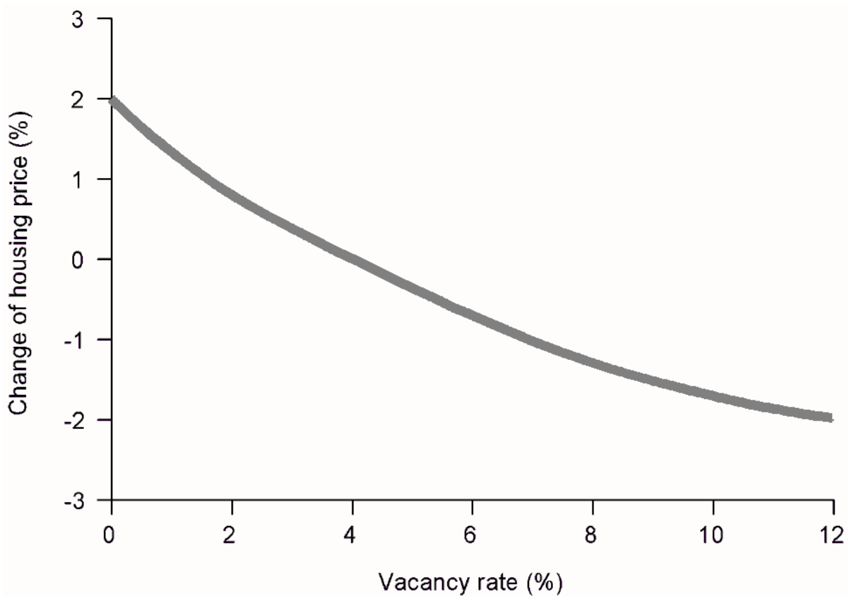


Figure 7. Elasticity of change of housing price v. vacancy rate

**Results**

As demonstrated in the previous section, the IRPUD model was extended by a module for energy retrofitting of residential buildings. The principle used was to first model the decision to invest in energy retrofitting in combination with other motivations for upgrading and then model the decision about the level of energy efficiency to be achieved. The experimental model extension was tested with data of the urban region of Dortmund, Germany.

To examine the sensitivity of the model to policy measures, the four payback scenarios shown in Table 1 were simulated: (1) a base scenario with the most likely framework conditions for retrofitting: moderate energy prices, low interest rates and no specific subsidies for energy retrofitting, (2) a subsidies scenario in which 33% of the cost of retrofitting are assumed to be taken over by the government, (3) a high energy cost scenario in which the costs of heating energy are assumed to be doubled and (4) a rental market scenario in which it was assumed that for rented buildings only 50% of the energy savings can be recouped from the tenants.

Figures 8-11 show selected results of the simulations between 1970 and 2030. The simulation of the past period serves to demonstrate that the model is able to reproduce the known trends of the past. The forecasts until 2030 show the combined results of investment decisions of landlords and developers.

Note that these results include the effects of higher energy efficiency standards applied to new residential buildings. It is assumed that the volume of new housing construction is controlled by a similar function of submarket vacancy rates as the one for upgrading of residential buildings shown in Equation 1 and Figure 3. On average, the volume of new construction is less than one per cent of the existing housing stock per year, compared with about half per cent of housing upgrades. It is further assumed that developers and landlords decide on the level of energy efficiency of new residential buildings based on the same function of payback period as shown in Equation 3 and Figure 5.

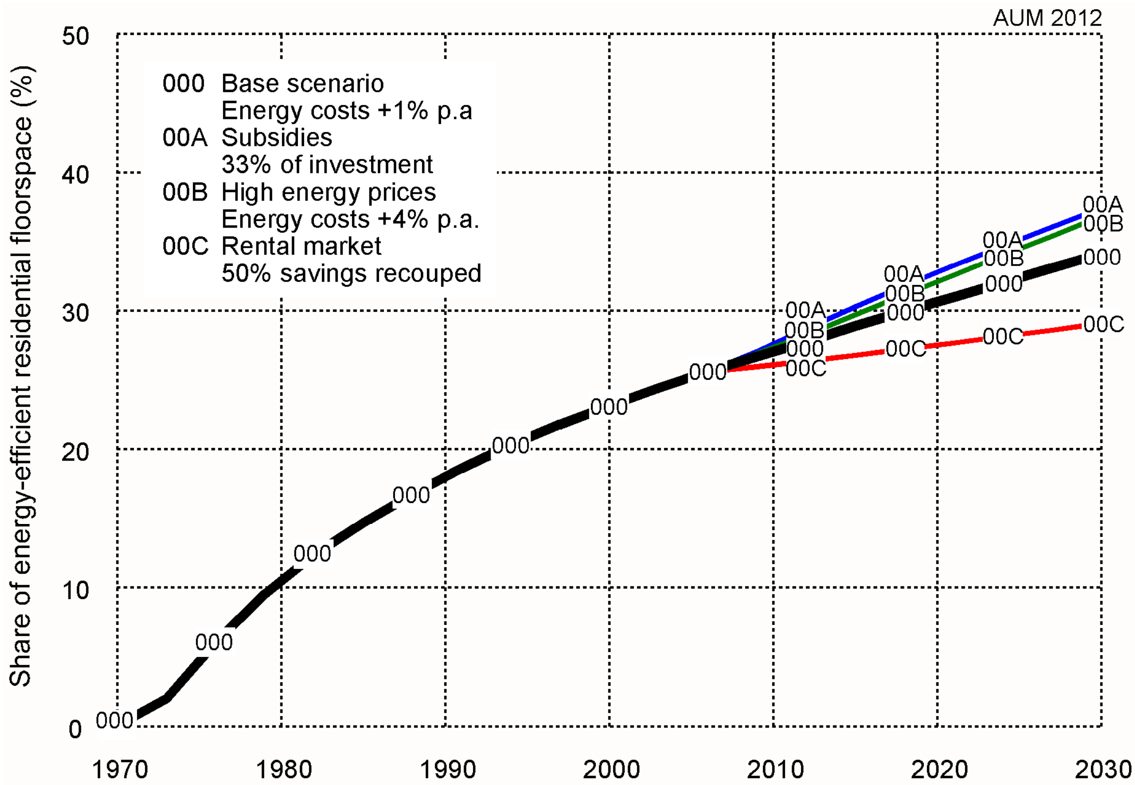


Figure 8. Share of energy-efficient residential floorspace

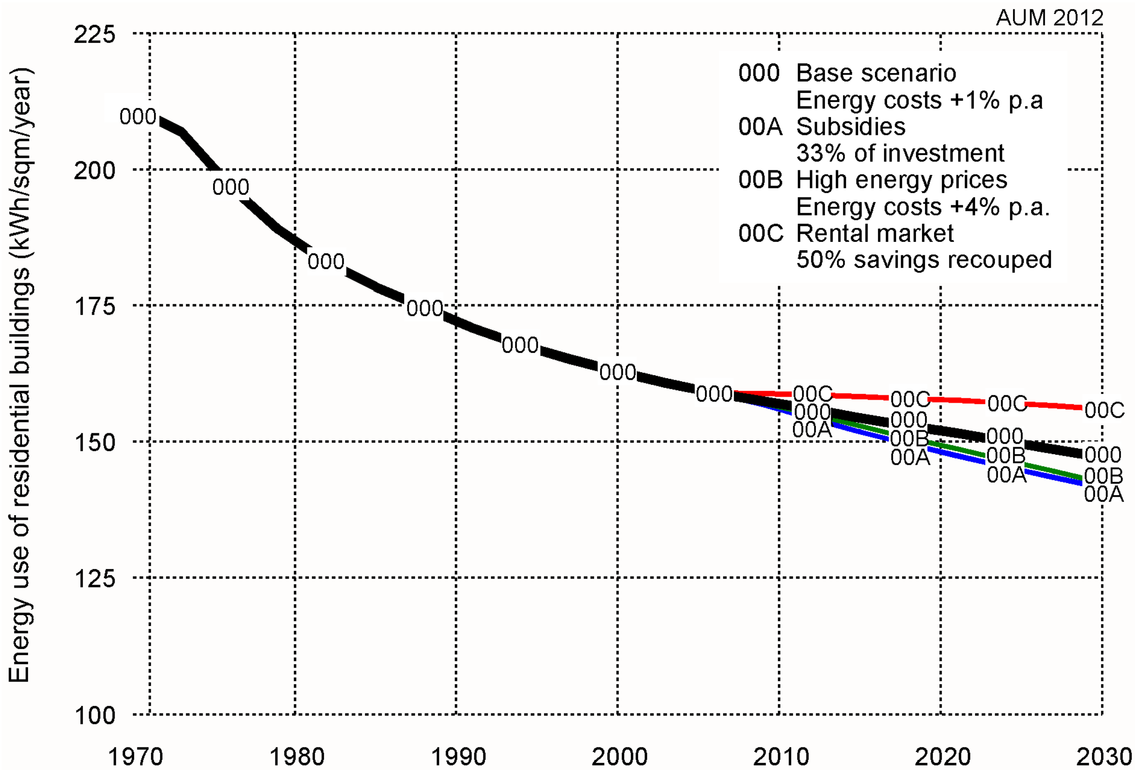


Figure 9. Energy use of residential buildings per sqm

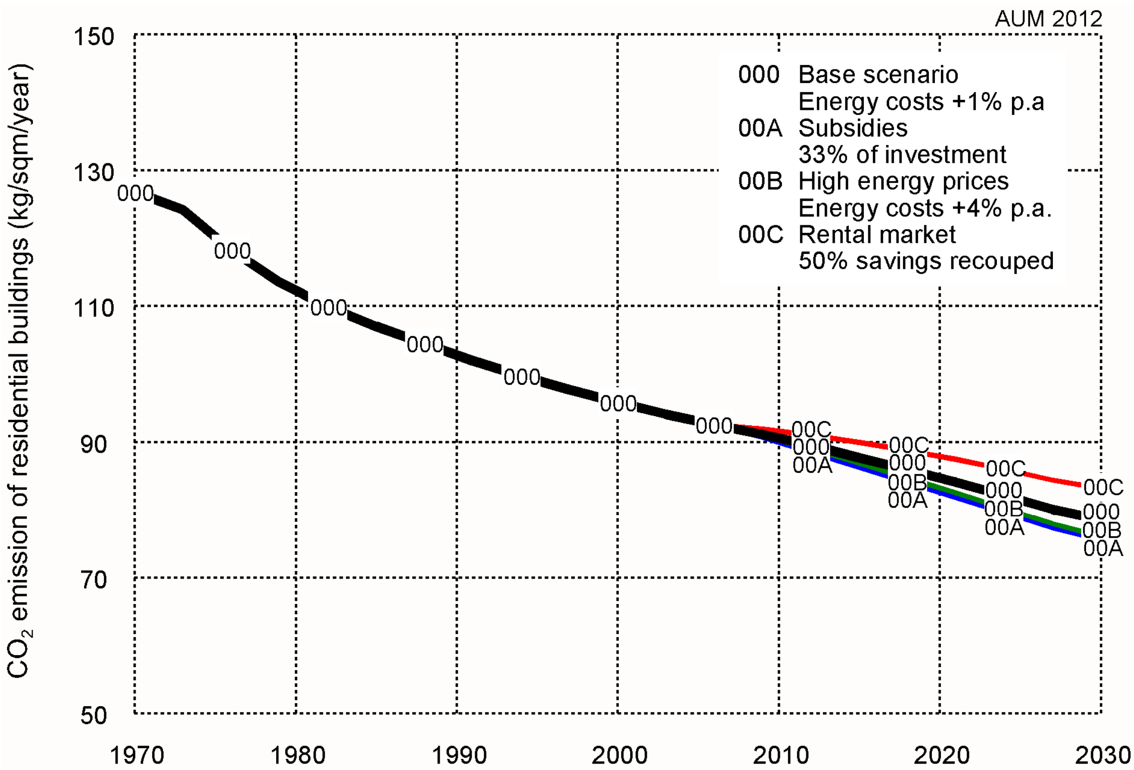


Figure 10. $CO_2$ emissions of residential buildings per sqm per year

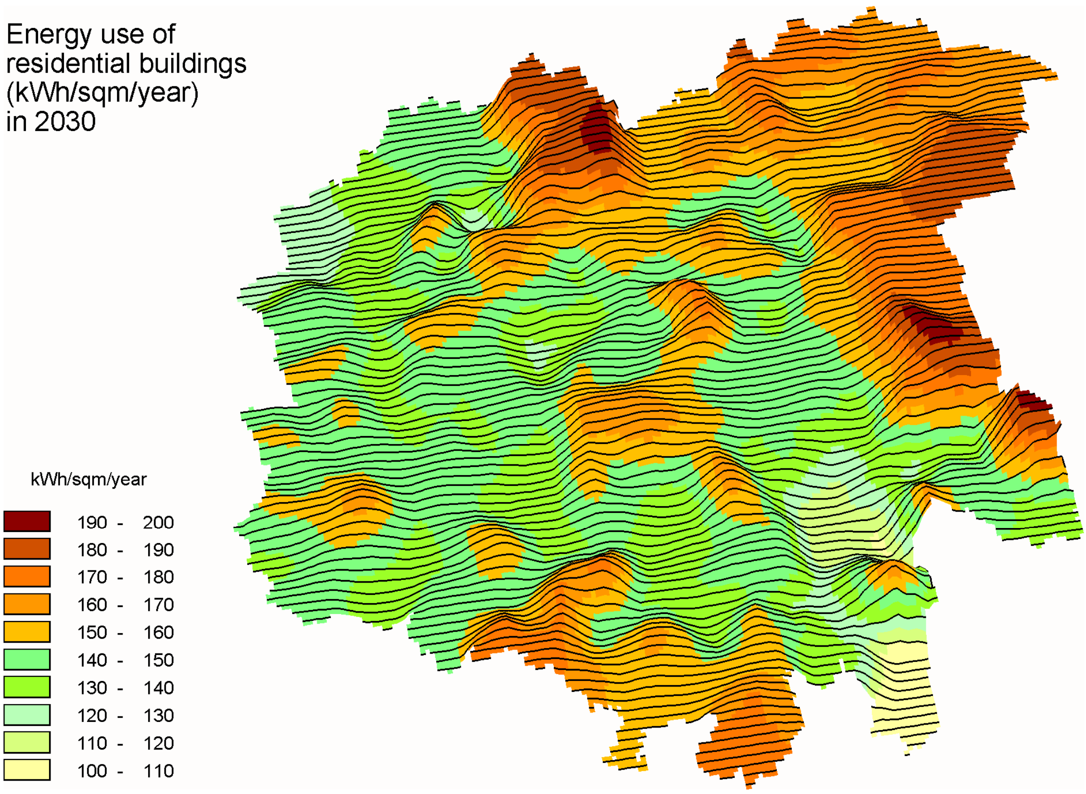


Figure 11. Energy use of residential buildings in the Base Scenario 2030

It can be seen that also in the base scenario the share of both new and upgraded energy-efficient residential floorspace tends to increase and that subsidies as well as high energy prices tend to accelerate that increase, while the growth is delayed if the costs of energy retrofitting can only be partly recouped from tenants (Figure 8). This is reflected in the declining energy consumption of residential buildings per sqm floorspace (Figure 9). The decline in $CO_2$ emissions per sqm floorspace is even stronger because of more efficient heating systems (Figure 10). However, on a per-capita basis $CO_2$ emissions continue to grow because of the growing space consumption due to higher incomes and smaller households so that the 20% greenhouse gas reduction goal of the EU2020 strategy of the European Union is not likely to be achieved.

## Conclusions

In conclusion, investments in energy efficiency of homes are characterised by several market imperfections and paradoxes. The empirical evidence on energy profiles of different house types and urban densities is mixed but there are strong indications that future new buildings will be much more energy-efficient due to higher standards imposed by building regulations. However, regulations for new buildings only affect a small proportion of buildings as they do not typically apply to the existing stock. For existing buildings to be upgraded voluntarily, pricing is a key mechanism. In particular, it depends on the willingness of home owners and landlords to invest in energy retrofitting under different market conditions, energy standards, energy prices and public subsidies.

These considerations have so far not been captured by urban models. We argue that a complete model of urban location choice should include the anticipated combined energy cost associated with a particular property and location, composed of both transport and building energy.

What does this mean for the prospect of achieving the energy saving and greenhouse gas reduction targets of national governments and the European Union? The preliminary results of the model runs with the prototype retrofitting submodel suggest that without substantial additional incentives the chances for achieving these targets are not too good.


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