How far can buildings take us in solving climate change? A novel approach to building energy and related emission forecasting

Diana Ürge-Vorsatz
Center for Climate Change and Sustainable Energy Policy (3CSEP)
Nádor utca 9, H-1051 BUDAPEST
Vorsatzd@ceu.hu

Ksenia Petrichenko
Center for Climate Change and Sustainable Energy Policy (3CSEP)
Nádor utca 9, H-1051 BUDAPEST
Petrichenko_Ksenia@ceu-budapest.edu

Andrew C. Butcher
University of Copenhagen
Himmerlandsvej 29, st TH, 2720 Vanløse, Denmark
andrew@kemi.ku.dk

Keywords

energy end-use efficiency, emission reduction, buildings, scenarios, lock-in effect

Abstract

The building sector is responsible for more than 30 % of global final energy demand and energy-related CO_2 emissions (IPCC 2007). At the same time, this sector provides the largest potential for lower-cost mitigation. The analysis of the existing literature has shown certain methodological shortcomings in assessing the full potential for building-related emissions and energy use reduction. Moreover, most of existing models do not reflect to full extent the recent substantial advances in construction and retrofit know-how and technologies.

The authors of this paper have elaborated a novel approach to energy forecasting in the building sector, and have developed a major model of global building energy consumption in a multi-year effort within the framework of the Global Energy Assessment's (GEA) scenario work, also supported by the UNEP's Sustainable Buildings and Climate Initiative. The paper presents the key findings of the model, the first time after the GEA is released.

The novelty of the method is that it follows recent developments in state of the art construction and retrofit; considering buildings as complex systems rather than sums of individual components. Such a performance-based approach is in line with recent policy trends that tend to regulate buildings on a performance basis rather than on a prescriptive piecemeal approach.

The paper shows that about 46 % of 2005 global space heating and cooling energy use can be saved by 2050 if the existing building design best practices are implemented, despite the several-fold increase in floor space and comfort during this period, and the eradication of energy poverty at the global level. However, the paper also highlights the major lock-in risk: if building codes are introduced and renovation rates ramped up, but stay behind the cost-effective state of the art levels, about 80 % of 2005 thermal energy consumption[1] will be "locked-in" by 2050, making the attainment of ambitious climate change mitigation targets impossible or extremely expensive.

Introduction

Climate change is considered as one of the greatest global challenges nowadays. The landmark 2007 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) estimated that 70 % growth of global greenhouse gas emissions in the period between 1970 and 2004 is caused by human activities (IPCC2007).

In this regard, one of the most important global tasks is stabilizing the planet's temperature increase at a level where substantial damage to ecosystems can be avoided. According to the IPCC report, the maximum acceptable global mean temperature increase is 2–2.4 °C above the preindustrial level (IPCC 2007). Maintaining this level requires a 50–85 % reduction in greenhouse gas emissions by 2050 as compared to 2000 levels (IPCC 2007). However, this target was argued to be insufficient for avoiding a devastating effect of temperature increase on the planet's ecosystem (Hansen et al. 2007, Ramanathan and Feng 2008).

1. Thermal energy consumption is the energy used in a building for space heating and cooling

Therefore, the scientific opinion that the concentration of CO_2 in the atmosphere should be reduced to 350 PPM CO_2 by 2100 (Hansen et al. 2008), rather than the 445-490 PPM concentration levels proposed to achieve 2–2.4 °C global temperature rise above pre-industrial levels proposed by IPCC's I Stabilization Scenario (IPCC 2007), is gaining more ground. Achieving such a concentration level requires extremely ambitious efforts from humanity to cut emissions, perhaps, even requiring the direct removal of CO_2 from the atmosphere.

One of the greatest and most cost-effective potentials for climate change mitigation can be realized through the building sector, with 5.3–6.7 Gt CO_2-eq reduction possible with a CO_2 price below \$100/tCO_2-eq (IPCC 2007; Ürge-Vorsatz and Novikova 2008).

In 2004 the building sector contributed 8.6 Gt CO_2-eq or 33 % of the total energy related CO_2 emissions (IPCC. 2007). If this sector reduces its global emissions by at least 50–85 % by 2050, it contributes roughly 16-26 % of the total emissions reductions needed to meet the climate stabilization requirements.

Far few studies have provided specific solutions to meeting this ambitious climate goal. New work under the umbrella of the Global Energy Assessment[2] (GEA) is producing scenarios on how much reduction is possible in building energy use through the application of different measures. Initial findings from this work suggest that if the present climate- and development-specific state of the art construction and renovation technologies and know-how proliferate and become the standard, global energy use in the building sector can be reduced to the levels required by such ambitious climate stabilisation targets. However, GEA results also demonstrate certain risks of how this mitigation potential can turn into massive locked-in emissions that are impossible or unfeasible to reduce for many decades to come.

Therefore, the main aims of this paper are, first of all, to demonstrate the major opportunities in the building sector to reduce energy use and, thus, mitigate climate change, and, secondly, to identify and quantify the major risks related to climate change mitigation efforts in the building sector with regard to the potentially locked-in emissions.

The paper first presents the opportunities in the global building sector for reducing energy use and greenhouse gas emissions and their role for mitigating climate change and other global issues, according to the scientific literature in this field. After this, the risks of losing these opportunities are discussed by introducing the concept of the lock-in effect. Then, the methodology section provides a brief description of the elaborated model, its main assumptions, approaches and data sources. The results section gives the main estimations of the potential to reduce global final thermal energy use through diffusion of existing best-practices in construction and renovation of buildings worldwide and comparison of related investment costs and energy cost savings. It also presents the results for quantification of the lock-in for the world and 11 analyzed regions. Finally, all the outcomes discussed in the paper are summarized in the conclusion.

Opportunities in the building sector

The direct energy use in the building sector is a major contributor to anthropogenic climate change impacts. It is responsible for approximately 31 % of global final energy demand; one third of energy-related CO_2 emissions, two thirds of halocarbon and 25–33 % of black carbon emissions (Ürge-Vorsatz et.al. 2011).

Moreover, other energy-related problems in the building sector, such as mortality and morbidity due to poor indoor air quality or inadequate indoor temperatures, can affect human health and productivity. Therefore, improving buildings and their equipment offers one of the entry points to solving not only the climate and energy crises but also these major challenges.

Figure 1[3] illustrates final energy use for space heating and cooling for single-family, multi-family, commercial and public buildings in 11 regions of the world. It can be seen, that energy use in buildings is high in the developed regions and economies in transition.

We aim to show that this level of energy consumption in the developed world can be considerably reduced and potential increases in the developing world mitigated by means of existing technologies at acceptable cost levels.

Several recent studies show that the building sector provides large cost-effective mitigation potentials. IPCC (2007) estimated on the basis of 80 studies focusing on residential and tertiary buildings that 29 % of the 2020 building-related baseline CO_2 emissions can be mitigated at negative cost. The result of a considerable cost-effective mitigation potential in the building sector is supported by several successful country studies. For example, mitigation potential is estimated as 20 % of the baseline 2020 emissions in the German building sector (McKinsey 2007), 29 % by 2025 in the Hungarian residential building sector (Novikova 2008) and approximately 37 % by 2030 in the Hungarian public buildings for space heating only (Korytarova *forthcoming*). The most recent global study by McKinsey (2009) found that the GHG mitigation potential up to the cost of 60 Euro/t CO_2e accounts for 3.5 Gt CO_2 equivalent. Approximately 70 % of this potential in the building sector can be achieved at negative cost by 2030 (McKinsey 2009).

Some other studies show that the potential of a considerable energy use reduction in the global building sector resulted from the implementation of various policy measures. For example, Energy Technology Perspectives (IEA 2010) estimates the potential for 32.5 %[4] reduction of energy demand in buildings by 2050 in relation to 2007 due to the rapid deployment of existing low-cost technology options for energy efficiency and low-carbon fuel sources, substantial renovation of existing buildings and the wide-spread deployment of new technologies in the building sector. Laustsen (*forthcoming*) illustrates 58 % of possible decrease of final energy use for space heating and cooling in buildings worldwide by 2050 in relation to 2005 as a result of introducing the policy packages aimed at considerable enhancement of energy efficiency in new buildings and deep renovation of existing buildings. Harvey (2010) shows that global final energy use from fuels in buildings can be decreased by

2. www.globalenergyassessment.org

3. Figure 1 is constructed using the data presented in the Table 2

4. Electricity, biomass and renewable energy are not taken into the account

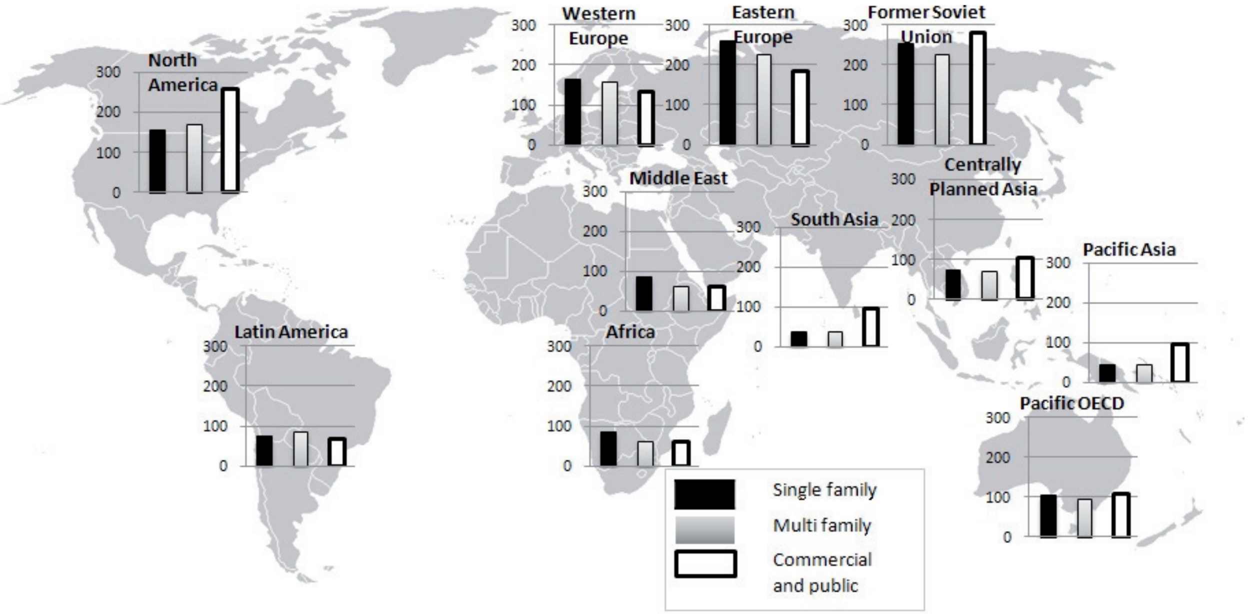


Figure 1. Final energy use for space heating and cooling in 11 regions of the world, kwh/m²/year. Source: The estimations of the authors'.

approximately 37 % by 2050 in relation to 2005 mainly resulted from reduction in energy intensities in buildings.

However, to the awareness of the authors of this paper, none of the existing studies taking the advantage of the opportunities offered by the newest frontiers of building energy know-how and state of the art construction techniques. Recent advances in materials and know-how make new buildings that use 10–40 % of the final heating and cooling energy of conventional new buildings cost-effective in all world regions and climate zones. Holistic retrofits can achieve 50–90 % final energy savings in thermal energy use in existing buildings, typically representing profitable[5] investments. The remaining energy needs can be met or supplied at the building-, community-, or regional level from distributed sustainable energy sources. As a result, a global scenario exercise in order to understand how far buildings can really take us in mitigation if we leverage these latest opportunities has been conducted. The novelty of the research presented here is that it also analyzes and quantifies the risk of losing these opportunities by applying the concept of the lock-in effect to energy savings in the building sector, which is one of the central concepts of this paper.

Risks in the building sector: Lock-in effect

Traditionally, the concept of the lock-in effect is considered in relation to the technologies' development. Recently it was also applied to the analysis of the links between technological and environmental change (Kemp 1994; Rip and Kemp 1998; Unruh 2000).

In this regard, the main conclusion derived from the literature is that developed economies are locked into a complex of hydrocarbon-intensive technologies and infrastructures (Rip and Kemp 1998; Arentsen *et al.* 2002). It explains the current situation in the world characterized by a growing concern about the negative impacts of fossil fuel use accompanied by great difficulties in switching to zero-emitting and low-energy substitutes. The reasons are learning effects and technological network development experienced by hydrocarbon technologies for several decades, which in combination hinder the innovation and diffusion of technologies that lie outside this fossil fuel technological paradigm.

Another reason for the lock-in effect is private and public institutions resistance to radical change. Many of them find it beneficial to maintain the current technological paradigm, which consequently contributes to reinforcing the lock-in effect (Kemp 1994; Unruh 2000).

The utilization of the lock-in concept in the literature is limited: very few literature sources cover such an application. For example, it is stated in Groot *et al.* (2001) that increasing investment subsidies for energy-saving technologies can lock energy saving potential into relatively inferior technologies. Once a new technology is adopted the knowledge and awareness of how to use the technology spreads, which results in a learning effect for the institutions that have not yet adopted the technology. Consequently, the technology evolves over time and ultimately matures. The risks to adopt a mature technology are much lower than those of an absolutely new one, which create the incentives for institutions to wait with adoption. This delay causes the lock-in effect of energy savings which could have been achieved in the situation when the majority of institutions adopt the technology at an early stage of its introduction. Thus, the lock-in of energy savings always goes hand in hand with the delay in the adoption of energy efficient technologies.

Norberg-Bohm (1990) and Mulder (2005) show that the widespread adoption of existing energy-saving technologies could significantly reduce energy use, especially in the short and medium term. Mulder (2005) uses the term "energy efficiency paradox" to describe the lock-in effect. Mulder defines it as "a considerable gap between the most energy efficient and cost-effective technologies available at some point in time and those that are actually in use" (Mulder 2005). Thus, the main

5. Investments that pay back during the remaining lifetime of the equipment/building are referred to as "profitable".

reason for the lock-in effect is the delay in adoption and slow diffusion of new and more efficient technologies.

Jaffe and Stavins (1994) provide certain explanations for a gradual diffusion of energy efficient technologies and the subsequent lock-in effect: market failures, information problems, principal/agent slippage, unobserved costs, private information costs, high discount rates, and heterogeneity among potential adopters. They demonstrate how the proliferation of energy efficiency technologies can be directly hindered by principal/agent problems in new residential buildings. Jaffe and Stavins also have revealed that "artificially low" energy prices and high discount rates can provide another explanation to the lock-in effect. Among the factors that may accelerate the diffusion of energy efficient technologies, they noted lower adoption costs, government programs in the form of subsidies or tax credits, departures from temperate climatic conditions, increases in income and education level.

The phenomenon of the lock-in effect in the building sector is not surprising. According to Rohracher (2001), it can be caused by low levels of innovation, mass production from large suppliers, and separation of design from construction. Dewick and Miozzo (2004) in their study of the Scottish building sector point out that "[t]he different aims of the parties involved in the construction chain may not be easily reconciled and traditional approaches to construction may reinforce these differences, hindering efforts to introduce innovation."

In this paper, the concept of the lock-in effect is considered as the share of energy savings achievable due to implementation of energy efficient best-practices in the building sector, but which will be lost if these technologies are not introduced. For providing the methodological information on how the lock-in effect was quantified in this study, it is necessary to describe the main principles of the elaborated model.

Methodology

In order to quantify the opportunities and risks in the global building sector outlined above, a model of final thermal energy use has been elaborated under the umbrella of Global Energy Assessment also supported by UNEP's Sustainable Building and Climate Initiative (SBCI).

The building model presented in this paper follows a paradigm shift seen in reporting and calculating energy consumption for buildings based on complete performance rather than individual components and uses this technique to analyze residential, commercial, and public buildings.

The essence of such a shift is that in most models and policies, buildings are traditionally considered as a sum of their components; dealing with energy savings and/or greenhouse gas emissions reduction resulting from separate measures such as changing windows, doors, insulating walls, roofs, ceilings, enforcing air tightness in a component-based approach. This approach is gradually winning positions in policy-making. For example, revised building codes in a number of countries (the USA, Canada, the United Kingdom, New Zealand, Australia, the Netherlands, Sweden, Norway, Singapore and Hong Kong) use a performance-based approach (Hui 2002). For example, Denmark has a performance-based building code which is supported with prescriptive u-values for some components (Laustsen 2008). Several countries such as Germany, Austria, the Netherlands and the United Kingdom committed to performance-based targets for new or existing buildings (Thomsen *et.al.* 2009). The performance-based regulations specify building codes based on energy use per square meter useful space, or other systemic performance indicators rather than those regulating individual building components. Such a philosophy presumes a system-based, holistic view of buildings, usually resulting in considerably higher energy savings due to deeper energy efficiency enhancements and synergistic improvements. It also gives more freedom to architects, designers and engineers as the same levels of energy performance can be obtained through different packages of energy-efficient measures (Laustsen 2008).

However, energy and climate scenario modelling related to buildings has not yet captured this change. Most such assessments used widely by decision-makers still utilize a component-based logic. The examples of such works include: IPCC (2007), McKinsey (2007), McKinsey (2008), McKinsey (2009), Joosen and Blok (2001), Lechtenböhmer et al. (2005), Novikova (2008), Mirasgedis *et.al.* (2004), Gaglia *et.al.* (2007), DEFRA (2006), Boardman (2007) and others.

Attempting to fill in this gap, an effort to present a performance-based approach in the building energy modelling has been elaborated. The main aim of this novel modelling work is to estimate the role of the global building sector in energy use and related emissions reduction, utilizing the latest energy efficient know-how and reflecting a systemic approach to buildings. This article presents the results of two scenarios: state of the art and sub-optimal - to illustrate the difference in final thermal energy use with and without implementing the best construction and energy efficient technologies available at the moment. The following section describes the model's logic and scenarios.

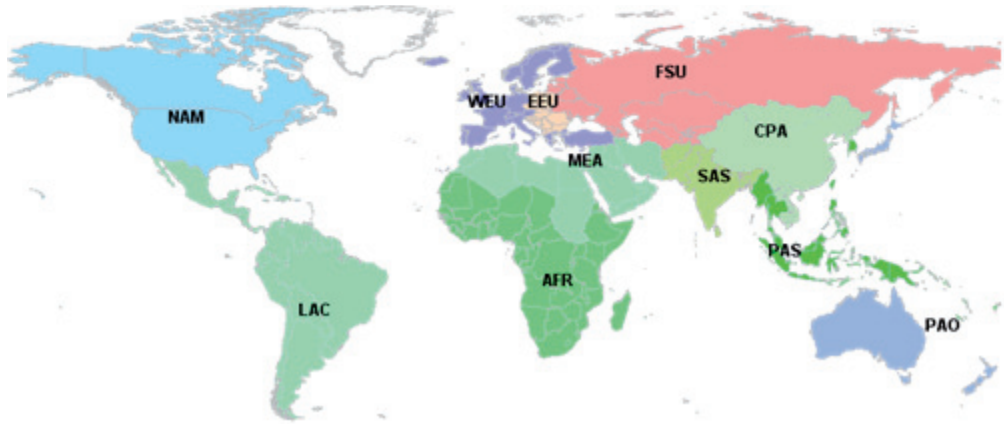
DESCRIPTION OF THE GEA MODEL

It is not the aim of this paper to describe the methodology of the GEA model in detail; however, it is necessary to outline its key assumptions, scope and methodological framework.

The model is devoted to estimating and forecasting final energy use for space heating and cooling in buildings worldwide from 2005 to 2050. Thus, it does not deal with other energy end-uses in the building sector, such as domestic hot water, appliances, cooking, etc. It differentiates among 11 regions presented in Figure 2.

The model also distinguishes different climate zones aggregated on the basis of the Köppen-Geiger world climate classification (Rubel and Kottek 2010) establishing four main climate types: warm moderate, cold moderate, tropical and arid.

As outlined above, the GEA model is grounded in a performance-based approach that considers buildings as complex systems. In this regard, the input data for the model are based on significant numbers of case studies of exemplary buildings within different world regions, climate zones and building types with measured, documented energy performance and associated investment costs. Such an approach gives the opportunity to reflect the advanced level of buildings' energy performance, which can be achieved in new and retrofitted buildings. A fundamental thesis of the model is that the key determinants of building energy performance are the level of utilisation of advanced construction technology in order to



NAM – North America, WEU – Western Europe, PAO – Pacific OECD, EEU – Eastern Europe, FSU – Former Soviet Union, CPA – Centrally Planned Asia, SAS – South Asia, PAS – Other Pacific Asia, MEA - Middle East and North Africa, LAC - Latin America and the Caribbean, AFR - Africa

Figure 2. 11 Regions covered by the model.

improve energy efficiency and climate conditions. The model's main assumption in this regard is that if exemplary buildings have achieved a certain advanced level of energy performance either through new construction or renovation, such levels are achievable by corresponding building types in other regions of the world in the same climate zone. The selection process of the best-practices for the model's input data were based on the lowest level of final energy use for annual space heating and cooling for a certain building type (single-family, multi-family or commercial and public buildings) and climate zone, which has been achieved in each region at a reasonable cost level. For the regions where such data are not available, data-points were transferred from other regions with similar climate conditions.

The advanced level of energy performance in most regions corresponds to the "Passive House standard" (approximately 15 kWh/m^2/yr useful thermal energy consumption). This level has been proved to be achievable in as diverse areas as Swiss Alps, China, India, Japan, Korea, Sweden, Norway, USA, Canada, Australia, Hungary, Poland, Germany, Austria (Gasser 2009, Feist et al. 2001, Waldseebiohaus 2009, Speith 2001, Csoknyai and Talamon 2009, Firlag 2009, Schuetze and Zhou 2009, Berkovitz 2010). In addition, this standard has been obtained by a combination of very different efficiency measures – some of these buildings having no heating system at all; some having no artificial heat recovery while others relying on this measure largely, etc.

It is then assumed that such advanced construction and renovation can become the standard (in case of the state of the art scenario), after a certain period of market transition (in the model it is 10 years: from 2010 to 2020), which gives the opportunity for all new and renovated buildings to achieve the advanced energy performance levels.

Other cornerstone assumptions of the model are the following:

1. Buildings are constructed and renovated in order to supply adequate thermal comfort – i.e. the full area of a building is heated or cooled sufficiently according to the function of the building area (based on actual energy usage of the exemplary buildings).
2. As a result of providing thermal comfort in all new and renovated buildings, energy poverty (i.e. the lack of access to modern energy services) is eliminated worldwide in case of market transition to more advanced building energy-performance standards. Energy poverty is admitted to be one of the greatest global energy challenges – approximately 1.4 billion people in the world do not have access to electricity and 2.7 billion people utilize low-quality fuels (OECD/IEA 2010).
3. Floor space in the residential building sector (single-family and multi-family buildings) changes proportionally to the population dynamics in each region, according to the data on floor space per capita in each building type, approaching floor area per capita levels of OECD countries.
4. Commercial floor area changes proportionally to GDP per capita in each region.
5. Renovation of existing buildings is conducted at a natural rate, i.e. major energy-efficient reconstruction of the building takes place only when a significant remodelling/maintenance of the building would take place. Since the data are very variable on retrofit rate, the model assumes a 1.4 % rate for 2005-2019 and a 3 % rate from 2020. The former value is the approximation of today's retrofit rates in different regions; while the latter is a forecast of an accelerated value, especially considering the spread of energy-efficiency policies worldwide.

Table 1 and Table 2 provide main input data for the model to calculate floor area and final thermal energy use, respectively.

SCENARIOS DESCRIPTION

This paper presents the results of two scenarios elaborated in the framework of the Global Energy Assessment: sub-optimal and state of the art efficiency scenarios.

The state of the art efficiency scenario estimates the maximum possible reduction of final thermal energy use in buildings worldwide which results from the utilization of best technologies and know-how available. The scenario assumes a market transition towards advanced energy performance of

Table 1. Floor area in 2005 per building type.

Region	SF (m^2/capita)	MF (m^2/capita)	C&P (m^2/$GDP)
NAM	45.8	28.0	567.6
WEU	45.8	28.0	424.2
PAO	45.8	28.0	384.9
EEU	30.1	19.7	540.4
FSU	30.1	19.7	638.1
CPA	32.0	25.5	5053.5
SAS	8.3	5.1	2438.7
PAS	8.3	5.1	648.6
MEA	14.2	9.3	466.9
LAC	12.5	9.5	630.4
AFR	14.2	9.3	1871.6

buildings from 2010 to 2020, after which all new and retrofitted buildings achieve state of the art level of energy performance in their categories, except a small number of heritage buildings (app. 5 % of building stock), represented mostly by cultural and historical buildings, where the application of modern technologies may be limited. This scenario assumes neither major application of renewable energy technologies in buildings nor energy conservation behaviour or lifestyle change. It does include the assumption that with increasing wealth, the demand for more thermal comfort and living/commercial floor space increases. The scenario presumes that all buildings constructed or renovated are supplied with full thermal comfort, but keeps all other trends as given in the sub-optimal scenario (such as increase in living and commercial floor space and population).

The main aim of the sub-optimal efficiency scenario is to show how much energy savings would be lost if the technological best-practices in the building sector are not implemented actively. This represents the "lock-in effect" because the possible energy savings will be locked in the building sector until the next renovation cycle or the end of the useful life of the building. At the same time, the scenario assumes an accelerated (3 % annually) retrofit rate from 2020 to reflect the trend that from this time most countries will recognise the necessity of energy efficiency retrofits and building codes. However, even assuming the introduction of more energy efficient building codes in each region, most new and renovated buildings do not reach the advanced level of energy performance. Only in Western Europe is the fraction of advanced buildings assumed to achieve 5 % of the regional building stock by 2020.

INVESTMENT COSTS AND ENERGY COST SAVINGS

For the state of the art scenario, cumulative investment costs of the advanced energy efficient technologies' proliferation are estimated. For this purpose the marginal costs of energy efficient construction and renovation have been taken into account for each region, each building type and each climate zone to achieve corresponding level of advanced energy performance. Marginal costs are considered as the additional costs to achieve an advanced level of energy performance in new or renovated buildings in comparison to conventional design.

In order to understand the feasibility and cost-effectiveness of energy best-practices implementation in buildings it is useful to compare the investment costs to energy cost savings which can be potentially provided by these improvements. To calculate energy cost savings, a separate business-as-usual (BAU)scenario has been elaborated, which is not considered in energy use analysis. The scenario presumes that the current energy performance (for 2005) of existing buildings remains constant during the whole analyzed period (from 2005 to 2050).

New buildings consume 25 % and retrofit ones 10 % less energy for space heating and cooling than existing ones. Advanced new buildings consume 20 % less energy than new buildings in all regions, except NAM and WEU, where it is 40 %; and advanced retrofit buildings consume 30 % less energy than retrofit buildings in all regions. Retrofit rate is fixed during the whole period at the level 1.4 % in all regions. Advanced new buildings are introduced in most regions in 2030 (except NAM and WEU, where they were introduced in 2020 and 2015, respectively) and by 2050 achieve 40 % of new building stock; for EEU and FSU regions this level is 50 %; for NAM -70 %, for WEU -80 %.

Energy cost savings are calculated as difference between energy costs for the BAU scenario and state of art scenario for six fuel types: biomass, liquids, gas, coal, electricity and district heat. Energy costs for each fuel type are calculated for each scenario by multiplying the energy price of fuel source by the final energy use of this fuel in each region.

Energy price data have been gained for the majority of regions from IEA statistics, covering the period from 1995 to 2008. The data have been obtained for a certain country, representing the whole region (WEU – Finland, PAO – Japan, EEU – Poland, FSU – Kazakhstan, SAS – India, PAS – Korea, LAC – Mexico, AFR – South Africa). Due to unavailability of data for MEA region they were transferred from LAC region. For NAM region energy price forecasts from 2007 to 2035 of US Energy Information Administration were used (US EIA 2010). Price data have been then extrapolated for the period till 2050 for regions without price projections assuming average growth rate not exceeding the natural inflation (1.4–3.5 % depending on fuel type).

Results

This section focuses on the main results of the research. First of all, the potential for the reduction of final thermal energy use in the building sector is presented as the opportunity to mitigate climate change. Secondly, the risk of losing this opportunity is quantified by the application of the lock-in concept to energy savings from the building sector. Thirdly, the estimations of the economic feasibility of such an opportunity are given as comparison between investment costs required and energy cost savings resulting from energy use reduction.

RESULTS FOR GLOBAL FINAL THERMAL ENERGY USE

The main output of the model simulation is the dynamics of final energy use for space heating and cooling in the building sector from 2005 to 2050. The results have been obtained for both scenarios for each of 11 regions and for the world with a split among different building types (single-family, multi-family, commercial and public buildings) or energy-performance level (standard, standard new, standard retrofit, advanced new

Table 2. Final energy use for space heating and cooling assumed in different regions, climate zones and builidng types (kwh/m²/year).

Region	Climate Type	Single Family					Multi-Family					Commercial and Public				
		Existing	New	Adv New	Retrofit	Adv Retrofit	Existing	New	Adv New	Retrofit	Adv Retrofit	Existing	New	Adv New	Retrofit	Adv Retrofit
NAM	Warm Mod.	150	65	15	105	20	170	65	10	119	15	220	65	15	154	17
	Cold Mod.	191	65	20	134	30	200	65	15	140	20	340	65	15	238	20
	Tropical	75	65	17	53	25	75	65	17	53	25	131	65	25	92	30
	Arid	87	65	12	61	20	87	65	12	61	20	114	65	20	80	25
WEU	Warm Mod.	160	50	12	112	15	155	50	10	109	15	130	50	10	91	17
	Cold Mod.	261	50	14	183	20	225	50	14	158	20	209	50	14	146	20
PAO	Warm Mod.	100	55	15	70	20	95	60	10	67	15	90	66	15	63	17
	Cold Mod.	150	65	20	105	30	130	80	15	91	20	90	66	15	63	20
	Tropical	65	55	17	46	25	63	55	17	44	25	131	65	25	92	30
	Arid	155	65	12	109	20	155	60	12	109	20	114	65	20	80	25
EEU	Warm Mod.	240	145	14	168	15	205	120	10	144	15	180	120	10	126	17
	Cold Mod.	280	123	20	196	20	245	150	15	172	20	280	111	14	196	20
FSU	Warm Mod.	240	150	15	168	25	205	130	15	144	20	180	120	10	126	17
	Cold Mod.	280	180	20	196	20	246	150	20	172	25	353	150	14	247	20
	Arid	210	100	12	147	20	210	100	15	147	20	210	65	18	147	25
CPA	Warm Mod.	65	42	15	46	20	65	42	10	46	15	96	62	15	67	17
	Cold Mod.	140	91	20	98	30	120	78	15	84	20	150	98	15	105	20
	Tropical	60	39	17	42	25	55	36	17	39	25	96	62	25	67	30
	Arid	70	46	12	49	20	55	36	12	39	20	96	62	20	67	25
SAS	Warm Mod.	65	42	15	46	20	65	42	10	46	15	96	55	15	75	17
	Tropical	35	23	17	25	25	35	23	17	25	25	96	65	25	75	30
	Arid	35	23	12	25	20	35	23	12	25	20	96	65	18	75	18
PAS	Warm Mod.	65	42	15	46	20	65	42	10	46	15	96	55	15	75	17
	Tropical	35	23	17	25	25	35	23	17	25	25	96	65	25	75	30
MEA	Arid	87	50	12	50	20	62	60	12	60	20	62	65	20	75	25
LAC	Warm Mod.	81	50	15	50	20	81	60	10	60	15	91	55	15	55	17
	Cold Mod.	196	50	20	50	30	170	60	15	60	20	209	65	15	65	20
	Tropical	63	50	17	50	25	63	55	17	55	25	131	65	25	65	30
	Arid	87	50	12	50	20	155	60	12	60	20	114	65	20	65	25
AFR	Warm Mod.	120	50	15	50	20	100	60	10	60	15	100	55	15	55	17
	Tropical	63	50	17	50	25	63	55	17	55	25	65	65	25	65	30
	Arid	87	50	12	50	20	62	60	12	60	20	62	65	20	65	25

Sources of data are diverse, ranging from national statistics through literature review to personal interviews and expert judgments, for regions without documented data.
Selected data sources: US DOE (2009a), US DOE (2009b), US EIA (2005), US EIA (2003), BMVBS (1993), ICC (2007), Feist et.al. (2001), Schnieders (2003), Mitthone (2010)

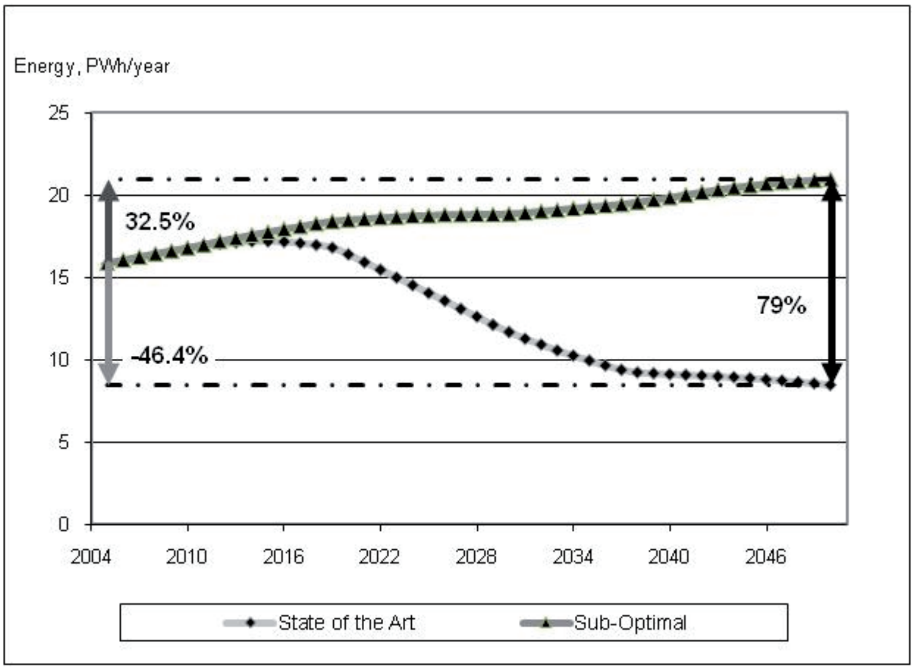


Figure 3. Global thermal final energy use in the state of the art and sub-optimal scenarios and the lock-in effect.

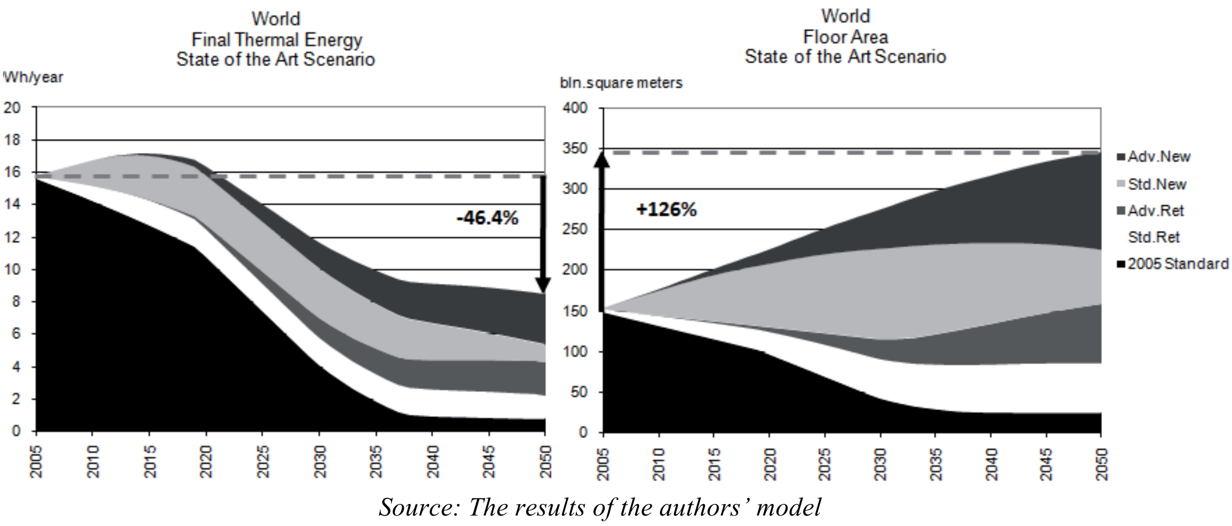


Figure 4. Final thermal energy use in buildings and floor area worldwide, state of the art scenario.

and advanced retrofit buildings). However, due to limited space only selected results are presented here. Therefore, the discussion of the results is focused on the global scale.

Figure 3 presents the results for global final energy use for space heating and cooling in buildings for both state of the art and sub-optimal scenarios. It can be seen from the figure that starting from the same level of energy use in 2005, by 2050 the results for these two scenarios are significantly different. The state of the art scenario shows that in case of the proliferation and full adoption of present energy efficient construction and renovation know-how by 2020 worldwide leads to more than a 46 % decrease in the final energy use. However, if such improvements are not introduced, it will result in a 33 % increase in the global final energy use in buildings for space heating and cooling by 2050, as illustrated by sub-optimal scenario's results.

Figure 3 also demonstrates the value of the lock-in effect. It has been calculated as the difference between final thermal energy use in buildings worldwide in 2050 for the sub-optimal scenario and the state of the art scenarios in relation to its level in 2005. As it has been noted above, the lock-in effect shows the share of energy savings, which will be lost in case energy efficient best-practices are not implemented in the building sector or if their implementation is not ambitious enough. Thus, if advanced solutions for energy efficiency improvements in the global building sector are not introduced by 2020 it will lead to 80 % of final thermal energy savings locked in the building sector for an uncertain time.

At the same time, if the lock-in effect is avoided by enhancing the energy efficiency of the global building sector, the final energy use for space heating and cooling can be almost halved at the global level by 2050 even in the situation of a significant increase in the global floor area, as it is shown in Figure 4. According to the model's results, by 2050 the floor area of the global building sector will go up by 126 % in relation to the 2005 level.

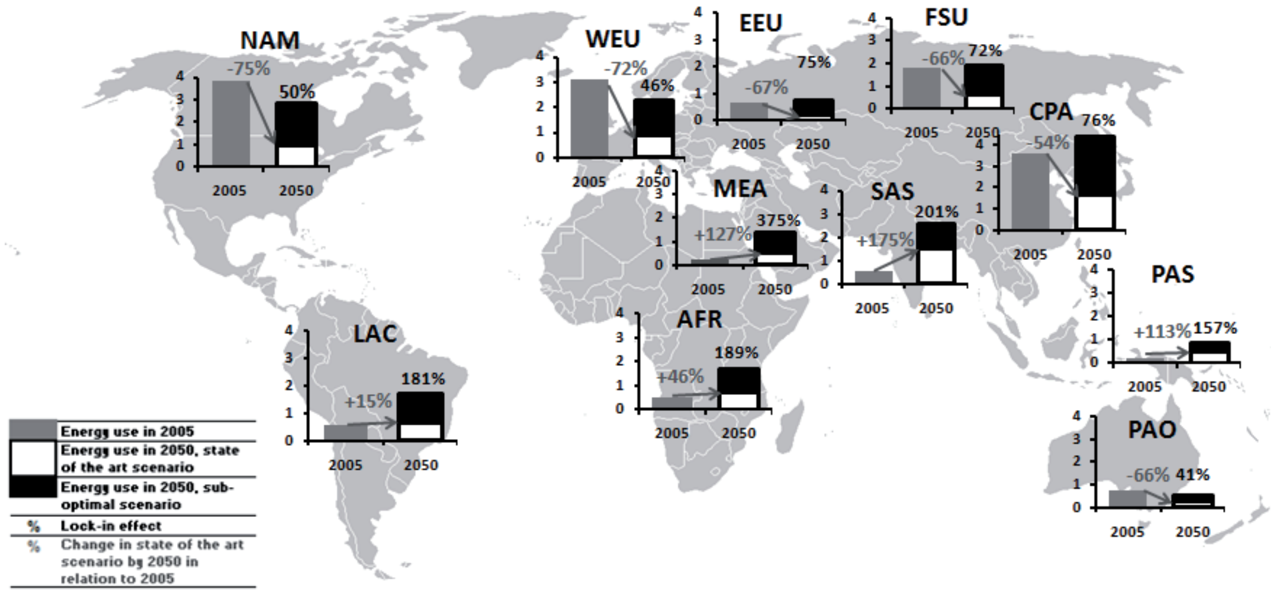


Figure 5. Final thermal energy use in buildings in 2005 and 2050 for different regions and the lock-in effect. Source: The results of the authors' model.

Such a tremendous growth is mostly explained by the population growth in developing countries, as well as the assumption that by 2050 developing countries will reach the level of the developed ones (OECD) regarding the floor area per capita. On the one hand, such an increase in the global floor area may cause a considerable growth in total final energy use in buildings as larger areas will have to be heated and/or cooled. On the other hand, the implementation of existing best-practices in new and renovated buildings worldwide offers the opportunity to eliminate this effect of the floor area growth and reduce final energy use for space heating and cooling by 46.4 % by 2050. Figure 5 shows the change in the final thermal energy use by 2050 for both scenarios and the lock-in effect for all 11 regions analyzed in the model. The figure demonstrates that pushing efficiency to the frontiers may reverse building energy trends even in regions where building energy consumption was foreseen to follow exponential increase(see IPCC 2007), and in developed regions this approach alone is able to reduce final thermal building energy use in 2050 by about 70 % as compared to 2005.

These results demonstrate two major effects of building construction trends on climate change mitigation. First, that the opportunities in the building sector are enormous: 46 % final thermal energy reduction by 2050 in the global building sector can be achieved only by the implementation of well-known energy efficiency measures. As energy use is a proxy for CO_2 emissions, these results can be roughly translated into a significant portion of the 50 – 85 % emission reduction targets set by the IPCC (2007).

However, if further improvements, such as utilisation of renewable energy technologies and life style change towards energy conservation, are implemented in the building sector, it will provide even more energy and emissions reduction. However, these are the subjects of future work and another paper.

The second important lesson to be learned is related to the risk of the possible lock-in effect of energy savings in buildings. As has been shown above, a huge share of energy saving in final thermal energy use can be locked in the building sector if the market transformation towards higher energy efficiency does not take place. It has an effect on both new and retrofitted buildings. If a new building is constructed without implementation of existing energy efficient best-practices, it means that the potential energy savings are lost completely or postponed till its renovation. In the case of renovated buildings the situation is similar: if a building is renovated without holistic utilisation of energy efficient technologies, so-called "deep" renovation, it will lock potential energy savings from such measures for the next 20-40 year until the next renovation takes place. This leads to an interesting implication: renovation works and major repairs without a significant energy efficiency improvement of buildings can be even worse in terms of the lock-in risk than the complete absence of any measures introduced in buildings, as they postpone the possibility of a "deep" renovation for decades.

RESULTS FOR GLOBAL INVESTMENT COSTS & ENERGY COSTS SAVINGS

As it has been outlined in the previous section, there is a huge opportunity to considerably reduce global final thermal energy use in buildings by worldwide utilisation of existing energy efficient best-practices. However, the market transition in the building sector towards higher levels of energy performance requires certain investments and expenditures. Thus, it is necessary to estimate the potential costs of such market transformation and compare them to the energy cost savings. In cost analysis only marginal costs required for higher energy performance levels in buildings are considered.

According to the model's results, the proliferation and full adoption of present state of the art energy efficient construction and renovation technological solutions worldwide requires 18.6 trl.USD (2005) of cumulative undiscounted investments by 2050 (without any cost learning[6]). Assuming

6. Cost learning here is considered as a technology's cost reduction due to its wide adoption and diffusion on the market

Table 3. Cumulative undiscounted investment costs and energy cost savings resulting from the implementation of existing energy efficient best-practices in the building sector in different regions trl.USD (2005).

Region	Cumulative Investments by 2050		Cumulative energy costs savings by 2050
	No cost learning	app.60% cost learning	BAU
WEU	2.5	2.0	11.1
NAM	2.6	2.0	9.6
PAO	0.7	0.5	2.7
EEU	0.3	0.2	2.5
FSU	0.8	0.6	7.4
CPA	3.0	2.4	12.9
SAS	3.2	2.3	3.3
PAS	1.1	0.8	1.5
MEA	1.9	1.4	2.0
LAC	1.3	1.0	3.5
AFR	1.3	1.0	1.5
World	**18.6**	**14.2**	**57.9**

Source: The results of the authors' model

cost learning as approximately 60 % cost reduction of marginal costs by 2050 this amount would decrease to 14.2 trl.USD (2005). Thus, considerable financial investment is needed to realize the existing potential for energy savings in the global building sector. However, the amount of required investments is much lower than potential energy cost savings provided by energy efficiency improvements during the same period (2005-2050). Cumulative undiscounted energy cost savings for this period are estimated as 57.9 trl.USD (2005), which is three times higher than required investments without cost learning. It is noteworthy that for energy cost savings calculation no cost or technology learning is assumed. The direct comparison between investment costs and energy cost savings is rather uncertain as the latter depends greatly on future energy price behaviour, which extremely hard to predict for such a long period of time.

Table 3 shows the results on cumulative investments and energy cost savings by 2050 for different regions of the world. As can be seen for all regions cumulative energy cost savings are higher than cumulative investment costs even in case of no cost learning. It shows that the implementation of existing best-practices is feasible and beneficial worldwide.

Conclusion

Globally the building sector can provide a great potential for the acute challenge of climate change mitigation. This can be done through the reduction of energy use in buildings by means of holistic building energy performance targets. This paper has illustrated that if existing energy efficient technologies for space heating and cooling are implemented, it will almost halve final thermal energy use in buildings worldwide by 2050, which roughly corresponds to a 16-26 % reduction of total emissions. Such an energy use reduction can be achieved even with a considerable increase in floor area and standards of living, as expected in developing countries. Therefore, the results illustrate that it is possible to have both increasing living standards and emission reductions in developing countries, which totally correspond to the concept of sustainable development. Moreover, the estimated reduction in final thermal energy use does not include utilisation of renewable energy in buildings and the shift to a sustainable lifestyle (when energy conservation receive significant attention in everyday life), which would result in considerable additional energy savings and greenhouse gas emissions reductions.

The paper has also shown that this potential is feasible from the economic point of view as energy cost savings resulting from building energy performance improvements exceed additional investment costs required in all regions of the world.

However, there is a huge risk of locking in unnecessarily high energy consumption in the building sector if energy efficient best-practices are not implemented. In this case, almost 80 % of energy savings will be lost by 2050 or postponed and, consequently, climate mitigation targets are unlikely to be met. Thus, actions are to be taken without any further delay. It can be done only through a holistic market transformation in the building sector towards high energy efficiency and low energy consumption, inevitably driven by cautious and well-designed policy measures.

References

Berkovitz, T.I. 2010. Green Solutions in Shanghai. IPHM International Passive House Magazine. URL: http://the-passive-house-magazine.info/event/green-solutions-in-shanghai/ [accessed on 27 December 2010]

Boardman, B. 2007. Transforming UK homes: achieving 60% cut in carbon emissions by 2050. Paper in the eceee 2007 Summer Study Proceedings.

California Public Utilities Commission, 2008. California Long-term Energy Efficiency Strategic Plan, State of California, USA.

Csoknyai, T. And Talamon, A. 2009. Passive houses in Hungarian environment. Paper presented at 15th "Building Services, Mechanical and Building Industry days", International Conference, 15–16 October 2009, Debrecen, Hungary.

DEFRA, 2006: Review and development of carbon abatement curves for available technologies as part of the Energy Efficiency Innovation Review. Final Report by ENVIROS Consulting Ltd.

Dewick, P. and Miozzo, M. 2004. Networks and innovation: sustainable technologies in Scottish social housing. *R&D Management*, 34(3): 323-333

EPBD. 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). The European Parliament and the Council of the European Union. URL: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF. [accessed on 15 December 2010]

Federal Ministry for Transport, Construction and Housing (Bundesministerium für Verkehr, Bau und Stadtentwicklung - BMVBS). 1993. Federal Building Code (Baugesetzbuch, BauGB). Berlin, Germany. English translation. URL: http://www.iuscomp.org/gla/statutes/BauGB.htm#I. [accessed in April 2010]

Feist, W., Pepper, S., Görg, M. 2001. CEPHUS – Projektinformation Nr. 36. Final technical report. Hannover, July 2001.

Firlag, S. 2009. Certified passive building in Poland. Presentation at the Passive house conference. February, 5, 2009.

Gaglia, A. G., Balaras, C. A., Mirasgedis, S., Georgopoulou, E., Sarafidis, Y., Lalas, D. P. 2007. Empirical assessment of the Hellenic non-residential building stock, energy consumption, emissions and potential energy savings. Energy Conversion and Management. Volume 48, pp. 1160-1175.

Gasser, J. F. 2009 A commercial Passive House in the Alps – looking back on ten record-breaking years. In: Proceedings of 13th International Passive House Conference 2009, 17-18th April 2009, Frankfurt am Main.

Groot, H.L.F., Mulder, P. and Soest, D.P. 2001. Subsidizing the Adoption of Energy-Saving Technologies. Analyzing the Impact of Uncertainty, Learning and Maturation. Erasmus University Rotterdam. URL: http://publishing.eur.nl/ir/repub/asset/813/rm0201.pdf. [accessed on 29 June 2010]

Hansen J, Sato M, Ruedy, *et al*. 2007. Dangerous human-made interference with climate: a GISS modelE study. Atmos Chem Phys, 7: 2287-2312.

Hansen, J., Sato, M., Kharecha, P., Beerling, D., Berner, r., Masson-Delmotte, V., Pagani, M., Raymo, M. Royer, D.L., Zachos, J.C. 2008. Target Atmospheric CO_2: Where Should Humanity Aim? Submitted April 7, 2008. Open Atmos. Sci. J., vol. 2: 217-231.

Harvey, L.D.D. 2010. *Energy and the new reality. 1, Energy efficiency and the demand for energy services*, London; Washington: Earthscan.

Hui, S.C.M. 2002. Using performance-based approach in building energy standards and codes. In Proc. Of the Chonqing-Hong Kong Joint Symposium: A52-61. 8-10 July 2002, Chongqing, China.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

International Code Council (ICC). 2007. California Building Code.

URL: http://publicecodes.citation.com/st/ca/st/CA-P-2007-999999.htm. [accessed in April 2010].

Jaffe, A.B. and Stavins, R.M. 1994. Energy Efficiency Paradox and the Diffusion of Conservation Technology. *Resource and Energy Economics*, 16: 91-122

Joosen, S. and Blok, K. 2001. Economic Evaluation of Carbon Dioxide Emission Reduction in the Household and Services Sectors in the EU. Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change. Bottom-up Analysis. Final Report. Ecofys, January 2001.

Kemp, R. 1994. Technology and the transition to environmental sustainability. *Futures*, 26 (10): 1023-1046

Korytarova, K. *Forthcoming*. Energy efficiency potential for space heating in the Hungarian public buildings. Contributing towards low-carbon economy. PhD dissertation. Central European University, Budapest.

Laustsen, J. *Forthcoming*. Reducing Energy use in Buildings with a Factor 4. An IEA Factor Four Strategy for Buildings. International Energy Agency.

Laustsen, J. 2008. Energy efficiency requirements in building codes, energy efficiency policies for new buildings. IEA Information paper. In support of the G8 Plan of Action. OECD/IEA, March 2008.

Lechtenböhmer, S., Grimm, V., Mitze, D., Thomas, S., Wissner, M. 2005. Target 2020: Policies and Measures to reduce Greenhouse gas emissions in the EU. A report on behalf of WWF European Policy Office. Final report. Wuppertal, September 2005.

McKinsey. 2007. Costs and potentials of greenhouse gas abatement in Germany. Report on behalf of BDI initiative – Business for Climate. McKinsey & Company, Inc. October 2007.

McKinsey. 2008. Costs and potentials of greenhouse gas abatement in Czech republic – Key findings. McKinsey & Company, Inc. November, 2008.

McKinsey. 2009. Pathways to a low-carbon economy. Version 2 of the global greenhouse gas abatement cost curve. McKinsey & Company.

Mirasgedis, S., Georgopoulou, E., Sarafidis, Y., Balaras, C., Gaglia, A. and Lalas, D.P. 2004. CO_2 emission reduction policies in the Greek residential sector: a methodological framework for their economic evaluation. *Energy Conversion and Management*, 45: 537-557.

Mitthone, J.P. 2010. Russia's neglected energy reserves. Carnegie Endowment. Washington DC, Moscow, Beijing, Beirut, Brussel

Mulder, P. 2005. The economics of technology diffusion and energy efficiency references. Edward Edgar Publishing Inc., Cheltenham, UK.

Norberg-Bohm, V., 1990, Potential for carbon dioxide emissions reductions in buildings. Global Environmental Policy Project Discussion Paper. Energy and Environmental Policy Center, John F. Kennedy School or Government. Harvard University, Cambridge, MA.

Novikova, A. 2008. Carbon dioxide mitigation potential in the Hungarian residential sector. PhD dissertation. Central European University, Budapest. URL: http://web.ceu.hu/envsci/projects/Potentials/Publications.html. [accessed on 20 December 2010]

OECD/IEA, 2010. Energy Poverty. How to make energy access universal? Special early excerpt of the World Energy Outlook 2010 for the UN General Assembly on the Millenium Development Goals. International Energy Agency (IEA), United Nations Development Programme (UNDP) and United Nations Industrial Development Organization (UNIDO)

Ramanathan, V. and Feng, V. 2008. On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead. *Proceedings of the National Academy of Sciences of the United States of America*, 105(38): 14245-14250.

Rip, A. and Kemp, R. 1998. Technological change. In: *Human choice and climate change: resources and technology*, ed. by Rayner, S. and Malone, E.L. Battelle Press, Columbus: 327-399

Rohracher, H. 2001. Managing the technological transition to sustainable construction of buildings: A socio-technical perspective. *Technology Analysis & Strategic Management*, 13(1): 137-150

Rubel, F., and M. Kottek. 2010. Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification. Meteorol. Z., 19, 135-141. DOI: 10.1127/0941-2948/2010/0430.

Schuetze, T and Zhou, Z. 2009. Passive Houses in East Asia – Transferring European Experiences in Korea and China. proceedings 8th Belgian Passive House Conference 11- 13

Schnieders, J. 2003. CEPHEUS – measurement results from more than 100 dwelling units in passive houses. Passive House Institute. ECEEE 2003 Summer Study – Time to turn down energy demand. Panel 2: Comfort and Energy Use in Buildings. URL: http://www.passiv.de/07_eng/news/CEPHEUS_ECEEE.pdf. [accessed in May 2010].

Sissine, F., 2007. *Energy Independence and Security Act of 2007: A Summary of Major Provisions*, USA: Congressional Research Servce.

Speith, J.G. 2001. Comfort in an Unheated Solar-Passive House at Manilla [Australia]: Two Years Data. Paper presented at a conference Firewood: a Burning Issue for the Twenty-first Century, Armidale, NSW, Australia, 25-26 May 2001.

Thomsen, K. B., Wittchen, K. B., Jensen, O., M. And EuroACE. Sbi 2009:03: Towards very low energy buildings – Energy saving and CO_2 emission reduction of changing European building codes to very low energy standards. Danish Building Research Institute, SBi, Aalborg University, Hørsholm, 2009.

Unruh, G. C. 2000. Understanding carbon lock-in. *Energy Policy*, 28 (12): 817-830

Ürge-Vorsatz, D. and Novikova, A. 2008. Potentials and costs of carbon dioxide mitigation in the world's buildings. *Energy Policy*, 36(2): 642–661.

Ürge-Vorsatz, D., Eyre, N., Graham, P., Harvey, L.D.D., Hertwich, E., Kornevall, C., Majumdar, M., McMahon, J., Mirasgedis, S., Murakami, S., Novikova, A. 2011. *Knowledge Module 10: Energy End Use: Buildings*. Global Energy Asseement.

U.S. Department of Energy (US DOE). 2009a. Buildings Energy Data Book. Prepared for the Buildings Technologies Program Energy Efficiency and Renewable Energy U.S. Department of Energy by D&R International, Ltd. under contract to Research and Development Solutions, LLC and National Energy Technology Laboratory.

U.S. Department of Energy (US DOE). 2009b. Buildings Database. Building Technologies Program. Energy Efficiency and Renewable Energy. URL: http://eere.buildinggreen.com/partnering.cfm. [accessed January – May 2010].

U.S. Energy International Administration (US EIA). 2003. Commercial Buildings Energy Consumption Survey (CBECS). URL: http://www.eia.doe.gov/emeu/cbecs/contents.html [accessed January - May 2010].

U.S. Energy International Administration (US EIA). 2005. Residential Energy Consumption Survey (RECS). URL: http://www.eia.doe.gov/emeu/recs/contents.html. [accessed January - May 2010].

U.S. Energy International Administration (US EIA). 2010. Annual Energy Outlook 2010 with projections to 2035. Report #:DOE/EIA-0383(2010). URL: http://www.eia.doe.gov/oiaf/archive/aeo10/index.html. [accessed 30 August 2010].

Waldseebiohaus 2009. Website of the Waldseebiohaus, passive building of Concordia Language villages. URL: http://www.waldseebiohaus.typepad.com/ [accessed 3 December 2009].

World Business Council for Sustainable Development (WBCSD). 2009. Transforming the market: Energy efficiency in buildings. ISBN: 978-3-940388-44-5. 70.