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REDUCTION OF CARBON DIOXIDE EMISSIONS IN THE GLOBAL BUILDING SECTOR TO 2050

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Executive Summary

Why do buildings matter?

Buildings are of crucial importance to mitigation of global greenhouse gas emissions, and likewise to the global demand for energy. The buildings sector contributes to approximately one-third of global final fuel and power consumption[1] whilst emitting 8.1 Gt of CO_2 per year[2]. OECD countries are primarily concerned with existing buildings while fast-developing economies such as China and India are focused on the large floor areas of new construction. The absolute energy demand of residential buildings in IEA member states has been stable in recent decades while global building sector energy demand has been rising at least since the 1970s. The magnitude of potential emissions savings is huge. By 2050 over 80% of global business-as-usual buildings' emissions (including indirect emissions from the power sector) could be avoided in low-Carbon scenarios that may limit global warming to 2^oC. Many of these savings are also cost-effective, but may be very hard to realise in practice. Why is this, given that such great opportunities exist for both new-build and retrofitting of existing buildings?

A multitude of obstacles remain in the way of decarbonisation of the global building sector

There have been very few effective policies for getting a real grip on existing buildings' emissions, although great progress has been made by appliance efficiency standards. Buildings in general have much longer lifetimes than appliances, and retrofit rates range usually at around 1–2% of the existing stock per year. There are a number of barriers to achieving successful policies to improve the existing building stock, including:

i. the diverse nature of the buildings stock, with older buildings requiring a range of interventions to improve their efficiency,
ii. the disruption and technical challenges of energy efficiency and low-Carbon heating measures,
iii. the relative lack of priority that many residential and commercial buildings users give to achieving energy bill reductions, and
iv. the lack of attention given to the social process that underlies the diffusion of new innovations.

Obstacles may be categorized as technological, behavioural and managerial (in terms of the organisation of efficiency measures).

Looking forward with (cautious) optimism

If countries can introduce tougher regulations with more effective enforcement and inspection then they will likely reap the benefits, however, buildings remain very much part of the political rhetoric. A range of technologies and policies offer efficient solutions to existing demands but public intervention needs to be pushed in the right direction if it is to fully deliver on the visualisation of a low-Carbon future. That this future does not look so different to the world today is an image which today's customer can buy into. Low Carbon buildings will not look or feel very different from today's buildings and people need not be concerned that they would threaten existing lifestyles.

Introduction

Global building sector

According to the IEA's Energy Technology Perspectives 2010[2], to be on track to limit global warming to 2 – 3 ^{o}C, global averaged greenhouse gas (GHG) emissions in the buildings sector should be reduced by 12.6 Gt of Carbon Dioxide (CO_2) per annum by 2050 against the baseline scenario. Emissions of CO_2 are the leading contributor to anthropogenic causes of climate change. Black Carbon, CH_4, HFCs, SF_6, OH, and individual aerosol species are also strong contributors[3,4,5]. Reducing emissions from the building sector is certainly easier said than done. Considering that an ideal building should provide a comfortable environment, a durable structure, and a visual and psychological appeal[6]; the following sections talk through the challenges and opportunities of imposing CO_2 based constraints onto building owners, designers, builders, and users.

This report begins by setting out the historical context which provides a brief overview of consumption trends, rates of retrofit, and previous public policies. Section 3 presents an overview of the current situation in China/India and the U.S./Europe with an emphasis on present and future trends in their respective building sectors. Existing obstacles to decarbonisation attempts are described. Section 4 forecasts the possible state of the global building sector in 2050. Mitigation options for the future building sector are offered and conclusions given in section 5. The conclusions are directed towards policy-makers and suggest strict mandatory building codes, stringent enforcement of building regulations, and impartial analysis of current policies. The central tenet is that lessons can be learned from research and analysis, and then applied to inform future decisions on policies in the global building sector.

Progress so far

Historical context

In terms of an aggregated global building sector, the scale of fuel and power demand has been rising unabated for many decades particularly in the residential sector, as shown in Figure 1. The concomitant CO_2 emissions grew at a globally averaged rate of about 2% per year from 1971 to 2004. Annual global building sector CO_2 emissions are currently estimated at about 8.1 Gt of CO_2[7].

To understand the causes of these rises in fuel, power and emissions over time requires at least partial answers to the questions of why building stock increases and why people demand more energy in buildings. The question of why building stock increases over time is not addressed here (see elsewhere for historical impressions see[8,9] and future projections[10,11]). A brief endeavour is made to answer the latter question.

Buildings are not simply a combination of bricks, mortar and steel. There is a social status attached to a building, whether the building is for residential or commercial use. One theory is that we represent our wealth through symbols (such as buildings), for instance whereby large houses indicate that the owner has at least as much money as the house can be bought for in an open auction[12]. People in general seek larger houses and more obvious consuming patterns such that others may notice their higher social status[13].

Why is this awareness of the social relevance of buildings important to this narrative? Current building policies are often predicated on the assumption that people are rational beings and under conditions of perfect information will choose the least expensive mitigation option available to them. This may be true but what if the low-cost option does not fit with an individual’s aspirations? The debate between rational behaviour of utility-seeking individuals and reasonable behaviour[14,15] is beyond the scope of this report. Moving from sociology to statistics, another important aspect of historical building stock is now presented, that of the lifespan of typical buildings.

In recent times, the lifespan of a typical building is estimated at between 40 to over 120 years[16] as illustrated in Figure 2. It is apparent that buildings last much longer than appliances, perhaps on average eight times longer. The historical use of appliance standards used by many administrations as a proxy for building stock standards, as discussed later, should be considered in light of this. The long lifespan of buildings is a key consideration to the achievement of significant energy efficiency efforts in the building stock (both new and existing) by 2050.

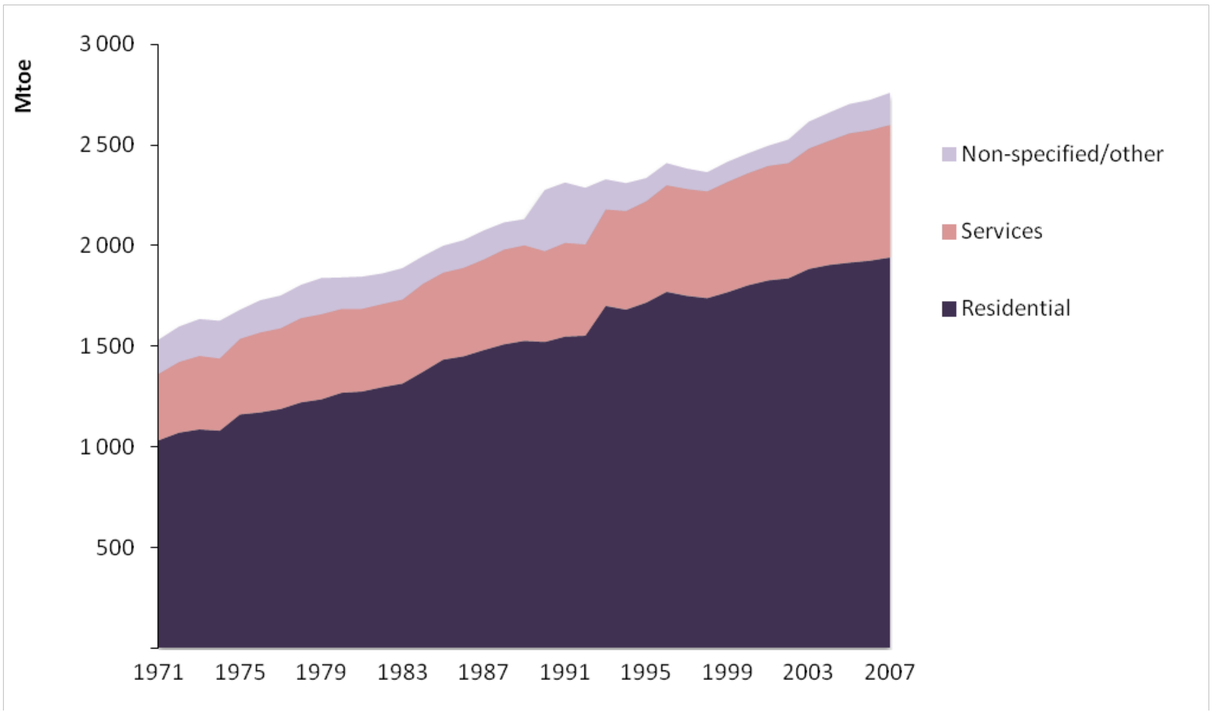

Figure 1: Global energy demand of buildings per building type from 1971 – 2007[17]

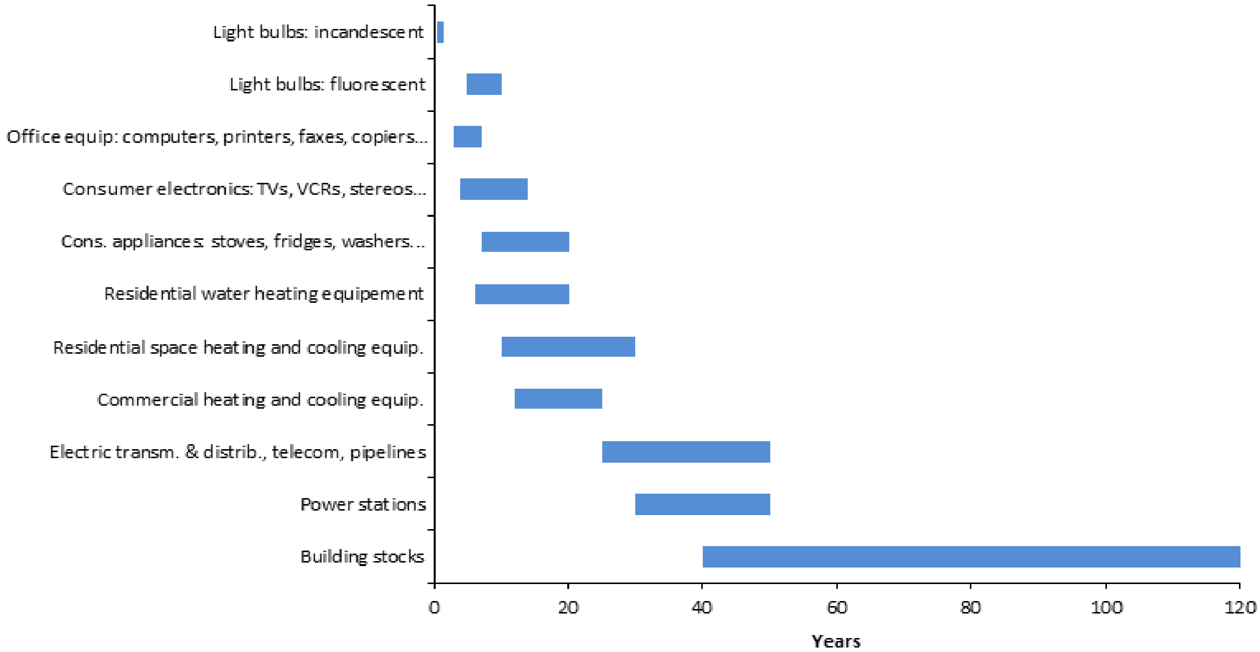

Figure 2: Typical lifespan of building appliances, services and stock[17]

The annual rate of building stock retrofit is difficult to measure at a national level. Where measured it has been seen to vary between countries. It should be noted that differences in metrics used for recording retrofits mean that national data are not directly comparable[18]. Data on the activity levels of building retrofits are generally poor[19]. Nonetheless, Table 1 gives an indication of the rates of retrofit projects in the countries shown.

Country	Rate of private retrofit	Rate of commercial retrofit	Rate of total building stock retrofit
U.S.	-	2 – 2.2%[20,21,22]	-
Germany	-	-	0.8 – 1 %[23,24]
U.K.	1 – 1.9%[25] (England only)	-	1 – 1.5%[26]

Table 1: Typical annual rates of national building stock retrofit, '-' denotes not available

At these rates it will take a relatively long time to completely refurbish the existing building stock. Take the case of England. She has an initial residential housing stock of 22.7 million in 2010, a rate of new build of about 1%[27] and 20,000 documented demolitions per year. Using these numbers the building stock in 2011 will then count 22.9 million. Assuming a retrofit rate of 1.5% of total building stock, it would take until 2062 to completely refurbish England's initial 22.7 million buildings from scratch.

Historical overview of policies

Buildings are very much part of the political process. In recent times, particularly as climate change has become more political[28], there has been an underlying assumption that public intervention is required to correct for market externalities. There is also an assumption by some that access to fuel and power is a human right; "an access level sufficient to meet basic human needs"[29,30]. With these assumptions in mind, an overview of historical building policies is presented. Planning policy is not considered here, although this has been well covered elsewhere[31].

It can be argued that it is difficult for democratic politicians to push through tough regulations on energy efficiency in buildings, as was seen in the angry response to a proposed mandatory federal energy efficiency standard for U.S. buildings in 1979 - over 1,800 public comments were received and the proposed standard was dropped[32]. Individuals may have strong attachments to their living spaces, and often will resist interference or perceived new costs in their homes. The costs of gas and electricity bills are cited in the media as a measure of the current popular feeling towards energy retail companies, and governments often publicly seek to be seen reducing the burden on the poor[33]. Thus many policies are brought in to deal with fuel poverty, although they are not regulated for in general.

Modern interest in applying energy based regulations to the building sector can be traced back to the 1970s, in particular beginning with the Arab-Israeli conflict of October 1973, when energy conservation became part of the political lexicon. Indeed ration books for fuel were handed out by the British government, such was the worry over resource supply[34]. Many government policies have funded large research and development (R&D) programs, such as programmes for improved understanding of heat transfer in windows in Sweden[35] and research on energy conserving building materials in China[36]. In tandem with R&D, often energy conservation codes were brought in for a particular service, such as the energy conservation design code for heating in residential buildings in China in 1986[37]. The energy conservation programs in the 1970s and 1980s were typically presented as cost effective projects to be incentivized by public agencies. The discounted value of energy savings for the customer would surpass the initial capital expenditure of an energy efficient investment[38]. The U.S. introduced federal tax credits of up to 15% of the cost of energy efficiency measures for residences[39]. During this time-period many appliance standards were formulated (the history of appliance standards is tabulated elsewhere[40]).

During the 1990s, both the environmental and climate change movement received more attention from governments, particularly after high profile events such as the 1992 UN Conference on Environment and Development. In the U.S. new legislation and strategies were produced that included labelling standards for 13 categories of residential appliances[41]. In the last decade, further reports of the Intergovernmental Panel on Climate Change (IPCC) and meetings of the United Nations Framework Convention on Climate Change (UNFCCC) have garnered both momentum and legislation surrounding the efficiency of buildings. For example, the EU's Energy Performance of Buildings Directive requires that all new buildings must meet minimum energy performance requirements[42], while India's Energy Conservation Act 2001 for the first time produced guidelines for the construction of energy efficient commercial buildings[43]. Much more detailed reviews of building energy efficiency policies, and related policies, are provided elsewhere[44,45,46]. The public policies aimed at reducing fuel and power usage in buildings are now assessed in terms of effectiveness.

Which policies were most effective?

The IEA categorises national energy efficiency policies for buildings into nine categories of which there are 408 policies listed. Of these 408, only 7 include policy evaluations[47]. However, the IEA's database is non-exhaustive and may not include many local measures. Nevertheless it hints at a lack of both analysis of and learning from previous policies. It could be argued that there are four interrelated questions surrounding the effectiveness of such public policies:

i. Was the announced policy fully implemented?
ii. Has the policy been analysed in terms of its estimated impact on fuel and power demand in buildings?
iii. Were there any perverse responses, unforeseen in the initial policy construction[48]?
iv. Did the policy deliver in a low cost/cost-saving way?

Focusing here on the second question, appliance standards appear to have had the most impact. A good example is the Japanese Top Runner program. The program obligates manufacturers/importers to improve the use-phase performance of new appliances to that of the most efficient product on the market (e.g. computers, space and water heaters). Use-phase refers to the operational phase of an appliance and does not include the efficiency of the manufacture and disposal, as in life cycle analyses. Savings from Top Runner of over 56 TWh in the commercial and residential buildings sector are expected by 2010, although various estimates exist of the savings delivered[49]. California is another example of successful appliance policies. Californian building standards/energy codes are calculated as saving 8 TWh of electricity use in 2000 with appliance and (consumer subsidised) utility programs saving another 27 TWh in commercial and residential buildings[50].

With regard to the use of economic incentives for improvements to existing buildings (e.g. loans, tax incentives or grants), the German KfW CO_2 reduction and building rehabilitation programs have been analysed as providing savings of about 14 MWh per dwelling between 1995 and 2005 (12.5 TWh in total[51]). This compares with a consumption of 792 TWh in Germany's residential sector in 2008[52]; a saving around 1.5% (recognising the different time periods). The key lesson from this program was that programs should start small, learn quickly from demonstration projects, before expanding the economic incentives to larger populations. The policy of linking financial support to the reduction of CO_2 emissions per square meter worked well, although in retrospect they recommend using the percentage reduction in energy demand per square meter as a better measure of success.

Other authors have provided ex-post and ex-nunc analyses of particular building energy efficiency measures[53,54,55,56]. For instance the Chinese existing retrofit and heat supply reform was modelled during the period 2006 – 2008, and a great divide was found between the targeted and achieved primary energy savings[57]. It remains that IEA members do not appear to have effective evaluations of the actual, on the ground, results of programmes to improve energy efficiency in buildings. This line of argument is taken up again in Section 3.2.3.

Present situation

China and India

China and India's burgeoning economies and populations imply that vast tracts of new buildings will be constructed in the decades to come. This presents both a huge opportunity and an equally large challenge in terms of CO_2 emissions. Both countries' building sectors are briefly discussed below.

China's fuel and power consumption in the building sector is third in the world, shown in Figure 4, after that of OECD North America and OECD Europe. However, the top two regions are relatively stable in terms of population and economic growth. In China, it is likely that a large proportion of the 1.3 billion people will improve their living standards in the coming years[58]. In parallel with improving living standards, China's building primary energy usage is modelled to continue to rise up to 2050, even if heating and cooling demands remain constant[59]. The heating and cooling levels will likely rise, however, for example in the Yangtse ('transition') region where currently there is often no domestic heating even in relatively cold weather.

Building construction could be said to have taken off since 2002 in China, but is expected by 2020 to go down to about half the rate it is at today. Meanwhile, China has almost half the world's construction activity. Growth in road construction and industrial activity will likely tail off in coming years, but residential construction is projected to continue to increase. From 1980 to 2010, the total output produced by the construction industry increased from 28.7 billion RMB to 9,520 billion RMB; jobs in the construction industry increased from 8.54 million to 35.97 million[60]. This growth will probably continue. The rising demand in the building sector in China is likely to create emissions from construction and fuel usage for building heating which more than offset the colossal emissions savings that are attributed to appliance efficiency by 2020. In Figure 3, energy savings from appliances are seen to be more than five times the output of the 3 Gorges Dam.

In spite of the huge growth expected in China, current consumption levels of the highest 10% of consumers are very similar to the average consumer in developed countries, in terms of annualised per capita energy consumption[61]. If China also goes for Western levels of comfort then this could cause a large increase in resource demand. There are concerns related to this increase.

In the midst of such a vast and vibrant economy there is a lack of disaggregate data for providing indicators in the building sector. So whilst China's 12th five year plan includes a call for a 15% reduction in urban building demand, there are few reliable statistical indicators measuring such progress. Further to the issue of measurements, the National Bureau of Statistics in China doesn't count commercial energy from buildings in rural areas. Rural areas appear to be left out of Chinese energy efficiency policies towards the building sector.

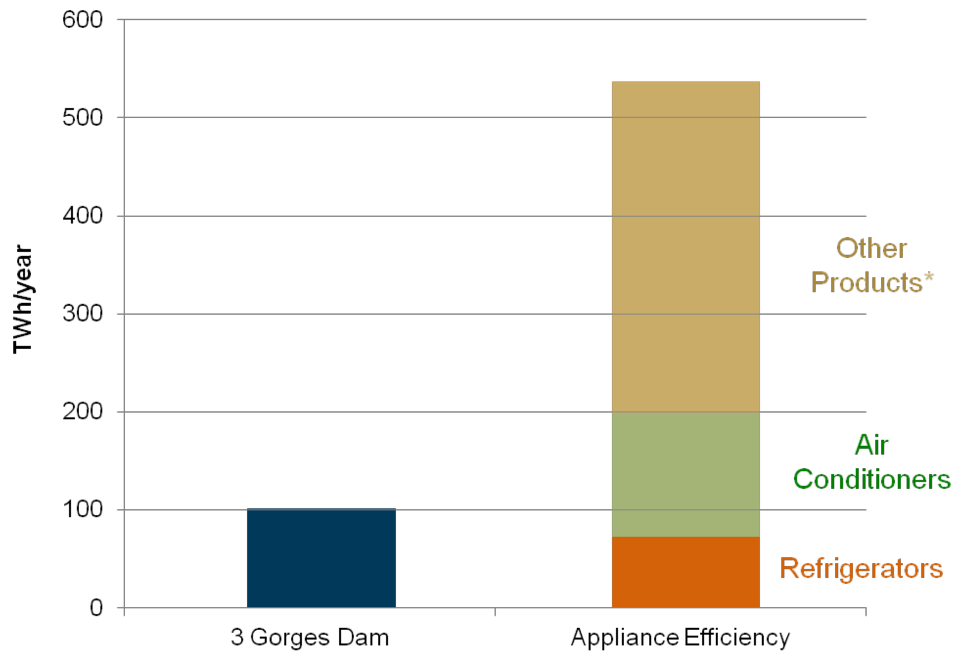

Figure 3: Annual generation from China's Three Gorges Dam compared to annual savings in 2020 from appliance energy efficiency standards[62]

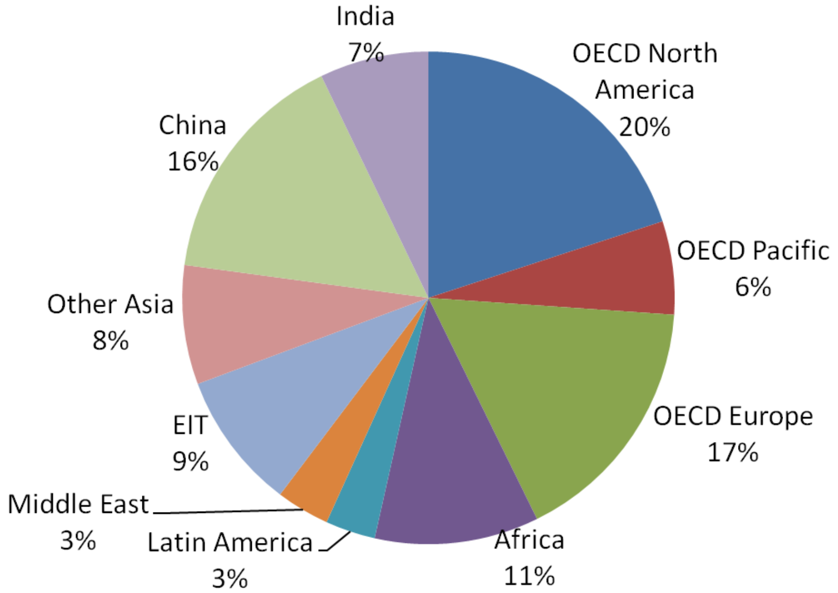

Figure 4: Energy demand in the building sector by country and region[63]

Another rising power is India. She has the third largest building sector demand by country (in terms of annual consumption of fuel and power) accounting for 200 Mtoe in 2009 (with the U.S. and China at 480 Mtoe and 450 Mtoe respectively, and OECD Europe at about 490 Mtoe[63]). In India, traditional biomass usage dominates, with about 855 million people relying on it for their daily needs. Pure dependence on biomass is to be found in rural areas, whilst the 25% of the population living in urban areas also rely on electricity and oil. About 400 million people live without electricity. Similarly to China then, there is a strong possibility that the most dynamic part of the population (those migrating from rural to urban and peri-urban areas) will drive large demand rises in India's building sector in the decades to come.

Europe and the U.S.

Europe and the U.S. face an altogether different issue – the question of how to reduce fuel and power demand in existing buildings. As illustrated in Figure 6, there is a wide range of age distribution of existing building stock in IEA countries, with the majority being built since the 1950s.

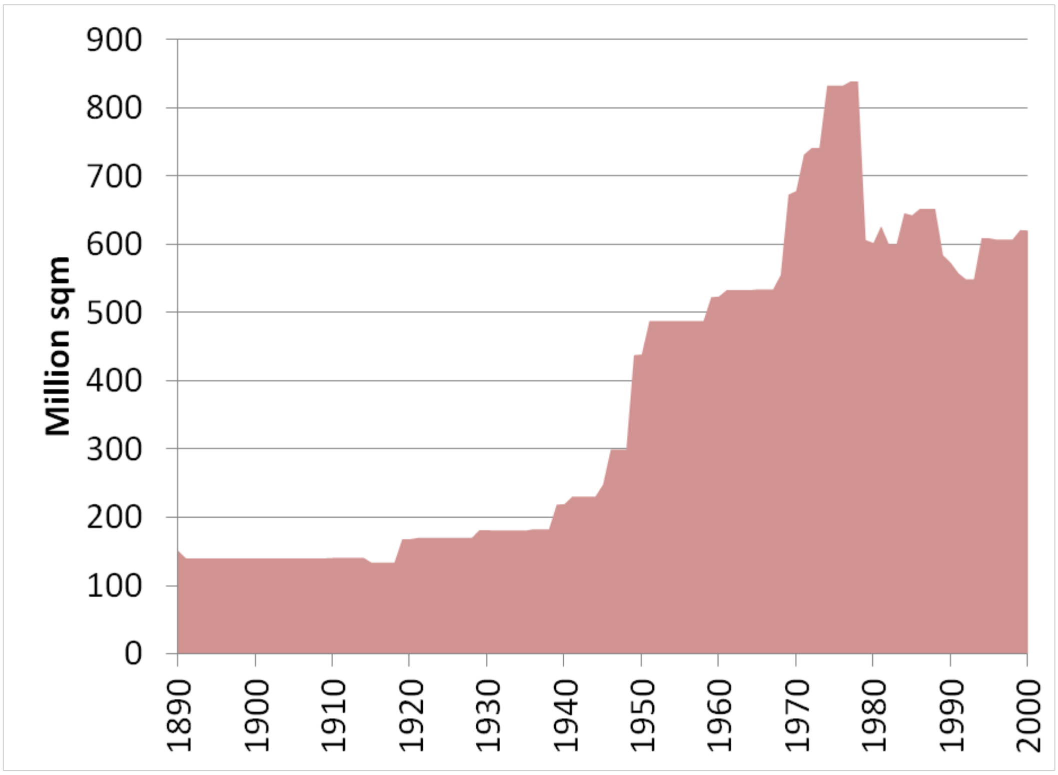

Figure 6: Age distribution of the building stock in IEA countries, in square metres of building area[64]

Individual countries hold specific styles of historic buildings. The U.K. contains 8 million houses over 60 years old – about 35% of the total stock[65]. Much of this old building stock may lend itself to retrofit improvements. Annual residential direct emissions from heating have been sustained at about 80 Mt CO_2 since 1970 (Figure 7). Nonetheless the U.K. stock needs improving if these emissions are to decrease dramatically to 2050. The case of the U.K. is not unique, however, and other developed countries face similar obstacles in reducing CO_2 emissions from their existing building stock.

New buildings in Europe and the U.S. do not face the same problems as those implicit for existing buildings, and in general new build have stricter standards in place. A number of countries have already altered (or are in the process of altering) their building regulations such that new buildings are designed to higher standards than set previously. France has set maximum levels of energy demand (kWh/m^2) that buildings are allowed to attain. The U.K. wants all new homes to be Carbon neutral by 2016 (i.e. emitting zero CO_2 emissions when averaged over the course of a year, aside from emissions attributed to appliances[66]).

Previous mistakes in building regulations have been and are being corrected by many countries. For instance, there was an assumption in previous U.K. building codes that there was little to no heat loss due to party cavity walls between houses (the cavity being enforced under acoustic regulations), but in fact air flow in the cavity causes heat losses due to the convection currents induced[67,68]. A final note on new build standards is that it is hard to measure the results provided by prescriptive regulation, but that prescriptive codes are easier to enforce than those based on performance. In light of the context set out above, a multitude of real-world obstacles to decarbonising both new and existing buildings are offered.

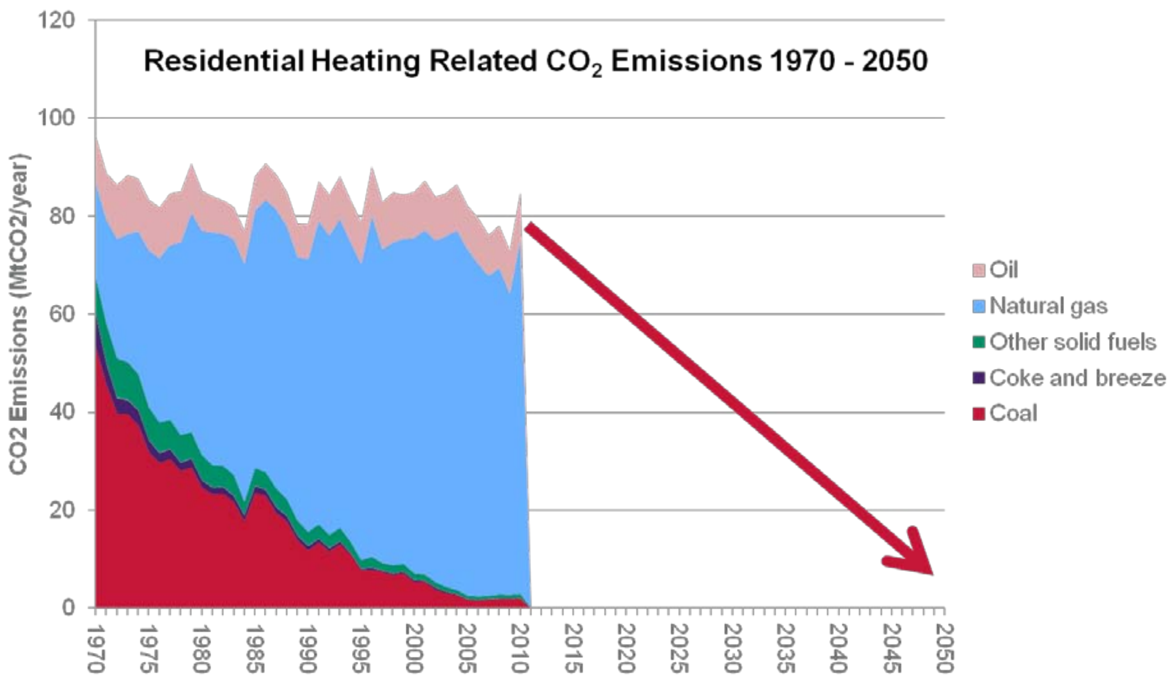

Figure 7: Residential Heating Related CO_2 emissions in the U.K.[69]

Present obstacles

Evidence for the existence of a large number of obstacles to providing effective energy efficient interventions in building stock can be found in the literature[70]. For simplification, the obstacles to effective retrofit and efficiency in new buildings are divided here into three categories: i) technological, ii) behavioural, and iii) managerial.

There is a common underlying assumption in policy making that energy efficient options would be chosen if only the rational customer had the necessary information to make an optimum investment decision. This assumption may be attractive to policy makers but has been criticised for not including theories of social constructs within which decisions related to building innovations take place[71]. It should also be noted that there are various competing explanations for residential demand decisions. The remainder of this section provides an overview of the obstacles which are typically held to blame for the limited progress in decarbonising buildings.

Technological

Technological barriers could be described in terms of their actual operation and their financing. Operational barriers query whether renewable-based solutions provide the same power as fossil fuel solutions. Financing barriers are related to both cost and price. It has been estimated that from now to 2050 the additional investments required to transform the buildings sector (so as to achieve reductions of 83% of CO_2 emissions in 2050) would be in the order of USD 12.3 trillion[72].

Technological solutions need not be complex or costly however, and the obstacles may arise from popular prejudices. For instance, whilst humid climates may require reheat air conditioning, dry climates can be argued to have no need for mechanical ventilation. However, in more complicated arrangements there is certainly a need for system design and appropriate controls. Take the example of older styles of district heating, which were often found guilty of heating apartments up to required temperature of the coldest unit, thereby overheating a number of other apartments.

Continuing the theme of poor design, technologies are part of a system and should be designed and commissioned as such. A recent study of 83 heat pumps in the U.K. found lower than expected coefficients of performance (COP) of 2.2 – 2.4, and determined that heat pump performance was sensitive to both installation and commissioning practices[73]. Furthermore if the design appears fool-proof, the actual installation or implementation may not be. For one, full insulation of cavities is quite rare[74]. Sometimes unfilled cavity pockets can be produced if the insulation is pumped in too quickly. Moreover, even if the design of a measure and its implementation are in line with the specifications, the end user may not use the technologies as intended. An example from the U.K. found that 80% of a sample of housing tenants used both gas fire heating and condensing boiler central heating[75].

A further barrier to improved technological solutions is the neglect of the use of the second law of thermodynamics in the details of top-down regulations and policies. Put simply, the first law states that energy is conserved in thermodynamical systems whereas the second law puts limitations on the possibility of converting heat into work[76]. Metrics for measuring the demand for fuel and power in buildings typically conflate hot water/space heating demand with electricity demand. In some cases there is a tendency for policy makers and academics to ascribe top-down technological solutions to local problems at local temperatures. There are varying degrees of useful work output of heat, and ascribing the same value to energy statistics at different heat levels makes no sense[77]. High pressure steam is more useful to industrial than residential buildings, and similarly luke warm bath water is more useful to residential than industrial buildings. However the higher heat supply can be used for many applications (and real world prices reflect this), but this representation of heat by temperature is usually absent in energy statistics and governmental policy.

The final obstacle of note may be defined as the perceived ability of technologies to improve performance at higher scales of usage. Take a particular individual at a given moment in time. If that person was to live in an urban or rural setting, it is assumed here that they will do roughly the same amount of heating, lighting, cooking, refrigeration, laundry and washing. There is little sharing done amongst urban dwellers as regards these services. The stationary urban energy demand (i.e. not including transport or manufacturing) can be considered density independent and quite similar to stationary rural demand[78]. On the other hand, the supply to this stationary energy demand can be shared amongst a number of buildings, the most obvious example being that of space conditioning. Power losses, daylighting and natural ventilation also offer possibilities for improved design based on density of buildings. A large hurdle to technological solutions of large agglomerations of buildings then may be the perception that stationary urban demand is density dependent. Trying to change a person's cooking patterns is a lot harder than improving the fuel/power supply for the cooking!

Behavioural

Behavioural obstacles are those characterized by human control and affect upon the intended outcome of fuel and power interventions in buildings. Irrational human behaviour has long been identified as the cause of many market failures[79] and rebound effects are well documented[80,81]. Others would argue that consumers are simply doing reasonable things[82,83,84]. Regardless, savings from energy efficiency measures are in general not what is expected. There is an underlying question of whether it is the behaviour that is at fault, or the theory describing the behaviour.

Take a specific example of the comfort levels in buildings. It cannot be denied that comfort levels are very important in buildings, and for example air conditioner usage was found to increase with increasing age of the dwellers in an apartment complex in China[85]. How do you include this in a cost-benefit policy analysis? Rather than ignoring the subtleties of human behaviour, household fuel and power consumption is a complex socio-technical problem that could lend itself to being tackled using inter-disciplinary perspectives[86].

Allied with the complexity of modelling building user behaviour is political behaviour. Politics may well influence the current and future decarbonisation of buildings. With this premise intact, political will can be seen to push forward strong drivers of change, but arguably this only occurs when there's a common objective or crisis. This was seen in the 1960s in the U.K. during the replacement of town gas with natural gas pipelines. Gas central heating was supported by politicians and well marketed in a concerted push. Yet the potentially unhelpful side of political intervention can be illustrated by two examples from the U.S. (which is by no means the sole offender). In the late 19th century there were fears of a coal shortage in the U.S. that drove the government to provide particularly attractive mineral rights for coal. When it became clear that there was no shortage, these mineral rights remained[87]. Such subsidies create an unnatural advantage for one particular resource or technology in general and this helps, it can be argued, form an inherently unstable system. A credible counterargument of fossil fuel lobbyists could be that energy efficiency incentives are simply another unnatural advantage for a different lobby.

Another example of a market restriction placed by governments is the fact that the U.S. Department of Energy is not permitted to conduct research related to behavioural science, although a recent bill (HR 3247) attempted to reverse this (unsuccessfully to date). This form of political protectionism is also seen in the activities of special interest groups – e.g. for the protection of historical facades.

Managerial

The final category of obstacles to decarbonising buildings is that of the management of building design and retrofit, i.e. the actual implementation, commissioning, and feedback. Data management, institutional capacity and organisation of the logistics of implementation are included in this category. *Vis a Vis* data, there are concerns at a lack of culpability when data is not verified correctly. People don't get sued for underperforming buildings, unlike fire safety! This also relates to the lack of enforcement of post-commissioning evaluations. Without data it is quite difficult to determine how an efficiency measure performed in reality.

A further footnote to data management is that the conversion of national indicators into normalised sets (for example by use of purchasing power parity) in part removes the usefulness of the initial data in describing what countries and cities actually do with their buildings[88]. Furthermore, national indicators produced by governments can remain unquestioned in terms of their validity, and a recent study showed that Great Britain's marginal emissions rate of power generation over the period 2002 – 2009 was actually about 35% above the systems average emissions factor commonly used in policy analysis[89].

Regarding the logistics of implementation, there may well be barriers set by the disaggregate nature of the construction industry. Since the building professions first materialized in the 1830s, the evolution and expansion of specialized design professions has helped isolate architects (design of buildings) from engineers (design of structures/processes) and from builders (who actually construct buildings)[90]. The sharing of innovation by builders, in particular, has been hindered by the fragmentation of the industry. As of 2011, in the U.K. there were over 75,000 construction firms, of which 64,300 firms have fewer than 5 employees[91]. In the U.S. it is a similar story, with fewer than 900 firms having more than 250 employees[92].

Current technologies and methods

The technologies and methods for producing well-designed and used buildings have been known for decades, and super-insulated homes have been built since the 1980s at least. More detailed descriptions of the current CO_2 mitigation options in buildings and equipment are provided elsewhere[93], such that only a concise overview is afforded here. Each option has its own drawbacks and benefits, and a recent Grantham Institute report recommended that holistic research be undertaken to better understand the tradeoffs of low CO_2 options in the residential heating sector[94]. Some of these options are discussed below.

Options in the heating sector include improvement of building envelopes, natural gas condensing boilers, micro-combined heat and power, ground source and air source heat pumps, and district heating[94]. Each has its own opportunities and challenges. For example an air source heat pump's (ASHP) performance is quite poor at low ambient temperatures, it may create noise levels of 40 – 50 dB, and ASHPs could need planning permission and extra radiators. However, ASHPs are relatively cheap and could provide low Carbon heating if the electric grid decarbonizes.

District heating includes the benefits of fuel flexibility and use of low-grade heat (i.e. less useful forms of energy) so that higher grade sources can be set aside for other ends[95]. The use of district heating is not widespread for various reasons, a possible reason being its association with socialised housing. Although in countries with strict planning laws there is thought to b no such association. In Denmark 60% of residential space and water heating is met via district pipelines supplying heat[96]. Solar energy also offers great potential although its use is affected by the urban form and texture, and the solar resource availability. Resource availability varies by locality, and season, with 1150 – 2570 kWh/m^2 per annum available in China compared with 750-1100 kWh/m^2 per annum available in the U.K.[97] As regards the technologies cited above, this brief note is by no means comprehensive nor detailed enough for robust analyses. Furthermore, a range of new equipment will likely diffuse into buildings in the run up to 2050; the increased use of controls is one particular promising option.

A brief case study is presented here to describe previous technological trajectories. The typical innovation narrative describes the evolution of an invention, such as air-conditioning, to that of a fully diffused innovation. The diffusion of innovations, as detailed by Rogers[98], is in effect a social process whereby different levels of information about a new idea are communicated from individual to individual. New users find out about and are then persuaded to use a new innovation through a highly respected agent in a particular social system.

The case of air-conditioning units penetrating the U.S. market is offered as an example of innovations diffusing through the sub-sectors of the building sector. Air conditioning was invented by John Gorrie. He produced refrigeration machines for cooling of medical patients. Air conditioning was then was used for conditioning indoor humidity in the early 1900s by Wolff, Cramer and Carrier. The use of 'process' air conditioning was initially adopted by factories, a very useful innovation for industry. In textile factories this was useful where open windows could disturb the fibres of materials, whereas air conditioning allowed for a more controlled internal environment[99]. Demand for air conditioning grew in the 1920s/1930s from premium buildings, such as soundproof broadcasting studios and the Rivoli theatre in New York[100]. Soon, commercial buildings began to employ air-conditioning and refrigeration as standard in the 1930s, whilst the development of a particular chlorofluorocarbon (Freon) allowed for the production of small packages of residential size conditioners[101]. By the beginning of the World War 2, only a scattering of residential buildings had installed air-conditioning, almost all of which had wealthy owners[102]. After World War 2, air-conditioning units diffused into smaller buildings and general residences of the less wealthy. By the 1970s, it was considered normal to have air-conditioning installed in public buildings in the U.S. Similarly, by that time in the U.K. it became 'commercial suicide' for investors to develop non air-conditioned space in public spaces[103].

The key lesson of such an example is that in building services there is no simple linear diffusion pathway from lab bench innovation to full market penetration[104]. Nor do innovations introduced in general housing migrate upwards into premium housing or industrial buildings. The example above provides a description of the contextual social systems into which the commercial viability of building service technologies should be assessed[105]. In general, it can be argued that innovations in buildings tend to transfer from industrial buildings into premium buildings, move onto commercial buildings followed by a diffusion into premium housing and finally general housing[106]. This diffusion pattern could be useful for policies seeking to incentivise the uptake of low carbon technologies in particular building sub-sectors.

To conclude this section on current technologies and methods a brief note is now provided on current mathematical methods employed in the building sector. These mathematical methods have a variety of uses for particular decision makers in the built environment. Currently there are at least six main mathematical methods of modelling urban energy systems, and their interactions with buildings. These are listed as methods associated with the following functions of urban areas: technology, buildings, urban climate, systems, policy, and land-use and transportation[107,108]. Current practitioners tend to use bottom-up models of the building sector.

One underlying challenge for such methods relate to the data; knowledge of existing sources, understanding of the feasibility of both the data sets and abstractions used for modelling, and corrections for uncertainties are all required for successful modelling. For example the build-out rates of efficiency measures could be deemed a key parameter to be analysed using uncertainty analyses[109]. There are a number of exciting methods currently being refined, such as that of structural equation modelling[110]. Methods typically fall into those of either simulation or optimisation, and it is beyond the scope of this report to provide an overview. Despite, or perhaps because of, the vast number of methods for programming/simulating the process of decarbonising buildings there remains a lack of convergence on which methods are best suited to the task.

Future projections, policies and possibilities

The world in 2050

Looking into the future of the global building sector could be said to involve the prediction of the unknown, the forecasting of possibilities, and the projection of probabilities[111]. Considering these three elements, this section forecasts possible trends and also projects emerging trends. For a start, it is probable that China and India will play a large role in building sector fuel and power demand in the years leading up to 2050. A number of premises form the foundation of such statements - such as the expectation that urbanisation growth rates will rise for China, peaking by 2030/2035, and that India population will continue growing rapidly. Subsequent models based on similar assumptions produce estimates of demand. The expected demand in 2050 is shown in Figure 8 for the IEA's baseline and Blue Map scenarios.

The world in 2050 may be forecast by use of models such as MARKAL and SynCity[112,113]. It may also be imagined by the employment of narratives in form of visualisation or economic stories. A visualisation of a low-Carbon building sector in 2050 shows a building sector that does not look so different to the one today. The future sector is one in which buildings still provide all the modern services but include currently unknown inventions (could anyone in 1974 predict the new technologies used in buildings in 2012?). It could also be construed as very likely that this future will involve similar patterns of innovation diffusion (and fuel and power use) to those found throughout the 19th and 20th centuries. It remains to be seen however, what role particular technologies, methods and policies will play in the decarbonisation of the global building sector.

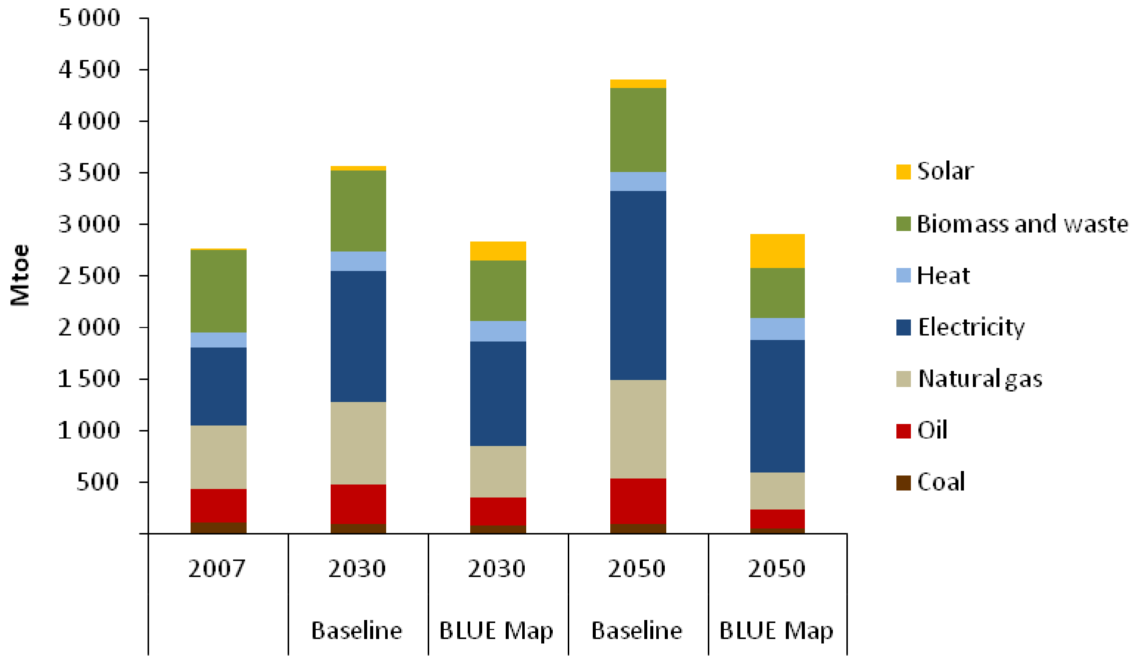

Figure 8: IEA baseline and BLUE MAP scenarios for the building sector to 2050. The BLUE MAP models a very different future for the building sector, in which aggressive policy action reduces energy demand dramatically[114].

Technologies looking forward

Currently it is evident that for the same style of living in a building there are many opportunities to design, install and commission building technologies a lot better. Industrial and premium buildings may look to the best practice technologies, and this is where there have been arguments (following from the success of programs such as Japan's Top Runner) that the best practice should be enforced as the minimum standard of achievement for appliance/equipment. However, the lifespan of buildings far outweighs that of the appliances they contain, and perhaps it is towards the building fabric that decarbonisation efforts should be focused (following the 'lower the demands first' practice of engineering). A non-exhaustive list below gives examples of efficient technologies for decarbonising different aspects of buildings[115,116,117,118]:

i. Envelope products:
   a. Insulation materials, glass, brick, and draught proofing.
ii. Processes:
   a. Green lighting, energy-saving elevators, new air-conditioning technology for data centers, active solar thermal, heat pumps for space heating and cooling, and hot water and thermal energy storage.
iii. Supply:
   a. Combined heat and power (CHP), fuel cells, bioenergy, zero coal new set of technologies in rural areas, power losses optimization and sharing of tiered grades of waste heat.
iv. Control/feedback systems:
   a. Efficient and distributed temperatures, air conditioning control in public buildings and optimized technology management in large-scale public buildings.

From the list above it is clear that there are a number of options for the future investments in technologies. Each technology confers its own social association, benefits, and drawbacks. The criteria of relevance to this report are the fuel and power reductions obtainable. An estimation of the savings attributed to certain deployment scenarios are provided in Figures 9 and 10.

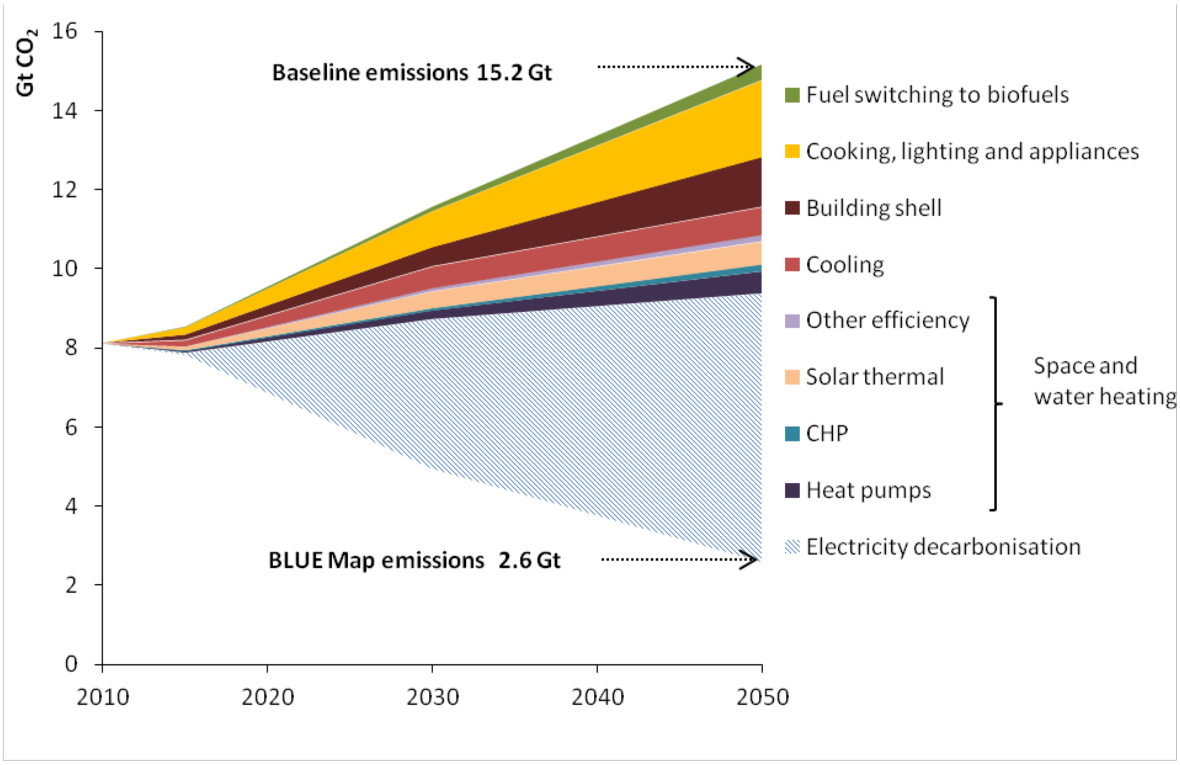

Figure 9: IEA baseline and BLUE MAP scenarios for the building sector to 2050. The BLUE MAP models a very different future for the building sector, in which aggressive policy action reduces energy demand dramatically[119].

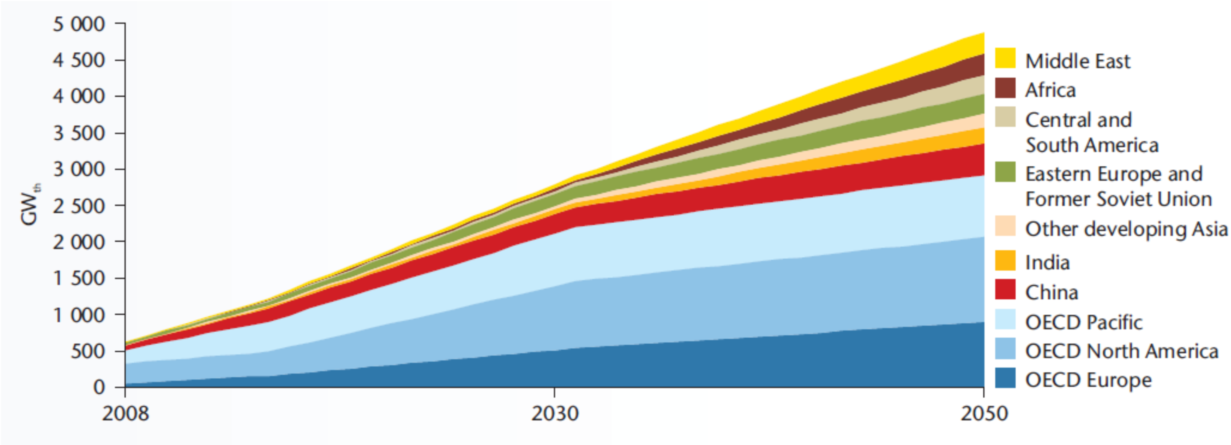

Figure 10: BLUE MAP scenario for heat pump rollout in the building sector to 2050[119].

Policies looking forward

As mentioned in earlier passages, for IEA member states at least, there is a clear dichotomy between the implementation of energy efficiency policies for the building sector and the actual enforcement and evaluation of the impacts of these policies. New policies seem to continue to be developed using cost-benefit calculations that do not consider on robust analyses of previous policies. Without knowing how previous policies have fared, how can governments learn from successes and failures?

Building abatement is both a technological and a social issue. Building abatement policies could use the systems engineering approach, for instance considering the interactions between buildings, the electricity grid, and fuel storage[120]. Moreover, policies could seek answers from the historical diffusion of innovations, rather than relying on a simplistic linear theory of innovation from R&D to full market penetration. Traditional innovation theory would suggest the targeting of respected and naturally innovative individuals in the particular system (e.g. those who supply the top-tier of architects and engineers) for the first adoption of new innovations[121].

Taking this in mind, it should be noted that there are many other competing viewpoints on what policies should be put forward for both existing buildings and new buildings. Below is a non-exhaustive list of potential policies with the following facets[122,123,124,125,126]:

i. Building regulations:
   a. Inclusion of exergy in building codes (as has been done in the Canton of Geneva).
   b. Require all new buildings, including those being retrofitted, to meet minimum energy performance standards.
   c. Including a percentage of energy reduction as a target.

ii. Policy design:
   a. Inclusion of stakeholders from all areas such that a systems based approach may be provided.
   b. Come to agreement on a goal and backcast an 'energy technology pathway' towards that goal.
   c. Heat pricing reform.
   d. Retro-commissioning of buildings.
   e. Allow fuel and power prices to rise over time to their natural level, whilst protecting the fuel poor.

iii. Management of policies:
   a. Major reform of administration of Chinese retrofit program.
   b. Set up a data oriented framework.
   c. Close supervision/inspection of what actually happens.

iv. Information provision:
   a. Information on financing options.
   b. Pilot studies of electronic controls.

v. Planning guidance:
   a. Provide suitable urbanisation ratios.

Conclusions

The global building sector is a crucial sector when attempting to mitigate the expected impacts of future changes to climate. This report considers the decarbonisation of buildings by 2050 in light of this. Different countries require different considerations. The structure of the building sectors are markedly different in the developed and developing countries, with the OECD countries faced with tackling emissions from existing buildings whilst rapidly expanding economies such as China and India must deal with increasing numbers of buildings. An attempt was made here to concisely surmise the major issues, historical context, and future pathways towards a low-carbon future, but this report does not claim to be comprehensive. Still, a number of discussion points were raised at the workshop and are repeated in outline below.

Recommendations

Overall, if governments are to play a leading role in mitigation attempts, then the buildings sector requires tougher regulation and more effective enforcement and inspection. Building codes and data should be made mandatory, regularly updated, and be performance based where possible. It is vital to have close supervision and inspection of the actual effects of current and future policies. In addition, a retrospective analysis of previous energy efficiency policies for buildings could provide lessons for new policies.

Realism

There are a number of obstacles seemingly in the way of progress which could be categorised as technological, behavioural, or managerial. Whilst these obstacles have been well documented in the literature, it remains a fact that there are few successful policies for setting a real grip on CO_2 emissions of the building sector. This report suggests that the inclusion of innovation theory in policy making could make use of the typical technology trajectories in the building sector. Regardless of the technology or policy in mind, it is fundamental that stakeholders converge on a particular policy and enforce it, measuring the results over time. If this is not completed, there is a danger that academics in this field will become historians.

Optimism

China may lead the way if she can deliver her 12th five year plan aspirations towards an ecological age - but she needs to address rural as well as urban buildings. Nonetheless, the fact that demand side efficiency has been increasingly addressed by politicians and stakeholders since the 1970s gives good hope for the future progress of more effective decarbonisation efforts in the global building sector. There are opportunities in areas such as construction, architecture, and marketing if the building sector is tackled on a large scale. It remains to be seen whether the challenge will be met.

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About this report

On 27th September 2011, Imperial College's Grantham Institute for Climate Change hosted a two-day workshop on the topic of 'The Reduction of Global Carbon Emissions in the Building Sector to 2050'. The International Energy Agency (IEA) were co-organisers. The objective of the workshop was to bring together a group of leading analysts from around the world to review the question of how major carbon reductions in the building sector could be achieved. The results were expected to contribute to both the work of the IEA in preparing Energy Technology Perspectives 2012 and to contribute to a Buildings Sector focused report to be published by the Grantham Institute. This paper is the resulting document, based upon but not limited to the opinions of the workshop participants. The list of presenters and their presentation titles is as follows:

- **Mark Levine** – *Can anything be done to tame energy use in new Chinese buildings, and if so what?*
- **Adam Hawkes** – *Presenting the 6^th^ Grantham Briefing paper on strategic pathways for low carbon residential heating.* (Introduction by **Sir Brian Hoskins**)
- **Bo Diczfalusy** – *The Low Carbon Energy System – how do we get there?*
- **Nathalie Trudeau** – *Energy Technologies Perspective 2010 findings & the way forward to ETP 2012*
- **Yamina Saheb** – *Analysis of buildings energy policies in the IEA countries*
- **Mark Levine** – *Past, Present and Future of Buildings Energy Use in China*
- **Hirohisa Yamada** – *Buildings Sector Analysis and Modelling for India*
- **Ute Collier** – *UK Carbon Budget: opportunities & challenges this brings from a policy perspective*
- **Borong Lin** – *Policy Study for Energy Efficiency and CO2 Reduction for Urban Consumption Sector in China*

- **Robin Wiltshire** – *District energy: local infrastructure, a global perspective*
- **David Fisk** – *Urban density matters – but should it? Tall buildings with big foot prints*
- **James Keirstead** – *Modelling transition in Urban Energy Systems*
- **Runming Yao** –*Use of solar energy in the urban context*
- **Angui Li** – *Standardization design and software development of solar energy utilization for rural villages in China*
- **Tadj Oreszczyn** – *Bridging the Gap Between Modelled and Actual Performance*
- ***S*cott Kelly** – *Do homes that are more energy efficient consume less energy? A structural equation model for England's residential model*
- **Adam Hawkes** – *What are the interdependencies in the energy system that relate to heating, and how should we model them?*

All the presentations are available to download as a zip file.