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Using epidemiological methods in energy and buildings research to achieve carbon emission targets

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ABSTRACT

Energy demand reduction from buildings is widely recognised as a key component of greenhouse gas abatement strategies. As governments shift towards large-scale sectoral interventions, a far more robust research and evidence base is needed to support the development, implementation, and on-going evaluation of energy demand policy.

The shift to a low carbon built environment will require both a step change in the energy performance of buildings alongside more efficient provision of energy services, and an aggressive decarbonisation of the energy used. Yet the prerequisite data of building stocks needed to support this essential shift in energy performance of buildings are not necessarily available or are inaccessible or incomplete. As more information on building energy use is collected through high frequency sensors and building form analytics become more sophisticated, the analysis methods applied to the myriad and diverse sub-sectors of the building stock 'population' need to be commensurate with the heterogeneity of the building stock.

This paper describes and illustrates the basis of the IEA EBC Annex 70: Building Energy Epidemiology, which draws on the health sciences to posit 'energy epidemiology' as a whole-system approach for empirical research that provides a methodological framework for building physicists, engineers, social scientists, and economists to engage in cross-disciplinary studies. It makes the case that the development and application of an epidemiological approach to investigating energy demand can advance understanding of the inter-related factors for policy guidance and evaluation and provide insights on the mechanisms that influence energy demand. The aim of the IEA EBC Annex 70 is to work in an international collaboration to identify user needs around energy demand in buildings and to establish best practice methods and harmonized formats for data collection, analysis and modelling.

To illustrate this process, we present an example from the UK on the application of energy epidemiological methods to building energy performance in the residential sector. The case study investigates the potential effectiveness of the policy and technical measures proposed by the UK Government.

Policy implementation for broad, deep, and urgent reductions in energy demand from the building sector requires a far better understanding of the underlying relationships between people, energy use, buildings and the environment.

1. Introduction

The International Energy Agency (IEA) have argued that a renewed focus on energy efficiency, including the energy performance of buildings, could half the rate of growth in energy demand and effectively buy time – substantially easing the transition to a low-carbon economy [1]. Recently, the Paris Accord set out a global framework for reducing global emissions to a level that would limit warming to 1.5 °C [2], which means for many high-income countries a carbon reduction of greater than 80% by 2050 from 1990 levels. For the built environment, this offers a formidable challenge. Building operation accounts for about a third of both global final energy consumption, with about half of this due to space heating, cooling, and hot water [3]. Many governments have already identified buildings as a key sector to contribute reductions in energy demand and help attain policy objectives for GHG abatement, alongside priorities for energy security and socioeconomic development, of which the potential for decarbonisation may evolve under rapidly changing circumstances [4]. Investment in buildings in OECD countries has increased by 9% between 2014–2015, despite falling natural gas prices of 10%, alongside the introduction of energy efficiency policies that have continued to increase in terms of improved building codes and standards [5]. In the EU-

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27 countries, all new buildings must be 'nearly zero-energy' by the beginning of 2021 [6] with the contribution from existing buildings seen as crucial to achieving the EU target of 80–95% emissions reductions by 2050 [7]. In the US, the most ambitious targets for lowering energy demand have been set at the state level, for example California aims to reduce energy consumption in existing homes by 40% by 2020 [8].

Mitigating climate change by transforming to a low carbon built environment pose pressing challenges for policymakers. Energy demand reduction from buildings is widely recognised as a key component of greenhouse gas abatement strategies. As governments shift towards large-scale sectoral interventions, a far more robust research and evidence base is needed to support the development, implementation, and on-going evaluation of energy demand policy. This shift to a low carbon built environment will require both a step change in the energy performance of buildings alongside more efficient provision of energy services, and an aggressive decarbonisation of the energy used. Yet at the national and regional setting, the prerequisite data of building stocks needed to support this essential shift in energy performance of buildings is often not available or are inaccessible or incomplete (e.g. energy meter data, physical building information, occupant details, etc. . .). There are a number of countries and settings where energy and building stock data is emerging and accessible (e.g. UK National Energy Efficiency Data-Framework, US DOE's Building Energy Performance Database, South Korea's Building Energy Integrated Database, or Sweden's Energy Performance Certificate Database), or where high-quality surveys are a part of the research landscape (e.g. US DOE's or Residential or Commercial Building Energy Surveys). However, as more information on building energy use is collected through high frequency sensors and building form analytics become more sophisticated, the analysis methods applied to the myriad and diverse sub-sectors of the building stock 'population' need to be commensurate with the heterogeneity of the building stock.

Policies focused on energy demand in buildings are developed in a complex environment of crosscutting multi-objective and interacting issues of climate change, prices and affordability, energy supply, market regulation, and health and wellbeing. To date, however, energy policy has not adequately recognised or been able to respond to this complexity, which has meant that policies have failed to deliver or adequately address many of these complex, socio-technical challenges in a timely manner, e.g. the rollback of the UK's building fabric targets in order to support the now defunct zero carbon building target [9,10]. More broadly, this failure is seen in the mismatch of the nationally determined contributions for the Paris Climate Accord and the needed actions to avoid 2 °C global warming [11]. Energy and building policy is focused at the population scale, but current research is largely carried out at the individual unit level (e.g. building, person, household) and small-scale, driven by single discipline perspectives. Beyond policy, the building industry and technology manufacturers create products that are focused at populations (e.g. national building stock, cities, building typologies). These industries rely on population data to understand their market whilst also carrying out technology field trials to determine product potential. However, the limited availability of detailed empirical data on energy demand in buildings makes it difficult to understand the market potential and impact of widely installed technologies. This has meant that deeper insights into problems around energy demand in buildings, their presence and persistence across the population, are severely limited, which in turn undermines effective policy, product development and deployment. As national sustainable development and decarbonisation plans are developed, government, research and commercial organisations will need better empirical data on building stocks to support intervention programmes, modelling exercises and to evaluate past and predict future practices.

2. An empirically-based transformation

The implications of a low-carbon transformation of the building stock have received growing recognition in terms of the scale of the reduction in energy demand proposed, the scope of change applied across diverse building sub-sectors, and the urgency needed to deliver robust outcomes [12,13]. Yet, the current empirical evidence base for understanding energy demand from buildings remains far from commensurate with the need to support robust implementation and evaluation of these policy measures or to suggest further initiatives [14]. For example, most countries and cities do not have accessible a consistent or frequently updated database on empirically measured energy and building performance for a large scale of their building stock, though some countries like those mentioned above remain exceptions. Initiatives such as the US DOE's Standard Energy Efficiency Data Platform (SEED) and the EU's Building Stock Observatory is designed to help address this by providing a standard data management platform [15].

The energy and buildings research community, therefore, faces an extraordinary challenge that requires a concomitant transformation in the culture and practice of the energy and buildings research [12]. It entails moving beyond research questions that just address technical aspects of energy demand to multidisciplinary studies that aim to disentangle the dynamic and interrelated effects of technical, social, lifestyle, economic and environmental factors that influence occupant behaviour and energy demand [16–19]. Instead, the prevailing approach across much of energy demand research is characterised by piecemeal small-scale studies and fragmented discipline-specific methods that struggle to identify emergent phenomena and unintended consequences of interventions in a complex multi-layered system[20]. This has led to a lack of clarity regarding the validity and applicability of predictions from building energy models in terms of their underlying theoretical limitations [21], for instance the degree they account for behavioural change in heating and cooling. As a consequence, the interpretation of research findings suffers in terms of their scope and generalizability to provide clear guidance for policy makers and industry [12]. Predictive models, whether national and sub-sector/population focused, require robust data to characterise the 'baseline' of energy and services demand – otherwise they are at risk of applying future technologies into socio-technical contexts that are not well defined.

Historically relatively little empirical broad scale evidence has been available to guide both strategic and detailed policy development. If we just consider improving the energy performance of residential buildings or dwellings a number of key questions arise, such as:

- What is the empirical distribution of energy demand of buildings across the population, and how heterogeneous is this demand across sub-groups of dwellings and household types? For instance, interventions are unlikely to provide the same reductions in energy demand for different dwelling types or for buildings occupied by different social groups.
- Do building components perform as expected in situ and under varying environmental conditions and over time, and does the source of any discrepancy lie in properties of building materials, poor installation methods, design flaws, or elsewhere? Building-related efficiency interventions often have lifetimes spanning decades and so if not correctly installed or otherwise fail to perform, are likely to prove difficult to rectify subsequently.
- How does the energy demand of sub-groups respond according to changes in external climatic conditions and socioeconomic

factors? With a policy agenda spanning decades, it is essential to understand the buildings sector as a dynamic energy system responding to numerous factors, including energy price, and to demographic and technological change.
- What are the energy savings to be expected from energy performance retrofits and how are these best quantified? To provide detailed guidance, we need to understand the various combinations of measures that are likely to be most effective in resulting in robust reductions in energy demand for specific buildings and households.

At the system level, therefore, rapid and effective implementation of energy efficiency measures across the building stock requires a more comprehensive understanding of energy demand interventions and their consequences – a research imperative that spans building physics and construction management practices to the social sciences and property law. Although the research environment is rapidly evolving, robust empirical evidence for key building performance parameters across sub-sectors of the building stock remains scarce, though there is an emerging evidence base [22,23]. However, as far as we are aware, no population-based longitudinal cohort studies of buildings or occupants are available that provide demand distributions, indoor temperature, or patterns of heating/cooling system operation – all of which are major dynamic determinants of energy demand in dwellings. In the health sciences, this predicament would be akin to addressing the obesity epidemic and its effects on chronic disease while not knowing heterogeneity and trends for key metrics, such as the distribution of weight or waist circumference of population sub-groups.

The paucity of evidence to support or evaluate interventions in the built environment is striking when compared with the health sciences where multidisciplinary teams work with large population based cohort studies, alongside clinical trials, intervention studies and systematic multi-study reviews. The epidemiological approach applied in health research provides a well-established methodological framework for developing a broad empirical evidence base to underpin public policy development and assessment as well as provide insights for social and biological models of health. The current predicament regarding building energy demand is similar to deploying a raft of energy efficiency 'treatments and interventions', without a commensurate investigation into their efficacy and optimal implementation or even their interactions and unintended side effects. Thus, we essentially ask *what would the energy and buildings research landscape look like if building energy demand were treated like a health condition?*

Health epidemiology refers to "*the study of the occurrence and distribution of health-related states or events in specified populations, including the study of the determinants influencing such states, and the application of this knowledge to control health problems*" [24]. With increased life expectancy and the relative decline in the impact of infectious diseases, however, research in epidemiology has increasingly focused on non-communicable diseases and public health issues. For example, obesity is not itself a disease but a strong risk factor for chronic diseases in later life, such as cardiovascular disease [25]. Modern health epidemiology represents an empirically driven and systems approach that provides a framework to add value, rather than displace, the evidence from other research methods.

We suggest that by adapting the approaches of the health sciences, a discipline of *'energy epidemiology'* can provide the innovative and disruptive shift in approach needed to advance multidisciplinary energy and buildings research. The emerging field of energy epidemiology represents a potential way forward and an overhaul of the culture and practice of energy demand research [26].

3. Building energy epidemiology

Building energy epidemiology is the study of energy demand to improve the understanding of variation and causes of difference among the energy-consuming population. It considers the complex interactions between the physical and engineered systems, socio-economic and environmental conditions, and individual interactions and practices of occupants.

Energy epidemiology provides an over-arching approach for all the disciplines involved, where findings from large-scale studies both inform energy policy while providing a context for conventional small-scale studies and information input for predictive models (Fig. 1). This approach can be used to study and describe the mechanisms of energy demand and determinants of conditions that

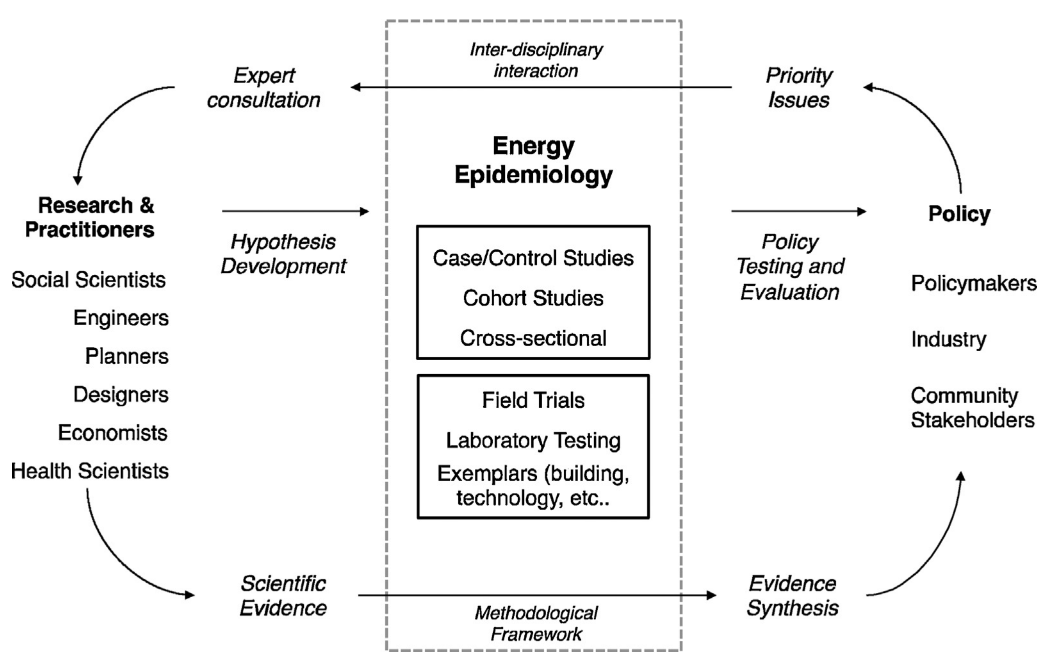

Fig. 1. Energy epidemiology in practice and interaction with policy development and evaluation.

lead to different levels of demand. Energy demand in buildings, like obesity, can be described along a spectrum with a host of interacting factors resulting in a particular defined and measured outcome. While individual features of buildings or consumer practices can highly influence the level of energy demand the combined knowledge and exploration of these key determinants can offer insight into certain types of outcomes, such as the causes of excessive use or underuse of energy for a given population. The core concepts of epidemiology that are applicable to energy demand in buildings include: cases, outcomes, conditions and events; measurement and definition; populations and sampling; change and variation; interventions and control; data collection; risk factors; causal pathways and causality; association; bias and confounding; policy and evaluation. These concepts are applicable to most applied sciences, but rarely use in energy and buildings research.

An energy epidemiology approach will be better suited to dealing with uncertainty through the use of methodological tools and analysis techniques that include: common definitions and metrics, population selection techniques, study designs for data collection, comparison and analysis, approaches to dealing with bias and confounding factors, guidelines for working towards identifying causal relationships, and systematic approaches to reviewing evidence.

The application of epidemiological concepts will provide a means of understanding the distribution and differences of energy demand phenomena among a population. Through the application of a methodological framework that supports these concepts, the drivers and factors that create differences among the population can be identified, examined and better understood. Also, the approach can provide insight into how those drivers and factors can be manipulated to manage and control phenomena in order to improve quality of life and access to energy, and manage the transition to a low- carbon society. Such an approach requires a broader commitment to fund both research and reporting the impact of an investment in improving building energy performance, which is necessary to both meet and verify the decarbonisation of the building stock. Therefore, having a global initiative that addresses the identification and classification of energy and building stock data and modelling and the role these play in decision making towards a low-carbon built environment is an important area for cooperative research.

4. IEA EBC Annex 70: building energy epidemiology

To address the challenges of collecting, describing and using high quality data on energy use and buildings for the purpose informing national development and low carbon pathways, the IEA Energy in Buildings and Communities *Annex 70: Building Energy Epidemiology* focuses on: stakeholder engagement in needs and uses of energy and buildings data; availability, collection methods and structure of building stock data; comparisons of actual and predicted energy performance in buildings; methods of empirical data analysis of populations of energy and buildings; data structures for building stock modelling. Building, energy and environment, building control and construction agencies need better quality data on buildings and their energy performance and energy demands for both forward planning and evaluation of past practices. The developers of energy efficient products need better market information and processes for describing real world impacts of their products on energy demand and performance. Also, building energy labels need to better represent performance in use. Focusing on data, its collection methods and analysis and use in stock modelling exercises, Annex 70 is identifying data gaps and provide stakeholders with resources, i.e. an observatory of data and methods, from which to draw for comparison, modelling and engagement.

The Annex specifically seeks to support decision-makers and investors in their efforts to transform to a low carbon and energy efficient built environment by focusing on developing best practice methods for collecting, accessing, analysing and building models with empirical data of energy demand in buildings and communities. The aim of the Annex is to support member countries (and more widely) in the task of developing realistic transition pathways to substantial and long-term reductions in energy use and carbon emissions associated with their buildings by:

1. Evaluating the scope for using real building energy use data at scale to inform policy making and to support industry in the development of low energy and low carbon solutions;
2. Establishing best practice in the methods used to collect and analyse data related to real building energy use, including building and occupant data; and,
3. Comparing across the national approaches to developing building stock data sets, building stock models, and to addressing the energy performance gap to identify lessons that can be learned and shared.

The Annex comprises three main subtasks (to operate in parallel) and comprise:

(A) Engaging with government, industry and technology manufacturers to identify user requirements for data and information upon which future strategy and policy can be based;
(B) Researching aspects associated with empirical building and energy use data for both the residential and non-residential building stock;
(C) Developing best practice guidance for undertaking surveys and for analysing and reporting building and energy use data; Developing metrics and performing international comparisons of building stocks and their energy use.

The main products of the Annex include: a) a registry on building stock surveys and models (with actual data when appropriate); and b) a series of best practice and information reports on international data, models and methods.

The results will facilitate the use of empirical data in undertaking international energy performance comparisons, policy review exercises, stock modelling and technology and product market assessments and impact analyses. The deliverables will promote the importance and best practices for collecting and reporting energy and building stock data.

5. Applying energy epidemiology: a UK case study of building energy demand

To illustrate the concept of energy epidemiology, we present a case study of energy and building research in the UK. The UK is both illustrative of the current predicament faced in implementing energy demand reduction and renewed interest by government and research councils for a more detailed understanding of factors that affect energy use. The UK Climate Change Act 2008 has set in legislation an overall target to cut GHG emissions by 80% by 2050 from their 1990 levels. The UK's Committee on Climate Change (CCC) has published a coordinated sector-by-sector roadmap for carbon emissions to 2050 [27]. In response, the UK government has released a Carbon Plan that details the various policies and initiatives they intend to undertake to ensure carbon emissions stay on the proposed downward trajectory [28].

For the buildings sector, the CCC has prescribed a 74% decline in carbon emissions (direct and power-related) from 2008 levels by 2030 which includes ~50% reduction for the residential sector [29]. Allowing for decarbonising of electricity generation, we estimate that this equates to ~25% reduction in space heating and hot water demand from the existing residential buildings by 2020 and a 38% decline by 2030. Equivalent reductions are specified across the entire building stock, including commercial and public sector buildings.

5.1. New residential buildings

The CCC carbon budget assumes minimal additional carbon emissions from new residential buildings, buildings, with regulated energy use (i.e. heating, cooling, ventilation and lighting – but excluding non-regulated energy use such as appliances) expected to be 'zero carbon' in the UK by 2016 [30] – though was not been adopted. Building codes or regulations – primarily 'Part L: Conservation of fuel and power'[31] – remains the main policy mechanism for reducing energy demand from new buildings. Over the last two decades, these have become increasingly stringent in their requirements for energy performance for the building shell and heating system, with expected declines based on energy models of 25% (from 2002) and 40% (from 2006) for carbon emissions compared to dwellings built under earlier regulations [32].

Yet a widely acknowledged discrepancy exists across the sectors between the energy demand expected from low-energy buildings at the design stage and measured energy use post-occupancy [33–36]. Numerous and potentially cumulative reasons have been advanced for this mismatch, including non-standard occupancy patterns, design or construction details that lead to unexpected thermal losses, and poor operational controls [33,37]. Few regulatory checks are done on-site to ensure compliance with building regulations, such as systematic testing of thermal performance of the building shell.

A longstanding issue with many studies on new buildings is that they serve to showcase innovative building technologies in exemplar buildings [38]. Subsequent findings based on what is possible for such exemplars are unlikely to provide a representative indication of performance in the shift from demonstration to mass deployment. For instance, often it remains unclear if a reported performance was achieved only after significant supervision and optimisation during construction and operation; interventions that may not occur in large scale deployment.

Research access to measured energy data for comparative research is another critical issue, with stakeholders historically reluctant to reveal disparities in energy performance for a range of perceived professional and legal reasons. Crucially, the recent combination of mandatory Energy Performance Certificates, which indicate the buildings category of energy performance based on modelled performance, with Display Energy Certificates that give an operational rating of energy performance based on actual metered energy consumption, provides an indication of the performance gap at the level of the individual building [6]. For some building sub-sectors, such as higher educational buildings, this information has become available at sufficient scale for researchers to begin to statistically quantify and identify factors associated with the difference between measured and benchmarked energy performance [39].

5.2. Existing buildings

Key to meeting CCC emissions targets over the next decade is reducing the energy demand of existing buildings. Due to low rates of demolition and construction of new homes, existing dwellings will represent 85–90% of the residential stock in 2022, with ~75% (22.4 m) built prior to 1990 [40]. To improve understanding of energy demand in the existing building stock, the UK Government announced in 2009 the National Energy Efficiency Database (NEED) framework, that includes annualised energy usage data from suppliers based on meter readings from all domestic and non-domestic consumers in Great Britain [41,42]. A representative random sample of 3.5 million properties was generated, including more than 2.7 m gas-heated dwellings, and matched as far as possible with a range of data sources for building characteristics and the presence of insulation and other energy efficiency measures.

The UK Government has used NEED to publish descriptive statistics on residential energy use in 2010 [43]. Fig. 2 shows the average energy demand for different dwelling sizes and age of construction categories, which corresponds approximately to historical construction periods and changes in energy efficiency related building regulations since the early 1970's. Focussing on larger dwellings (more than 50 m^2), where building regulations would be expected to have the greater impact on reducing energy demand, the results show that a general pattern is evident of newer dwellings having lower energy demand than older dwellings of equivalent size, with the newest ones having the least energy demand, though not by as much as is expected from building energy models; dwellings the 1919–1944 category had the highest consumption, rather than those in the oldest category (pre-1919). Also, that energy demand increased with floor area, though again improvements in the building shell and heating systems in the post-1999 dwellings would be expected to result in a markedly lower gradient, which is not the case. This general pattern of some types of older 'energy inefficient' buildings using less energy than expected while relatively recent 'energy efficient' dwellings have higher than predicted by building energy models is evident in international studies [44].

Although this energy in buildings 'problem' among the population is identified from national data, the question remains for how to manage the problem and what approach should be used to predict the impact of any intervention?

5.3. Energy savings from boiler replacement intervention

Improvements to heating systems have been identified as a major source of energy savings in home heating in the UK houses[45] for which boilers in gas central heating systems make up 96% of all heat systems [40]. The estimated efficiency of all UK residential boilers is 75% [40], standard non-(i.e. non-condensing) boilers operate at approximately 65% efficiency, while new condensing boilers may achieve around 90% efficiency, offering 15–25% in theoretical savings. Under the 2008–2020 pathways, the CCC propose that 13 Million condensing boilers are installed as part of the residential sectors emission reduction plans. Major energy efficiencies could be realised if predicted savings were achieved.

Since 2005, the UK has been mandating the installation of condensing boilers, which substantially improve thermal efficiency compared to conventional gas boilers via heat recovery through condensing the water vapour in combustion exhaust fumes. Installation rates have run at around 1.1-1.3 million units per year since 2005, consistent with rates expected from stock replacement. Under the CCC's 'Extended Ambition' scenario this rate of condensing boiler installation (~1.1 M/yr) is expected to continue to 2020. It is known from small scale field trials that condensing boilers perform about 5% below that expected from efficiency ratings, though at ~85% this is still well above the estimated average heating system efficiency in the UK of 70% [40], while the CCC cite efficiencies of up to 90% in their estimates for condensing boilers [27].

What impact might these boilers have on energy demand when applied to the broader population? The energy epidemiological objective is to describe the change in gas demand following a condensing boiler replacement compared to an equivalent sample of homes with no boiler replacements and to determine factors associated with high rates of change.

Using components of the NEED database, which contains information on dwelling characteristics including the range of energy efficiency measures installed in the UK since 2005 [46], a random

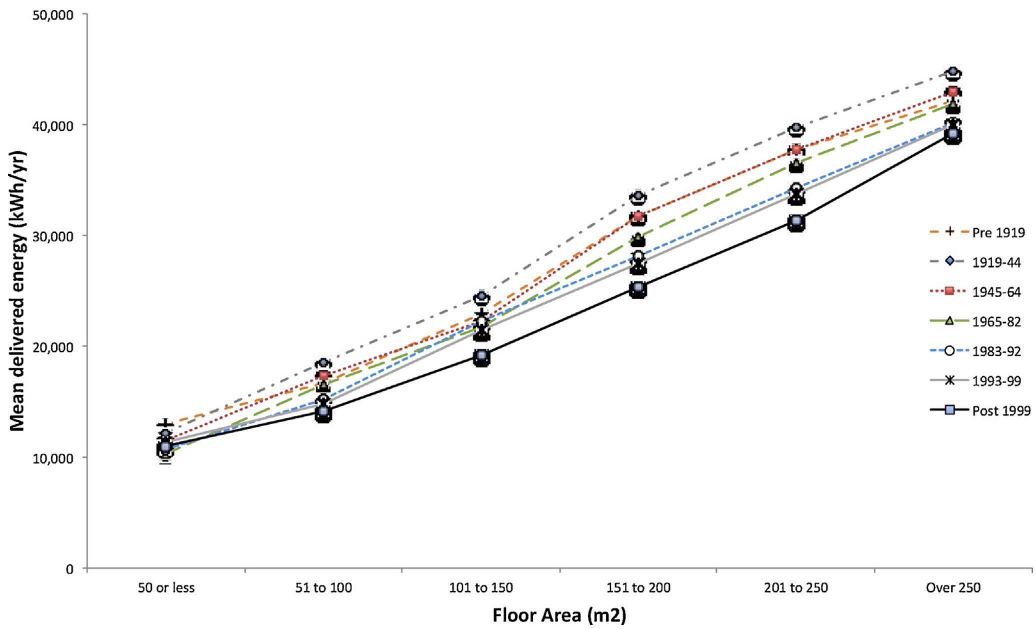

Fig. 2. Average 2010 energy demand from gas-heated dwellings in the NEED sample, by floor area and age category [43].

Table 1
Annual gas consumption per dwelling from 2005 to 2007 by quartile based on a sample of representative British dwellings (N = 50,000) from NEED.

	Label	Mean (SD)	Lower Quartile	Median	Upper Quartile
Gas consumption (kWh/yr)	2005	19,088 (9781)	12,660	17,647	23,605
	2007	17,327 (9248)	11,247	15,881	21,559
% change 2005–2007		−9%	−5%	−11%	−10%

Table 2
Rate of change in gas consumption per dwelling from 2005 to 2007 by quartile with the prevalence of condensing boilers by quartile of decline in gas consumption.

	Label	Mean	Lower Quartile	Median	Upper Quartile
Rate of change in gas consumption (%)	2005 to 2007	−7%	−20%	−8%	3%
Dwellings with condensing boilers (%)	2005	19%	23%	19%	16%
	2007	38%	45%	32%	25%

sample (N = 50,000 dwellings) was drawn so as to be representative of the UK stock in 2005 in terms of key characteristics of dwelling type, size, age, region, and wall type as well as occupant tenure. The data were then analysed to determine levels of gas consumption and its change from 2005 to 2007. The proportion of those dwellings with condensing boilers was determined for each quartile of change in gas consumption over the study period. Then, to identify the effect of condensing boilers alone, a case-control study was undertaken using a random selection of dwellings (N = 3615) that had a condensing boiler installed in 2006 but no other interventions over the study period. These were matched one to four by a control group (N = 14,560) on the basis of region, occupant tenure and dwelling type, size, age, wall type.

Change in gas consumption were compared by quartiles for each group and a logistic regression was used to determine the odds ratios of dwellings with condensing boiler installation in 2006 of achieving a relative decline in gas consumption equal or better than the upper quartile group identified in the first analysis between 2005 and 2007, compared with dwellings without a condensing boiler.

The analysis shows that the mean annual residential gas consumption was 19.1 MWh/yr in 2005 (Table 1) with a mean decline of 9% from 2005 to 2007, with both figures similar to those obtained from national consumption statistics of 18.8 MWh/yr and 11% decline respectively [47]. The distribution of gas consumption is skewed towards high consumption dwellings, reflected in a median consumption of 17.6 MWh/yr in 2005. When looking at the rate of change between 2005–2007 (Table 2), for the quartile of dwellings with the largest decline in gas demand (-20%), the proportion with condensing boilers almost doubled to 45%, compared with just one in four dwellings (25%) with a condensing boiler by 2007 in the quartile with the least decline – in fact this group had a small increase in gas consumption of 3% over the study period.

Findings from the case-control study (Table 3) indicate that for all quartiles of consumption, the decline for condensing boiler group is larger than for the control and is also evident in the shift in distributions for gas consumption given in Fig. 3. The mean decline in gas demand for dwellings with a condensing boiler was by 16% from 19.4 MWh/yr. The difference in the percentage decline between the case and control groups increased across quartiles of gas demand from 15% and 10% respectively in the lowest quartile of consumption to 17% and 10% respectively in the upper quartile. Moreover, these dwellings with just condensing boilers installed in 2006, 40% reported a decline in gas consumption equal to or greater than the upper quartile of decline seen in the representative sample above (≥20%), compared with only 16% of dwellings in the control group. Thus, those with a condensing boiler were more than twice as likely to attain UK upper quartile savings or better (odds ratio 2.6; 95%CI 2.4–2.8).

This brief analysis is meant to illustrate how an epidemiological approach would begin a process of investigating the effect of an intervention in buildings on energy demand more widely among

Table 3
Annual gas consumption per dwelling from 2005 to 2007 by study group (case = condensing boiler in 2006, control = no boiler upgrade).

Intervention Group		Gas Consumption (kWh/yr)				
		N	Mean (SD)	Lower Quartile	Median	Upper Quartile
Case	2005	3615	19,402 (10,462	12,524	17,631	23,772
	2007		16,308 (9147)	10,606	14,753	19,763
% change 2005–2007			−16%	−15%	−16%	−17%
Control	2005	14,560	19,431 (9453)	13,117	17,950	23,869
	2007		17,917 (9112)	11,811	16,426	22,183
% change 2005–2007			−8%	−10%	−8%	−7%

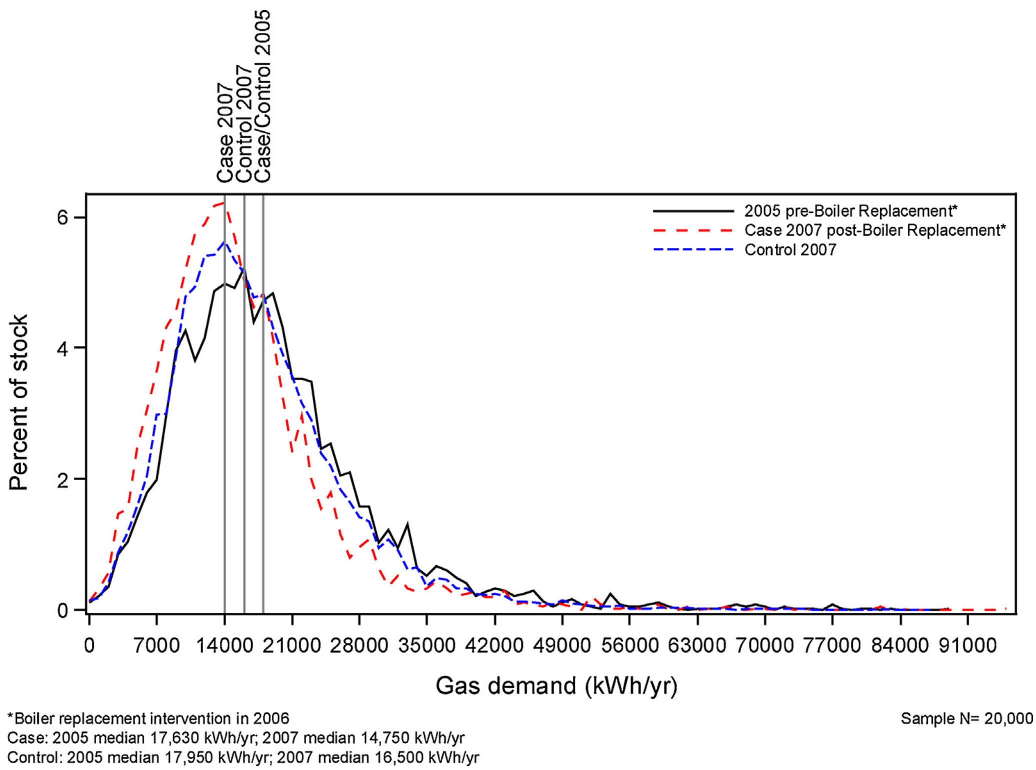

Fig. 3. Distribution of gas consumption in 2005 compared with 2007 for dwellings with a condensing boiler installed in 2006 (N = 5000) and the control group (i.e. no boiler replacement) (N = 15,000).

the housing stock population and how the 'intervention model' can inform future programmes by identifying the attributable effect of boilers. Other studies have examined the effect of combinations of retrofits in the general UK housing stock [22].

6. Discussion

6.1. Energy epidemiology as a multidisciplinary way forward

Central to the objectives of the IEA EBC Annex 70 is that the guidance needed to support energy demand policies requires a shift to multidisciplinary research and a systems approach to disentangle the dynamic and interrelated effects of technical, social, lifestyle, economic and environmental factors that influence occupant behaviour and energy demand [12,16,18]. Essentially, we suggest a way forward is to reframe the standard modus operandi of much energy and buildings research and instead ask: what would the research landscape look like if building energy demand were treated like an adverse health condition in the population?

The implication of an energy epidemiological approach for energy and building stock modelling is to improve both the data foundation that underpins the characterisation of the building stock and also the evidence base of the specific mechanisms that underpin many of the physics-engineering model parameters. Building energy stock models often suffer from a lack of population data, meaning that the heterogeneity of the actual stock is reduced into archetype forms or selected representative samples [20,48]. The other challenge for stock modelling is that many of the systemic conditions (e.g. faults or system operations) are unknown to the modelling, requiring assumptions on the factors that drive the energy modelling gap. It is understood that these implications have occurred due to a range of challenges around lack of funding for measurement and emergence of high-powered computing [26]. However, these conditions undermine stock modelling validity and put negative pressure on whether buildings can actually achieve higher levels energy performance in situ. Work by Galvin et al. also illustrate how a lack of robust data and evidence results in a systemic problem for evaluating energy savings [44].

Related to the issues of stock modelling are methods for including a broader range of socio technical and practice-based research findings on energy use and buildings. Energy demand research uses many different methods that are largely drawn from the disciplines within which any given energy-related issue is being studied. From an energy epidemiology perspective, these include: end-use energy processes and systems (i.e. engineering and physical sciences), end-use energy practices (i.e. socio-behavioural interactions) and the end-use energy context (i.e. structure and conditions of systems and practices). The epidemiological model (or 'population level end-use' model) focuses on describing and explaining end-use energy demand patterns and using this information to develop policies and programmes to address problems or modify physical and institutional structures to effect change. It relies on the insights provided by the other research to inform the development of the interacting pathways or identify putative factors that might affect the outcome of interest.

This over-arching structured approach alongside systematic collection of performance measures contrasts with the *ad hoc*, small-scale, and discipline specific studies, that characterise much of energy demand research and which greatly limit the extent that a detailed consensus can be formed from a comprehensive assessment of evidence. A recently published Cochrane Review, which reflects the increasing interest by health researchers in the role of built environment, has examined the impact of housing improvements – much of it related to energy and thermal performance – on health and socio-economic outcomes [49]. It commented on the variability of the research designs and study methods used and concluded that many of the studies were not of sufficient standard for inclusion in the meta-analysis and were subject to a high risk of bias affecting the results.

In response to these societal, policy, and scientific challenges, we suggest that by adapting the approaches of the health sciences, a new discipline of *'energy epidemiology'* can provide the disruptive shift in approach needed to advance energy and buildings research [26]. Some key characteristics of this new discipline have already emerged as an over-arching approach to guide building and occupant related energy research:

- Energy epidemiology provides a framework for multidisciplinary research that represents 'neutral territory' for diverse perspectives ranging from engineering and building physics, to sociology and economics, that to date have had limited collaborative success.
- The formal establishment of research methods and protocols, for instance in dealing with sampling, measurement error, and missing values, or even measurement of building parameters. This is supported by on-going systematic synthesis and evaluation of evidence identifying best research practice.
- Using the results of comprehensive population level studies to place finding from laboratory testing, technical analysis, and small scale studies in appropriate context at building stock level, and providing insights for potential mechanisms or identifying areas needing further detailed investigation.
- Findings are focused on reducing risk of adverse outcomes over the long term, not simply identifying the technical performance of buildings for its own sake, but an emphasis on research translation and knowledge synthesis that can usefully guide policymakers and others in terms of the most effective type, timing, and targeting of initiatives in a dynamic environment.

While some of these approaches and initiatives may have been attempted in energy demand research in the past, energy epidemiology provides an opportunity for a more comprehensive and coherent approach. Rapid systemic change in end-use energy demand lies is inevitably a complicated process of individual and societal adjustment. Critically we need to move beyond simple descriptive statistics as the metrics of choice, such as the average reduction in energy demand or carbon saved from some specified energy efficiency measure; instead we need a more sophisticated understanding of what combinations of social, technical, and other factors are operating to undermine savings in the quartile of buildings with the worst energy performance and equally what explains the delivery of robust performance gains in the best quartile.

Table 4
Rate of change in gas consumption per dwelling from 2005 to 2007 by study group (case = condensing boiler in 2006, control = no boiler upgrade).

Intervention Group	Rate of change in gas consumption (%)			
	Mean	Lower Quartile	Median	Upper Quartile
Case	−13%	−29%	−15%	−1%
Control	−6%	−17%	−7%	3%

Adapting the epidemiological approach to end-use energy demand studies provides the means to describe the trends and patterns of demand and begin to establish causal factors that lead to outcome events. It also provides the means to undertake and contextualise more complex intervention studies among real world applications. The benefits of such an approach will be to strengthen the empirical foundation from which evidence is drawn to inform policy decisions and evaluate past intervention programmes or regulatory actions while also acknowledging the complex environment within which the studies occur (Table 4).

7. Conclusions

The transformation to a low energy economy over the next decades poses a fundamental challenge for applied energy research. Policy implementation for broad, deep, and urgent reductions in energy demand from the building sector requires a far better understanding of the underlying relationships between people, energy use, buildings and the environment. Energy epidemiology adapts an existing research framework from the health sciences to encourage co-ordinated multidisciplinary research and the use of empirical data collection from population based studies. By learning from the health sciences approach to public health, energy epidemiology holds the promise of providing the timely and detailed evidence needed to guide the development and targeting of effective technologies, building practices, and behavioural strategies.

The results of Annex 70 will facilitate the use of empirical data in undertaking international energy performance comparisons, policy review exercises, national stock modelling and technology and product market assessments and impact analyses. The deliverables will promote the importance and best practices for collecting and reporting energy and building stock data.

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Appendix A. Subtask activites.

Subtask A – User Engagement
Activity A.1. Identify energy and buildings stock data users (government, academia, industry, NGO) who are relevant to the collection, creation, access and use of energy and buildings stock data. Develop and pilot a survey instrument that is able to capture current uses/needs, strengths and weakness of current practice and use of energy and buildings data.
Activity A.2. Create a conceptual framework for the survey results to evaluate and review stakeholders' needs for energy and buildings stock data. Administer the surveys to identified groups using the framework to establish current uses/needs, strengths and weakness of current practice and use of energy and buildings data. Exploratory interviews with a selection of users for further description of their data uses and needs to inform the use cases.
Activity A.3. Report on lessons learned from stakeholder engagement on the needs of energy and buildings stock data and recommendations for future engagement. Reporting will include best practice recommendations from users on data collection, reporting and access methods. The reporting will also include Use Cases that can help meet user needs on: e.g. energy and buildings data for scenario planning in respect of building retrofit programmes, deployment of renewable energy and district energy systems, and changing social practices.
Subtask B – Data Access and Methods
Activity B.1. Develop a classification for energy and building stock data for use within the data survey and evaluation Activity (B2) in response to user needs (A2)
Activity B.2. Create a registry of energy and building stock data. Undertake a survey of building data and related energy data. The survey will identify building stock and relevant occupant data, both national and sub-national surveys and field trials in the participating countries (and beyond where feasible). The data will be reviewed and evaluated using the structure defined in Activity B.1. The findings will be recorded in the registry of datasets.
Activity B.3. From the identified datasets, review methods for data collection, processing and reporting of national building stocks and energy use and field trials including: collection techniques, data sources, applicable standards, access and reporting mechanisms. Investigate innovative methods for data aggregation that deal with single building data privacy and disaggregation which distinguishes different end-use and end-users in the energy use data.
Activity B.4. Linked to B3, review data reporting processes and access mechanisms of identified energy and building stock data. Identify and report on best practices on data access, harmonisation, anonymization and approaches for addressing privacy associated with energy and building stocks data.
Activity B.5. Produce a schema for energy and building stock data for developing and emerging economies. Using the review of existing datasets and IEA data methods and best practices, create a data template for reporting energy and buildings stock data.
Subtask C – Building stock modelling and analysis
Activity C.1. (A) Review, develop a classification system of models covering: e.g. methods and outputs, uncertainty etc. . .; (B) Apply classification to construct a register of available national/sub-national energy and building stock models.
Activity C.2. Undertake an international exercise to identify building stock model validity testing, uncertainty analyses, and stock level distribution outputs. Define and apply a common activity to compare and contrast validity, uncertainty and outputs of the stock models undertaken by the group and describe the findings. The activity will draw on and aim to address the user's needs identified in Activity A2. The activity will comprise defining energy and buildings stock model validation processes by examining available existing models and validation techniques. Best practice on data and tests will be defined.
Activity C.3. Draw together the results of the energy and building stock model validation, uncertainty and output exercises and report findings. Develop recommendations for best practice in the development, use and reporting of different types of building stock models which clearly identifies the strengths and weaknesses, uncertainty, fitness for purpose.
Activity C.4. Develop a limited set of high level defined energy and building performance metrics for stock models to enable the comparison between countries, such as normalised energy annual use intensity values for distinct segments of the building stock.

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