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Energy epidemiology: a new approach to end-use energy demand research

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The call for action to transform the built environment and address the threats of climate change has been clearly made. However, to support the development, implementation and on-going evaluation of energy demand policy, a strong evidence base is needed to identify associations and establish underlying causes behind outcomes and variations in end-use energy demand within the population. A new approach to end-use energy demand research is presented which is founded on the interdisciplinary health sciences research framework of epidemiology, along with the establishment of a research centre. A case is made that through an 'energy epidemiology' approach a strong, population-level, empirically based research foundation can be advanced. Energy epidemiology is a whole-system approach that focuses on empirical research and provides a methodological framework for building physicists, engineers, sociologists and economists to engage in interdisciplinary work. The adaptation of the epidemiological approach to end-use energy demand studies will provide the means to observe and describe the trends and patterns of energy demand, to undertake and contextualize interventional studies, and to establish strong associations between factors that lead to an energy demand-related outcome or event. Such an approach would strengthen the evidence base to inform policy decisions and evaluate past intervention programmes or regulatory actions.

Keywords: buildings, built environment, energy demand, epidemiology, evidence base, interdisciplinary, public policy, research

Il a été clairement lancé un appel pour mettre en place des mesures propres à transformer le cadre bâti et à faire face aux menaces du changement climatique. Néanmoins, pour soutenir l'élaboration, la mise en œuvre et l'évaluation en continu de la politique relative à la demande énergétique, il est nécessaire de disposer d'une solide base de données factuelle pour identifier les associations et établir les causes sous-jacentes des résultats et des variations de la demande énergétique des utilisateurs finals au sein de la population. Il est présenté une nouvelle approche pour l'étude de la demande énergétique des utilisateurs finals, qui est fondée sur le cadre interdisciplinaire de l'épidémiologie utilisé pour les recherches dans les sciences de la santé, ainsi que sur l'établissement d'un centre de recherche. Il est fait valoir que, par une approche basée sur une « épidémiologie de l'énergie », il est possible de faire progresser la fondation d'une recherche empirique solide au niveau de la population. L'épidémiologie de l'énergie est une approche systémique globale qui est axée sur la recherche empirique et fournit un cadre méthodologique aux physiciens, ingénieurs, sociologues et économistes du bâtiment afin qu'ils participent à des travaux interdisciplinaires. L'adaptation de l'approche épidémiologique aux études relatives à la demande énergétique des utilisateurs finals donnera les moyens d'observer et de décrire les tendances et les schémas de la demande énergétique, d'entreprendre et de contextualiser des études interventionnelles, et d'établir les associations fortes entre les facteurs qui conduisent à un résultat ou à un événement lié à la demande énergétique. Une telle approche renforcerait la base de données factuelle afin d'éclairer les décisions en matière de politique et d'évaluer les programmes d'intervention passés ou les mesures réglementaires prises.

Mots clés: bâtiments, cadre bâti, demande énergétique, épidémiologie, base factuelle, interdisciplinaire, politique publique, recherche

Introduction

Over the past decade, across the world, there has been a resounding call for action to improve end-use energy efficiency and reduce energy demand. Such changes are predicated on the need to address a host of issues, from global climate change and national-level greenhouse gases (GHGs) abatement targets, energy security and price stability, economic productivity and consumer access, to health and well-being. However, to achieve targets, deploy appropriate technologies and change the practices related to end-use energy demand, the call for action needs an equally strong foundation of evidence-based policies and strategies, a call that has been made frequently in recent years (Lomas, 2009; Lowe & Oreszczyn, 2008; Oreszczyn & Lowe, 2010; Skea, 2012; Sorrell, 2007a). This evidence should be based upon relevant research that is properly designed, conducted, interpreted and presented; making sense of the complex, diverse and contextually driven nature of energy demand frequently requires an interdisciplinary approach to research.

This paper describes how the newly funded Research Council UK Centre for Energy Epidemiology (CEE) will provide a multidisciplinary environment for undertaking interdisciplinary projects, and thus begin to address the gap in the evidence needed to support policy development and direct change. In doing so, CEE will address the challenge of defining and supporting an interdisciplinary research culture for end-use energy demand. The approach used in health sciences research, in particular epidemiology, offers a relevant and compelling framework for undertaking research in end-use energy demand. The lessons to be learned from health sciences research are discussed for developing both the practical requirements of interdisciplinary research on the complex and diverse nature of end-use energy demand, including data sharing, ethical standards and protocols for evaluation and development of the needed evidence base. The energy epidemiology approach is outlined and an example is provided of how it can be employed to address problems in energy demand research. Finally, consideration is given to how CEE and the energy epidemiology approach can respond to the future challenges of providing high-quality evidence for decision-making and developing policy, along with the benefits to researchers and policy-makers of using such an approach.

Call for action

Whether for economic or security reasons, concerns for quality of life or meeting abatement targets, energy demand and energy efficiency in buildings are high on the international agenda (Jollands *et al.*, 2010). Energy used in buildings is estimated to account for approximately 30% of both total final energy use and global anthropogenic GHG emissions, with this proportion increasing to between 40% and 50% in most developed countries (International Energy Agency (IEA), 2008, 2011; Pérez-Lombard, Ortiz, & Pout, 2008). Many governments have identified this sector as a key contributor to national and regional policy objectives for GHG abatement and have developed policies that aim to improve the building stock over the medium term (California Public Utilities Commission (CPUC), 2008; Dixon, McGowan, Onysko, & Scheer, 2010; European Commission, 2010, 2011a; Lutsey & Sperling, 2008). These policy agendas for the coming decades will see a substantial investment of economic resources in technologies and techniques to improve energy efficiency in buildings and change demand behaviour (Department of Energy and Climate Change (DECC), 2010; European Commission, 2011b; Lahidji, Michalski, & Stevens, 1999, p. 159; Sagar & Holdren, 2002; United Nations Environment Programme (UNEP), 2011). This period will also mark other determining changes, such as a shift in the demographics of many countries, changes in living standards, emerging technologies, changes in global markets, and changes in climate that will all have a significant effect on fuel sources and the demand for energy.

The call for action to transform the built environment and respond to the threat of climate change, its scale, scope and urgency has been clearly made and the reasoning behind such action is sound (European Commission, 2011b; Metz, Davidson, Bosch, Dave, & Meyer, 2007; Stern, 2007). What remains is the development of plans and strategies that are able to direct effort and resources to achieve these changes in the most effective manner, while building support for both their investment and expansion across multiple sectors of the built environment. Yet to date, policy-makers have neither had, nor in many cases sought, empirical evidence for the impact of policies (Lowe, 2007). Although the buildings sector may represent one of the largest opportunities for potential CO_2 emission reductions (UNEP, 2007), the ability to achieve these reductions is limited by knowledge gaps at multiple levels. Of course, end-use energy demand is not limited to buildings, but for the purposes of this paper the issues are explored in relation to energy demand research in the built environment, focusing on buildings.

Call for evidence

As many governments move towards implementing large-scale energy-related intervention programmes, a far more comprehensive evidence base is needed to support the development, implementation and ongoing evaluation of energy demand policy (Clery, 2007; Oreszczyn & Lowe, 2010; Skea, 2012; UK Committee on Climate Change (UK CCC), 2010, p. 375;

Whitesides & Crabtree, 2007; Wilkinson, Smith, Beevers, Tonne, & Oreszczyn, 2007). Delivering such a transformation in the way energy is used in buildings will require a deeper level of understanding of the underlying relationships between energy use and socio-cultural practices, engineered systems, physical processes and environment so that effective technologies, practices, and behavioural changes can be adopted and supported through evolving policies (Dietz, 2010; UNEP, 2007, 2011). Appraising evidence and providing feedback to policy-makers on the evolution of applied policies, while addressing the complex, contextual environment will help to identify the key determinants of successful interventions and policy mechanisms and also the degree to which unsuccessful policies were the result of poor delivery and/or flawed measures and controls (Lowe & Oreszczyn, 2008; Rychetnik, Frommer, Hawe, & Shiell, 2002; Skea, 2012; Sorrell, 2007a).

Moving beyond purely technical approaches, this requires empirical data from cross-disciplinary studies analysed within a common research framework able to disentangle the dynamic and interrelated effects of environmental, socio-cultural, lifestyle, and economic factors that influence occupant practices and energy demand (Attari, DeKay, Davidson, & Bruine de Bruin, 2010; Dietz, 2010; Sorrell, 2007b; Wilhite, Shove, Lutzenhiser, & Kempton, 2000). The current paucity of evidence to support or evaluate interventions that seek to alter energy demand is striking when compared with, for example, health research where findings from large interdisciplinary cohort studies, alongside clinical trials and intervention and other studies, underpin public policy development and assessment and provide insights for further progress of theory and medical and public health practices (Brownson, Chriqui, & Stamatakis, 2009; Pearson, Jordan, & Munn, 2012; Silva & Fraga, 2012).

In contrast, energy demand research in the built environment remains characterized by piecemeal studies and fragmented discipline-specific methods and perspectives that can limit, rather than expand, the broader relevance of findings (Lowe & Oreszczyn, 2008; Whitesides & Crabtree, 2007). Overall, theoretical understanding of social and technical factors that influence energy demand remains underdeveloped (Schweber & Leiringer, 2012). The prevailing approach struggles to identify associations and establish underlying causes behind outcomes and variations in energy demand seen within a population. As an example, although there has been some decline in average UK household delivered energy in recent years (DECC, 2012a), it remains unclear the extent that this is attributable to improvements in building fabric and energy systems, occupant behaviour in response to increases in energy prices, the global financial crisis and other factors.

The sheer scale of interventions being proposed to reduce building-related energy demand requires an approach that is capable of dealing with population-level observations and interventions, while supporting and learning from other disciplines and strands of work, including field and case studies. The evidence base must be capable of supporting the development and application of well-targeted abatement measures that identify critical areas for investment and transformation while also being able to evaluate historic efficiency programmes and activities.

Given the importance of the building sector in providing CO_2 savings and the pressing need to deliver energy savings through well-targeted and economically feasible interventions, the funding levels associated with energy efficiency have historically been low (Whitesides & Crabtree, 2007). For example, in the United Kingdom the total annual investment (adjusted for inflation to 2012[1]) in energy research in 1974 was £9.7 billion ($£_{1974}$1.15 billion), of which energy demand accounted for approximately 5% or £485 million ($£_{1974}$50 million) (UK Energy Research Centre (UKERC), 2013). The annual funding in energy demand research rose to almost £970 million per year by 1983 ($£_{1983}$100 million), before falling to less than £8 million per year ($£_{1994}$1 million) by 1994 (UKERC, 2013). This steep decline in public research investment followed the deregulation of the energy markets in the early 1990s. Beginning in the early 2000s, the RCUK investment in end-use energy demand was approximately £5.3 million per year ($£_{2000}$1 million) and had increased gradually to around £25 million per year by 2011 (Research Councils UK (RCUK), 2010, p.28) along with a further £1.6 million per year from the Energy Technology Institute (ETI) since 2007 (ETI, 2012). This increase in funding coincided with many national and international climate abatement policy activities. The recent investment by the UK research councils of approximately £39 million over five years (or £7.8 million per year) for end-use energy demand research helps to maintain the commitment to fund energy demand research, along with several other sources of funding (*e.g.* other Engineering and Physical Sciences Research Council (EPSRC) sources, ETI, the Technology Strategy Board, and unreported private investment from energy suppliers, industry, etc.), to assist in the development of a much needed evidence base. Government funding in energy demand research, however, is approximately 12% of the RCUK's investment under the energy programme portfolio in 2011–2012.

This paper addresses the predicament for the energy research community of lagging behind the evolving policy agenda, and in a number of cases, practice, to reduce energy demand from the built environment. The existing approach to studying technologies, socio-cultural practices, and the deployment of technologies and other interventions in the field, limits both the generalizability of findings, and the range of challenges to which existing models and theories and can be subjected. It leaves policymakers and other stakeholders flying blind (Bordass, 2001), and limits the ability to achieve effective change. As set out above, many of the problems or limitations faced reflect the underlying disconnect between the different disciplines involved, from engineering and building physics to social sciences, economics and health. A host of factors, such as the low prioritization for funding and limited empirical data (Gupta & Gregg, 2012; Kelly, 2009; Schweber & Leiringer, 2012; Skea, 2012), has led to an overreliance on models that are often poorly informed or outdated (Lowe, 2007; Laurent *et al.*, 2013). Overall, this has meant that a methodological framework that captures the complex interactions between people, energy and the built environment is only just beginning to emerge from within the field.

A multidisciplinary environment for interdisciplinary outcomes

In response to the call for action and the need for evidence, the EPSRC has funded five end-use energy demand research centres that will undertake research to support energy demand and efficiency policy. Each of the research centres focuses on a particular theme through a multidisciplinary approach, including ‘Big Data’, ‘Food’, ‘Materials Use’, ‘Practices’ and ‘Technological Transitions’. At a national level, these centres will represent the bulk of funding in end-use energy demand (RCUK, 2010).

To assist the transition in the energy demand and buildings landscape the RCUK Centre in Energy Epidemiology (CEE) at University College London (UCL) (under the ‘Big Data’ theme) is seeking to address the issues around the need for more empirical data on a broader measure of factors related to energy demand. Through its interdisciplinary organization, the CEE has set out to undertake a transformative research programme based on four mutually supportive work streams:

- measurement of the real world (*i.e.* metrology)
- a data framework to link and archive data monitored in the real world
- the application of novel techniques to support analysis and interpretation of the data based on an epidemiological approach, which in turn supports
- the development of innovative models

CEE’s unique approach to the study of end-use energy demand is being informed by health sciences’ research, which has a long experience of dealing with complex problems and bringing together evidence from a host of disciplines (*e.g.* clinical, biochemical, genetic, epidemiology and socio-behavioural).

Unlike energy demand, there are a number of bodies and organizations that undertake epidemiological health studies with many focusing on a select set of issues with the primary aim of designing, conducting, interpreting, and presenting relevant and timely research. For example, the UK Medical Research Council (MRC) funds seven epidemiology-related institutes, units and centres that are mandated with:

> adopting broad multidisciplinary approaches to address major challenges in health-related research often requiring ground breaking methodology and technology development.
>
> (MRC, 2013)

These institutions are governed by the MRC’s ethics and research guidance, including detailed plans on undertaking trials, data sharing, ethical standards and public participation, open access publishing, to protocols for emergency situations. Another international health research organization is the Cochrane Collaboration, a network of researchers along with 17 global centres that adheres to a strict set of protocols when undertaking evaluations for the purpose of providing evidence-based healthcare (Cochrane Collaboration, 2013; Higgins & Green, 2011). Two essential features of these organizations is the clarity of the standards and regulations that have been established to govern and guide the research taking place while identifying the need for multiple disciplines to address the complex issues related to health. Without a rigorous standard or operating process, the outputs of research activities may be critically faulted and judged as being unable to support an evidence base. For instance, a recently published Cochrane Review on improvements to houses and the impact on health and socio-economic outcomes found that many of the studies were not sufficient for meta-analysis due to the variability in the research designs, study methods and were subject to a high risk of bias affecting the results (Thomson, Thomas, Sellstrom, & Petticrew, 2013). An implication of the issues raised around the quality of the studies reviewed was that the evidence base was undermined by the inconsistent or inadequate methodology and analysis techniques, leading to a risk that the evidence would be unable to support conclusions or inform effective policy development.

Challenges for CEE

There are numerous challenges facing CEE, in terms of both the ability to achieve and the share access to ‘big data’ along with the interdisciplinary approach being advocated. Perceptions and practices of disciplines can be barriers to interdisciplinary research. The need for a strong (independent) methodological framework, along with definitions and detailed and consistent studies can help to encourage a sense of collective understanding and foster an environment of interaction.

The absence or limited access to high-quality people and buildings' data and high-resolution energy data of the statistical and methodological quality that other disciplines would consider a prerequisite for the pursuit of good science and robust conclusions is a major challenge. Along with this, limited research capacity currently exists to organize or archive data, despite significant sums of money invested to collect data through individual projects. It will be essential that research data are captured along with detailed meta-data allowing for use by other researchers and held in a suitably accessible repository for future analysis and connection. Without this detailed and comprehensive data collection there is little basis for systematic reviews of research findings to support project-by-project learning, the result of which has been that observational data studies have had a limited impact on the policy process.

Alongside the problems of data, coherent analytical methods have yet to be refined and applied. The need to build an interdisciplinary culture capable of illuminating the complex co-evolution of practices and infrastructure that ultimately drive energy demand is a major task both for CEE and the rest of the UK research community. The theoretically parsimonious approach of epidemiology and its pragmatic approach to data and method, in principle allows a wide range of disciplines both to take part in its application, and to draw on the insights that it provides. Large scale, longitudinal and inter-cultural studies are routine in health epidemiology. They demand a scale and duration of organization that is capable of transforming the current research culture in energy demand studies, in which small, transient teams of researchers have historically undertaken the bulk of the work. The need to harmonize and document techniques and protocols for data gathering, handling and analysis, and the expectation that any given piece of work will form part of a cumulative and intergenerational programme of research, will place much greater emphasis on communication within the research community and on documentation and archiving of research. CEE is in a position to play a catalytic role in all of these processes.

The most immediate challenge facing all researchers focused on energy demand is the need to provide results at a rate which is probably an order of magnitude faster than has been the case in the previous three decades, due to the pressing need to meet steeply falling CO_2 budgets. Increasing collection of, and access to, high-quality data and information along with the use of sound methodological and analysis frameworks will allow for these immediate challenges to be met at the same time as laying the basis for inter-decadal comparisons and evaluation to be carried out.

Learning from health sciences

Access and use of data

The focus of the CEE is aimed at better understanding end-use energy demand among the population and across the building stock. In this context the notion of a population can refer to individuals, households, communities, buildings or groups of buildings, or any other collection of entities that engage in and draw from the complex energy system. To assist those undertaking analysis in the built environment, CEE will seek to negotiate access to large datasets and undertake a process of linking and matching data in order to extract value from a diversity of existing datasets. The process of linking and matching will be a particular challenge to CEE, but will be essential to extracting value from the many smaller field trials and focused studies that have taken place and that are proposed in the coming years. Where large datasets exist that are capable of being linked in order to increase the knowledge for a set of individuals, this must be undertaken but in a manner that ensures privacy is respected. In this context, linking means physically joining two individual data points together (*e.g.* linking together a gas meter and various efficiency measures for the same physical address). However, in many cases, highly specific studies for a small set of individuals may not allow for linking, instead the main values may lie in providing the means for findings from small studies to be placed in the context (*i.e.* matched to an appropriate group) of the target population (*i.e.* the 'real' population of interest that the study population and sample are meant to represent).

At present, the barriers to accessing the data for research have meant that analysis is often limited to small datasets and results are not applicable more broadly due to an absence of context or baselines. The CEE is seeking to work with government and agencies such as the Open Data Institute to provide access to data in a secure and ethical way to academic, government and industry researchers. This means addressing the issues and perceptions around privacy and commercial sensitivity by offering a secure domain with appropriate assurances to data providers (and their subjects) on privacy. In the health sciences, the need to link data (argued as a public good) to address urgent or critical health problems or events has overcome the concerns of individuals' privacy by putting in place the National Information Governance Board (NIGB) for Health and Social Care, whose task it is to oversee how an individual's data are used, stored and shared. They have a legal obligation to review research requests that would make use of individual's data outside its original collection purpose and judge whether the research is significant enough to allow access to anonymised data to proceed (UK Parliament, 2006). While the field of energy demand and information on the built environment does not have the same legal or governance background as health data, there is a slowly growing momentum to collect and make accessible such data. Under the Energy Act of 2011, for example, the Secretary of State for the Department of Energy and Climate Change (DECC) has the ability to collect information on energy efficiency measures installed in UK houses. This, along with the licensing and management requirements of storing and accessing high-frequency energy data output from UK 'smart' meters will further add to the necessary legal framework (DECC, 2012b). Further, the UK government has committed to making data available under its open data strategy (HM Government, 2012). For energy and the built environment, departments such as DECC are making 'big' data available, under appropriate privacy controls, for use by industry and research, including the above-mentioned energy efficiency details of Green Deal and smart meter data, but also energy performance certificates for houses and display energy certificates for non-domestic buildings (DECC, 2012c, p. 9). In the CEE, access to private energy-related data will be sought and, if possible, these could be granted following an ethics committee examination of a research request for data and used under mutual agreement between the researchers and the providers.

CEE's main focus will be to engage with and assist government, industry and academia to define problems in end-use energy demand and support wider access to new and existing datasets. While CEE focuses on large population-based datasets, it will expand the analysis approach used to study energy demand of individuals at a population level through an interdisciplinary research approach.

Interdisciplinary nature of research

CEE is founded on a principle of interdisciplinarity in order to gain more robust insights into end-use energy demand issues. Interdisciplinarity is the interaction and collaboration of multiple disciplines working jointly on a problem, with the aim of integrating techniques and synthesizing theories (Choi & Pak, 2006; Cooper, 2002). In practice, this means drawing on expertise from a variety of disciplines (*e.g.* social sciences, economics, engineering and physics) and collaborating on research problems to obtain findings that account for wide-ranging socio-cultural, economic and technical factors. Earlier work on this topic for the built environment has highlighted that disciplinary boundaries are not so clear, that interdisciplinary working practices are time-intensive, and that working methods that transcend discipline boundaries is essential to identifying and resolving problems (Cooper, 2002). This highlights two important points that the CEE will address – the need for:

- environments housing multiple disciplines working collaboratively on complex and integrated problems of end-use energy demand
- a methodological framework that provides common tools and techniques and is capable of supporting collaboration and integration.

At present, however, there is little experience of integrating the engineering and physical sciences-oriented research with the insights provided by social sciences, nor is there an environment of empirically collected *in situ* data at a population level. It is therefore difficult to contextualize first principles models and laboratory testing and to derive realistic assessments of real-world performance of engineered systems. The means to propose and test hypotheses related to energy demand phenomena in the field and elucidate behavioural drivers and interactions related to end-use energy demand and decision-making is lacking. The development of new ideas, technologies and techniques that can begin to address the multifaceted nature of end-use energy demand certainly needs deeper and broader insights, but in support of this it also requires an approach capable of synthesizing across the spectrum of disciplines that impinge on energy demand. Interdisciplinary working teams in a multidisciplinary environment can work towards establishing approaches that transcend the disciplines and provide models for understanding problems that integrate the perspectives of the disciplines involved.

Over the past several decades, the health sciences have grappled with issues of interdisciplinarity and although it is difficult to achieve in practice, its outcomes can be highly beneficial to the problems addressed (Choi & Pak, 2006, 2007). For example, the control of severe acute respiratory syndrome (SARS) during the 2003 and 2004 outbreaks in Canada and Hong Kong (China) relied on the health community's ability to follow quickly from the initial clinical presentation of symptoms and identification of an unknown disease strain to laboratory testing and aetiology, the development of infection dispersion models, and putting in place control interventions to limit exposure and the spread of disease reduced the extent of the outbreak (Anderson *et al.*, 2004). It is possible to envisage circumstances at the national and regional level in which a similar response would be needed (Salagnac, 2007); but in the energy sector, the research community, policy-makers and professional and industrial stakeholders lack the experience and the structures to act in a such a concerted manner. One of the functions of CEE will be to work for the development of high-quality interdisciplinary and multi-sectoral research capacity to deal with emergent problems in end-use energy demand.

Integrated model of research

It is proposed that end-use energy demand research can reinterpret the health sciences research structure in order to found a robust research and analysis framework (Figure 1), from which to address the pressing issues surrounding end-use energy demand. The major advances in health sciences research seen over the last 150 years have been the product of both individual disciplines and their interactions within an integrated model of research. The health research system includes a series of models and practices, *e.g.* the *biomedical* model (*e.g.* pathology, biochemistry and physiology), the *socio-behavioural* model (*e.g.* psychology and sociology), the *genomic* model (*e.g.* genes and social/environmental 'switches'), along with the *epidemiological* model (*e.g.* population studies). Laboratory research and testing, clinical diagnostics, surveys and registries and a range of long-term and in-depth data-collection exercises are in place to support this integrated health research system. The proposed structure for end-use energy demand includes at least three parts (Table 1): *end-use energy processes and systems* (*i.e.* engineering and physical sciences), *end-use energy practices* (*i.e.* socio-behavioural interactions), and *end-use energy context* (*i.e.* structure and conditions of systems and practices).

The authors see the structure being interdependent, with findings from the various models being shared and built upon. Although the population-level 'epidemiological model' encompasses the other three models, this should not imply a hierarchy. Rather, it means to emphasize how an epidemiological approach uses theory, and findings derived from empirical observations, to drive forward the detection of patterns related to energy demand at the population level. Physical processes and engineered systems related to end-use energy demand, *e.g.* the engineered and designed system of the service, building or built environment and the physical processes through which the environment and user interacts with it. Studies within this model may be both quantitative and qualitative and seek to describe functions and boundaries of a system. It is possible to liken the cardiovascular system, circulating oxygenated blood through the body, to a heating system that circulates hot water for space heating via radiators through a boiler. End-use energy practices include the practices embodied in end-use energy demand through the behaviours and norms, personal beliefs and values, and communication of social institutions. Where engineered systems historically viewed users as passive, the social model sees users as actively and unintentionally interacting with the energy system to 'demand' services. For example, CEE researchers might try and understand how cultural norms and social structures affect the amount of resource used, studying such variables as the use of gas (as a heating fuel) related to temperature

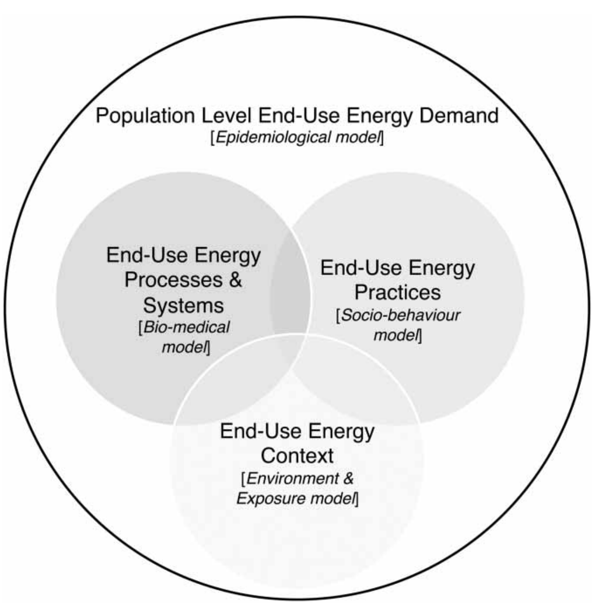

Figure 1 End-use energy demand energy epidemiology research concept

Table 1 End-use energy demand energy epidemiology research approach

Domain	Features
End-use energy physical processes and systems	The *physical systems* (*e.g.* thermo/fluid physics and engineered/technological) devised for service *demand*, within a *context* Focus: To study the physical processes and technological systems and mechanisms that support the use of energy within a given context
End-use energy practices	The *interactions* of users with a *physical system* for a service, within a *context* Focus: To examine the motivations, values and reasons through which to interpret the relationship between physical mechanisms and social–cultural practices that contribute to the development of phenomena in energy demand
End-use energy context	The given *context* of both *practices* and *physical processes and systems* Focus: To examine the structure and conditions of the physical processes and systems, socio-cultural practices in context with a wide range of factors that act on the complex energy demand structure

in houses, in ways analogous to studies by public health and medicine of the intake of calories as in obesity studies. These studies may straddle both quantitative and qualitative methods and play an important role when exploring new areas, building theory and describing experiences and insight into practices. The end-use energy context model describes the societal, political and environmental features that define and determine the engineered structures (*e.g.* regulation and standards) and within which user interactions take place. Whilst both the physical and social models shape context, this area of research focuses on the environment, not only the natural environmental conditions, but also on 'place' and the social and political structures. CEE researchers might consider how regulatory frameworks such as the application (or not) of building regulations affect the energy performance of buildings. The population level end-use model or epidemiological model focuses on describing and explaining end-use energy demand patterns and using this information to develop policies to address problems or modify physical and institutional structures to affect change. For example, identifying how widespread structural deficiencies, such as thermal bypasses via party walls, might be within the housing stock. The authors see the research structure making use of the strong existing expertise in buildings research through which a common methodological framework can be established.

An emerging field of energy epidemiology

Epidemiological approach and energy

Given the need to focus energy demand research at the population level and the proposal for the CEE to adapt the research practices used in the health sciences, it is worth briefly outlining what energy epidemiology means. In doing so, parallels are drawn between particular research features and make a case for its wider adoption within the energy demand research field.

Epidemiology is literally defined as 'the study of what is upon the people'. However, the health field is primarily concerned with:

> 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.
> (Porta, 2005, p. 81)

End-use energy demand describes the desire or requirement of consumers to use energy for a service, or 'energy supplied to the final consumer for energy-related services' (IEA, 2012). As a research field its definition is less clear but it seeks to describe the drivers of the demand for energy, its sources and fuels, services and uses, practices and norms, across the interacting sectors and actors within the built environment.

In its initial stages, health epidemiology was driven forward by the need to solve health issues that threatened the lives of many urban populations, such as cholera, dysentery and the spread of influenza. Health epidemiology, as a research field, is now closely associated with understanding disease occurrence among a population and using this knowledge for prevention and control (Bhopal, 2008). The focus of recent epidemiological research, particularly in developed countries, is mainly focused on non-communicable outcomes highly related to public health and social conditions (Horton, 2013), highlighting the importance of social factors in affecting health. Indeed, the very cutting edge science of genetics has developed a concept of the epigenome as a method of adding social factors as antecedents of gene expression and thus health (Diez Roux, 2007). In health epidemiology, a main goal of undertaking research is to use the qualitative and quantitative evidence along with systematic reviews (reviews that assess the results of primary studies against demanding criteria) to inform public health policy development, to evaluate past practices and to develop active interventions (Brownson et al., 2009); epidemiology, like energy research is fundamentally action-oriented. For policy-makers, using this evidence requires a clear and timely message that can inform the political debate (Petticrew, Whitehead, Macintyre, Graham, & Egan, 2004), while researchers require that evidence is detailed and adheres to standard study practices allowing for thorough evaluation (Whitehead *et al.*, 2004).

For end-use energy demand, the need to control energy use for reasons of climate change abatement and socio-economic issues of security and access is similar in nature to the need to prevent and control the prevalence of adverse health outcomes. However, in order to develop appropriate interventions for a population or building stock, the detailed findings from research measuring physical processes and monitoring engineered systems need to be integrated with a knowledge of the social practices that affect the demand for energy. For example, it has been found that many energy efficiency interventions in UK houses have not achieved the expected 'modelled' savings (Hamilton, Steadman, Bruhns, Summerfield, & Lowe, 2013), but there is little understanding or quantification of the factors that are playing out. There are many examples of high-quality energy demand studies that highlight social practices as factors affecting energy demand (Ek & Söderholm, 2010; Healy & Clinch, 2004; Shipworth *et al.*, 2010) and equally as many that detail the physical processes and engineered systems of energy demand (Lowe, Wingfield, Bell, & Bell, 2007; Oreszczyn, Hong, Ridley, & Wilkinson, 2006;

Summerfield *et al.*, 2007), but few make the connection between systems, practices and context.

The epidemiological approach offers both a set of tools and a methodological framework within which to undertake analysis in search of aetiology, socio-technical models and to frame results and findings (Coggon, Barker, & Rose, 2003). The approach is based broadly on four main functions (Coggon *et al.*, 2003), which are:

- to describe and measure the distribution of a condition adverse outcome
- to explain that distribution by its determinant factors (*e.g.* biological, environmental, social and behavioural)
- to predict the changes expected in that distribution from interventions and control measures
- to evaluate and shape policies to improve population health

End-use energy demand research contains many different methods that are largely drawn from the disciplines within which an issue is being studied. Broadly speaking, these are an engineering/physics-based approach that tackles mechanisms and engineered systems and sociological and economic approaches that investigates effects related to social activity and 'behaviours'. Each approach draws research designs and analysis techniques primarily from their respective founding disciplines with the purpose of offering insight into domain specific questions, *e.g.* building facade performance, temperature in houses, the value of social network in diffusion of energy efficiency practices or price elasticity of energy demand. Unlike health epidemiology, no unifying methodological framework exists within which to undertake interdisciplinary studies of energy demand and therefore these research activities are more commonly disparate than concerted, creating isolated pillars of understanding that risk being undermined by limited knowledge of their relevance or uncertainty within the broader energy demand context.

One useful parallel to understand the potential application of epidemiology to energy demand research lies in the growing obesity epidemic, itself a global threat whose study is fraught with complex interactions (Caballero, 2007). As a condition, obesity does not necessarily represent a direct health issue; rather, it is a strong risk factor for subsequent adverse health outcomes in later life. Moreover, the very condition itself is difficult to define accurately or with respect to what is a 'normal' weight range for individuals, despite its ready depiction (Canoy & Buchan, 2007). Energy demand, like obesity, can be described as a range along a spectrum with a host of interacting factors leading to a particular measured outcome. Although individual features highly influence the level of energy demand defined with a given metric, knowledge and exploration of these key determinants can offer insight into causes of excessive use, or under use (*e.g.* fuel poverty), for a given population. Further, the concept of the 'Obesegenic environment', which has been defined as:

> the sum of influences that the surroundings, opportunities, or conditions of life have on promoting obesity in individuals or populations
> (Swinburn & Egger, 2002, p. 292)

makes an interesting framework through which to examine analogous trends in energy use.

The primary aim of energy epidemiology is to investigate causes and effects of key factors on energy demand within a population or subpopulations, where as was noted above this may refer to various scales from individuals and buildings to communities or building complexes. It should consider the complex interactions between the physical and built environment, socio-economic characteristics, and individual interactions and practices. It should also offer a description of the broader context and provide an environment within which individual studies can be contextualized and systematically assessed.

Whilst epidemiology is commonly considered an observational science using empirical data (Bhopal, 2008), it has also sought to make headway into the use of qualitative studies. An emerging body of health epidemiology work using mixed methods has sought to integrate the discursive and experienced narrative into studies that quantify health outcomes in order to improve the methodological quality and analysis of data when investigating complex health problems (Borkan, 2004; Creswell, 2004). Recent best practice guidance by the US National Institutes of Health (NIH) has outlined the need and manner through which multi-method studies can take place in the health sciences (Creswell, Klassen, Plano, & Smith, 2011). In particular, the NIH highlight that mixed methods can help researchers to 'view problems from multiple perspectives' and to 'develop a more complete understanding of a problem'. However, it must also be recognized that the successful application of such approaches, whether in addressing complex problems of end-use energy demand or health problems, are not straightforward. A number of researchers in the energy field have highlighted that barriers relating to different world views, language, and methodological practices make the integration difficult and that careful and consistent attention to practices displayed by researchers can help (Cooper, 2002; Shipworth, 2005; Wilhite *et al.*, 2000). However, the authors see the strong methodological foundation of the quantitative research methods and analysis techniques used in epidemiology as an advantage, primarily because it is sufficiently robust to provide flexible framework for using qualitative approaches.

There are, of course, many challenges being faced throughout the field of health epidemiology and it is not suggested that its adaption is a panacea for the problems in energy demand research. For example, although there is a strong body of evidence linking smoking and various forms of cancer (Cornfield *et al.*, 2009), which has been a driving force behind a great deal of regulation and campaigns to reduce smoking, the evolution of the certainty around this issue has taken time and required a host of efforts across a number of health-related disciplines. Even still, there remains the need for more research on how various underlying factors, such as gene expression, affect the mechanisms that result in cancer in smokers. There are numerous other examples, but what is clear from the epidemiological approach is how, through appropriate hypothesis formulation and a strong methodological foundation, the field advances and sheds light on problem areas and challenges both itself and associated disciplines to address gaps in knowledge.

The transfer of the epidemiological approach to energy demand, therefore, is not a direct application, but rather an adaption of those tools and methods that can best serve the study of the complex interactions between behavioural, physical and environmental factors that lead to an energy demand level outcome. However, in keeping with the basic approach, the epidemiological study of energy demand must:

- describe and measure the distributions of variable(s) of interest, *e.g.* energy demand per unit of observation
- explain the distribution by its determinant factors: physical, environmental, social, behavioural and economic
- support models that predict the changes expected in the distribution due to interventions, particularly energy efficiency and behavioural control measures
- provide an evidence basis for informing policy related to the management of end-use energy demand.

This 'energy epidemiological' approach aims to develop a methodological framework that consists of established analysis techniques and study designs that are drawn from the epidemiological world, along with those techniques used in both the engineering and sociological spheres that are suited for adaption into this interdisciplinary and complex approach.

Applying epidemiology: the case of solid walls

A recent debate in the UK around solid wall houses has highlighted the deficiencies that surround the existing approach to understanding end-use energy demand and developing interventions that achieve expected energy savings outcomes. The problem is that solid wall houses are highly inefficient and that there are approximately 6 million in the UK, or 28% of the housing stock, of which fewer than 2% may be insulated (DECC, 2012d; Palmer & Cooper, 2013, p. 145). These properties are classed as high heating energy users and may exhibit colder indoor temperatures than their modern contemporaries (Hamilton *et al.*, 2013; Hong, Oreszczyn, & Ridley, 2006; Shipworth, 2011). The fact that these dwellings are not well studied has led to several problems that relate to a limited knowledge of their physical characteristics and the use of outdated model assumptions for the development of policies that are seeking to improve their fabric efficiency and thus reduce energy demand. A series of field trials were undertaken to determine the fabric thermal heat loss of solid wall houses prior to the application thermal insulation. The models assumed that these dwellings had average wall *U*-values of 2.1 W/m^2K, but the measured trials showed more than a 2:1 range in values, with a mean around 1.6 W/m^2K, leading to significantly lower potential energy savings (Rye, Scott, & Hubbard, 2011). The problem is then to develop detailed explanations for the new observations, and sets of indicators for lower and higher *U*-values in particular sub-sectors of the solid wall housing stock, coupled with estimates of their prevalence.

Plans proposed by the UK government have specifically focused on these 'hard to treat' homes (DECC, 2012e), where the cost of a fabric insulation efficiency measures can be expensive, disruptive and difficult to reconcile with architectural/planning conservation designations or the desire to maintain heritage character. These multiple factors may hinder owners' uptake. Broadly speaking there are two types of solid wall insulation: internal and external. Both have their particular problems; where external insulation offers better thermal sealing by reducing thermal bridges, it affects the external appearance of properties, impacting the cultural heritage of urban areas; internal insulation tends to be more disruptive, makes it harder to control thermal bridging through junctions of internal walls and floors and reduces the living space (a problem in smaller Victorian homes). It is also more vulnerable to moisture build up between the insulation and the fabric, leading to risk of increased mould growth and decay in the insulation materials (Rye, Scott, & Hubbard, 2012). This can have health implications for occupants, for instance the severity of mould in dwellings has been linked to increased risk of asthma occurring among children (Oreszczyn, Ridley, Hong, & Wilkinson, 2006; Preval, Chapman, Pierse, & Howden-Chapman, 2010).

Even if the insulation is undertaken and applied correctly, the predicted energy savings will not necessarily be achieved. There is a tendency for older solid walled houses to be colder (Shipworth, 2011), leaving the occupants perhaps more likely to enjoy a portion of the insulation efficiency as warmer temperature than energy savings (Hong *et al.*, 2006; Oreszczyn, Hong, Ridley, & Wilkinson, 2006). This effect, often referred to as 'rebound' or take-back, is not sufficiently understood to allow policy to be developed around these issues; instead a practical approach to the problem has been to make corrections to model predictions to account for these effects (DECC, 2012f).

How could an epidemiology approach help with this problem? First, the development of a new conceptual framework can express the issue in terms of the influences, drivers and pathways that act on a given set of identified outcomes. A central paradigm in epidemiology is that:

> patterns of ill health and disease in populations may be analysed systematically to understand their causes and to improve health.
> (Bhopal, 2008, p. 3)

In the case of solid walls this could be to consider how a range of factors influences the effectiveness of insulation in reducing energy demand.

Second, working from this conceptual framework of potential mechanisms, it would be necessary to begin to build a description of energy use and its drivers (*e.g.* fuels, service demands, timing, occupant patterns and preferences, etc.) in a range of building types in order to provide a baseline of energy use. Some recent work by Hamilton *et al.* (2013) provides a cross-sectional, population-level description of energy demand, although more work is needed to understand its drivers better.

Third, interviews with residents could help to elucidate factors that could affect their decision to accept or invest in insulating their home and the influence that social institutions may have.

Fourth, extending the observation surveys such as the English Housing Survey, for example, with its detailed surveys of building and occupant characteristics to examine pressing issues as they arise (as was the case for damp in 2009–2010). Using a prioritized set of hypothesis would provide a consistent cross-sectional foundation on which to build an empirical evidence base, while also allowing for greater contextualization of past and present field trials.

Fifth, these broader population-level studies would provide a route through which more detailed factors associated with energy demand outcomes (*i.e.* changes in gas demand, or 'savings') could be investigated at the field trial level. Finally, undertaking robustly designed field trials that investigate well-defined problems to establish how observed practices or systems (*i.e.* mechanisms) and interventions affect energy demand. The purpose of such trials would be to determine whether statistical evidence for particular mechanisms can be established, and whether interventions are sufficiently effective and well delivered to form the basis for practical policies.

The work being undertaken in current field trials is studying in detail the thermal and physical characteristics of the home and methods for parameterizing these features (*i.e.* *U*-value measurement techniques), but it remains to be seen how social or occupant practices will be ascertained. Under an epidemiological approach, studies of the 'behavioural' drivers of energy savings would need to be constructed under research designs that are focused on the socio-cultural practices and environmental conditions, along with the physical systems that modify energy savings. By expanding the range of research designs available for use in energy demand studies with ones that focus on different levels of analysis (*e.g.* population to individual), it will be possible to improve the ability to identify differences and similarities in energy outcome events (*e.g.* energy demand or savings). Building up a picture of the factors that affect these events through well-designed observational studies of a descriptive or analytical type and interventional studies will prove to offer a much stronger evidence basis on which to develop policy and evaluate control programmes.

Responding to future challenges

A transformative approach

The effective allocation of resources and effort in reducing end-use energy demand means that decisions regarding implementing a policy or changing a practice must be sufficiently well informed so as to deliver desired results and minimize risk of unintended outcomes (Davies & Oreszczyn, 2012). Doing so means gathering evidence of the potential benefits, harms and costs, along with their magnitude and accuracy, so as to compare possible outcomes. The scale of changes required to decarbonize the building stock underlines the importance of gathering evidence through a methodological framework that allows for common definitions, a robust set of study designs applicable to both individuals and populations levels, along with collaboration between disciplines. Adapting the epidemiological approach to end-use energy demand studies will provide the means to describe the trends and patterns of energy demand and begin establishing causal factors that lead to outcome events. It would also provide the means to undertake and contextualize interventional studies. The benefits of such an approach would 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.

The breakthroughs required for the step change increase in efficiency and reduction in energy demand will be facilitated by the unprecedented availability of and access to new energy and buildings data. For example, through the installation of high-frequency metering and sensors a huge amount of information can be accessed to describe patterns of demand, manage peak loads and allow consumers to interact with the supply system and be charged an accurate and fair price. These changes in technology make an epidemiological approach more feasible; data collection is becoming cheaper and more accessible than ever before. In the near future, minute-to-minute data from high-frequency meters could become more widely available. These data will be subject to high levels of protection for privacy; however, with the development of suitable controls and under aegis of the government, access to anonymized data to could be extended across the research community to create an unprecedented, open environment for empirical testing of theory, policy and technology. The buildings and energy demand field must build on the lessons learnt around data access and protection in the health research field. Just as record linkage to health service utilization has led to the development of epidemiology as an indispensible part of public health policy development, the authors believe the availability of individual and sub-metre high-frequency data and collection of building and occupant data through robust research designs can greatly add value to the energy epidemiological approach, essential for evidence-based energy demand policy development.

The role of researchers and practitioners

The tools and methods described here are not solely the domain of epidemiologists. The types of studies mentioned above have been (and are still) commonly used in energy demand studies. For example, in the early 1980s the Open University undertook a 'case-control' study of sorts in Milton Keynes known as the Pennyland Project (Chapman, Lowe, & Everett, 1985). The study looked at the energy performance of dwellings with a passive solar design at two levels of insulation. Along with the Pennyland estate, a companion group of dwellings at the nearby Neath Hill estate offered a 'solar control group'; the buildings were nominally constructed to the same standard as the less well-insulated group at Pennyland, but were "randomly" oriented and overshaded. The results of the solar comparison were unexpectedly and inexplicably large. It took a further 10 years for the mechanisms at work – convective bypassing caused by a new construction technique (drylining with plasterboard on dabs) – to be identified and fully appreciated. Despite this, the study highlighted the impact that building to a high-energy performance (equivalent to 2006 Building Regulations) and air-tightness can 'protect' against 'high' energy demand levels compared with their standard control group. The social sciences have been using a range of qualitative and quantitative research designs and methods to study end-use energy demand since the mid-1970s. In the ground-breaking Twin Rivers, New Jersey studies undertaken by Sonderegger (1978) and Socolow (1978), a cohort-style analysis described the monitoring of several hundred homes that looked at the effect that differences in occupant practices had on energy demand in similarly constructed dwellings. This certainly suggests that an epidemiology concept would not be foreign to many practising researchers. However, although these methods have been employed to study energy demand, they have not been applied with the frequency, consistency or context ascribed to epidemiological studies. Work on the scale of the Pennyland field trial was not to be attempted again until the Stamford Brook project, two decades later. Among the consequences of this was the impossibility of sustaining the capacity to undertake such work at scale. A central tenet of the epidemiological approach is the identification of robust relationships, established over time and across multiple studies that can provide insights for causal models. At present, many end-use energy demand studies findings are isolated. However, given the experience of many researchers with these concepts, and a renewed interest on the part of funding bodies in empirical research, the authors think these can be overcome within the energy epidemiology framework.

The implications of employing an interdisciplinary approach through a common methodological framework should not be underestimated, although nor should it be seen as the final solution. Establishing a centre where studies on the factors that affect end-use energy demand using an epidemiological approach that focuses on the individual at a population level through the use of 'big data' will advance the development of a robust empirically based foundation of evidence. Without this robust and timely evidence, derived from systematic data collection, there is a greatly increased risk of policies not delivering the expected savings from the buildings sector. This in turn has the potential to compromise other parts of the road map to a lower carbon economy.

Conclusions

This paper has described the call for action to control and change end-use energy demand related to the need to address a host of global and national issues. Meeting the challenge to act requires an evidence base that can address the complex nature of the interactions between people, energy and the built environment. This evidence must be based on a strong theoretical foundation, be representative of the population being assessed, account for differences, and be undertaken at scale commensurate with the problem at hand. The evidence should come from studies that are carried out with consistency, are properly designed, conducted, interpreted and presented with the necessary details to make findings transferable and able to withstand scrutiny. Doing so will provide policy-makers with greatly improved evidence for how policies and technologies work or do not work in practice – and why. Feedback on the real performance of technologies will also support learning within the construction industry and among suppliers of components, systems and services.

In support of developing this much needed evidence base, the RCUK CEE will focus on large population-based datasets, it will expand the analysis approach used to study energy demand of individuals at a population level through an interdisciplinary research approach. For end-use energy demand, the need to control energy use for reasons of climate change abatement and socio-economic issues of security and access is similar in nature to the need to prevent and control the prevalence of adverse health outcomes. CEE will provide an environment housing multiple disciplines working collaboratively on complex and integrated problems of end-use energy demand; and work on the energy epidemiology methodological framework to provide the common tools and techniques needed to support collaboration and integration in end-use energy demand research.

The authors propose that end-use energy demand research can reinterpret the health sciences research structure of epidemiology in order to found a robust research and analysis framework from which to address the pressing issues surrounding end-use energy demand. Energy epidemiology aims to investigate the causes and effects of key factors on energy demand within a population or subpopulations at various scales (*e.g.* from individuals and buildings to communities or building complexes). It should consider the complex interactions between the physical and built environment, socio-economic features, and individual interactions and practices and provide a methodological framework within which to identify and describe the broader interacting factors acting on the complex energy demand system.

Whilst every method of study has limitations, there is considerable evidence from the successes and on-going challenges of public health over recent decades that an epidemiological approach can address complex issues, deal with entrenched interests and advance knowledge. Given that a major change in the culture and practice is needed to meet the energy policy agendas – epidemiology offers a research framework that is attractive in terms of its emphasis on methodological structure, use of definitions and well-structured reviews, the use of evolving protocols and standards, in addition to the specific research designs and analysis techniques. The main limitation of health epidemiology is that observational studies usually identify evidence in terms of association or increased risk, rather than 'causality'. Nevertheless, the epidemiological approach can provide evidence (such as dose–response relationships for specific interventions) to support policy development and targeting. It can also yield crucial evidence of unexpected mechanisms at work, and thus of where and from what perspectives, more detailed case-based and forensic studies should look for explanations, new insights and new opportunities.

Adapting the epidemiological approach to end-use energy demand studies will provide the means to describe the trends and patterns of energy demand and begin establishing causal factors that lead to outcome events. It will also provide the means to undertake and contextualize interventional studies.

In providing a suitably robust evidence base, the effective allocation of resources and effort in reducing end-use energy demand means that decisions regarding implementing a policy or changing a practice would be better informed so as to deliver the desired results and minimize risk of unintended outcomes. The benefits of such an approach would 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 accounting for the complexity of the system within which the studies occur.

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References

Anderson, R. M., Fraser, C., Ghani, A. C., Donnelly, C. A., Riley, S., Ferguson, N.M., et al … (2004). Epidemiology, transmission dynamics and control of SARS: the 2002–2003 epidemic. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *359*(1447), 1091–1105. doi:10.1098/rstb.2004.1490

Attari, S. Z., DeKay, M. L., Davidson, C. I., & Bruine de Bruin, W. (2010). Public perceptions of energy consumption and savings. *Proceedings of the National Academy of Sciences, USA*, *107*(37), 16054–16059. doi:10.1073/pnas.1001509107

Bhopal, R. (2008). *Concepts of epidemiology: An integrated introduction to the ideas, theories, principles and methods of epidemiology* (2nd ed.). New York: Oxford University Press.

Bordass, B. (2001). *Flying blind: Everything you wanted to know about energy in commercial buildings but were afraid to ask*. London: Association for the Conservation of Energy.

Borkan, J. M. (2004). Mixed methods studies: a foundation for primary care research. *Annals of Family Medicine*, *2*(1), 4–6.

Brownson, R. C., Chriqui, J. F., & Stamatakis, K. A. (2009). Understanding evidence-based public health policy. *American Journal of Public Health*, *99*(9), 1576–1583. doi:10.2105/AJPH.2008.156224

Caballero, B. (2007). The Global Epidemic of Obesity: An Overview. *Epidemiologic Reviews*, *29*(1), 1–5. doi:10.1093/epirev/mxm012

California Public Utilities Commission (CPUC). (2008). *California long term energy efficiency strategic plan: Achieving maximum energy savings in California for 2009 and beyond*. Sacramento: CPUC.

Canoy, D., & Buchan, I. (2007). Challenges in obesity epidemiology. *Obesity Reviews*, *8*, 1–11. doi:10.1111/j.1467-789X.2007.00310.x

Chapman, J., Lowe, R., & Everett, R. (1985). *The Pennyland Project*. Milton Keynes: Open University.

Choi, B.C. K., & Pak, A.W. P. (2006). Multidisciplinarity, interdisciplinarity and transdisciplinarity in health research, services, education and policy: 1. Definitions, objectives, and evidence of effectiveness. *Clinical and Investigative Medicine*, *29*(6), 351–364.

Choi, B. C. K., & Pak, A. W. P. (2007). Multidisciplinarity, interdisciplinarity, transdisciplinarity in health research, services, education and policy: 2. Promotors, barriers, and strategies of enhancement. *Clinical and Investigative Medicine*, *30*(6), 224–233.

Clery, D. (2007). A sustainable future, if we pay up front. *Science*, *315*(5813), 782–783. doi:10.1126/science.315.5813.782

Cochrane Collaboration. (2013). The Cochrane Collaboration: Cochrane Reviews. *Cochrane Reviews*. Retrieved from http://www.cochrane.org/cochrane-reviews

Coggon, D., Barker, D., & Rose, G. (2003). *Epidemiology for the uninitiated* (5th ed.). London: BMJ Books.

Cooper, I. (2002). Transgressing discipline boundaries: is BEQUEST an example of 'the new production of knowledge'? *Building Research & Information*, *30*(2), 116–129. doi:10.1080/09613210110097406

Cornfield, J., Haenszel, W., Hammond, E. C., Lilienfeld, A. M., Shimkin, M. B., & Wynder, E. L. (2009). Smoking and lung cancer: recent evidence and a discussion of some questions. 1959. *International Journal of Epidemiology*, *38*(5), 1175–1191. doi:10.1093/ije/dyp289

Creswell, J. W. (2004). Designing a mixed methods study in primary care. *Annals of Family Medicine*, *2*(1), 7–12. doi:10.1370/afm.104

Creswell, J., Klassen, A. C., Plano, V., & Smith, K. C. (2011). *Best practices for mixed methods research in the health sciences*. Bethesda: National Institute of Health (NIH).

Davies, M., & Oreszczyn, T. (2012). The unintended consequences of decarbonising the built environment: a UK case study. *Energy and Buildings*, *46*(0), 80–85. doi:10.1016/j.enbuild.2011.10.043

Department of Energy and Climate Change (DECC). (2010). *The Green Deal*. London: DECC.

Department of Energy and Climate Change (DECC). (2012a). *Energy consumption in the United Kingdom 2012: Domestic energy consumption*. London: DECC.

Department of Energy and Climate Change (DECC). (2012b). *Smart Metering Implementation Programme Smart Energy Code: Consultation*. London: DECC.

Department of Energy and Climate Change (DECC). (2012c). *DECC's open data strategy*. London: DECC.

Department of Energy and Climate Change (DECC). (2012d). *Great Britain's housing energy factfile report 2011*. London: DECC.

Department of Energy and Climate Change (DECC). (2012e). *The Green Deal and energy company obligation: Government response to the November 2011 consultation*. London: DECC.

Department of Energy and Climate Change (DECC). (2012f). *How the Green Deal will reflect the in-situ performance of energy efficiency measures*. London: DECC.

Dietz, T. (2010). Narrowing the US energy efficiency gap. *Proceedings of the National Academy of Sciences, USA*, *107*(37), 16007–16008. doi:10.1073/pnas.1010651107

Diez Roux, A. V. (2007). Integrating social and biologic factors in health research: a systems view. *Annals of Epidemiology*, *17*(7), 569–574. doi:10.1016/j.annepidem.2007.03.001

Dixon, R. K., McGowan, E., Onysko, G., & Scheer, R. M. (2010). US energy conservation and efficiency policies: challenges and opportunities. *Energy Policy*, *38*(11), 6398–6408. doi:10.1016/j.enpol.2010.01.038

Ek, K., & Söderholm, P. (2010). The devil is in the details: household electricity saving behavior and the role of information. *Energy Policy*, *38*, 1578–1587. doi:10.1016/j.enpol.2009.11.041

Energy Technologies Institute (ETI). (2012). *Delivering the UK's future energy technologies: Affordable, clean and secure energy solutions for 2050*. Loughborough: ETI.

European Commission. (2010). European Commission Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Brussels: European Commission.

European Commission. (2011a). *A roadmap for moving to a competitive low carbon economy in 2050*. Brussels: European Commission.

European Commission. (2011b). *Energy Efficiency Plan 2011*. Brussels: European Commission.

Gupta, R., & Gregg, M. (2012). Appraisal of UK funding frameworks for energy research in housing. *Building Research & Information*, *40*(4), 446–460. doi:10.1080/09613218.2012.683240

Hamilton, I. G., Steadman, P. J., Bruhns, H., Summerfield, A. J., & Lowe, R. J. (in press 2013). Energy efficiency in the British housing stock: energy demand and the Homes Energy Efficiency Database. *Energy Policy*. doi:10.1016/j.enpol.2013.04.004

Healy, J. D., & Clinch, J. P. (2004). Quantifying the severity of fuel poverty, its relationship with poor housing and reasons for non-investment in energy-saving measures in

Ireland. *Energy Policy*, *32*(2), 207–220. doi:10.1016/S0301-4215(02)00265-3

Higgins, J., & Green, S (Eds.). (2011). *Cochrane Handbook for systematic reviews of interventions*, (5.1.0 ed.). Cochrane Collaboration

HM Government. (2012). *Open Data White Paper: Unleashing the potential*. London: The Stationery Office (TSO).

Hong, S. H., Oreszczyn, T., & Ridley, I. (2006). The impact of energy efficient refurbishment on the space heating fuel consumption in English dwellings. *Energy and Buildings*, *38*(10), 1171–1181.

Horton, R. (2013). Non-communicable diseases: 2015 to 2025. *Lancet*, *381*(9866), 509–510. doi:10.1016/S0140-6736(13)60100-2

International Energy Agency (IEA). (2008). *The World Energy Outlook 2008*. Paris: OECD/IEA.

International Energy Agency (IEA). (2011). *Energy-efficient buildings: Heating and cooling equipment*. Paris: IEA.

International Energy Agency (IEA). (2012). *Glossary of terms*, Retrieved from http://www.iea.org/glossary/glossary_A.asp

Jollands, N., Waide, P., Ellis, M., Onoda, T., Laustsen, J., Tanaka, K., ... (2010). The 25 IEA energy efficiency policy recommendations to the G8 Gleneagles Plan of Action. *Energy Policy*, *38*(11), 6409–6418. doi:10.1016/j.enpol.2009.11.090

Kelly, M. J. (2009). Retrofitting the existing UK building stock. *Building Research & Information*, *37*(2), 196–200.

Lahidji, R., Michalski, W., & Stevens, B. (1999). The long-term future for energy: an assessment of key trends and challenges. in *Energy: The next fifty years*. Paris: Organisation for Economic Co-operation and Development (OECD).

Laurent, M. H., Allibe, B., Tigchelaar, T., Oreszczyn, T., Hamilton, I. G., & Galvin, R. (in press 2013). Back to reality: how domestic energy efficiency policies in four European countries can be improved by using empirical data instead of normative calculations. Paper to be presented at the ECEEE Summer Study.

Lomas, K. J. (2009). Decarbonizing national housing stocks: strategies, barriers and measurement. *Building Research & Information*, *37*(2), 187–191.

Lowe, R. J. (2007). Addressing the challenges of climate change for the built environment. *Building Research & Information, 35*(4), 343–350.

Lowe, R. J., & Oreszczyn, T. (2008). Regulatory standards and barriers to improved performance for housing. *Energy Policy*, *36*(12), 4475–4481. doi:10.1016/j.enpol.2008.09.024

Lowe, R. J., Wingfield, J., Bell, M., & Bell, J. M. (2007). Evidence for heat losses via party wall cavities in masonry construction. *Building Service Engineering Research and Technology*, *28*(2), 161–181. doi:10.1177/0143624407077196

Lutsey, N., & Sperling, D. (2008). America's bottom-up climate change mitigation policy. *Energy Policy*, *36*(2), 673–685. doi:10.1016/j.enpol.2007.10.018

Medical Research Council (MRC). (2013). *MRC institutes, units and centres. MRC research*. Swindon: MRC. Retrieved March 13, 2013 from http://www.mrc.ac.uk/Ourresearch/Unitscentresinstitutes/index.htm.

Metz, B., Davidson, O. R., Bosch, P. R., Dave, R., & Meyers, L. A. (Eds.). (2007). *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Oreszczyn, T., Hong, S., Ridley, I., & Wilkinson, P. (2006). Determinants of winter indoor temperatures in low income households in England. *Energy and Buildings*, *38*(3), 245–252.

Oreszczyn, T., & Lowe, R. (2010). Challenges for energy and buildings research: objectives, methods and funding mechanisms. *Building Research & Information*, *38*(1), 107–122. doi:10.1080/09613210903265432

Oreszczyn, T., Ridley, I., Hong, S. H., & Wilkinson, P. (2006). Mould and winter indoor relative humidity in low income households in England. *Indoor Built Environment*, *15*(2), 125–135.

Palmer, J., & Cooper, I. (2013). *United Kingdom housing energy fact file 2012*. London: Department of Energy and Climate Change (DECC).

Pearson, A., Jordan, Z., & Munn, Z. (2012). Translational science and evidence-based healthcare: a clarification and reconceptualization of how knowledge is generated and used in healthcare. *Nursing Research and Practice*, *2012*, 1792519. doi:10.1155/2012/792519

Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings*, *40*(3), 394–398. doi:10.1016/j.enbuild.2007.03.007

Petticrew, M., Whitehead, M., Macintyre, S. J., Graham, H., & Egan, M. (2004). Evidence for public health policy on inequalities. 1: The reality according to policymakers. *Journal of Epidemiology and Community Health*, *58*(10), 811–816. doi:10.1136/jech.2003.015289

Porta, M. (Ed.). (2008). *A Dictionary of Epidemiology* (5th ed., p. 320). New York, USA: Oxford University Press.

Preval, N., Chapman, R., Pierse, N., & Howden-Chapman, P. (2010). Evaluating energy, health and carbon co-benefits from improved domestic space heating: a randomised community trial. *Energy Policy*, *38*(8), 3965–3972. doi:10.1016/j.enpol.2010.03.020

Research Councils UK (RCUK). (2010). *Progressing UK energy research for a coherent structure with impact: Report of the International Panel for the RCUK Review of Energy 2010*. Swindon: RCUK.

Rychetnik, L., Frommer, M., Hawe, P., & Shiell, A. (2002). Criteria for evaluating evidence on public health interventions. *Journal of Epidemiology and Community Health*, *56*, 119–127.

Rye, C., Scott, C., & Hubbard, D. (2011). *The SPAB Research Report 2: The performance of traditional buildings – the SPAB Building Performance Survey 2011 interim findings*. London: Society for the Protection of Ancient Buildings (SPAB).

Rye, C., Scott, C., & Hubbard, D. (2012). *The SPAB Building Performance Survey 2012 interim report*. London: Society for the Protection of Ancient Buildings (SPAB).

Sagar, A. D., & Holdren, J. P. (2002). Assessing the global energy innovation system: some key issues. *Energy Policy*, *30*(6), 465–469.

Salagnac, Jean-Luc. (2007). Lessons from the 2003 heat wave: a French perspective. *Building Research & Information, 35* (4), 450–457.

Schweber, L., & Leiringer, R. (2012). Beyond the technical: a snapshot of energy and buildings research. *Building Research & Information*, *40*(4), 481–492. doi:10.1080/09613218.2012.675713

Shipworth, M. (2005). Transdisciplinarity in the sociology of energy use. IN *37th World Congress of the International Institute of Sociology, Stockholm, Sweden*. Stockholm: WCIIS.

Shipworth, M. (2011). Thermostat settings in English houses: no evidence of change between 1984 and 2007. *Building and Environment*, *46*(3), 635–642. doi:10.1016/j.buildenv.2010.09.009

Shipworth, M., Firth, S. K., Gentry, M. I., Wright, A. J., Shipworth, D. T., & Lomas, K. J. (2010). Central heating thermostat settings and timing: building demographics. *Building Research & Information*, *38*(1), 50–69. doi:10.1080/09613210903263007

Silva, S., & Fraga, S. (2012). Qualitative research in epidemiology. In N. Lunet (Ed.), *Epidemiology - Current Perspectives on Research and Practice*. Rijeka, Croatia: InTech. Retrieved from: http://www.intechopen.com/books/epidemiology-current-perspectives-on-research-and-practice/qualitative-research-in-epidemiology

Skea, J. (2012). Research and evidence needs for decarbonisation in the built environment: a UK case study. *Building Research & Information*, *40*(4), 432–445. doi:10.1080/09613218.2012.670395

Socolow, R. H. (1978). The twin rivers program on energy conservation in housing: Highlights and conclusions. *Energy and Buildings*, *1*(3), 207–242. doi:10.1016/0378-7788(78)90003-8

Sonderegger, R. C. (1978). Movers and stayers: the resident's contribution to variation across houses in energy consumption for space heating. *Energy and Buildings*, *1*(3), 313–324. doi:10.1016/0378-7788(78)90011-7

Sorrell, S. (2007a). Improving the evidence base for energy policy: the role of systematic reviews. *Energy Policy*, *35*(3), 1858–1871. doi:10.1016/j.enpol.2006.06.008

Sorrell, S. (2007b). *The rebound effect: An assessment of the evidence for economy-wide energy savings from improved energy efficiency*. London: UK Energy Research Council.

Stern, N. (2007). *The economics of climate change*. Cambridge: Cambridge University Press.

Summerfield, A. J., Lowe, R. J., Bruhns, H. R., Caeiro, J. A., Steadman, J. P., & Oreszczyn, T. (2007). Milton Keynes Energy Park revisited: changes in internal temperatures and energy usage. *Energy and Buildings*, *39*(7), 783–791. doi:10.1016/j.enbuild.2007.02.012

Swinburn, B., & Egger, G. (2002). Preventive strategies against weight gain and obesity. *Obesity Reviews: Official Journal of the International Association for the Study of Obesity*, *3*(4), 289–301.

Thomson, H., Thomas, S., Sellstrom, E., & Petticrew, M. (2013). Housing improvements for health and associated socio-economic outcomes. *Cochrane Database of Systematic Reviews (Online)*, *2*, CD008657. doi:10.1002/14651858.CD008657. pub2

UK Committee on Climate Change (UK CCC). (2010). *Fourth carbon budget*. London: UK CCC.

UK Energy Research Centre (UKERC). (2013). The conduct of energy research & development. *Research Atlas*, Retrieved March 7, 2013 from http://ukerc.rl.ac.uk/ERA002.html

UK Parliament. (2006). *National Health Service Act 2006. Statute Law Database*.

United Nations Environment Programme (UNEP). (2007). *Buildings and climate change: Status, challenges and opportunities*. Paris: UNEP.

United Nations Environment Programme (UNEP). (2011). *Towards a green economy: Pathways to sustainable development and poverty eradication*. Paris: UNEP.

Whitesides, G. M., & Crabtree, G. W. (2007). Don't forget long-term fundamental research in energy. *Science*, *315*(5813), 796–798. doi:10.1126/science.1140362

Whitehead, M., Petticrew, M., Graham, H., Macintyre, S. J., Bambra, C., & Egan, M. (2004). Evidence for public health policy on inequalities. 2: Assembling the evidence jigsaw. *Journal of Epidemiology and Community Health*, *58*(10), 817–821. doi:10.1136/jech.2003.015297

Wilhite, H., Shove, E., Lutzenhiser, L., & Kempton, W. (2000). The legacy of twenty years of energy demand management: we know more about individual behaviour but next to nothing about demand. In E. Jochem, J. Sathaye, & D. Bouille (Eds.), *Society, Behaviour, and Climate Change Mitigation* (Vol. 8, pp. 109–126). Dordrecht: Kluwer.

Wilkinson, P., Smith, K. R., Beevers, S., Tonne, C., & Oreszczyn, T. (2007). Energy, energy efficiency, and the built environment. *Lancet*, *370*(9593), 1175–1187. doi:10.1016/S0140-6736(07)61255-0

Endnote

[1]Investment is adjusted using Bank of England inflation figures based on the UK goods and services price index.