The low carbon transition in the UK building sector must make financial sense: a hybrid system dynamics bottom up modelling framework

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Abstract

The building sector contributes significantly to global energy consumption and CO_2 emissions. It is urgent to reduce them through the retrofit of existing buildings and improved new building designs. The investments for energy saving retrofits in public and private sector buildings must make financial sense and have an attractive return on investment. The diffusion of related energy performance contracts is instrumental in improving the performance of the building stock. This paper develops a hybrid bottom up and system dynamics modelling framework to assess the energy savings potential and related changes in Indoor Environmental Quality of building archetypes that are representative of the total office stock. The bottom up modelling is used to provide estimates of potential energy savings. This serves as input to the system dynamics diffusion model which is developed to assess the diffusion potential of environmental performance contracts. The framework will provide the basis for scenario and policy analysis.

Keywords: energy performance contracts, office archetypes, bottom up, diffusion, low-carbon transition.

1. Introduction

In 2010, buildings accounted for 32% of total global final energy use, 19 % of energy-related GHG emissions (including electricity-related) (IPCC, 2014). Buildings in the EU account for 40% of primary energy and more than two-thirds of the electricity consumed. It is estimated that energy efficiency strategies can reduce a building's energy consumption by 50% to 70% (Zervos et al., 2010). Moreover, the energy used in buildings is a major source of carbon emissions in developed countries, accounting conservatively for something in excess of 45% of current UK emissions (Oreszczyn and Lowe, 2010). Indoor environmental conditions are also becoming more important (Davies and Oreszczyn, 2012).

In 2009, the UK government adopted an 80% emissions reduction target over the baseline of 1990 by 2050. However, there is significant inertia in the building sector due to the long building lifecycles. Achieving the UK target by 2050 would require faster emission reduction rates (Oreszczyn and Lowe, 2010). Urgent and ambitious measures for adoption of state-of-the-art performance standards, in both new and retrofitted buildings are required (IPCC, 2014). The significant CO_2 reduction targets by 2050 cannot just depend on technologies and combinations of technologies that have dominated over the last three decades or simply a continuation of the current trends (Lowe, 2007).

A sociotechnical transition is required because these objectives and their likely consequences go far beyond anything that has been attempted historically by technology policy in the UK (Committee on Climate Change, 2008). The aim of this paper is to contribute towards the difficult challenge the UK and other developed countries face over the next few decades: reduce operational building energy use and emissions of the built stock and maintain appropriate indoor environment quality (IEQ) for building occupants. The paper is developed with the aim to combined case study and system dynamics research. Modelling and simulation has been proposed as a complementary methodological tool to transition case studies (Papachristos, 2012; Papachristos, 2014a), explored in Papachristos (2011; 2014b; 2017) and developed methodologically further in (Papachristos and Adamides, 2016; Papachristos, 2018).

Operational building energy use is included in Energy Performance Contracts (EPC) which are slowly being implemented in the UK and elsewhere (Sorrell, 2007). An extension to EPC to include IEQ is necessary because it may result in increased energy consumption and affect the health and well-being of building occupants (Davies and Oreszczyn, 2012). The modeling framework developed in this paper thus considers Environmental and Energy Performance Contracts (EEPC). The issue that the paper aims to address is whether a holistic approach to quantify the operational energy use savings, and IEQ in the procurement process of a building, or in a building retrofit, could diffuse to the stock of office buildings in the UK. The framework aims to facilitate exploration of EEPC diffusion in office buildings, and potential policy interventions that can accelerate the process.

The paper focuses on the UK office building stock which accounts for a significant percentage of the UK energy consumption and 17% of carbon emissions of the UK non-domestic buildings[1]. This is of relevance in a European context as commercial buildings provide the highest potential for energy use reduction in the building sector (Commission of the European Communities (CEC), 2006). To realise this potential, research needs to engage with the complex building industry context and the issues that arise in technology deployment and learning cycles.

The paper develops a modelling framework that combines bottom-up building energy modelling and system dynamics (Figure 1). The first uses building archetypes to estimate the energy savings potential and impact on indoor environmental conditions. System dynamics is used to explore whether the potential savings translate into financially attractive market prospects for the implementation of EEPCs. The set of tools considered in this paper can be refined over time as data on UK office building stock become more readily available.

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[1] source: BPIE, 2011. Europe's Buildings under the Microscope.

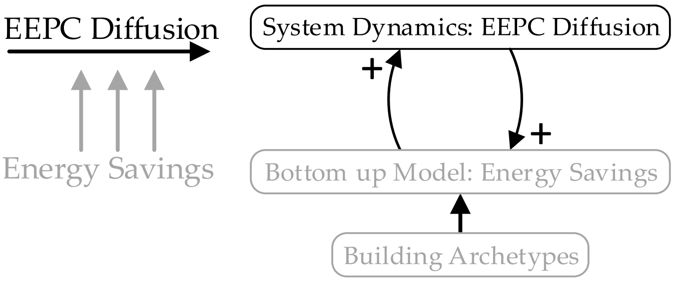

Figure 1 Conceptual illustration of the modelling framework

The rest of the paper is structured as follows: section 2 provides background in office buildings and modelling techniques. Section 3 presents background in modelling and the framework that is developed in this paper. Section 4 presents and discusses the results of the study and section 5 concludes the paper.

2. Background to Environmental & Energy Performance Contracts

2.1 Supply/Demand Energy Use Reduction

Building energy use reduction requires an understanding of the factors that affect it (Neto and Fiorelli, 2008; Peng et al., 2011; Oldewurtel et al., 2012): (i) building design characteristics: civil, mechanical, and electrical engineering systems, (ii) building system operation and use by building managers and occupants, and (iii) external factors e.g. weather conditions. The latter cannot be controlled or modified therefore energy use reductions are limited to improvements in the first two factors.

Policy instruments to promote building energy savings address both the supply-technical and demand-behavioural sides of energy use but often prioritize the supply side. A range of technological solutions is discussed in the research literature: the use of more efficient building envelopes, office equipment, lighting systems, and heating, ventilation and air conditioning systems (HVAC) (US Environmental Protection Agency (EPA), 2010; Escrivá-Escrivá et al., 2010; Daouas et al., 2016). These solutions are promoted on a national scale through energy-related policies, appliance standards, building energy codes and labeling, financial incentives, and public-sector energy leadership programs that include procurement policies to encourage investments in these solutions (Levine and Urge-Vorsatz, 2007; Jennings et al., 2011; Lopes et al., 2012).

Significant energy savings on the demand side can come from the behaviour of building managers and occupants which can deviate from the behaviour assumed in building designs and thus result in energy demand that cancels any savings coming from the supply side and technology efficiency solutions (Levine and Urge-Vorsatz, 2007; Augenbroe et al., 2009; Azar and Menassa, 2012). Behaviour deviations on the demand side often generate significant differences between the desired energy use levels obtained during the building design phase and the observed levels during building operation phase, that contribute to the so called "performance gap" (de Wilde, 2014).

A large part of this gap is attributed to the lack of understanding and control of human actions, and control of building systems (Henze, 2001; Levine and Urge-Vorsatz, 2007; Augenbroe et al., 2009). Occupant efforts to control their building environment and improve their perceived indoor environmental quality (IEQ) usually result in increased energy consumption. Research addresses increasingly operation-focused solutions such as energy management and occupancy interventions, and their integration in energy policy efforts (Cabinet Office, 2011; Lopes et al., 2012; Ucci et al., 2012).

Such interventions have been tested already in a piecewise manner in the UK building industry: (i) to optimize the performance of different building systems can achieve thorugh regular maintenance, energy audits, and energy monitoring (Escrivá-Escrivá et al., 2010; Colmenar-Santos et al., 2013), (ii) to encourage occupants to adopt energy conservation practices through educational programs and/or feedback and incentives (Carrico and Riemer, 2011; Azar and Menassa, 2012). However, they have not been integrated into related policies, so their adoption potential and related energy conservation benefits remain underexplored (Levine and Urge-Vorsatz, 2007; Urge-Vorsatzt al., 2009; Allcott and Mullainathan, 2010; Lopes et al., 2012).

A broad awareness of this fact exists among all of the building supply chain actors: architects, building services designers, contractors, facility managers, researchers, and policy makers. It is clear there is a need to improve actual building operations performance for energy conservation alongside supply side building design standards, and integrate the corresponding operation-focused solutions in energy policy frameworks (Cabinet Office, 2011; Lopes et al., 2012; Ucci et al., 2012).

2.2 Energy Performance Contracts

Operational building energy use comes under the scope of Energy Performance Contracts (EPC) which are slowly being implemented in the UK and elsewhere (Sorrell, 2007). EPCs are broadly distinguished in two types: guaranteed savings, and shared savings contracts where the client is guaranteed a level of savings or shares energy savings achieved with the energy service company (ESCO). It is necessary to extend the scope of EPC to include Indoor Environmental Quality (IEQ) as it may result in increased energy use and in health and well-being implications for building occupants (Davies and Oreszczyn, 2012).

The integration of EEPCs in energy policies that target a large number or stock of buildings requires a detailed quantification of the potential energy savings that can be achieved across the building stock. Few studies in the literature have quantified energy savings from improved operation of commercial buildings. Most studies are limited to a small sample size with results that are hard to generalize for a large stock of buildings. (Webber et al., 2006; Sanchez et al., 2007; Masoso and Grobler, 2010). These studies are divided into two main categories: energy audits (Webber et al., 2006; Sanchez et al., 2007; Masoso and Grobler, 2010), and feedback strategies (Staats et al., 2000; Carrico and Riemer, 2011; Granderson et al., 2011). These studies identify potential energy savings through a more efficient operation of building systems by occupants and facility managers.

There is a clear need to quantify the impact of human actions on building performance, both on the energy supply and demand side. This task remains challenging to perform for operation-focused solutions due to several reasons (Levine and Urge-Vorsatz, 2007; Urge-Vorsatz et al., 2009; Lopes et al., 2012; IPCC, 2014). First, building energy modeling tools adopt a systems-focused approach to building energy use analysis, but they typically overlook the important role of human actions in building energy performance (Turner and Frankel, 2008; Hoes et al., 2009; Azar and Menassa, 2012). Second, the feedback strategies evaluate the impact of providing building occupants with information related to their energy consumption levels in different contexts to encourage energy conservation (Staats et al., 2000; Carrico and Riemer, 2011). Third, studies that consider human behaviour to energy conservation with a few exceptions are mostly qualitative, without quantitative energy calculation and measurable results for energy policy purposes (Zhang et al., 2011; Lopes et al., 2012; Papachristos, 2015). For instance, Ucci et al. (2012) developed a theoretical framework of the mechanisms affecting pro-environmental behaviors but do not translate the findings into quantitative energy savings values for a large number of buildings that can motivate energy conservation efforts.

In conclusion, it is difficult to evaluate potential behaviour related energy savings that arise from improved operation of a stock of commercial buildings. This is a limitation that may have contributed significantly to the low adoption of operation-focused solutions in energy policies and initiatives (Allcott and Mullainathan, 2010; IPCC, 2014). Several concomitant issues arise from this:

- Insufficient bottom-up data lead to top-down, supply oriented, rather than demand side-oriented decisions.
- Insufficient data about energy saving opportunities and costs influence decisions and the allocation of funding resources.
- The accumulation of more detailed building energy use data and the influence of occupant behaviour and lifestyle will lead, in due time, to the establishment of best practices.
- Fine grained energy use data over the building life cycle will allow quantification and monetization of positive and negative effects and accounting for them in decision making processes.
- Continuous building monitoring will allow timely update of building codes with potential for energy savings. This would provide the basis for better policy making, education of future designers, and capacity building in the industry.

3. Background to the Modelling Framework

Energy consumption models have been developed for national building stocks, despite the apparent paucity of consistent data (Summerfield and Lowe, 2012). These models use building archetypes to represent the building stock and model energy demand (Swan and Ugursal, 2009). Archetypes are treated as actual buildings, with data obtained from existing stock measurements. The results of the analysis are valid for the building stock as a whole rather than for individual buildings, given the level of aggregation of input data, in particular of technologies and fuels for heating, cooling lighting, etc.

The assessment of the techno-economic and market potential for energy saving and CO_2 emission reductions of building archetypes, enables the estimation of the effect that energy policies and key technologies can have on the stock. Several bottom up models for research in the residential sector, use archetypes to estimate energy consumption for different segments of a building stock and see whether they meet energy use and emissions targets (Swan and Ugursal, 2009; Kavgic et al., 2010). This approach has been used to study energy use developments in the entire Finnish building stock (Tuominen et al., 2014), the residential stock of Germany and Czech Republic (McKenna et al., 2013; Vásquez et al., 2016), Ireland (Dineen et al., 2015), Sweden (Mata et al., 2013), and Italy (Delmastro et al., 2016). There are also studies that address several EU countries simultaneously (Broin et al., 2013; Ballarini, et al., 2014; Holck-Sandberg et al., 2016).

While the use of building archetypes is an established research approach for residential sector energy use, there are few attempts to develop bottom-up frameworks to quantify and aggregate the energy savings potential of commercial buildings. This has been done in the case of US where a framework was developed to quantify the energy savings potential from the improved operation of any given stock of commercial buildings (Azar and Menassa, 2014). The framework includes the impact of human control and actions on the energy performance of different building systems and it is used to address: (i) the level of energy savings from the efficient operation of the building stock, (ii) the characteristics of buildings that exhibit the greatest savings potential, so it could be prioritized to reap the "low hanging fruit" first, and (iii) the contribution of different building energy systems to the energy savings (e.g. lighting, HVAC equipment).

The methodology of Azar and Menassa (2014) combines three areas: building energy modeling, studies on the impact of human actions and control on energy use, and survey techniques. The first phase involves data collection on the stock of buildings of interest to develop building archetypes representative of the total stock. These archetypes vary with main buildings characteristics that have an important influence on energy use. The actual number of buildings represented by each 'typical' commercial building is calculated to obtain 'weighting factors'. In the second phase, one building energy model is developed for each commercial building archetype. These are then calibrated to emulate the energy performance of the 'typical' buildings they represent. The third phase explores building performance under alternative operation conditions that can result in lower energy use levels. For example, the thermostat temperature is set to levels that avoid excessive cooling or heating loads, equipment and lighting use is reduced for unoccupied periods, natural ventilation and blinds and shade use when possible, among other measures (Moezzi, 2009; Azar and Menassa, 2012).

An important assumption in their work is that alternative building operation conditions are such that they: (i) do not affect the work tasks, occupancy rates or daily schedule of occupants, (ii) meet existing building energy standards, and (iii) maintain good indoor conditions and high occupancy comfort levels. Then the energy models are run under the two sets of parameters, base case and alternative, and the differences in building energy performance are observed.

Mata et al. (2014) follow a similar approach for residential and non-residential buildings in France, Germany, Spain, and UK. The national building stock is segmented and represented by building archetypes that are fully specified using available information. A weight coefficient is derived for each archetype to determine the distribution of archetypes in the building stock. Finally, dynamic models of the archetypes are developed and validated for a reference year. The modelled archetypes are then used to explore energy conservation measures (ECM) that include building management and user behaviour, and analyse their implications in terms of indoor temperature. This analysis addresses both the technical side of operational energy use through maintenance, and the occupant behaviour that comes in response to IEQ, but can have clear implications for energy use.

In conclusion, frameworks to quantify the energy savings potential from improved operations of a commercial building stock have been developed. Nevertheless, it is necessary to combine them in a framework with a diffusion element to assess the extent to which these savings may diffuse to reduce energy use and CO_2 emissions on national level. Such a framework can be used to support policy-making efforts with clear energy conservation targets. The integration of operation-focused solutions in energy policy frameworks is essential to justify any investment costs and thus their attractiveness to the private sector (Levine and Urge-Vorsatz, 2007; Urge-Vorsatz et al., 2009; Allcott and Mullainathan, 2010; Lopes et al., 2012). In addition, other decision-makers such as energy utility companies or building stock owners e.g. universities, can also benefit from the framework to identify energy conservation opportunities in their buildings and develop appropriate and targeted energy conservation strategies e.g. educational campaigns.

Our research approach to the UK office building stock follows and adapts the approach of Azar and Menassa (2014) and Mata et al. (2014). This is necessary as there is not enough data in the case of UK office stock, but more importantly because the aim of our work is different. Our framework is used to see: (i) how the potential energy savings and IEQ improvements can come about through EEPCs and drive their diffusion in the industry, and (ii) how the market could respond rather than continue to operate in a top-down manner driven by regulation, a slower and at times ineffective political process as evidenced in the case of the UK building sector (Cohen and Bordass, 2015).

The diffusion component of the framework uses system dynamics to explore policy related insights for EEPCs. System dynamics has been used to address highly diverse issues in the building sector: the replacement of installed household appliances by more efficient ones (Dyner et al., 1995), the factors affecting energy efficiency in New Zealand's residential sector (Elias, 2008), competitiveness in the UK construction sector (Dangerfield et al., 2010), the complexity of the socio-technical system of household energy consumption and CO_2 emission (Motawa and Oladokun, 2015), the effect of smart meter diffusion on household electricity consumption (Papachristos, 2015), and project management (Ford and Sterman, 1997; Parvan et al., 2015). System dynamics is used in the framework to complement typical energy simulation programs (e.g. EnergyPlus). They perform building simulation for a maximum time frame of 1 year and currently do not account for the long term operational energy consumption of a building including the effect of dynamic building performance on energy usage (Thomas et al., 2016).

4. The Modelling Framework

Azar and Menassa (2014) and Mata et al. (2014) develop bottom-up models to identify the level of potential energy savings from an office building stock. The delivery of these savings requires some contractual arrangement for each building that can be applied repeatedly and diffuse within the market. Two modelling components are necessary to explore this: a bottom-up energy calculation component and a system dynamics diffusion component (Figure 2).

The first component involves the development of archetype buildings that follows two steps: building stock segmentation and characterization, quantification and validation of the final energy demand in the building stock for a reference year. The number of archetype buildings is developed from a combination of segmentation criteria:

- building type, defined from the use of the building, its layout (one or several floors) and the way it is attached to neighbouring buildings e.g. detached, semi-detached or terrace houses.
- construction year, determined from the updates of the building regulation codes but also according to historical events and changes in construction technologies
- main heating and ventilation system specifications
- climate zone (within a country), defined in accordance with the climate zoning suggested for winter periods in the building regulation codes.

The diffusion component will account for the investment involved in a building retrofit, the energy and financial savings accrued over the life time of individual archetypes. Importantly, it will take account of the improvements on the supply side that arise from learning by doing and economies of scale. The dynamics of diffusion then will depend on the:

- Potential and achieved EEPC savings achieved for individual building archetypes.
- Net present value of EEPCs that are available, and the magnitude of energy savings they can deliver.
- Improvements in the industry sector that arise from learning and economies of scale, that will improve the financial viability of EEPCs.

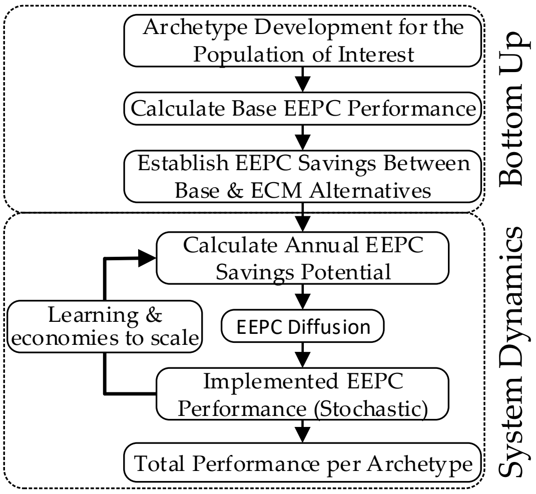

Figure 2 Simplified overview of modelling framework

The combination of two modelling methodologies will facilitate the analysis of the effects and costs of different energy conservation measures (ECMs) and their potential diffusion. This involves a number of additional steps:

- Review the current office building stock data for UK, identify key issues and the main data gaps to define archetype buildings.
- Describe and apply a methodology for building stock aggregation applicable to the UK office building stock
- Describe and apply a methodology to assess the potential for ECM diffusion.

4.1 The EEPC Modelling Framework

The framework aims to explore the diffusion of energy savings-related contractual work in the building sector market in order to deliver the increased performance and potential savings, and it is based on Azar and Menassa (2014) and Mata et al., (2014). Our framework is an extension to their work in that bottom-up modeling is combined with system dynamics simulation to explore the potential diffusion of EEPCs in the UK sector and the impact they can have in terms of energy use and IEQ. The framework consists of the following steps (Figure 3):

1. Collection of required information from the building stock of interest. A set of characteristics that impact energy use and indoor environmental quality is used e.g. size, age, HVAC type and power rating of mechanical and electrical systems, lighting, office equipment. We assume new building characteristics by extrapolation from the data we have on existing buildings, and that nothing will change in the way buildings are designed built and delivered.
2. Development of building archetypes, representative of the majority of the focal office building stock. The archetypes vary in characteristics that have a direct effect on energy use. In the case of UK office buildings, archetypes are developed by building research experts and available data. The frequency distribution for each archetype in the stock is calculated to obtain weight factors. This indicator is equal to the ratio of sample size represented by each archetype to the total building stock of interest.
3. Development of a building energy model for each of the archetypes defined for the stock to establish its base Energy and Environmental (EE) performance. There are several methods available for calibration (ASHRAE, 2002; Yoon et al., 2003; Azar and Menassa, 2012).
4. Use of Carbon Buzz data[2] to explore the energy performance savings of ECMs of different scope and depth (Sorrell, 2007) and alternative building operation conditions that result in lower energy use levels. This is done under the assumption that they: (i) do not affect the work tasks or schedule of occupants, (ii) meet existing building energy standards, and (iii) maintain good indoor conditions and high occupancy comfort levels. Then the energy models are run under the two sets of parameters, base case and alternative, and observing any differences in building energy performance.
5. Development of a system dynamics model to represent the archetype buildings, their weight factors, and their annual energy savings potential. A range of scenarios will be explored where savings are achieved stochastically when contractual arrangements are put in place based on financial returns.
6. Calculate the net present value (NPV) of potential EEPCs on offer in the market. This will provide a range of retrofit options for each building archetype and enable exploration of the conditions under which adoption of these contractual arrangements is highest in the UK market. We assume that EPCs in current buildings can drive learning and improvements in the industry so that higher performance is enabled that will drive EPC adoption in and future buildings alike.
7. Explore the EEPC diffusion pathways in the UK. The condition for EEPC diffusion is that the owner, or user of a building decides to adopt an EEPC such as Display Energy Certificate (DEC) A rating, for its operation (de Wilde, 2014).

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[2] http://www.carbonbuzz.org

8. Calculate the implemented EEPC performance and how this shapes customer expectations and learning about future performance of EEPCs on offer.
9. Calculate the aggregate performance per archetype.
10. Use the weights calculated in 2 to calculate the aggregate EE performance for the stock of buildings. The assumption is that the current frequency of commercial buildings archetypes identified will continue in the future, but policy related changes can be explored.

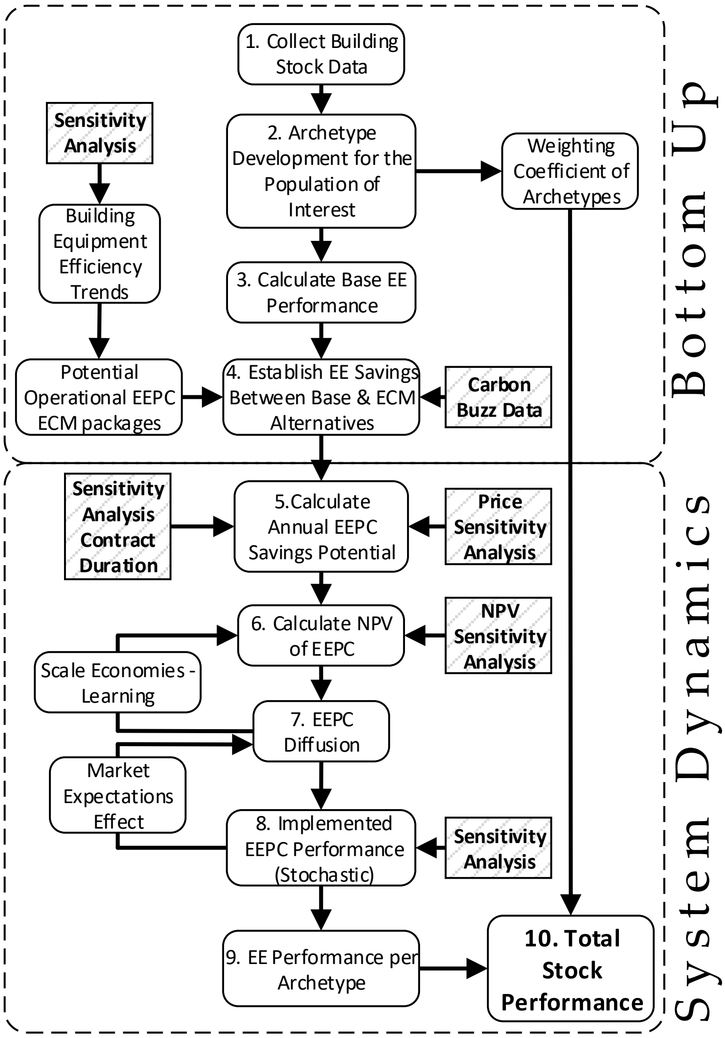

Figure 3 Modelling Framework

4.2 The System Dynamics Module

An EEPC consists of a combination of ECMs of different scope depth that form an Energy Conservation Package (ECP) (Sorrell, 2007). It is assessed as to the level of expected gas and electricity savings it can deliver (Figure 4). The *Total Savings* are then combined with price trends and a level of guaranteed energy savings is determined, taking into account a 10% risk margin for the energy service company (ESCO) (Fennell et al. 2016). The expected payback period is calculated taking into account ESCO production and transaction costs for the ESCO and the client. This determines the *Guarantee Period Offered* for *ECPi* and whether it is chosen or not. If chosen the actual level of savings is determined. If there is a shortfall in contracted energy savings and ECM is within the guarantee period then this results in a payment by the ESCO. When the guarantee expires then any energy savings or shortfall is remain with the client.

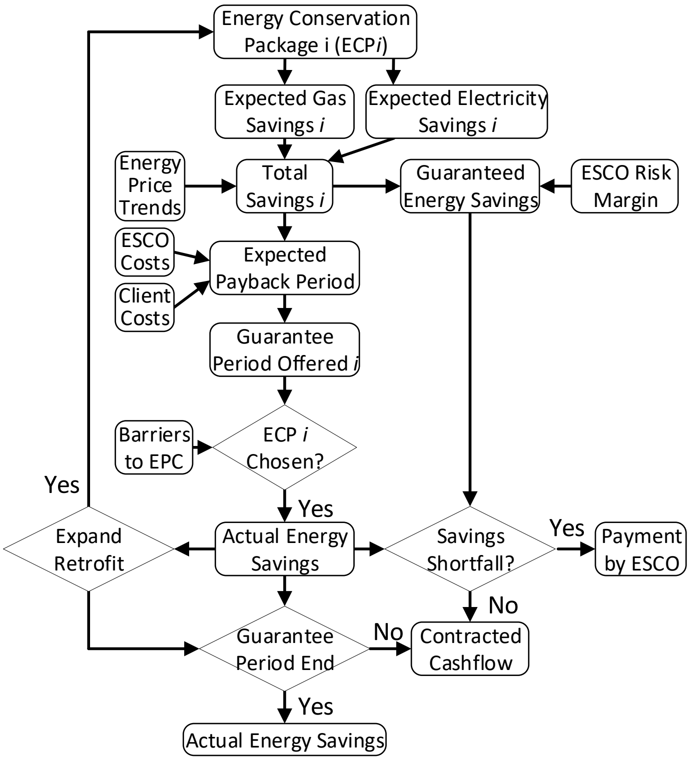

Figure 4 The EEPC decision process

4.3 ESCO and Client Costs

Following Sorrell (2005, 2007) we define: P_{CL} = Total production costs incurred directly by client, P_{CON} = Total production costs incurred by contractor, T_{CL} = Total transaction costs incurred by client, T_{CON} = Total transaction costs incurred by contractor, R = Payments to contractor by the client. Superscripts *IN* and *OUT* are used to refer to in-house and outsourced provision. Then a particular EPC must be attractive for the client and the ESCO. From the client perspective this happens when the total costs for providing the energy services in-house exceeds the cost of outsourcing it plus payments to the ESCO (eq. 1). From the ESCO perspective when revenues exceed total costs (eq. 2).

$$P_{CL}^{IN} + T_{CL}^{IN} \geq P_{CL}^{OUT} + T_{CL}^{OUT} + R \tag{1}$$

$$P_{CL}^{OUT} + T_{CL}^{OUT} \leq R \tag{2}$$

Combining the two, the following inequality must hold for an EPC to be attractive to both parties.

$$(P_{CL}^{IN} - P_{CL}^{OUT}) - (T_{CL}^{OUT} - T_{CL}^{IN}) \geq R \geq P_{CL}^{OUT} + T_{CL}^{OUT} \tag{3}$$

The client will choose EPC scope and depth to maximise cost savings, while the contractor will seek to propose scope and depth so as to maximise profits. The decision rules for whether to include an additional ECM within the scope of the contract, or an additional organisational activity within the depth of the contract, is as follows:

- Client: the additional contract payments must be less than the additional savings achieved.
- Contractor: the additional contract revenues must exceed the additional costs incurred.

4.4 EEPC Barriers in the UK

Even if the costs for the ESCO and the client satisfy the conditions above, a range of barriers on the side of the client has to be overcome including awareness, complexity, risk, and organizational ones (Sorrell, 2005; 2007). Clients may be unaware of the value an EPC can deliver. Even when they are aware, complexity of what EPC involves and the contractual arrangements required adds to the difficulty of adopting one. Complexity may lead to distrust, since an EPC can appear to offer energy savings out of nothing. Finally, the potential benefits from energy savings may appear small compared to human resource costs for example, since clients may not monitor their energy costs adequately in the first place.

Energy savings accumulate in time so EPCs require a long-term view to demonstrate their viability. The uncertainty in the private sector about business prospects and their long-term energy needs makes it risky to commit. An additional perceived risk is equipment reliability and production continuity. Clients may prefer to maintain in-house building control and operation for reasons of industrial process confidentiality, rather than transfer it over to an ESCO.

Organizational barriers may also be significant. Management may be unaware or unwilling to admit that there are more opportunities to improve efficiency, and be reluctant to share them if they can be achieved in-house. As a result, time, resources and staff are better spent on more immediate priorities. The difficulty to prioritize energy savings is compounded because energy management is usually split between several departments within an organization. If these difficulties are overcome, then resistance may come due to staff reductions or changes in employment terms the EPC may involve. A concomitant issue is trust. A stepwise approach, where scope and depth increase incrementally, may be preferred to a comprehensive EPC without having prior experience of its costs and benefits.

4.5 EEPC Scope and Depth

Each EEPC involves k ECMs each corresponding to a single energy service. The scope S for EEPC is given by:

$$S = \sum_{k=1}^{K} k \tag{4}$$

Each *k* involves *n* activities that can come under the control of the ESCO. Assuming each *n* and *k* contribute equally to depth *D* of an EPC, it is given by:

$$D_k = \sum_{k=1}^{K} n_k \tag{5}$$

The scope and depth of an EPC are related to its risk (Sorrell, 2005; 2007). The level of financial risk for an EPC project is generally proportional to its size (Caron et al., 2007). However, projects which promise the same return could present highly different levels of risk and consequently more or less significant losses for the contractor. In order to account for this in the model, it is assumed that EEPC risk increases with *k* as it involves a greater number of energy technologies and systems. Risk decreases with *D*, and activities *n* required to provide the service that is under the control of the contractor. This is because the more control the contractor has, the less risk it assumes (Sorrell, 2007). In the model it is assumed that risk is proportional to the ratio of *S/D* for each EPC. It is assumed that *S* and *D* of the adopted EPC contribute equally to the capacity of the ESCO, they increase the scale of operations and the EPC future value (Sorrell, 2005; 2007). It is also assumed that they equally contribute to transaction cost T_{CL}^{OUT}. To simplify, it is assumed that an EPC of a given *k* and *n* has a particular inherent level of risk attached to it for the type of building it will be applied to.

4.6 Net Present Value

The Net Present Value (NPV) is based on project cost over the EPC evaluation period. It is calculated as the difference between the discounted energy savings and the total retrofit costs for all saving measures *k*, which include capital *c*, installation *f*, and transaction costs *x*. It is given by:

$$\text{NPV} = \sum_{t=1}^{T} \frac{E_t - C_t}{(1+d)^t} - \sum_{k=1}^{K} (c_{i,j}^{j} + f_{i,j}^{j} + x_{i,j}^{j}) \tag{6}$$

Where is *d* the discount rate over the assessment period, $b_{i,k}^{j}$ is the cost for the *jth* alternative EPC considered for the *kth* building. *E* is the EPC annual savings cashflow after the retrofit and C_t is the maintenance cost. These are formulated as:

$$E_i^j = \sum_{k=1}^{K} a_{j,k}^{i} \cdot P_t \tag{7}$$

$$C_i^j = \sum_{k=1}^{K} b_{j,k}^{i} \times k_i^j \tag{8}$$

Where $a_{j,k}^{i}$ is the energy savings *a* of ECM *k*, for EPC *j*, for building *i*, and *p* is the energy price time series used for electricity and gas. *E* is shared to percentage *D* during the EPC period with *t*=1..n, and after its end the ownership of the investment is transferred from the ESCO to the owner for *t*=n..N. In the literature on building retrofits there are various implementations of NPV for single and multi-stage investments (Menassa, 2011).

Energy saving guarantees are calculated as 90% of the expected energy saving and are constant over the life of the guarantee (Fennell et al., 2016). It is likely that the impact of any building degradation would be small enough and counteracted due to the effect of the discount rate. Degradation has two components: of the technical equipment and of the behavior related savings in the retrofitted buildings.

The UK Treasury Social Discount rate of 3.5% is used for client NPVs as this is the mandated rate for consideration of investments by the UK government (Fennell et al., 2016). Payback periods are likely to be shorter in private sector projects than in public due to the shorter tenure of property. This significantly limits the range of ECMs that can be considered (Davies and Chan, 2001; Goldman et al., 2005; Heo et al., 2011). Inflation was assumed to be constant at 2%. A variation in the rate of inflation would have the same effect as varying the energy prices so this was not modelled separately (Fennell et al., 2016).

4.7 Uncertainty and Project Risk

While the NPV is adequate to value project returns that are certain, it is less so when there is project risk. In this case, the use of a single discount rate to account for project risk has a number of drawbacks that can lead to over, or under, estimating the project value (Espinoza and Morris, 2013; Espinoza, 2014; Espinoza and Rojo, 2015). The NPV-at-risk method calculates parameter value α at which a percentage of possible project NPVs are smaller than the minimum acceptable value and 1-α% that are larger (Sudong and Tiong, 2000). So, a particular project is acceptable with a confidence level of 1-*a* if NPV_a at the given confidence level is greater than 0. This is implemented in the model with a confidence interval of 95%.

$$a = P(NPV < NPV_a) = \int_{-\infty}^{NPV_a} f(x)dx \tag{9}$$

Once an EPC is adopted there are additional risks due to volatilities intrinsic and extrinsic to the project (Mills et al., 2006; Lee et al., 2015), which involve: (i) project-intrinsic volatilities—those energy consumption elements that are directly affected by changes within the building, which are measurable, verifiable, and controllable such as the energy volume risk (quantitative changes in energy use), asset performance risk, and energy baseline uncertainty risk, and (ii) project-extrinsic volatilities—those energy consumption risks that are outside the building, and hedgeable. These include energy price risk, labour cost risk, interest rate risk, and currency risk (for cross-border projects). We explore alternative building operation conditions that (i) do not affect the work tasks of occupants i.e. alternative operation conditions that result in reduced working hours are not explored, (ii) meet building energy standards, and (iii) maintain good indoor conditions and high occupancy comfort levels.

4.8 Actual Energy Savings

EPC benefits include savings from more efficient energy consumption that result in reduced life cycle costs and higher property value. These potential benefits determine the investment payoff and represent the major risk factor in the evaluation of the investment. In this paper these benefits are assumed to represent exclusively energy savings, since there is no legislation framework in place for the effect of energy retrofits on property values. The change in the benefits accrued for capital projects is assumed to follow the same Geometric Brownian Motion (GBM) distribution (Menassa et al., 2009; Menassa, 2011; Deng et al., 2014)

$$dE_t = \mu E_t dt + \sigma E_t dW \tag{10}$$

Where μE_t is the drift term with percentage drift μ of energy savings, and σE_t is volatility of the process with percentage volatility σ of energy savings and $dW_t = \lambda\sqrt{dt}$ with $\lambda \sim N(0,1)$. Then annual energy savings from the energy retrofit are $E_t = dE_t \cdot E_o$. Annual project revenue R is assumed to come solely from annual energy savings thus: $R_t = E_t \cdot P_t$. Where P_t is the annual energy market price for gas and electricity. To simplify NPV calculations, it is assumed that the building lifecycle is 30 years (control systems lifecycle is even less) and that all of the ECM packages are used for the same time period in the building. Non-hourly variable rates are assumed for electricity and gas for all offices and buildings. We also consider discrete cash flows and discrete compounding.

4.9 Shared Savings Cashflow

The total annual revenue is shared between the owner and the ESCO $R_t = R_{t,esco} + R_{t,client}$. In the EPC assumed in this study, there is a savings guarantee G for the client. Then,

$$R_{t,client} = \alpha G + max\left(0, \beta(E_t - G)\right) \tag{11}$$

Where α is the client savings fraction within the ESCOs guarantee, and β the fraction of client savings when they exceed the guarantee. The NPV for the client is given by:

$$\mathrm{NPV}_{\mathrm{client}} = \sum_{t=1}^{t} \frac{aG + \max\left(0, \beta\left(E_t - G\right)\right)}{(1+d)^t} + \sum_{t=t+1}^{T} \frac{E_t - C_o - C_m}{(1+d)^t} \tag{12}$$

The first term denotes client revenue during the EPC from t=1 to t, and the second term revenue beyond the EPCs duration. The inherently non-symmetrical nature of guaranteed savings returns in EPC projects that arises from the fact that ESCOs bear the costs of lower savings than anticipated but do not benefit from higher than expected savings, makes a probabilistic approach even more important to gain a full picture of uncertainties (Fennell et al., 2016).

5. Contribution and Policy Relevance

The contributions of this paper are significant as they fill gaps identified in literature and they are relevant for policy making purposes. First, the proposed framework can be used to inform policy making to develop policy measures for EEPCs to reach wider market segments of the UK building sector. Measures could include supply side technical specifications that will alter the ECMs available in the market and their value, and demand side incentives to reduce the risk for the uptake of such contracts. This will contribute to the UK energy and CO_2 emission goals for 2050.

Second, the collection of more detailed data, will provide a better starting point for the framework to facilitate the exploration of potential energy savings by end-use and energy source, and hence allow more detailed analysis of EEPC diffusion. Third, the framework is scalable and can incorporate more data about more buildings as they become available. This should provide policy makers with an incrementally better ability to aim and plan for large-scale energy savings initiatives at the city, state, or country level. This ability will be strengthened in a stepwise fashion in the future as, with more detailed data, it will be possible to study EEPC diffusion taking individual rather than aggregate building data into account. In addition, other stakeholders can also benefit from the framework, such as utility companies e.g. for energy load levelling, or educational institutions e.g. campus-wide energy conservation efforts.

Moreover, the quantification of the energy savings potential of human actions is expected to increase interest and boost research on the different techniques that can be used to achieve those energy savings during a building's lifecycle and make EEPC more attractive in the UK market. Future research, therefore, can explore different energy management strategies and occupancy interventions that could be part of EEPC and strengthen their diffusion in the market. So far, this type of research has been very limited in commercial buildings. However, the proposed framework provides a facility to evaluate building stock energy saving opportunities. It will focus research efforts on improvement of specific energy conservation methods to achieve the desired energy savings and assess their impact on the market.

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Appendix A UK gas and electricity prices (p/kWh)

https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2015

Year	Services - Low retail prices	Services - High retail prices	Services - Low retail prices	Services - High retail prices
2001	5.510	5.510	1.502	1.502
2002	5.268	5.268	1.564	1.564
2003	4.842	4.842	1.567	1.567
2004	5.112	5.112	1.692	1.692
2005	6.328	6.328	2.099	2.099
2006	7.947	7.947	2.703	2.703
2007	8.280	8.280	2.625	2.625
2008	8.935	8.935	2.897	2.897
2009	10.427	10.427	3.023	3.023
2010	8.641	8.641	2.614	2.614
2011	8.801	8.801	2.736	2.736
2012	9.412	9.412	2.904	2.904
2013	9.450	9.450	3.072	3.072
2014	9.768	9.768	3.015	3.015
2015	9.214	10.594	2.283	2.893
2016	9.689	11.794	2.200	3.161
2017	10.034	12.591	2.115	3.340
2018	9.850	12.728	2.024	3.460
2019	10.449	13.482	1.939	3.566
2020	11.439	13.825	2.022	3.763
2021	11.305	14.718	2.085	3.940
2022	12.050	14.693	2.148	4.117
2023	12.024	15.223	2.210	4.293
2024	12.840	15.913	2.273	4.470
2025	13.445	16.478	2.336	4.647
2026	13.300	16.149	2.398	4.647
2027	13.799	16.513	2.461	4.647
2028	13.675	15.845	2.524	4.647
2029	13.777	15.634	2.586	4.647
2030	13.906	15.623	2.649	4.647
2031	13.906	15.623	2.649	4.647
2032	13.906	15.623	2.649	4.647
2033	13.906	15.623	2.649	4.647
2034	13.906	15.623	2.649	4.647
2035	13.906	15.623	2.649	4.647