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Integrating building modelling with future energy systems

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Abstract
The low-carbon building design process for a building engineer is often confined to construction, building services and occupancy. However, as we see coincident changes in climate, technologies, fuels, and operation, it becomes important to extend this understanding to include wider energy systems, whilst clarifying the importance of the built environment within that system. With energy systems, such as the National Grid, involving multiple actors from different disciplines, a key challenge is to provide guidance and future projections that are translated into different discipline-specific vernaculars, but with a genesis of common assumptions. More generally, integration across the disciplines must be reflected by modelling approaches, policy-making frameworks, and outputs. This paper will demonstrate the initial stages of the energy demand research of the CESI project, where novel modelling techniques are being used to explore the effect of future buildings on national energy systems.

Keywords: Energy Systems; Building modelling; Future projections

Practical Application
The tools and techniques described within this article are designed with future industry practice in mind. The driver is the increased importance of external factors outside the traditional building envelope in determining the energy and carbon performance of a building (or buildings). Building Engineers, and others within building design teams, require a new portfolio of tools and resources to better account for the impact of buildings on wider energy systems, and vice versa. The role of such practitioners is therefore likely to evolve.

1.0 Introduction
Traditionally, “energy system” modelling and building performance modelling have been two quite separate disciplines. This is because, despite the areas being clearly related in reality, the form of the modelling and the practitioner communities likely to engage in such models are often different. The concept of an overarching energy system, describing
generation, transmission/distribution and demand of energy can be applied to both electricity and gas networks in the UK. The modelling of such networks, as a system of systems, is relatively well developed through MARKAL-based (MARKet and ALlocation) models (1) and also more top-down approaches (2). Such models allow us to consider relationships between energy supply and demand over, usually, long periods of time (days/months) and across whole countries (or large regions of countries). In this way, they can assist policy development and energy system design for a range of future scenarios, and therefore be of use to both policy-makers and those involved in network design (e.g. distribution network operators).

Modelling the performance of individual buildings is a different scale of modelling. Whereas energy system models attempt to see a whole picture, with a limited view of detail within specific sectors, building modelling tends to draw model boundaries that focus on specific onsite detail and, at best, represents external factors by simple metrics that can be used by building software. For example, although hourly weather files can be quite detailed when used with some dynamic simulation software (including the use of future climate scenarios (3)), other externalities such as carbon intensity of fuels or occupant activities are quite generic and updated infrequently.

For periods when vectors of change are insignificant, the fact that these two modelling worlds have limited connectivity does not have to be a problem. For example, traditional assumptions about the context within which a building currently exists (sources of energy, available technologies, working/living practices etc) might already be directly or indirectly reflected within the assumptions of a building model. However if we want to project forward multiple changes, whether this is climate- or technology-driven, the idea that such models can operate in isolation becomes flawed. Furthermore, these models become even less appropriate if there is a direct correlation between what might happen in our energy systems and what we should be aiming to do with buildings design/engineering; and, on occasion, vice-versa. Specifically, there is a need to communicate a detailed understanding of building energy performance to those modelling multi-sector energy demand within national systems, but also a simultaneous need to reflect the changes of energy networks within the design guidance of buildings. Without such integration, technologies being recommended for low-carbon and resilient buildings now might not actually be consistent with overarching assumptions about what a low-carbon, resilient energy system might look like in the future. Examples of this are discussed in Section 3.

When proposing an ambitious pathway to a low-carbon, resilient future, it is important to reflect the passing of time during this journey. Not only must projections of change over the coming decades be considered within a given discipline (like building engineering), but there is a need for a degree of consistency with projections of other disciplines. If those in the energy supply industry are using quite different future visions to those involved with energy demand (building practitioners, those in industry and transport sectors etc) then it is difficult to imagine a future where these pathways meet.

The UK Centre of Energy Systems Integration (CESI), a £20M EPSRC research consortium, is responding to this concern (4). This paper will focus on issues more relevant to energy demand, though CESI (led by Newcastle University, but partnered by Heriot-Watt, Edinburgh, Durham and Sussex Universities and a host of industry partners) has a wider remit than this.
This paper will help frame the problem, present feedback from different sectors of industry as to how problems might manifest, and introduce the first stages in the development of dealing with the wider issue of using new modelling techniques.

2.0 Defining the problem

To define the nature of the problem it is necessary to highlight the format of information that is used when specifying building-related energy demand within an energy system. It is possible to miss potential risks within larger energy systems when detail is not explored at adequate resolution or with suitable scrutiny. Below are key areas where detailed building analysis is particularly important.

2.1 Temporal resolution

Assessments of energy consumption of buildings can be carried out in many different ways. Some can have a strong empirical base (using high resolution electricity and gas data) while others are largely theoretical (ranging from compliance models to more detailed design tools). Models can be designed for understanding detailed energy demands of individual buildings (with complex descriptions of the thermal physics of a specific building), or use very generic archetypes of multiple buildings (with, for example, simple, steady-state heat loss calculations) to provide a description of a building stock (either regional or national).

In energy system modelling, it is often more convenient to keep building energy demand relatively simple (e.g. annual energy consumption or finite time-slices of design days) so that upscaling is possible. For example, if 4000kWh/yr was deemed an acceptable average for domestic annual electrical consumption of an individual home, then upscaling to even millions of homes is trivial, thus achieving an estimate of total energy consumption for a region of buildings. This could then be morphed for different future scenarios, such as the impact of fuel switching on gas and electricity consumption or the effect of market transformation programmes on the efficiency of appliances (using relatively broad-brush estimates of these changes).

However, to understand the impact of the built environment on the electricity or gas grids (or, indeed, any future energy grid) higher temporal resolution is required. For electricity this often stems from metered data, whereas for thermal demand physical modelling can play a greater role (explored in Section 4). Such resolution allows for an analysis of peak demand at specific times and, therefore, whether the energy supplied at those times is appropriate. As an example of this, Figure 1 shows a daily electrical demand profile taken from an individual dwelling in winter (5) at different temporal resolutions.
It can be seen that key features are lost when minutely data is averaged over hours, and days. Data at 5-minute resolution still exhibits spikes of demand (e.g. kettles, heating elements etc) and refrigeration profiles, but an hourly profile will lose such definition. A stock model might only be concerned with annual (or monthly) averages of demand. The challenge here is that, unlike simple annual estimates of individual building energy consumption, upscaling detailed demand data to regions of buildings (and, ultimately, national scale) requires an understanding of diversity and, in simple terms, the fact that people use different technologies in buildings, or the same technologies at different times. A further discussion of this can be found elsewhere (6).

The result of this is that, for the new breed of energy system models, this greater need of temporal resolution requires a different type of input from those analysing buildings. While traditional stock models (7) can still play a role in forming policy around energy efficiency, the use of real metered data and more transient energy demand modelling will be required to form a more complete picture of the energy demand of the built environment. A further challenge will involve taking an existing picture that is of this form and transforming it for future scenarios.

### 2.2 Spatial resolution

As well as providing energy use over very broad periods of time, traditional energy system models have not always been able to highlight the energy demand requirements of smaller regions of built environment. Existing models have an element of regionalisation of energy. For example, updates to MARKAL have increased spatial resolution as well as providing a “two-region” version of MARKAL that splits Scotland from the rest of the UK (8), and the ESME (Energy System Modelling Environment) model uses 12 regions to describe the UK (9). Appendices to some of these models have enabled a degree of further disaggregation by area (10). However, for those attempting to understand cause-
and-effect between specific choices in our buildings and resulting energy demand characteristics, this is still limited. Such a problem of scale is not new in areas of both building and energy system modelling. An individual, rather than stock, building model can display clear correlation between specific technologies, and uses of that technology, and resulting energy demand characteristics (as discussed in 2.1). Parameters relating to that building, such as floor area, construction, heating technologies and occupant demographics (and assumed behaviour), can be linked to patterns of energy consumption. Morphing this situation to a future scenario (future climate, updated technologies, other forms of working/living behaviours) becomes relatively straightforward, albeit beholden to the assumptions behind those inputs.

“Upscaling” is quite common in building energy stock models that use generic descriptions of our building stock, with a breakdown of important parameters (e.g. proportion that are gas heated or construction types). However, this does not produce the level of temporal resolution described in section 2.1. Taking more detailed descriptions of the building stock, where individual buildings are described with multiple parameters, produces building/household archetypes that require more information to fully define them. Put another way, if a stock of buildings can be defined by 10 parameters, the upscaling can be achieved from a relatively small sample. If we require, due to the need to improve temporal and spatial resolution, the stock be described by 100 parameters, a larger starting sample will be necessary and/or a limit placed on how far this upscaling process can go. It could be, therefore, that detailed energy demand modelling of the type described here (in section 4) will only be appropriate for small regions of the country rather than the entire country; or this modelling requires the application of further extrapolation methods.

2.2 Terminology and vernacular

It is clear that, within a full energy system model, the number of actors is vast. On the demand-side, as well as building engineers, there are practitioners involved with industry and transport. On the supply-side, there are those involved with network modelling, electrical engineers, distributed network operators and engineers working on specific energy generation technologies. It is unsurprising, therefore, that communication between different disciplines can be a problem. This can sometimes be due to the use of similar terms but in different ways. For example, an energy system modeller might refer to a “bottom-up” model. This would be a model that allows for technologies used across the country to be input and changed. The effects of these choices could then be observed on the outputs of those models. However, a building modeller might view the term “bottom-up” as referring to a description of a building stock that starts with single (or small numbers of) buildings, or even individual technologies within those buildings.

Research elsewhere (11) has referred to the use of some energy system models as boundary models; that is, they operate on the boundary of different disciplines. The mode of communication across these boundaries is important with respect to the metrics used, the facility to project these metrics in the future, and the ability to optimise around different parameters that have some meaning across those disciplines.
It is therefore necessary for those with the required specialisms to be able to translate their work into a vernacular that can be understood, and used, by those from other disciplines. Without adequate communication across these discipline boundaries, the danger is that policy and action in one area will act in contradiction to that in another, related, area. The implications of this can be evidenced by exploring future energy scenarios across different sectoral areas, as explored in the next section.

3.0 Examples of discordant scenarios

Building regulations are designed to produce lower-carbon, healthier buildings that are more likely to function in a future climate. However, these regulations and related guidance must have an understanding of other parts of the energy system if they are to succeed in meeting such targets. A previous workshop (12), carried out by the author, brought together a range of practitioners and academics interested in some of the above issues. This included architects, building engineers and planners, as well as those from the energy supply industry.

3.1 Workshop scenarios

To begin the workshop, a series of future energy scenarios were provided (see Table 1) that were based on the Department of Energy and Climate Change (DECC) 2050 Pathway tool (13). Five groups, with 6-8 participants in each group, were each given a slightly different future scenario, though each scenario had a requirement to demonstrate a low-carbon future. More detail can be found in the aforementioned workshop report, though the below discussion will focus on risks that demonstrate the importance of buildings within these systems. These discussion points are also chosen to highlight the synergy between decisions made in different sectors. Choices for large-scale energy generation can impact what technologies those designing buildings might be encouraged to adopt, within some future scenario. Likewise, adoption of a building technology en masse (for example, if a technology becomes effective in meeting a building regulation requirement) might cause issues for those attempting to balance energy supply and demand on a regional or national level.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very low-demand; High electrification; High growth in renewables; 80% reduction in CO₂ emissions</td>
</tr>
<tr>
<td>2</td>
<td>Limits to demand reduction; High electrification; 79% reduction in CO₂ emissions</td>
</tr>
<tr>
<td>3</td>
<td>Limits to demand reduction; Limited increase in electrification; 66% reduction in CO₂ emissions</td>
</tr>
</tbody>
</table>
3.2 Identified risks

With each group having a different set of future criteria to consider, a different set of risks were identified that were often quite specific to that future scenario. Some examples of these are provided below. As well as needing to be a low-carbon future, it was assumed in the discussions that significant climate change would be present in this future as described by latest climate projections (14). These risks should not be viewed as an exhaustive list, but merely relevant examples that emanated from a workshop of different participants. The scenarios themselves should also only be viewed as background information from which discussion points can be explored. Although they are chosen to be distinct, the aforementioned DECC Pathway tool can be used to create innumerable scenarios, though the ones chosen here are designed to have a level of consistency across the chosen parameters of that scenario.

When discussed below, Group 1 shall refer to the group investigating Scenario 1, Group 2 investigated Scenario 2, and so on.

3.2.1 Assuming a low electrical demand in a high electrification future

Scenario 1 achieved ambitious carbon saving targets through extensive demand reduction (e.g. 24million homes insulated, drop in heating set-point temperatures of 1.5°C), mass electrification of domestic heat, non-domestic heat and transport, and a high percentage of renewables to generate this electricity.

Group 1 suggested that, in a warmer climate, the assumption of a dramatically reduced energy demand would need to reflect an adequate understanding of cooling in the non-domestic and domestic sectors. The concern was expressed that, in reality, this scenario might see overheating of buildings (as mechanical forms of ventilation and cooling would not be consistent with this very low-demand scenario) or have significantly higher electrical demand during peak-times than previously expected if cooling systems were used more in the future.

3.2.2 Technologies not suited to high electrification

The second scenario had similarities to the above but assumed that demand reduction targets might be more modest (whether due to lack of political will, financing or technological limitations). Only 7 million homes undergo insulation programmes (perhaps reflecting current trends of efficiency programmes, where we appear to approaching a plateau (15)), and average temperatures in homes are seen to increase by 2.5°C. Non-domestic energy use also increases, particularly relating to the need for cooling in this warmer climate. Electrification of heat is still seen as the preferred route to a low-carbon future.
Due to the lack of demand reduction, compared to the previous scenario, Group 2 suggested a potential problem relating to peak electrical demand. With substantial heating and cooling loads now mostly being met through electricity across multiple building sectors, decisions made in designing those buildings are likely to have a detrimental impact on the National Grid. Such a scenario magnifies existing concerns about mass penetration of electric heat pumps, and also exemplifies what could happen when communication between different areas of energy policy (and practitioners working within those areas) is not effective. Such a technology becomes attractive to a building engineer as, in a highly decarbonised electricity grid, it is likely to be effective in reducing the carbon emissions of a building and perhaps meet the requirements of future building regulations (or energy/carbon compliance). To an engineer attempting to balance out peak demands of electricity through demand side management, where less flexibility might exist on the grid due to high level of renewables for energy generation, this technology could prove disruptive without adequate planning and grid management.

3.2.3 The role of bioenergy in meeting carbon targets
In a scenario where there is less electrification of heat, other options must be chosen to heat buildings to achieve overall carbon targets. Scenario 3 is heavily reliant on bioenergy as a means to this end; 27% of all energy supplied to the UK would be from bioenergy in some form. Like Scenario 2, there is also an assumption that demand reduction options become more limited. This raises the prospect that those assessing and designing buildings become proponents of biomass/bioenergy based heating systems, as a route to meeting carbon targets for the built environment. The DECC 2050 tool generating these scenarios suggests that, with other demands for bioenergy from other sectors, 17% of land in the UK would have to be set aside for energy crops. There is also a need for substantial use of Carbon Capture and Storage (CCS).
Group 3 therefore questioned the likelihood of this, and imagined a scenario where the infrastructure for adoption of bioenergy at such a scale in our buildings would have to be far more advanced than at present, with the additional environmental implications (land-use, transport, storage etc) that might accompany that.

3.2.4 Overly ambitious targets for demand reduction
Scenario 4 returns to more ambitious targets for demand reduction (similar to Scenario 1), but in a future with less of a requirement for electrification. Gas and oil (particularly imports) are significant, the latter being mostly required for transport.
It was noted by Group 4 that this scenario places a large responsibility on those designing buildings, and attempting to retrofit existing buildings. Unlike Scenario 1, decarbonised electricity is not the panacea to achieving low-carbon targets and gas and gas CHP are likely to be prominent sources of heat in buildings. In addition, although not of huge significance to country-wide energy use, this scenario would see 60% of all hot water generated by rooftop solar thermal, though solar photovoltaic panels are less significant. Those involved in building assessment and design might therefore question whether future policy vehicles (an improved version of the Renewable Heat Incentive for example) would achieve such ambitious targets.
3.2.5 Existing natural gas infrastructure

Scenario 5 was chosen to address an often ignored concern. Due to the relative ease, on paper or in a model, at which a decarbonised electricity supply can meet electrified heat (and transport) in a low-carbon future, the current existence of a highly developed gas grid is somewhat overlooked. The UK Committee on Energy and Climate Change has actively pushed for an all-electric future (16), which questions what happens with the gas infrastructure which, as well as successfully providing heat through gas, could also play a role in the hydrogen economy as well (17).

In addition, the gas grid provides an important means of energy balance between supply and demand, with regional gas networks able to export and import between each other as demand (largely relating to the built environment) fluctuates. Scenario 5 therefore assumes that this gas network will still be utilised in the 2050 future – with 43% of energy supply emanating from gas – almost all of which will be imported due to availability and extraction cost issues of North Sea gas. Aside from the security of supply issues that this may produce, Group 5 noted that there would be clear implications for the building engineer. Again, there is a substantial burden on demand reduction in the built environment, and the ability of policy and regulation to reach this level of reduction might be questioned.

The grid is also less decarbonised directly and therefore requires CCS to meet the overall carbon targets. This makes the addition of other electrical loads on the grid, such as electric heat pumps and increased air-conditioning due to the impact of climate change, even more problematic as they are likely to be fuelled by higher carbon intensive electricity than for other scenarios. This could be partly addressed if the required demand reduction strategy is designed to be adaptive; that is, any building refurbishment programme (and regulations used for new buildings) ensures that measures are in place to ensure that buildings will perform in a future climate. This might reduce the risk of high summertime electrical loads that are likely to challenge our ability to meet carbon targets.

4.0 An integrated modelling approach

The work around Energy Demand of the CESI project is currently in progress and will develop some of the techniques described here, within the context of sections 2 and 3. Below are some initial approaches to dealing with problems of resolution and the desire to link specific building design/technologies to energy demand within an energy system model. The examples are mainly focussed on the residential sector but are applicable to non-residential buildings also.

4.1 Electricity demand – a semi-empirical approach

It is likely that, in the future, the rise of smart meters and new approaches towards big data will see much greater availability of high-resolution electrical (and potentially gas) demand data (18). At present, the use of minutely (or similar resolution) electricity demand datasets of significant numbers of individual dwellings is relatively uncommon. This gap in the data would therefore suggest a value in synthesising demand profiles, such that a small sample of data can be extrapolated to a larger number of buildings. The
process proposed, and detailed elsewhere (19), is to create a number of detailed demand profiles of buildings that can then be aggregated together and produce something akin to a substation profile of demand data. Such a process would have to take into account the diversity of demand (mentioned in Section 2.1), as well as being within the upscaling limitations of such an algorithm (as mentioned in Sections 2.1 and 2.2).

Figure 2 shows some example measured data from a winter and summer day in a single dwelling from a previously used database of nine dwellings (5), taking a weekday in (a) January and (b) July respectively. It displays characteristics of electricity demand that any synthesis would want to replicate, without duplicating (as diversity is required in any “new” synthetic profile). These figures also demonstrate why such temporal resolution is important; it allows for a judgement to be made about technologies used in the building (even if information about the building is not known), and provides a “signal” for the building itself – an office, school, or retail building would have their own characteristics that provide clues as to the nature of energy use in that building.

Figure 3 shows similar graphs but as generated from the demand synthesis algorithm, using a statistical process of Hidden Markov Modelling (HMM) trained on the above data sample of just nine homes. In essence, this algorithm estimates a value of demand at a given time based on that time of day and what is typically observed within the empirical database. These profiles have visible forms that might be identified as domestic electrical demand profiles, but have slightly different patterns of demand over time which are in keeping with the whole demand dataset. Certain characteristics are better represented than others, and the synthesised profiles do exhibit more stochastic patterns than the empirical database. Work is currently under development to improve this part of the synthesis.

Figure 4 demonstrates an important application of this synthesis, namely the ability to aggregate demand profiles of multiple dwellings. Whilst a nine-dwelling profile will not be diverse (or “smooth”) enough to be useful for energy system models, the aggregation of synthetic profiles is. This has also been compared to real substation data elsewhere by the author (6). The use of 225 dwellings in this aggregation relates to the aforementioned report, and the alignment with substation data serving a similar number of buildings.

Figure 2 – (a) Winter and (b) Summer daily demand profiles of an individual dwelling from empirical dataset
As well as fine-tuning these algorithms, work is currently in progress to create a correlation between transient demand characteristics and building/household typology, so that demand profiles can be generated for buildings with different input parameters. This will enable modellers to reflect issues of Section 3 in a more meaningful way, linking to changes in technologies and uses of those technologies for future scenarios.

### 4.2 Thermal demand – dynamic simulation

Modellers tend to approach thermal demand of buildings slightly differently to electrical demand. This is because there is, often, a stronger correlation between physical characteristics of a building and thermal demand than there is with electrical demand (though, of course, this changes with the existence of electrical forms of heating). Even with concerns of the “Performance Gap” between real buildings and their modelled equivalents, thermal building models can play a crucial role in understanding how our building stock, and resulting energy demand, might change in the coming decades. As intimated in Section 2, there is a bridge to be built between the detailed dynamic simulation modelling of individual buildings, and the need for overarching criteria (e.g.
peak demand) of regions of buildings – and the need for input from the building engineer to help define changes in those buildings.

It has been demonstrated (20,21) that dynamic modelling, with a more complete understanding of building physics than the steady-state models used for basic energy compliance (22,23), could play a greater role in modelling regional energy demands of groups of buildings. Whilst more work is required in this area, developing this link between detailed, individually modelled buildings and aggregated energy profiles of the stock will enhance understanding of cause-and-effect. Testing the boundaries of this approach to building, and energy system, modelling will further aid the objective of bringing these disciplines closer together.

An example of a working, dynamic, local-scale stock model, is described elsewhere (24) but summarised, in a simplified form, in Figure 5. This method allows for inputs/knowledge of building engineers to be potentially reflected at the level of a larger energy system. The upscaling process is only as robust as the starting input data (and suitability of chosen archetypes in representing the stock, as with more conventional stock models) but, by placing a stock of buildings within a thermal model, the modeller would have the ability to morph aggregated energy profiles (e.g. thermal demand) for any range of technology or scenario that the dynamic model can capture. The process also transforms building modelling inputs into energy system modelling outputs, an important translation of discipline-specific terminology.

![Figure 5](image-url) – The structure of a dynamic, local-scale stock model
5.0 Conclusions

This paper has discussed areas of research that are not always seen as core knowledge for a building engineer. However, the role of the building engineer (both as a source of information and recipient of this research) is crucial to developing pathways to a low-carbon future. As well as providing a philosophical discussion around the importance of integrating practitioners on the demand-side with those designing energy supply systems, tools have been presented that will aid that integration in real terms. With workshop feedback from practitioners included in this discussion, it is suggested that there is a need for:

- Common vernacular amongst a range of practitioners and modellers operating within different parts of an energy system
- Common methods of future scenario-building with shared assumptions over what those scenarios might be
- New tools that link the above and provide a means to link the detailed knowledge of a building engineer with the overarching scope of energy system models

Work of the CESI project, amongst others, will be looking to frame and, ultimately, provide solutions to this problem in the near future. Such solutions, though not predicting a future with great certainty, will allow for much deeper investigation into the impact of a range of different futures, and the necessary action to ensure that the design of buildings and associated energy systems is resilient to these future uncertainties and consistent with low-carbon targets.

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