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Using Urban Building Energy Modelling (UBEM) to support the new European Union's Green Deal: Case study of Dublin Ireland

Niall Buckley [a], Gerald Mills [a], Christoph Reinhart [b], Zachary Michael Berzolla [b]

[a] School of Geography, UCD, Dublin, Ireland

[b] Sustainable Design Lab, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

***Corresponding author Niall Buckley**

E-mail Address: niall.buckley1@ucdconnect.ie

Abstract

The European Unions (EU) Green Deal plans for a carbon neutral economy by 2050. Achieving this goal will require actions across all economic sectors, especially the building sector, which currently accounts for 40% of energy use. Residential energy use is a significant contributor, much of it due to an aging, poorly insulated building stock, much of which is concentrated in urban neighbourhoods. This research focusses on the application of an Urban Building Energy Model (UBEM) to support the Green Deal and the planned 'renovation wave'. An archetype approach is used to efficiently derive the building data needed to run the Urban Modelling Interface (UMI) to test the efficacy of energy retrofitting policies for neighbourhoods, using a case-study area of 9,000 residential buildings in a European city. Initially, UMI simulations of energy use intensity are evaluated against reported energy performance certificate data in the study area. The UBEM is then used to quantify the most cost-effective mix of envelope retrofit and onsite energy production to achieve a 60% reduction in greenhouse gas emissions by 2030. The methodology shown here is based on residential building archetypes that are available for many EU countries and the method outlined can be replicated in other urban settings.

Keywords: Urban Building Energy Model (UBEM), Building Archetypes, European Green Deal, Renovation Wave.

1. Introduction

The EU has published ambitious plans as part of a Green Deal to reduce greenhouse gas emissions to at least 50% below 1990 levels by 2030 and to be carbon neutral by 2050 [1]. Achieving these goals will require implementing diverse strategies such as investment in green technologies, industrial innovations, circular economies, decarbonising transport and energy production and upgrading the existing building stock, much of which is energy inefficient [2, 1]. In the EU, as in many other global economies, buildings are responsible for 40% of energy consumption and 36% of GHG emissions with residential households responsible for 26% of the former. As a result, buildings are a major focus of energy policy, owing to their long lifespans and embedded energy inefficiencies [3][3]. It is estimated that 80% of the current building stock will still be in use in 2050 and current renovations rates of 1% per annum will not be sufficient to meet the Green Deal goals. To address carbon emissions from this sector, the EU has proposed a 'renovation wave' that will double the rate of refurbishment, improve energy standards and pool these efforts to benefit from economies of scale. However, specific measures and timelines have not been published.

Cities, where much of the building stock is located, are ideal places to apply the renovation wave for a number of reasons including the concentration of energy inefficient houses in neighbourhoods and the opportunities afforded by the proximity of buildings with different occupancy patterns and energy needs. However, to support an urban approach we need: better understanding of the economic and ecological benefits of building energy efficiency measures; better assessment of energy saving policies (e.g. retrofits and renewables) and appropriate financing mechanisms; and a scientific infrastructure that includes details on the physical state and geography of the existing building stock and modelling tools to evaluate the impact of interventions [4]. This paper focuses on the development of an infrastructure to support decision-making at neighbourhood scales to meet the goals of the Green Deal.

Historically, building energy models (BEMs) have formed a core component of the science that underpins energy policy formulation and management. These models can simulate energy demand to a high accuracy and evaluate responses to changes in occupation patterns, design, materials and technological interventions [5]. BEMs are used to simulate energy demand for both generic building types and for high performance buildings. For the former, general information on envelope and HVAC properties (such as construction materials and glazed fraction) and standard occupancy patterns are used to simulate energy demand using typical meteorological weather files. These models then generate solutions that can be used to create simple spreadsheet look-up tables which can be used for rapid assessment of energy efficiency, often expressed as annual energy use intensity (EUI in $kWhm^{-2}$) that are used to create Energy Performance Certificates (EPCs). Databases of EPCs are commonly used to assess the quality of national building stocks. For bespoke buildings, a BEM is used as part of the design process to simulate variable EUI energy demand associated with dynamic energy loads associated with both internal energy use and external gains and losses due mainly to radiation gain and loss and outdoor air temperature. Creating an urban BEM (UBEM) to simulate large groups of buildings has, until recently, employed generic building types and simply mapped these building types (or EPC values) to identify energy inefficient neighbourhoods. By comparison, applying individual BEM to all the buildings in an area is a daunting, resource intensive undertaking. If the question posed is simply, 'what typical energy savings one may expect from applying certain sets of measures to multiple buildings?', then this approach is probably not a worthwhile investment of resources. Recent advances in modelling and technology have allowed the development of UBEMs that employ simplified building physics to simulate energy use for large groups of buildings [6]. These models are ideally suited for meeting many of the challenges set by the Green Deal as they can support policies that can address issues of economy of scale and the mutual dependency of buildings in proximity.

In this paper, an UBEM is used to simulate energy demand for a large group of buildings that comprise a diverse housing stock in Dublin (Ireland). We combine geographic information on urban layout with a database of building archetypes (and associated properties) to create a near complete description of a neighbourhood. The resulting data are employed within the Urban Modelling Interface (UMI), which integrates several sub-models that simulate components of the urban system including energy modelling. The building archetypes are drawn from the Irish contribution to the Episcope Tabula project, which was designed to aid the energy refurbishment processes in the European housing sector by making the energy needs of buildings and the retrofit options more transparent and effective [7]. Although this paper is focussed on a case study in Dublin, the process can be applied to any European housing stock for which the Tabula or equivalent archetype data is available.

In the following we present the recent literature on urban-scale building energy models, outline the process used here to link UMI to geographically referenced archetype data, evaluate UMI simulations by comparison to measured building energy ratings, present simulation results and discuss pathways to meet Green Deal targets.

2. Literature review

In the building energy literature two approaches (termed 'top-down' and 'bottom-up') have been employed to assess energy demand and use at a neighbourhood scale [8,9]. A top-down approach partitions measured energy use at a neighbourhood scale among its constituent buildings using statistical relationships that have been established between occupancy patterns, population and building properties (such as age and floor area). By comparison, a bottom-up approach simulates energy use for all buildings individually. While the former can provide a rapid assessment of energy demand and guide energy management policies, it lacks the granularity needed to test place-specific interventions. Moreover, as a statistical exercise, top-down approaches cannot evaluate the potential for energy harvesting and sharing among buildings. The bottom-up approach however requires an enormous amount of detailed information on individual buildings and considerable computational resources. Typically, data acquisition is accomplished by disaggregating the national building data using segmentation and characterization; segmentation filters the building stock into groups based on dimensions, age, use and characterisation describes the construction materials, thermal properties, usage patterns and heating/cooling systems of these groups [6]. The acquisition process can be greatly simplified by using archetypes that categorise buildings into types based on shared properties that are linked to historic national/cultural construction methods. Although the use of archetypes requires that individual building detail is lost, the fundamental differences between types of buildings is captured in the associated data which can be used in UBEMs.

2.1 Building archetypes

The archetype approach to generate the building data needed to run energy simulations have been used to study urban energy use intensity (EUI). In North America, Farahbakhsh *et al*. [10] and Huang and Brodrick [11] developed archetypes to simulate building energy use under different future scenarios. Heiple and Sailor [12] used DOE archetypes to run a BEM (eQuest) to generate building energy profiles; these archetypes were linked to a geographic building database for a case-study area in Houston. The estimated aggregated building energy use compared well with observed data at this scale. Davila *et al.* [13] used a similar process to generate building data suited to running a UBEM for thousands of buildings across Boston.

In the European Union, the Energy Performance of Buildings Directive [14] prompted surveys of the building stock within each member state. The data generated have been used to create building archetypes that could be employed to estimate annual energy use for space heating and cooling using a consistent methodology (ISO EN 13790) [15]. The archetypes permit evaluation of energy saving measures (ESMs) based on technology and policy interventions applied to the aggregate building stock [8,17]. Heeren *et al.* [17] used building archetypes created by the Swiss Federal Office of Energy to simulate different energy saving scenarios based on current and future energy saving plans. Mata et al. [19,18] also assessed ESMs across the Swedish national and regional building stock using a BEM and hourly climate data to account for dynamic outdoor conditions. Simulations on 1400 sample buildings were used to assess 12 ESMs applied to the entire Swedish housing stock; the results indicated that these measures could reduce the overall residential energy demand by 53%. *Mata et al*. [20] extended this work to create building archetypes for Germany, Spain, France and the UK that were used to estimate final energy use for residential and non-residential building stock. In Ireland, the dwelling energy assessment procedure (DEAP) uses ISO EN 13790 to generate building energy performance certificates (EPCs) that are required for buildings that are sold and/or rented [21]. Famuyibo *et al*. [22] and Ali *et al.* [24] used these data to generate archetypes using clustering techniques that were subsequently used to simulate energy use and evaluate ESMs at a large scale.

Tabula was designed to inform property owners, developers, and stakeholders on the best ESMs to implement for different types of buildings. This was facilitated by a webtool that shows photographs that typify residential building archetypes along with data on construction properties and heating systems [25]. Tabula data includes the information needed to run a thermal model to estimate annual energy demand (kWhm^{-2}) based on typical weather information. Moreover, the results of different ESMs, such as wall/roof insulation are also included in the webtool. Tabula building data have been standardised to reduce complexity and enable comparison of building energy performance within Europe [26]. Ballarini *et al*. [27] and Dascalaki *et al*. [28] have linked Tabula archetypes with census information on the building stock in Italy and Greece, respectively to estimate the potential for implementing ESMs at the urban scale.

2.2 BEMs and UBEMs

Applying BEMs to archetypes has proved to be an effective way to examine energy use of building stocks at a coarse level where assumptions of occupancy patterns, internal/ external shading, HVAC system specifications, etc. are reasonable approximations. Most often this approach has used steady-state conditions that greatly reduce the computational demand needed to simulate energy demand across multiple buildings with sufficient accuracy. These results may have been validated for the averaging period under examination using dynamic conditions that have accounted for weather and varying occupation patterns [30,31,17]. The commonly used BEMs are EnergyPlus, DOE2, TRNSYS and ESP-r which are described as dynamic or transient models, although they can be run in a near steady-state mode [32,17]. In most of the literature, urban-scale modelling is based on scaling the BEM results for individual building archetypes to a defined building stock based on its archetypal make-up. Where information on the building stock is available at a finer geographic level (such as via links with Census data), the results are more refined. However, this up-scaling approach does not account for the spatial relationships between buildings that affect the ambient environment and external loads of individual buildings.

Recent advances in large-scale simulation allows dynamic simulations of neighbourhoods comprised of diverse building types and urban layouts within UBEMs [32]. These models support spatially precise ESMs that account for the relative geography of buildings. In contrast to the scaled BEM approach, fully developed UBEMs permit examination of energy generation and distribution systems, commuting patterns, outdoor landscaping and so on. In one of the first applications of a UBEM, over 90,000 georeferenced buildings in Boston were simulated using the Urban Modelling Interface (UMI), which incorporates EnergyPlus [13]. This study illustrated the potential of UBEMs to assess building energy demand at high spatial and temporal resolution to support grid energy management and test energy management scenarios. However, to perform these building simulations across an urban landscape, simplifications are needed. A common approach is to divide the floors of buildings into four zones representing façade orientation, each with a core and perimeter space; simulations are performed on the external and internal load of the conditioned perimeter spaces [33]. Wang *et al.* [34] applied a UBEM to three neighbourhoods in Switzerland to simulate future retrofit scenarios in line with projected climate change and the Swiss Energy Strategy 2050. Model simulations compared favourably with energy observations at a district level. Nevertheless UBEMs, even in their simplified forms, are extremely demanding of computer resources, which greatly limits their potential for routine testing of energy management scenarios across large urban areas. To overcome this obstacle, Dogan and Reinhart [32] developed a sampling approach that select representative building zones across a neighbourhood that enables efficient dynamic energy simulations of multiple buildings. As a result it allows rapid evaluation of ESMs at building and neighbourhood scales and supports energy grid management [35].

The UBEM and scaled-BEM approaches share the same need for detailed information on building characteristics that are met using geographic databases that include relevant information on HVAC systems, glazing fractions, infiltration rates, thermal insulation, etc. [36]. This means that the capacity to simulate individual buildings is limited by the available data and its representativeness. In this paper we utilise an EU database (Tabula) that contains much of the data required by UMI to perform neighbourhood simulations. While the paper reports on a case-study neighbourhood in Dublin (Ireland) the approach can be replicated for any neighbourhood in EU where the Tabula archetypes have been mapped to a geographically-referenced and categorised building stock.

3. Methodology

Figure 1 depicts the workflow methodology followed here, which consists of two streams that are merged within the UMI modelling framework. The first stream of work creates a GIS database of buildings each of which is categorised into a Tabula archetype; the details of this work are described elsewhere [37] and are summarised here. The second stream describes the conversion of the Tabula database associated with each archetype into templates suited for running UMI. Here, we have used ClimateStudio, a dynamic BEM that uses the EnergyPlus engine, to create the UMI templates; this has the advantage of allowing us to evaluate BEM simulations against the annual EUI data associated with each Tabula archetype. The products of these two streams are merged to create a geographic database of building templates for UMI, which is used to simulate EUI across a neighbourhood and test the efficacy of place-based climate change policies.

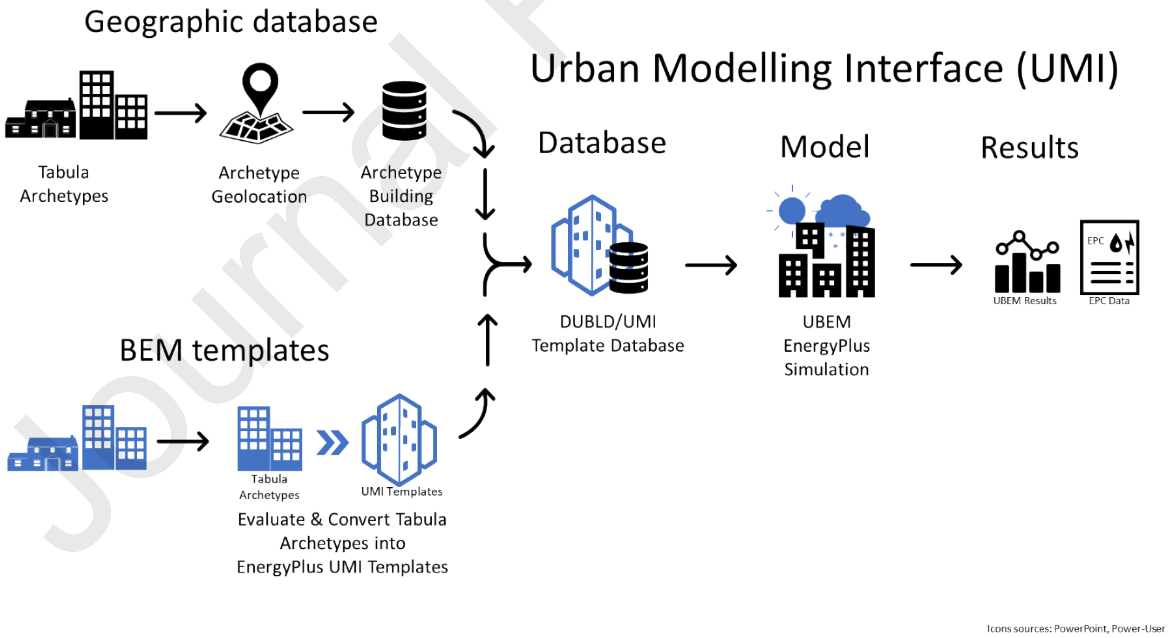

Figure 1. The workflow used in this project. The geographic database categorises georeferenced building envelopes into Tabula archetypes and generates a GIS database. The BEM templates are created from Tabula data and generate EnergyPlus template files. The geographic database is integrated with the BEM templates within UMI.

3.1 Geographic archetype database

The first workflow stream is the creation of a geographically referenced database of building archetypes. The absence of suitable building data is a major obstacle to the implementation of an UBEM. Buckley *et al.* [37] describes the creation of a database of 28,000 buildings in Dublin's city centre using a combination of building footprint data and Tabula archetypes. Each building was categorised into an archetype based on age of buildings and visual inspection (Table 1, Figure 3). Although the methodology employed was efficient it was also time consuming; in the future, it can be made more efficient using image recognition software to rapidly classify buildings in selected neighbourhoods. The advantage of the Tabula archetypes is that they are available across much of Europe and their use of readily recognisable visual examples.

In this paper, we select a study area in Dublin that consists of 2.46 km^2 of residential land-use comprised of single-family homes, mostly. The area was selected based on its aged housing stock, which makes it a good candidate for applying the neighbourhood-based energy policies envisaged by the Green Deal. Table 1 shows the seven most common residential building types in the area, which together account for 80% of the stock; Table 2 shows the number of buildings by approximate age with categories chosen to match other sources of data. There are over 9,000 buildings in the study area and more than 75% were built before 1950 and have a solid wall construction. Another 8% were built between 1950 and 1982, which corresponds to a period of cavity block construction. Much of the urban layout during these building phases consists of single-family terraced housing. The remaining stock was built in an era of increasingly stringent energy regulations and after 2000, most of the new stock consist of multi-household apartment buildings. Figure 2 shows a map of the distribution of the archetypes categorised by age into those constructed before and after 1980, which corresponds with the date of the first building energy regulations.

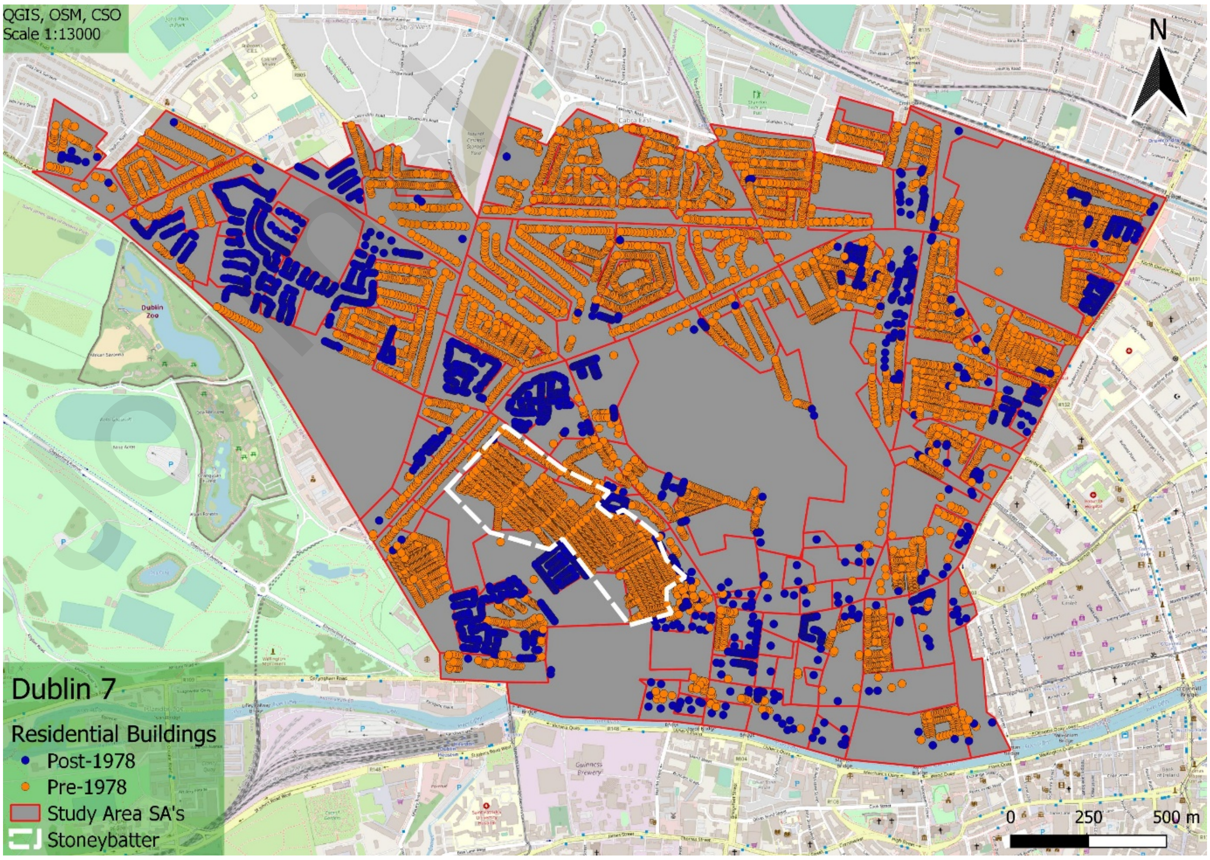

Figure 2. The distribution of buildings in the study area, categorised into those built before and after 1980.

The Irish national household census, which took place in April 2016, is an independent source of information on the building stock. However, unlike the Tabula data described above, census information refers to households, defined as a single person or group of people who reside together in the same accommodation. In other words, there may be many households within a building, either because it was constructed as an apartment complex or a single-family residential building has been subdivided. The subdivision of large older houses is a common feature of this part of Dublin.

Table 2 shows age assessment of the building stock and population based on the census data. The study area accommodates nearly 37,000 residents and 16,000 households and 64% of the population live in buildings constructed before 1980. Since 2007 any dwelling that is sold or rented is required to have an energy performance certificate (known as a building energy rating, BER) which is based on the estimated annual energy use intensity (EUI in kWHm^{-2}) that is categorised into grades (A to G), see Table 1. BER grades are assigned to households (not buildings) following an inspection and the data are used to evaluate the state of the current building stock (based on original build and any retrofits). EUI statistics (number of assessments and mean/median and maximum/minimum values) are available for census areas. Here, these data are used to evaluate the results of the UMI simulations. Table 2 shows the number of BER evaluations in the study area categorised by age. Of note, is that the information available for the older stock (much of which is not covered by the BER regulations) is limited. Given that BER data are used to guide retrofit policies, the lack of data on the poor performing building stock is a weakness that a well-calibrated UBEM could overcome.

Label **Tabula Type** **Number of buildings in study area**	**Description**
Stone SFH 1899 96 (1%) buildings	Buildings constructed of uninsulated stone walls (300-400mm thick) before 1900. Pitched roof with insulation between joists. Solid floors. Single glazed windows with wooden frames.
Georgian SFH Pre-1900 1101 (11.4%) buildings.	Buildings constructed of uninsulated brick wall (225-325 mm thick) before 1900. Front pitched roof with 100mm of mineral wool in ceiling joists. Rear pitched roof with no insulation. Single glazed windows with wooden frames.
Brick SFH 1900 4672 (48.4% buildings)	Built between 1900-1930 using uninsulated brick walls 325 mm thick. Pitched roof with 50mm of mineral wool in ceiling joists. Single glazed windows with wooden/steel frame
Concrete SFH 1930 1603 (16.6%) buildings	Built between 1930-1949 using solid mass concrete. Pitched, insulation between the joists. Single gazed, metal frame windows.
Brick AB 1950 24 (0.2%) buildings.	Apartment block buildings Front wall and stairwells of mass concrete. Rear wall: 325mm solid brick. Flat roof concrete slab. Single glazed windows and wooden frames.
Cavity block SFH 1970 347 (3.6%) buildings	Built between 1978-1982 using cavity block 300 mm cavity block walls, partially filled. Pitched, insulated between the joists. Double-glazed windows, metal frame, 6 mm gap

Cavity block SFH 1990 1028 (10.7%) buildings	Bult between 1994-2004 Cavity walls, partially filled. Pitched, insulated between the joists. Double glazed windows with PVC/wood frames and 12 mm gap.
Cavity block AB 1990 216 (2.2%) buildings.	Apartment block built between 1994-2004. Cavity walls, 300 mm partially filled. Flat concrete roof insulated. Double glazed windows with PVC/wood frames and 12 mm gap.
Cavity block SFH 2000 67 (0.7%) buildings.	Built between 2005-2001 using 300 mm thick, partially filled cavity walls. Pitched, insulated between the joists. Double glazed windows with PVC/wood frames and 12 mm gap.
Cavity block AB 2011 54 (0.6%) buildings.	Apartment block built after 2011 using partially filled cavity walls. Flat insulated roof. Solid concrete insulated floors. Double glazed windows with PVC/wood frames and 12 mm gap.

Table 1. Common Tabula residential building archetypes in the study area categorised by occupancy (single family home (SFH) and apartment blocks (AB) for different construction periods. The associated information describes the walls, roof and glazing features as originally built. There are 9644 buildings in the study area and 436 (<5%) are not categorised above.

AB on top and SFH on the bottom

Georgian SFH Pre-1900

Council Flat Brick AB 1950

Cavity Wall AB 2011

Solid Brick House SFH 1900

Cavity Block Wall SFH 1970

Cavity Wall SFH 1990

Figure 3. Examples of apartment blocks (AB) and single-family houses (SFH) built in different periods in Dublin (see Table 1 for details).

Year of Construction	Buildings GIS	Dwellings BER	Year of construction	Households Census	Population Census
<1950	7080	3559	<1945	8058	17290

1950-1982	741	871	1945-1980	2657	6447
1982-2004	1310	2633	1980-2000	3456	8172
>2004	121	501	>2000	1999	4759
Total	9252	7564	Total	16169	36668

Table 2. A comparison of the age of housing in the study area based on Tabula classification of buildings (GIS), on dwellings (BER) and on households (Census). The age categories used by each source differ somewhat. The final column is population count from the 2016 household census.

3.2 Building UMI templates

The second workflow stream is the generation of data templates suited to running UMI. Table 1 shows some of the basic information available for each archetype; Figure 3 shows examples of the single-family houses and of apartment blocks in the study area. Tabula data includes the physical attributes of the building template such as floor area, glazing fraction and envelope surface area. It also includes details on the thermal properties of the envelope and the heating and ventilation systems, infiltration rates, etc. of each archetype based on original construction. Tabula also provides typical EUI data for each archetype based on standard and deep retrofits. The calculation of the EUI treats the building as a single conditioned zone with a fixed height that covers an area equivalent to the floor area of the actual building.

Here, Climate Studio[1] was used to prepare Tabula archetype data for integration with UMI. Climate Studio (CS) is a plugin for Rhinoceros 3D (Rhino) that examines building environmental performance including energy efficiency, daylight access, visual and thermal comfort, and other measures of occupant health. It performs multi-zone thermal simulations using EnergyPlus and uses the industry standard simulation files (.idfs) that are also used by UMI. Rhino is used in this work to capture the geometric (dimensions) data for each archetype, which were then linked to the non-geometric data using the CS plugin. The value of adding an additional step to this workflow stream (that is, using Climate Studio) is that it allows us to validate the templates we create by comparing CS simulations of the annual EUI for each archetype against those available as part of the Tabula database. A successful evaluation of the CS simulations will provide confidence in the UMI simulations that follow.

The ClimateStudio (and UMI) template requires data on the thermal properties of the layers of materials used to construct the building envelope but Tabula provides a single resistance (U) value for each façade (Figure 4). These values must be decomposed into its parts using the construction details provided in Tabula [7,39] alongside information on older buildings that is not provided [39]. Material thicknesses were modified to ensure a match with the U-values provided. Tabula also provides a window to wall ratio for each façade and type of glazing that is readily converted into the CS template. Figure 4 shows the information on the floor area and material composition used by ClimateStudio and the partitioning of the indoor space into core and conditioned spaces.

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[1] https://www.solemma.com/climatestudio

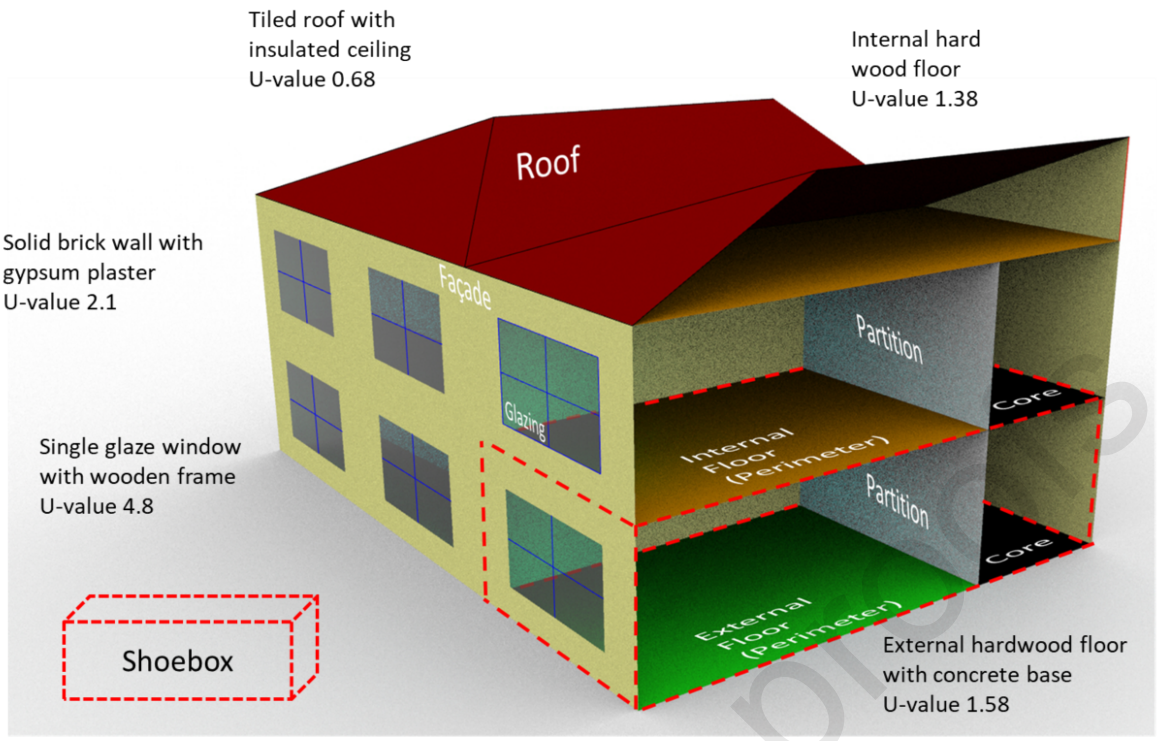

Figure 4. A cross section of a generic residential building in Tabula that shows the dimensions, materials and thermal (U-value) data provided for a Brick SFH constructed between 1900 and 1930 (Figure 3). The ClimateStudio model partitions indoor space into a core and conditioned area requires information on the properties of the floors, roofs, walls and glazing for its input templates. Also shown is the outline of a 'shoebox' that UMI selects as a sample space within a neighbourhood of buildings.

The CS template also requires information on: the rate of air change per hour within the conditioned zone; the internal thermal gains due to solar transmission through glazed surfaces and equipment; and the nature of HVAC systems including the Coefficient of Performance (CoP). Tabula provides infiltration rates and assigns a constant value (3 Wm^{-2}) for internal gains due to equipment, lighting, and occupants. In CS, geographic location and associated weather files are used to assess internal solar gain. Here, the typical meteorological year data for Dublin Airport (less than 5km from the study area) was used; these data are available as an EPW file from EnergyPlus**.** Tabula only considers residential heat demand and identifies the means of heating and its CoP; it does not consider the cooling demand (which is small in the EU). In Ireland, the heating is attributed to central boiler heating and open fireplaces, which supply a percent of the space heating demand. In CS, which permits just one heating system, the CoP is estimated as the weighted averages of the Tabula listed heating systems.

To evaluate the Tabula-derived template in CS, we compared annual simulated EUI simulated for each archetype with the simplified, steady-state results reported by Tabula (Figure 5). Overall, the difference between ClimateStudio and Tabula EUI values was -24.5 $kWHm^{-2}$; the largest difference was in the Stone House SFH (1899), which was underestimated by 80.6 kWh and the smallest was Cavity Wall SFH (1990) which was overestimated by 4.7 kWh. Houses built before 1980 (prior to building energy regulations) had larger differences (35.3 kWh) on average compared with modern houses (11 kWh). This systematic difference may be explained by the simple energy calculation performed by Tabula (that is, the ISO EN 13790 standard) to estimate heat loss through the envelope, which has been shown to perform poorest on older buildings with little insulation [26]. Overall, the results indicate that the use of Tabula building data to run a building energy model is sufficiently accurate to implement on a wider scale.

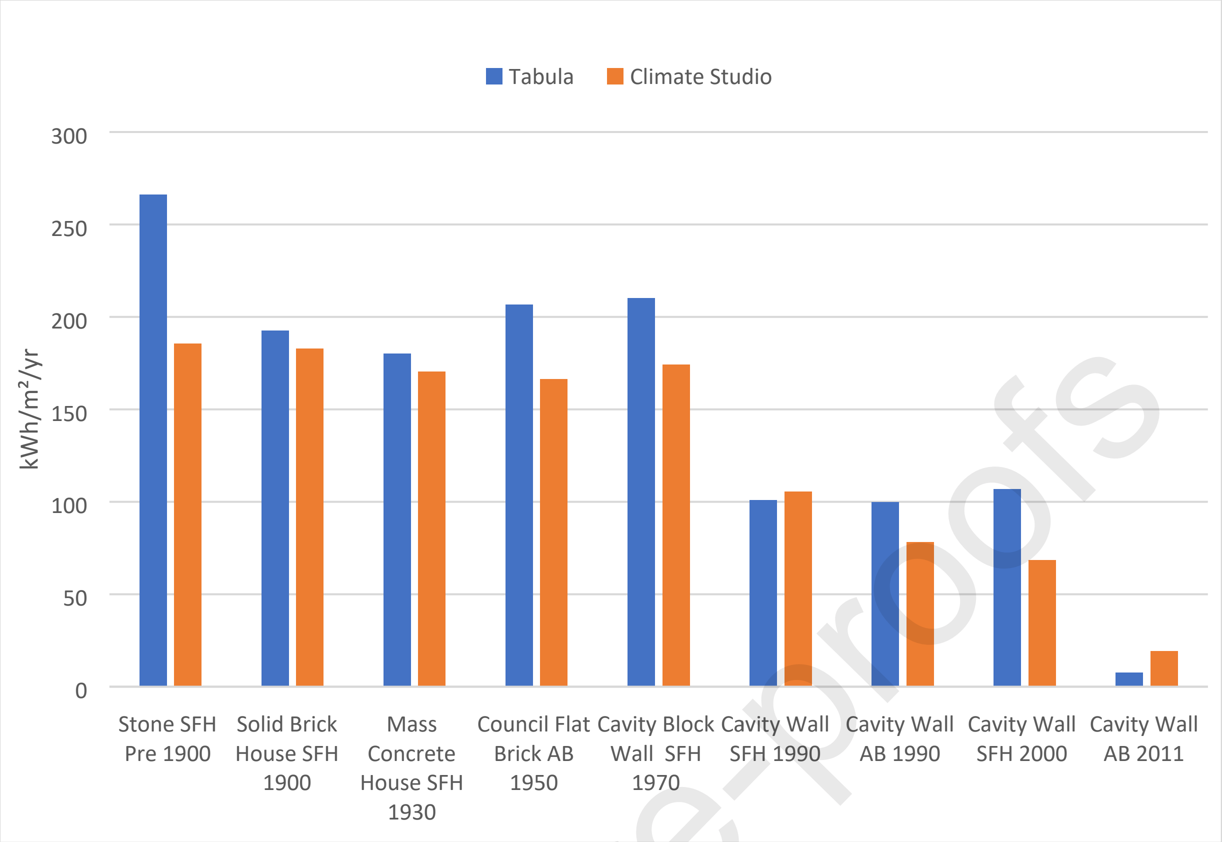

Figure 5. A comparison of annual EUI for Tabula archetypes based on ISO calculation and simulations using ClimateStudio based on templates created from Tabula data.

3.3 Urban Modelling Interface (UMI)

The MIT Sustainable Design Lab developed UMI as an urban-scale simulation tool used to perform dynamic modelling of neighbourhood. To speed up the energy simulations of multiple buildings, UMI uses the 'Shoeboxer' algorithm, which uses clustering techniques to bin buildings by archetype, façade orientation, and façade solar radiation receipt. For each cluster, a conditioned core and perimeter zone energy model (shoebox) is created (Figure 4). These two zone shoeboxes are simulated using the local EnergyPlus weather file and the results are extrapolated by floor area to all the buildings in the cluster [32]. UMI has been validated against industry-standard multi-zone EnergyPlus models and shown to be accurate to within 10% at the archetype level [32]. Un-calibrated urban building energy models, such as the UMI model created here, have been shown to be accurate to within 19% of archetype-aggregated measured energy use intensity [6]. Thus, UMI provides a fast and accurate way to simulate different urban energy interventions.

UMI requires both the geographic (location) and non-geographic (materials, dimensions, etc.) attributes of buildings. In previous UBEM studies, collecting and cleaning these data sets has been a time-consuming yet critical task [13]. The Tabula-derived CS templates developed here provide all non-geographic data needs for UMI. By leveraging these data, a substantial amount of time and effort can be saved while still creating accurate templates. UMI uses its own custom template database but EnergyPlus simulation files (.idfs) can be imported using Archetypal [40]. Finally, archetypes are stored in a custom library that is linked with the GIS database and covers the geometric building information and when combined with the UMI template database, a full imported into UMI model can be created.

The UMI model can also account for aspects of the urban climate effect on the weather files using the Urban Weather Generator (UWG), which is available as a plugin. UWG modifies the EPW weather files to include the heat island effect, for example which would result in warmer outdoor air temperatures and reduce the winter heating demand. The UWG is not used here as Dublin's climate, which is both wet and windy, has a weak climatological heat island effect.

4. UMI Results

The model results are presented in two parts: an evaluation of simulations using available BER data and simulations to test district-level energy policies to meet Green Deal targets.

4.1 Evaluation

A BER certificate is required of all dwellings sold or rented since 2007 and is assigned following a Dwelling Energy Assessment Procedure (DEAP) survey that, as of 2020, has been carried out on just over half of the national building stock[2]. The survey is based on spreadsheet calculations that estimates the monthly space heating energy balance from October to May and the hot water energy demand based on the size of dwelling, its material properties and HVAC systems. The calculations employ the ISO standard 13790 and, while the DEAP data are geocoded precisely, information is only available publicly as statistical summaries (number, mean, median, maximum and minimum values) for census areas. As a result, it is not possible to directly link simulations of individual buildings in UMI to equivalent DEAP scores. Also, in Ireland the DEAP survey is done for dwellings (households) of which there may be many within a building. The following evaluation is based on a comparison of aggregate information for each census area (182) within the study area (Figure 2); 30 census areas were excluded as they each had less than 20 BER assessments.

DEAP assessments by dwelling								
EUI	BER	Dwellings		0-20%	20-40%	40-60%	60-80%	80-100%
75-150	B	115	2.0%	0	0	1	0	1
150-225	C	1026	17.8%	3	6	3	4	3
225-300	D	1443	25.1%	1	7	6	6	13
300-380	E	1963	34.1%	0	1	3	7	37
380-450	F	982	17.1%	0	0	0	3	20
>450	G	230	4.0%	0	0	0	0	8
Sum		5759	100%	4	14	13	20	82
UMI assessments by building								
EUI	BER	Buildings		0-20%	20-40%	40-60%	60-80%	80-100%
75-150	B	340	3.7%	1	0	0	2	6
150-225	C	607	6.6%	2	3	3	2	0
225-300	D	830	9.0%	0	5	2	5	1
300-380	E	494	5.3%	0	3	1	3	3
380-450	F	3592	38.9%	0	1	5	5	35

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[2] https://www.cso.ie/en/releasesandpublications/er/dber/domesticbuildingenergyratingsquarter12020/

>450	G	3382	36.6%	1	2	2	3	37
Sum		9245	100%	4	14	13	20	82

Table 3. EUI results for 152 census areas that comprise the study area. The rows represent the BER ranges (EUI and grade). The columns show the number and percent of dwellings (DEAP) and buildings (UMI) and the proportion of dwellings/buildings constructed before 1980.

Table 3 shows that there is broad correspondence between the aggregate values for the census areas but the simulated UMI values are generally lower. Overall, the average EUI from UMI simulations for the study area is 407 kWh/m²/yr while the average EUI of the DEAP assessments is 352. Part of this difference can be explained by the bias inherent in the DEAP process, which over-represents newer (more energy-efficient) buildings, many of which are apartment blocks with multiple dwellings. In addition, the UMI templates assume limited improvement on original build whereas simply upgrading heating systems in older dwellings to be more efficient will improve the DEAP assessment. Figure 6 shows the simulated monthly energy use for the study area by selected building archetype. It shows the outsized role that older buildings play in driving energy demand. Figure 2 shows the concentration of these buildings in the study area; in fact, over 50% of energy demand originates from just 0.6 km^2 of the built landscape. Table 4 emphasises this pattern Considerable progress toward a more energy efficient built environment can be achieved by focussing on these poorly performing buildings that are clustered in space.

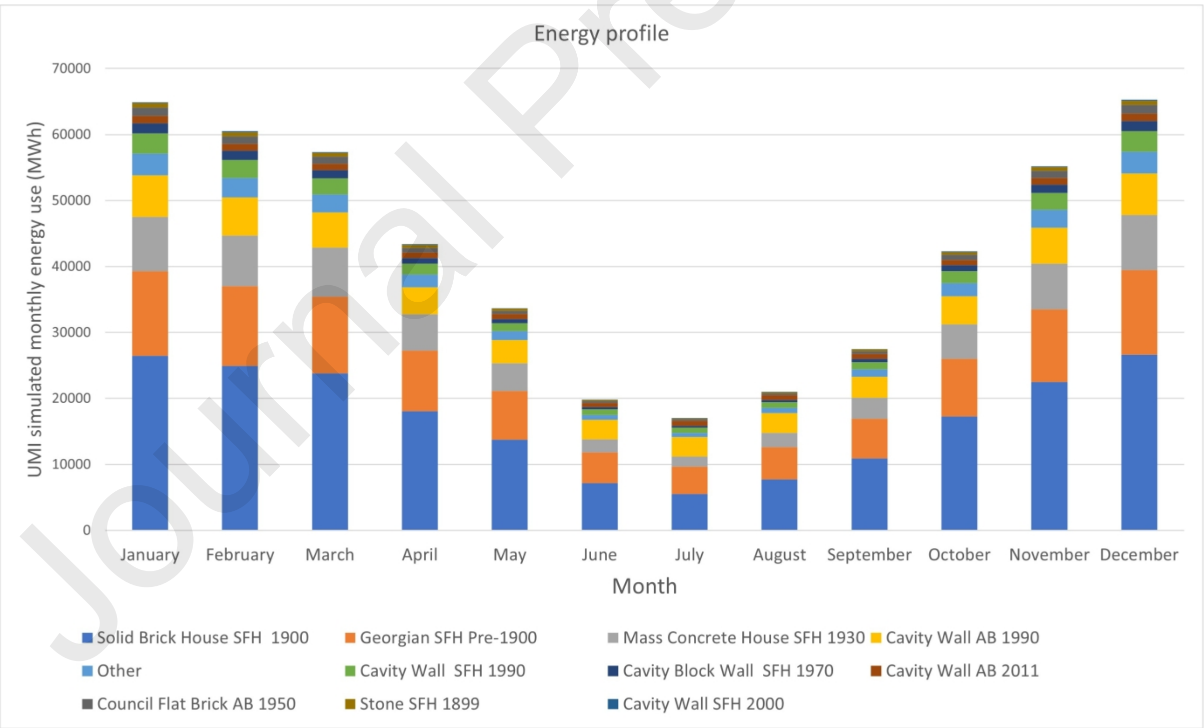

Figure 6. Simulated monthly energy use (MWh) for the study area decomposed into Tabula archetypes (see Table 1).

Label	Number	Floor area (m^2)	Annual energy use (MWh)

Brick SFH 1900	4672	48.4%	505777	26.1%	204834	40.3%
Georgian SFH Pre-1900	1101	11.4%	512035	26.4%	105360	20.7%
Concrete SFH 1930	1603	16.6%	160922	8.3%	62336	12.3%
Cavity block AB 1990	253	2.6%	407182	21.0%	53237	10.5%
Other	436	4.5%	70300	3.6%	23519	4.6%
Cavity block SFH 1990	1028	10.7%	109448	5.6%	22174	4.4%
Cavity block SFH 1970	347	3.6%	36590	1.9%	10757	2.1%
Cavity block AB 2011	17	0.2%	80041	4.1%	10438	2.1%
Brick AB 1950	24	0.2%	37330	1.9%	9113	1.8%
Stone SFH 1899	96	1.0%	11791	0.6%	4967	1.0%
Cavity block SFH 2000	67	0.7%	8670	0.4%	1234	0.2%
Total	9644		1940086		507969	

Table 4. The distribution of simulated annual energy use by building type and floor area (see Table 1).

4.2 Energy upgrade scenarios

The value of using a UBEM to test the efficacy of different energy management strategies can be demonstrated for a small neighbourhood (Stoneybatter) within the study area (Figures 2 & 7). This area is comprised of 1247 terraced brick houses (Brick SFH, Table 1 & Figure 4) with a total conditioned floor area of 82300 m^2. These buildings have an energy rating of 'G' based on a simulated EUI of 464 $kWhm^{-2}$ using the original building properties; this corresponds to an estimated annual cost of €3889 per dwelling (equivalent to 7.26 tCO_2) to meet the indoor comfort levels specified by Tabula. A standard retrofit (window replacement, wall and roof insulation and heating system upgrade) for these buildings will change a BER rating from F to B and cost about €30,000[3]. These changes would reduce the estimated annual energy costs and CO_2 emissions by 85% and a 'payback' of about 10 years.

In the following analysis we use these values to test the most cost-effective policy options for this neighbourhood, bearing in mind that the Green Deal 2030 target is a reduction of building emissions by 60%; this is equivalent to a change from F to C energy rating or 250 $kWhm^{-2}$. While there is an obvious energy (and expenditure) benefit from retrofits, the level of investment depends on several factors, including whether the dwelling is owner-occupied or rented; Stoneybatter is about 50% owner occupied. Surveys of homeowners indicate that the mean 'willingness to pay' (WTP) is 0.127 per kWh in Ireland[4]. For the houses under consideration reducing heat loss by 250 $kWhm^{-2}$ equates to about €2000, which is worth bearing in mind when considering the balance between subsidies and owner investment.

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[3] https://www.seai.ie/grants/home-energy-grants/deep-retrofit-grant/key-findings/

[4] https://www.seai.ie/publications/Policy-Insights-Rport.pdf

Table 5 shows a series of retrofits options for these buildings and their simulated impact on EUI, energy cost and CO2 emission. The focus here is on changes to the physical envelope of buildings, rather than the energy systems:

- Additional roof insulation (250mm of fibreglass) changes the U-value on this part of the envelope from 0.68 to 0.13 W m^{-2} K^{-1}.
- The effect of draft excluders to manage infiltration losses is captured in UMI by changing the air changes per hour (0.4 based on Tabula data) to 0.2.
- Replacing single pane to double glazing windows alters the U value from 4.8 to 1.2 W m^{-2} K^{-1}.
- Wall insulation using dryline insulation to the interior surface change the U-value from 2.1 to 0.26 W m^{-2} K^{-1}.

Each of these changes has an associated cost and impacts on heat loss (Table 5). The largest benefit for a modest investment is to limit heat loss by infiltration, which would have a payback of less than 1 year. Roof insulation is the next most cost-effective retrofit but taken together, these two changes will reduce the EUI by just 33 $kWhm^{-2}$ (from a G to F rating). The most significant retrofit is to insulate the solid brick walls of the house, through which most heat is lost; this change alone reduces the EUI by 200 $kWhm^{-2}$ but is costly. Replacing the windows would cost nearly the same as insulating the walls but has a smaller impact. So, managing infiltration and insulating the ceiling and walls will change the rating to C, reduces the estimated energy costs to €1760 and the CO_2 emissions to 45% of the starting value. UMI estimates that solar panels (20 m^2) attached to a south-facing roof would generate an additional 25 $kWhm^{-2}$ over the year, with an installation cost of about €15,000, which is an expensive investment and has a relatively small impact at this scale. The cost of implementing all of these measures is close to €40,000 but the most cost-effective way of meeting the EU's 2030 target (55% reduction in CO_2 emissions) for a dwelling is to focus on infiltration and wall and roof insulation. The associated cost of these changes is well above the WTP threshold and are unlikely to take place without incentives. Currently, homeowners can apply for grants to recover a proportion of costs once the work is completed.

Retrofit	**EUI $kWhm^{-2}$**		**Energy (€)**	**t CO2**	**Green Deal**	**Retrofit (€)**	**gCO2 per €**
No Retrofit	464	G	3889	7.26	100	-	-
Roof Insulation Only	439	F	3680	6.87	95	800	488
Infiltration Only	433	F	3629	6.77	93	150	3267
Window Only	407	F	3411	6.37	88	12,250	73
Walls Insulation only	267	D	2238	4.18	58	11,500	268
Walls + Infiltration	238	C	1995	3.72	51	11,650	304
Walls, Roof, & Infiltration	210	C	1760	3.28	45	12,450	320
Walls, Roof, Windows, & Infiltration	146	B	1224	2.28	31	23,770	210
Solar installation 20 m^2	121	B	1014	1.89	26	15,000	26

Table 5. Policy options for an energy inefficient neighbourhood. Energy costs are based on electricity generation in Ireland (0.25 €/kWh). Retrofit costs based on [42] for materials and labour for a semi-detached home with a floor area of 90m^2; values have been scaled by two-thirds to reflect dwelling floor area. The CO_2 emissions are based on the carbon intensity of electricity production in Ireland (334 gCO2/kWh).

A neighbourhood approach to retrofits would take advantage of the arrangement of buildings into terraces (composed of 10 to 15 buildings) so that the shared walls between houses would not require insulation. This effectively treats a terrace as a single building with an extensive exterior wall, which would be insulated on the inside or outside. The latter offers advantages as the outer wall façade could be retrofitted using a consistent application. The cost per building is equivalent to that for the internal value listed in Table 4 but the terraced neighbourhood offers economies of scale. Similarly, the extensive roof area afforded by terraced houses with a southerly aspect provides an opportunity for extensive application of solar panels. There is approximately 27,738 m² of roof space in Stoneybatter and there are few shade trees which could generate nearly 700 MWh of energy annually. This source varies considerably throughout the year but could be used to offset water heating in the summer months or even to charge electric vehicles. The neighbourhood could reach the Green Deal targets through a mix of single house interventions (infiltration and roof insulation) and terrace interventions on the outside of houses (exterior wall insulation and solar panels).

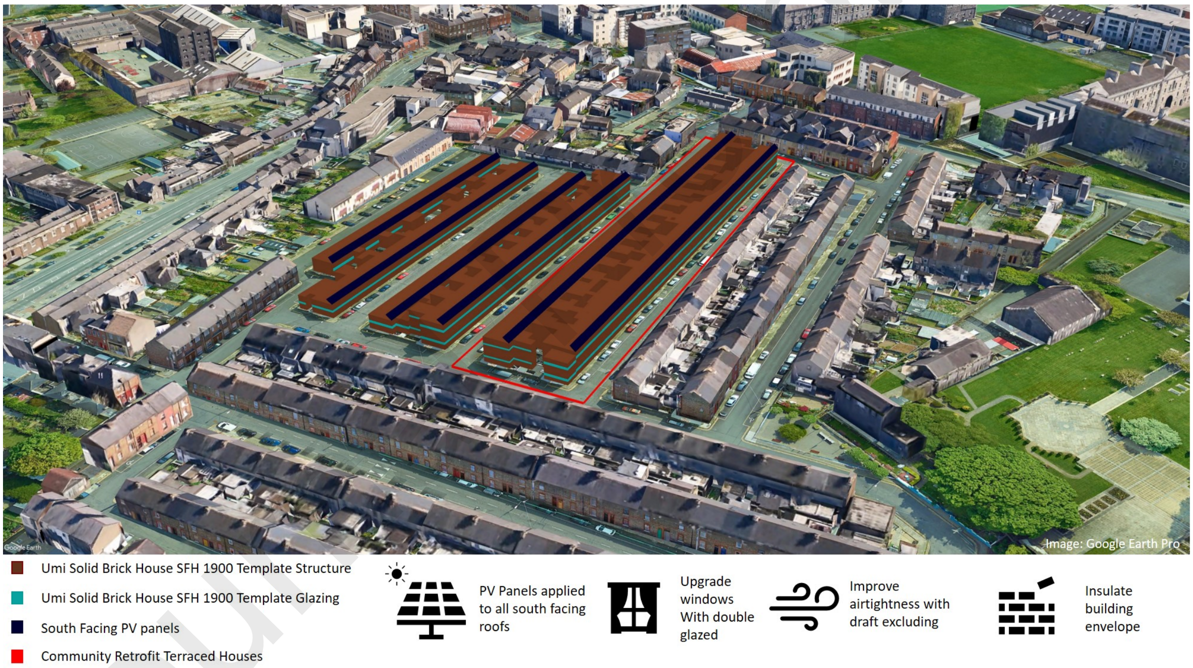

Figure 7. Three dimensional UMI render of Stoneybatter with dwelling and community retrofits.

4. Discussion & Conclusions

Modelling of the building stock, rather than individual buildings, is the next frontier for managing energy demand and use from this sector. Urban building energy models (UBEMs) can simulate dynamic energy use for large number of buildings simultaneously, accounting for the effects of buildings on each other and on the nearby atmosphere. The UMI tool allows for the application of a sophisticated dynamic thermal model to thousands of buildings simultaneously while accounting for variable energy efficiencies and occupation patterns. Its geographic framework enables consideration of renovation changes at scale and the potential for integrating on-site renewable energy generation and heating systems with energy grids to harvest and share carbon-neutral energy at neighbourhood scales [13][35]. As the computational obstacles to urban simulations are overcome, the challenge is to generate the appropriate input data using a consistent methodology.

This research employs an archetype approach (Tabula) that is used to categorise a geographic database of buildings into types. The data associated with individual archetypes are used to generate templates for building energy simulations. These templates are merged with the geographic database to provide the input data for UMI. This novel approach allows us to generate UBEM input data relatively quickly and is independent of systematic errors associated with some existing building databases; for example, Monteiro et al., [37] found that building age data for the Portuguese census may be up to 69.1% inaccurate. Developing the UMI database could be made even more efficient using training images to categorise buildings into archetype categories based on image recognition. Ali *et al.* [24] suggested that national archetypes do not capture significant variations in the building stock at small scales that are needed by UBEMs. However, the results here indicate that the Tabula archetypes are sufficient to the task of providing accurate assessments of EUI at a neighbourhood scale and evaluating district-level energy policies. The success here may be partly accounted for by the selected case-study area which is relatively consistent in its residential make-up. However, many urban neighbourhoods with significant number of buildings were built at the same time using the same construction techniques and exhibit considerable homogeneity.

The methodology described here is best suited for testing retrofit scenarios at a neighbourhood scale and is ideally suited to designing pathways to meet goals of the European Green Deal. As Tabula archetypes have been developed for 21 countries in Europe, the approach used here shows that it is possible to build a database that can support urban-scale energy policies.

Acknowledgments

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- UBEM proven tool in testing building energy strategy for EU's Green Deal objectives
- Novel georeferenced building archetype database successfully integrated in an UBEM
- Method is reproducible elsewhere in Europe where building archetypes are available